WATER RESOURCE MODELS

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Contents

Summary

Water resource systems are most comprehensively represented in watershed models and, therefore, watershed models, many different types of which are in current use, are the focus of this chapter. A clear understanding of these models is critical for their appropriate use. In this chapter, eleven commonly used watershed models, namely AGNPS, AnnAGNPS, ANSWERS, ANSWERS-Continuous, CASC2D, DWSM, HSPF, KINEROS, MIKE SHE, PRMS, and SWAT, are described. AnnAGNPS, ANSWERS-Continuous, HSPF, and SWAT are continuous simulation models useful for analyzing long-term effects of hydrological changes and watershed management practices, especially agricultural practices. AGNPS, ANSWERS, DWSM, and KINEROS are single rainfall event models useful for analyzing severe actual or design single-event storms and evaluating watershed management practices, especially structural practices. CASC2D, MIKE SHE, and PRMS have both long-term and single event simulation capabilities. The mathematical bases, the most important and critical elements of these mathematical models, are identified and compiled. A comprehensive summary of the compilation is presented in tabular form. The governing flow equations and their solution methods used in each of the eleven models are discussed. The compilation of the mathematical bases of these models is useful to determine the problems, situations, or conditions for which the models are most suitable, the accuracies and uncertainties expected, their full potential uses and limitations, and directions for their enhancements or new developments. AGNPS, AnnAGNPS, DWSM, HSPF, MIKE SHE, and SWAT have all the three major components of a watershed model: hydrology, sediment, and chemical, applicable to watershed-scale catchments. SWAT is a promising model for continuous simulations in predominantly agricultural watersheds and HSPF for mixed agricultural and urban watersheds. Among the single event models, DWSM provides a balance between the simple but approximate and the computationally intensive models, and therefore, is a promising storm event model for agricultural watersheds.

1. Introduction

Flooding, upland soil and stream bed and bank erosion, sedimentation, and contamination of water from agricultural chemicals are critical water resources, environmental, social, and economical problems throughout the world. Understanding and evaluating the natural processes in a watershed leading to impairments and problems are continued challenges for scientists and engineers. Watershed models simulating hydrology, upland soil and stream erosion; transport and deposition of sediment; and mixing and transport of chemicals with water and sediment processes are comprehensive analytic tools to understand some of the water resource and environmental problems (flooding, upland soil and streambed-bank erosion, sedimentation, contamination of water, etc.) and to find solutions through land-use changes and best management practices (BMPs). These models are also called nonpoint-source pollution models because they simulate surface water pollutants, including sediment, nutrients, pesticides, and other chemicals, originating from nonpoint or diffuse sources. These models can assist in the development of Total Maximum Daily Load (TMDL) estimations, required by the Clean Water Act of the US, and in the evaluation and selection of alternative land-use and BMP scenarios, the implementation of which can help to meet the water quality standards and reduce damaging effects of storm water runoff on water bodies and the landscape. The TMDL is the maximum amount of a pollutant from point (e.g., wastewater treatment plant) and nonpoint sources that a water body can receive and still meet specific water quality standards.

All the watershed models do not simulate all the watershed processes described above. For example, some models, such as the US Army Corps of Engineers' Hydrologic Engineering Center-1 (HEC-1) Flood Hydrograph Package, simulate only the hydrologic processes. In this chapter, hydrologic models without sediment and chemical simulations are not discussed. Some watershed models simulate hydrologic and soil erosion-sediment transport processes only, not the chemicals. Some of these models are described here. Developing reliable watershed simulation models and validating them on real world watersheds with measured and monitored data are challenging. The unique hydrology in many of the agricultural watersheds in the Midwestern US, associated with flat terrain and presence of extensive tile drainage, causes more challenges in modeling and searching for the most suitable model.

The eleven watershed-scale hydrologic and nonpoint source pollution models described here are Agricultural NonPoint Source pollution (AGNPS) model, Annualized Agricultural NonPoint Source (AnnAGNPS) model, Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS), ANSWERS-Continuous, CASCade of planes in 2-Dimensions (CASC2D), Dynamic Watershed Simulation Model (DWSM), Hydrological Simulation Program – Fortran (HSPF), KINematic runoff and EROSion (KINEROS) model, the European Hydrological System (MIKE SHE) model, Precipitation-Runoff Modeling System (PRMS), and Soil and Water Assessment Tool (SWAT). These eleven models are chosen because they are physically-based, suitable for watershed-scale modeling, and their applications are commonly found in the literature.

There are many field-scale models which simulate hydrology, sediment, and chemical on small catchments. US Department of Agriculture’s (USDA) Chemicals, Runoff, and Erosion from Agricultural Management System (CREAMS) and Water Erosion Prediction Project (WEPP) are examples of widely used field-scale models. Simulated Water Erosion (SIMWE) model of Mitas and Mitasova is a field-scale soil erosion model. Field-scale models are not described here.

Individual components of the water resource systems are represented by many other models. US Army Corps of Engineers’ HEC-2 Water Surface Profiles and Unsteady flow through a full NETwork of open channels (UNET) model are examples of river flood routing models. US Army Corps of Engineers’ HEC-6 Scour and Deposition in Rivers and Reservoirs is an example of river sediment transport model. US Army Corps of Engineers’ HEC-5 and HEC-5Q are examples of reservoir flood routing and reservoir water quality analysis models. However, watershed-scale models represent the water resource systems more comprehensively than these other models.

The main focus of this chapter is to give a clear picture of the eleven commonly used physically-based and watershed-scale hydrologic and nonpoint-source pollution models and discuss their mathematical strengths in simulating and addressing different watershed processes and problems, respectively. AnnAGNPS, ANSWERS-Continuous, HSPF, and SWAT are continuous simulation models, and are useful for analyzing long-term effects of hydrological changes and watershed management practices, especially agricultural practices. AGNPS, ANSWERS, DWSM, and KINEROS are single rainfall event models useful for analyzing severe actual or design single-event storms and evaluating watershed management practices, especially structural practices. CASC2D, MIKE SHE, and PRMS have both long-term and single event simulation capabilities.

Some of the models are based on simple empirical relations having robust algorithms and the others physically based governing equations having computationally intensive numerical solutions. The simple models are sometime incapable of giving desirable detailed results and the detailed models are inefficient and could be prohibitive for large watersheds. Therefore, finding an appropriate model for an application and for a certain watershed is quite a challenging task. For certain applications, it is desirable to have a balance or compromise between the simple approximate and detailed computationally intensive models.

The mathematical bases of different components of the eleven models, the most important and critical elements of these mathematical models, are identified and compiled here. Summary of the compilation is presented in tabular forms. The flow-governing equations and their solution methods used in each of the models are discussed. Flow routing is a basic and critical component of hydrologic, as well as nonpoint source pollution models. Performance and wide applicability of a model depends greatly on this key component.

The compilation of the mathematical bases presented here could be useful to determine the problems, situations, or conditions for which the models are most suitable, the accuracies and uncertainties expected, their full potential uses and limitations, and directions for their enhancements or new developments. Based on these compilations, promising models are identified. Uses and performances of the promising models, based on reviews of their applications, are discussed in another chapter (*see: Watershed Modeling for Water Resource Management*).

2. Watershed-Scale Models

Sources and brief backgrounds of the eleven models are presented here. AGNPS was developed at the USDA Agricultural Research Service (ARS) North Central Soil Conservation Research Laboratory, Morris, Minnesota. It is an event-based model simulating runoff, sediment, and transport of nitrogen (N), phosphorous (P), and chemical oxygen demand (COD) resulting from single rainfall events. The model is currently undergoing extensive revisions and upgrading at the USDA-ARS National Sedimentation Laboratory (NSL), Oxford, Mississippi and one of its upgrades is AnnAGNPS for continuous simulations of hydrology, soil erosion, and transport of sediment, nutrients and pesticides. It is designed to analyze the impact of nonpoint source pollutants from predominantly agricultural watersheds on the environment.

ANSWERS, developed at Purdue University, West Lafayette, Indiana, uses a distributed-parameter concept to model the spatially varying processes of runoff, infiltration, subsurface drainage, and erosion for single event storms. The model has two major components – hydrology and erosion responses. Similar to AnnAGNPS, ANSWERS-Continuous emerged from ANSWERS as a continuous model at the Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

CASC2D is a physically based model, initially developed at the Colorado State University, Fort Collins, Colorado and further modified at University of Connecticut, Storrs, Connecticut. It simulates water and sediment in two-dimensional overland grids and one-dimensional channels and has both the single event and long term continuous simulation capabilities. Similarly, MIKE SHE, based on SHE, the European Hydrological System, is a comprehensive, distributed, and physically based model simulating water, sediment, and water quality parameters in two dimensional overland grids, one dimensional channels, and one dimensional unsaturated and three dimensional saturated flow layers. It also has both the continuous long-term and single-event simulation capabilities. The model was developed by a European consortium of three organizations; the Institute of Hydrology (UK), the French consulting firm SOGREAH, and the Danish Hydraulic Institute (Denmark).

DWSM was put together at the Illinois State Water Survey (ISWS), Champaign, Illinois, based on research conducted over many years at several institutions (University of Mississippi, USDA-ARS NSL, Rutgers University, and ISWS). DWSM simulates distributed surface and subsurface storm water runoff, propagation of flood waves, upland soil and streambed erosion, sediment transport, and agrochemical transport in agricultural and rural watersheds during single rainfall events. Similarly, KINEROS is a distributed rainfall-runoff and soil erosion-sediment transport model for single rainfall events, developed during the 1960's-1980's at the USDA-ARS, Fort Collins, Colorado.

HSPF, first publicly released in 1980, was put together by a group of consultants for the US Environmental Protection Agency (USEPA). It is a continuous watershed simulation model that produces a time history of water quantity and quality at any point in a watershed. HSPF is an extension of several previously developed models; the Stanford Watershed Model (SWM), Hydrologic Simulation Program (HSP) including HSP Quality, Agricultural Runoff Management (ARM) model, and Nonpoint Source Runoff (NPS) model. HSPF has been incorporated as a Nonpoint Source Model (NPSM) into the USEPA's BASINS, Better Assessment Science Integrating Point and Nonpoint Sources, developed by Tetra Tech, Inc. for the USEPA. The main purpose of BASINS is to use in analyses for TMDL developments nationwide.

PRMS, developed at the US Geological Survey (USGS), Lakewood, Colorado, is a modular-design, distributed-parameter, physical-process watershed model that was developed to evaluate the effects of various combinations of precipitation, climate, and land use on watershed response. Watershed response to normal and extreme rainfall and snowmelt can be simulated to evaluate changes in water-balance relations, flow regimes, flood peaks and volumes, soil-water relations, sediment yields, and groundwater recharge. PRMS has both long-term and single storm modes. The long-term version of PRMS is only a hydrological model. PRMS storm mode has a sediment component as well. Only the PRMS storm mode is discussed here.

SWAT was developed at the USDA–ARS Grassland, Soil and Water Research Laboratory, Temple, Texas. It was developed to assist water resources managers in predicting and assessing the impact of management on water, sediment and agricultural chemical yields in large ungaged watersheds or river basins. The model is intended for long-term yield predictions and is not capable of detailed single-event flood routing. It is an operational or conceptual model that operates on a daily time step. The model has eight major components – hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Similar to HSPF, SWAT is also incorporated into the USEPA's BASINS for nonpoint source simulations on agricultural lands.

3. Flow-Governing Equations

Flow governing equations are basic to all the water resource models. Performance and applicability of a model depend largely on these basic equations. A brief background of the flow governing equations and their uses in each of the eleven models are discussed here.

3.1. Dynamic Wave Equations

The basic flow governing equations are the dynamic wave equations, often referred to as the St. Venant equations or shallow water wave equations. These consist of the equations of continuity and momentum for gradually varied unsteady flow, respectively, expressed as:

$$\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial h}{\partial x}=g\left(S_0-S_f\right) \qquad (2)$$

where
h = flow depth (m)
Q = flow per unit width (m^3 s^{-1} m^{-1})
u = water velocity (m s^{-1})
g = acceleration due to gravity (m s^{-2})
S_0 = bed slope (m m^{-1})
S_f = energy gradient (m m^{-1})
t = time (s)
x = longitudinal distance (m).

There is no analytical solution of Eqs. (1) and (2). Approximate numerical solutions of these two equations have been used in river flood routing models, such as the UNET model and the National Weather Service OPERational Dynamic Wave (DWOPER) model.

The dynamic wave equations have not commonly been used in watershed models because of its computationally intensive numerical solutions. Only the CASC2D model uses these equations on a limited basis for flow routings through rivers and streams. Some of the models use approximations of these equations, ignoring certain terms in the momentum equation (Eq. (2)), as discussed below.

3.2. Diffusive Wave Equations

The diffusive wave equation consists of the continuity and simplified momentum equations, respectively expressed as:

$$\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad (3)$$

$$\frac{\partial h}{\partial x} = S_0 - S_\mathrm{f} \qquad (4)$$

where
q = lateral inflow per unit width and per unit length ($m^3\ s^{-1}\ m^{-1}\ m^{-1}$).

Equations (1) and (3) are both continuity equations however the later only includes lateral inflows. Equation (3) is suitable for routing flows in watersheds where lateral inflows are dominant, whereas, Eq. (1) is suitable for routing flows in rivers and streams where lateral inflows are negligible in comparison to tributary contributions at confluences. The simplified momentum equation (Eq. (4)) expresses the pressure gradient as difference between the bed slope and energy gradient, and is derived from Eq. (2) after ignoring the first two terms, representing respectively the local and convective accelerations.

Similar to the dynamic wave equations, there is no analytical solution of the diffusive wave equations (Eqs. (3) and (4)). Watershed models CASC2D and MIKE SHE use approximate numerical solutions of these equations for routing surface runoff over overland planes and through channel segments. While solving these equations Manning's formula is used to compute flow, which is expressed as:

$$Q = \frac{1}{n} A R^{2/3} S_\mathrm{f}^{\ 1/2} \qquad (5)$$

where
n = Manning's roughness coefficient
A = flow cross-sectional area per unit width ($m^2\ m^{-1}$)
R = hydraulic radius (m).

3.3. Kinematic Wave Equations

The kinematic wave equations are the simplest form of the dynamic wave equations. The governing equations consist of the continuity equation with lateral inflow (Eq. (3)) and the simplest form of the momentum equation, ignoring all the acceleration and pressure gradient terms of Eq. (2), expressed as:

$$S_0 = S_\mathrm{f} \qquad (6)$$

The momentum equation (Eq. (6)) expresses simply as energy gradient equal to bed slope. Any suitable law of flow resistance can be used to express this equation as a parametric function of the stream hydraulic parameters. A widely used expression is:

$$Q = \alpha\, h^m \qquad (7)$$

where
α = kinematic wave parameter

m = kinematic wave exponent

α and m are related to channel (or plane) roughness and geometry. Manning's formula (Eq. (5)) may be used to define α and m in terms of Manning's roughness coefficient (n) and channel or plane geometry.

Equations (3) and (7) constitute the kinematic wave equations. The advantage of these equations is that they have an analytical solution. The equations generate only one system of characteristics, which means that they cannot represent waves traveling upstream direction as in the case of backwater flows. Research suggests that for most cases of hydrological significance, the kinematic wave solution would give accurate results. In open channel flow, dynamic waves always occur. The friction and slope terms modify the wave amplitudes, and modifications are made to such a degree that dynamic waves rapidly become negligible and the kinematic wave assumes the dominant role.

The analytical solution of Eqs. (3) and (7) does not apply when two characteristics intersect forming a shock wave, physically representing a larger and faster wave superseding a smaller and slower wave. Approximate numerical solutions of Eqs. (3) and (7) do not recognize the shocks. Therefore, the numerical solutions can be used under any situation. However, the numerical solutions smooth out the waves and the hydrographs. With the analytical solution, the kinematic wave theory represents salient features of a hydrograph, including the sharp rising part under shock forming conditions.

Watershed models DWSM, KINEROS, and PRMS are based on the kinematic wave equations. KINEROS and PRMS use approximate numerical solutions of Eqs. (3) and (7) where as, the DWSM uses the analytical and an approximate shock-fitting (closed form) solution.

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Bibliography

Borah, D.K. and M. Bera. (2003). Watershed-scale hydrologic and nonpoint-source pollution models: Review of Mathematical bases. Transactions of the ASAE, **46**(6), 1553-1566. [This presents the original research findings on reviews of the models described in this chapter with their sources and citations].

Borah, D.K. and M. Bera. (2004). Watershed-scale hydrologic and nonpoint-source pollution models: Review of applications. Transactions of the ASAE, **47**(3), 789-803. [This presents reviews of applications of the SWAT, HSPF, and DWSM models with sources and citations of the model application studies].

Borah, D.K., G. Yagow, A. Saleh, P.L. Barnes, W. Rosenthal, E.C. Krug, and L.M. Hauck. (2006). Sediment and nutrient modeling for TMDL development and implementation. Transactions of the ASABE, **49**(4), 967-986. [This presents an extensive review of water resources models, including loading models, watershed models, and receiving water quality models].

Singh, V.P., ed. (1995). Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, CO. [This book presents 26 water resource models, including five of the models described in this chapter].

Singh, V.P. and D.K. Frevert, ed. (2002). Mathematical Models of Small Watershed Hydrology and Applications. Water Resources Publications, Highlands Ranch, CO. [This book presents 23 water resource models, including three of the models described in this chapter].

Singh, V.P. and D.K. Frevert, ed. (2002). Mathematical Models of Large Watershed Hydrology. Water Resources Publications, Highlands Ranch, CO. [This book addresses the issues and challenges facing modeling of large watersheds and presents several available models].

Singh, V.P. and D.K. Frevert, ed. (2006). Watershed Models. CRC Taylor & Francis, Boca Raton, FL. [This book presents 23 models having capabilities to simulate various physical and chemical processes in watersheds and streams that are necessary for water resource planning and management, including latest updates on three of the models described here].

Biographical Sketch

Dr. Deva K. Borah is a hydro-environmental modeler with 27 years of water resources and hydro-environmental modeling experiences. Dr. Borah earned his Ph.D. degree in Engineering Science from the University of Mississippi and through collaborative research with the USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi and worked for the University of Mississippi, TAMS Consultants, Inc., Rutgers University, OMNI Environmental Corporation, and currently for the Illinois State Water Survey. Dr. Borah is the lead developer of five state-of-the-art computer models, including the storm event watershed model DWSM, discussed in this chapter. He has over 150 publications published in peer-reviewed journals, conference proceedings, and as book chapters and research/project reports.