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A flexible modeling package for topographically based watershed hydrology

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Abstract

An OBJect-oriented TOPographic-based (OBJTOP) hydrological model with a graphical user interface (GUI) was created using object-oriented design (OOD) methods and the objected-oriented programming (OOP) language-C++. OBJTOP presents an array of alternative TOPMODEL hydrological processes of (1) saturation excess or the mixture of infiltration/saturation excess overland flow, (2) exponential or power law decay of hydraulic conductivity with soil depth, (3) topographic index (TI) or soil topographic index (STI) weighting of run-off likelihood, and (4) simulations with or without channel routing, to explain watershed response and increase flexibility and applicability. OBJTOP utilized an object-oriented design (OOD) approach, including the 'inheritance' concept to study individual objects (or processes) at multiple levels, and the 'aggregation' concept to study the interactions of objects (or processes). Further, OOD readily provides for model extension, creating a description of hydrologic processes in a natural, direct, concise, and adaptable manner distinct from procedurally designed and implemented models. The OBJTOP GUI provides an efficient tool for data input, parameter modification, simulation scheme selection and model calibration with three objective functions, including Nash-Sutcliffe. Graphical outputs include time series plots of precipitation depth, partitioned run-off volumes, watertable depth (average or TI/STI based), and map graphics of TI, STI, and depth to watertable. Applications illustrating OBJTOP ability and flexibility include simulation of the TOPMODEL standard Slapton Wood, UK dataset, and simulation of Ward Pound Ridge, NY a small forested catchment with power function decay of hydraulic conductivity and extensive impervious surfaces.

Keywords: Hydrological model; Object-oriented design (OOD); Objected-oriented programming (OOP); C++; Topmodel

1. Introduction

Hydrological models are employed for addressing a wide spectrum of environmental and water resources problems, and remain simplified representations of hydrological processes in a watershed. This simplification mainly comes from two sources (Wang et al., 2000): (1) any hydrological model is a reflection of our limited understanding of the physical processes in a watershed, and (2) the model is incapable of handling all known phenomena (Singh, 1995). As a result of the first source, the quality of the model

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results is no better than the quality of our understanding of the system. There are many hydrological phenomena and processes that up to now we still do not understand well, such as evapotranspiration (Rudra et al., 2000), run-off processes (Endreny and Wood, 2001), and subsurface flow (McDonnell et al., 1996). As a result of the second source, most models take a focused and simplified description of the hydrological processes central to the target watershed and research questions. The errors or uncertainties due to process simplification must be tolerated for the particular study.

Increasing model flexibility to consider alternate controlling processes should advance research efficiency. Further, constructing this model in a design that facilitates future extension of new processes should further reduce unproductive research efforts. This paper presents the development of a new hydrological model, OBJect-oriented, TOPgraphic based model (OBJTOP), developed with an object-oriented approach and a generalized set of assumptions about watershed hydrological phenomena. Section 2 of this paper presents the flexible process features of OBJTOP, Section 3 its simulation algorithms, Section 4 the guiding design theory to facilitate extension, Section 5 the OBJTOP user interface, and Section 6 initial model results. Section 7 closes with a discussion on contributions made by this research.

1.1. Components of object-oriented modeling

Widespread development of object-oriented watershed models requires a paradigm shift in how hydrological events are conceptualized and programs written to overcome the trend to use procedural languages and routines (e.g. C or FORTRAN) (Wang et al., 2005). Modeling literature records that procedural approaches have been dominant since the first watershed model, known as the Stanford Watershed Model (Singh, 1995), through recent soil, vegetation, atmosphere, transfer scheme (SVATS) models developed for remote sensing based hydrology (Wigmosta et al., 1994; Peters-Liddard, 2000). Object-oriented design (OOD) methods and the objected-oriented programming (OOP) language-C++, however, make it possible to create an incremental model that can be applied to different watershed conditions (Wang et al., 2005). In addition to ease of extension, simulation of complex natural systems is more closely replicated by object-oriented design/programming (OOD/OOP) due to its coupling of objects and actions.

In procedural programming languages, programming tends to be action oriented, with the unit of programming being the function. In procedural languages, data and functions are separate. Watersheds and their component soils and rivers are not like data nor are they like functions, and instead these complex real-world objects have both *attributes*, which are equivalent to data in a program, and *behaviors*, which are functions that work on the data. Coupling, rather than separating, data and functions results in a closer approximation of real-world objects (Lafore, 2002). In OOD, a *class* represents a blueprint or description of a number of similar objects, and objects are instances of class. The OOP in this work created user-defined classes, and each class contains data as well as the set of functions that manipulate the data. For example, a soil class may contain soil transmissivity, T, as data and a function to simulate soil moisture using T. OOP provides a more natural and intuitive way to view the programming processes, by modeling real-word objects, their attributes and behaviors.

There are a few applications of OOD in hydrological simulation in the past decade (Wang et al., 2005; Band et al., 2000). These applications have made valuable attempts using OOP in hydrological modeling, but there is no detailed discussion of OOD principles and how to systematically implement them in watershed model design. Yet, it is the OOD and the class concepts that provide the powerful conceptual tool to describe complicated hydrological processes. Further, none of these few applications mentioned utilizing C++ class templates and standard template library (STL) container, both of which are exploited in OBJTOP to incorporate different assumptions into one model using class templates and to create dynamic containers using STL for data storage.

1.2. Constraining watershed model complexity

To build a model, complexity is always one of the major concerns. Fully distributed models can describe the variations in a hydrological system in time and space through physically consistent formulations and parameters related to watershed properties. They can explicitly account for spatial variability and land use changes of a catchment. Practical difficulties appear in the implementation of some distributed models requiring considerable expertise and extensive data availability. Lumped models reduce these needs, but conceptualize the whole system as a single unit and are efficient to calibrate and remain effective in many instances, such as operational flood forecasting. A deficiency of lumped models is that they are not able to handle landscape interactions, areal heterogeneity, and test governing spatial theory. Kirkby (1993) stated that, the best hope for reaching an overall understanding of the hydrograph response at a level between the lumped and distributed approaches seems to be the treatment of the response in a number of partitions. Becker (1992) and Schultz (1993) proposed a sub-division of the catchment into smaller hydrologically similar units (HSU), which may cluster areas of similar land use, soil, slope and vegetation, instead of having a completely distributed structure. ARC/EGMO (Becker, 1975; Becker et al., 2002) and TOPMODEL (Beven and Kirby, 1979) are examples of semi-distributed hydrological models utilizing HSU theory.

TOPMODEL concepts area a generalized semi-physical representation of rainfall run-off dynamics parameterized with watershed topographic data and initial conditions of soil moisture (Beven and Kirkby, 1979). The TOPMODEL concepts use the physical relation that elevation drives water distribution, and have become increasingly popular in recent years as they provide a relatively simple and robust framework for the use of widely available DTM (digital terrain model) data and incorporate a computationally efficient prediction of distributed hydrological responses (Saulnier et al., 1997). The original version of TOPMODEL is appropriate in small, humid, homogeneous watersheds in which the saturation excess overland flow process can be expected to dominate surface run-off, and soil transmissivity exponentially decreases with soil depth. TOPMODEL concepts have been disparately expanded, and include alternative internal hydrological processes (Beven, 1997), but the complete set of theory has not been organized into a single model. This paper presents OOD/OOP work that created the OBJTOP model to modify and organize TOPMODEL concepts into a single, highly flexible, readily extendable, simulation package.

2. Features of OBJTOP

In OBJTOP, the following alternative TOPMODEL governing theories were incorporated:

1. Both saturation and infiltration excess overland flow mechanisms are included, which makes OBJTOP applicable to a watershed with different run-off generation mechanisms.
2. Both exponential or a generalized power function forms are available to describe how hydraulic conductivity decays with soil depth, which allows the model to be suitable for different soil types.
3. Both soil topographic index (STI) and topographic index (TI) mechanisms were incorporated. This enhancement means the watershed does not have to be homogeneous.
4. Simulations can be performed with or without channel routing.

Incorporating the above theories, or assumptions, into one model package OBJTOP provides 16 schemes for hydrological processes simulation, increasing adaptability to alternate watershed conditions and soil types.

OBJTOP is designed to represent heterogeneity in topography, soil and rainfall, all known to cause spatial differences in run-off (Wood et al., 1990). In OBJTOP, the topographic index (TI) or soil topographic index (STI) can be used to represent different degrees of heterogeneity of topography and soil according to necessity and data availability. OBJTOP users select the type and number of discrete intervals (HRUs) from the OBJTOP interface, where HRUs reflect heterogeneity. The STI can be used to represent soil heterogeneity, and T_0 (saturated surface soil transmissivity) can be provided for each cell, or for several blocks of cells representing different soil types. Rainfall data can be selected for each sub-watershed whose size should be small enough for uniform rainfall inputs. Simulation mechanisms in OBJTOP provide ways to address the heterogeneity problems in hydrological modeling.

Some of the other features of OBJTOP are discussed below:

- OBJTOP allows a watershed to be compartmentalized, which allows a large watershed to be divided into multiple sub-watersheds for simulation. Each sub-watershed would have its own set of data and parameters. This is very useful to study the watershed with different land use types and soil types, and the simulated watershed does not have to be small to meet the uniform rainfall assumption.
- The dynamic data container provides no limitations for data storage. Because of the use of the standard template library (STL) sequential container vectors to store all the time series and spatial data (like DTM), OBJTOP can be used for any length of time series and any size of watershed hydrological process simulation, a feature that is impossible at present time for most watershed models designed and coded in procedural languages.
- OBJTOP incorporates a user-friendly graphical user interface (GUI). The GUI provides easy and efficient ways for data input, parameter modification, simulation scheme selection and model calibration. Various graphical outputs are available, including time series precipitation, run-off (total, subsurface, surface), watertable depth, as well as the TI or STI spatial patterns and water table 2D distribution.
- OJTOP has built-in objective functions for efficiently checking manual calibration. Three criteria functions (CRF1, 2, and 3) were used for the calibration and model performance evaluation.

  CRF1 $\left(1-\sum_{i=1}^{n}(Q_{\mathrm{obs},i}-Q_{\mathrm{cal},i})^2/\sum_{i=1}^{n}(Q_{\mathrm{obs},i}-\bar{Q}_{\mathrm{obs}})^2\right)$ tends to emphasize calibration with respect to the higher flows (Nash and Sutcliffe, 1970).

  CRF2 $=\left(1-\sum_{i=1}^{n}|Q_{\mathrm{obs},i}-Q_{\mathrm{cal},i}|/\sum_{i=1}^{n}|Q_{\mathrm{obs},i}-\bar{Q}_{\mathrm{obs}}|\right)$ is potentially useful in a forecasting context. It puts more emphasis on simulations at every time step (Ye et al., 1997).

  CRF3 $=\left(1-\sum_{i=1}^{n}\left(\sqrt{Q_{\mathrm{obs},i}}-\sqrt{Q_{\mathrm{cal},i}}\right)^2/\sum_{i=1}^{n}\left(\sqrt{Q_{\mathrm{obs},i}}-\sqrt{Q_{\mathrm{obs}}}\right)^2\right)$ is used for a more all-purpose calibration and emphasizes lower flows (Perrin et al., 2001). No automatic calibration is provided in OBJTOP at present time.
- OBJTOP is easy to implement. Compared to most physical based watershed models that need large quantities of parameters to run the model, the semi-distributed OBJTOP only needs 6–12 parameters, depending on the purpose and simulation scheme, for hydrological process simulation.
- OBJTOP is designed to be easy to extend. OBJTOP is designed to make the model open for extension and closed for modification, which yields the greatest benefits claimed for object-oriented technology, i.e. reusability and maintainability.

3. Simulation theory of OBJTOP

The present version of OBJTOP is a rainfall-run-off model that incorporates and extends the hydrologic concepts developed in the original version of TOPMODEL. A major advantage of TOPMODEL is its robustness and simplicity which comes from the use of the topographic index, TI $=\ln(a/\tan\beta)$, where a is the upslope contributing area per unit contour length and $\tan\beta$ represents the local slope. TI is used as an index of hydrological similarity. Therefore, it is only necessary to make calculations for points with different index values, spanning the index distribution function for a catchment. The original version of TOPMODEL is appropriate in small, humid and homogeneous watershed. Exponential decay of soil transmissivity with depth, subsurface flow, and saturation-excess overland flow processes are included in OBJTOP capturing original TOPMODEL assumptions (Beven et al., 1995; Hornberger et al., 1998).

Additional governing processes and assumptions in the original TOPOMODEL are as follows:

1. The dynamics of the saturated zone can be approximated by successive steady state representations. Recharge rate R does not vary with catchment location, which requires the simulated watershed to be small.
2. The hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope, which requires a shallow soil.
3. The dynamics of the water table can be approximated by uniform subsurface run-off production

per unit area over the area a, draining through a point.

soil transmissivity $T(z)$ decreases with soil depth exponentially ($T(z) = T_0 \exp(-S_i/m)$), and the function of $T(z)$ is assumed spatially constant in the catchment. In this formula, T_0 is the transmissivity at saturation, S_i is the local saturation deficit, and m is a scaling parameter. This implies the catchment should be homogeneous.

Several enhancements to the original TOPMODEL concepts were introduced into OBJTOP. First, the saturated surface transmissivity $T(z)$ of the soil can vary freely over the area of the catchment. The topographic index TI ($\ln(a/\tan\beta)$) for each point can be replaced by a soil topographic index STI ($\ln(a/T_0 \tan\beta)$). This provides more flexibility and capability for the model to deal with heterogeneity of the catchment.

A second enhancement is power function decline of transmissivity with soil depth, rather than exponential. Exponential decay leads to the index TI ($\ln(a/\tan\beta)$) and STI ($\ln(a/T_0 \tan\beta)$), and Beven (1984) has shown that this profile is appropriate for a variety of soil hydraulic conductivity data sets. A generalized power function decay is given as $T(z) = T_0(1 - S_i/m)^n$, as reported by Ambroise et al. (1996) and Iorgulescu and Musy (1998), which was incorporated into OBJTOP to be suitable for different soil types. The user can select a value of n for a simulation, and increases the flexibility in modeling different forms of hydrograph recession and variations of soil transmissivity with depth.

Inclusion of two forms of the soil depth–transmissivity relationships required two forms of the Topographic and Soil Topographic Indices, as well as two forms for Subsurface Flow, as described below. The indices using exponential decay were shown above, as given by Beven (1984), while for the generalized power function decay, the indices have the following forms: $\mathrm{TI} = (a/\tan\beta)^{1/n}$ and $\mathrm{STI} = (a/T_0 \tan\beta)^{1/n}$.

3.1. Simulation of subsurface flow

OBJTOP equations are given in this section. For exponential decay:

$$q_{\text{subsurface}} = T_z c \tan\beta = T_0\, \mathrm{e}^{-S_i/m} c \tan\beta \tag{1}$$

Using topographic index: $S_i = -m \ln(R/T_0) - m \ln(a/\tan\beta)$, while using soil topographic index: $S_i = -m \ln R - m \ln(a/T_0 \tan\beta)$. For generalized power function decay:

$$q_{\text{subsurface}} = T_z c \tan\beta = T_0 \left(1 - \frac{S_i}{m}\right)^n c \tan\beta \tag{2}$$

Using topographic index: $S_i = -m[1 - (R/T_0)^{1/n}(a/\tan\beta)^{1/n}]$, while using soil topographic index: $S_i = -m[1 - (R)^{1/n}(a/T_0 \tan\beta)^{1/n}]$.

Mean subsurface discharge $\bar{q}_{\text{subsurface}}(L/T)$ can be calculated by integrating Eqs. (1) and (2) with again different forms depending on the form of the soil depth-soil transmissivity relationship. For exponential decay, using the topographic index.

$$\bar{q}_{\text{subsurface}} = T_0\, \mathrm{e}^{-\lambda} \mathrm{e}^{-\frac{\bar{s}}{m}} \tag{3}$$

in which $\lambda = 1/A \int \ln(a/\tan\beta)\mathrm{d}A$ is average topographic index, and $\bar{s} = -m \ln(R/T_0) - m\lambda$, is the average soil moisture deficit under λ. Using the soil topographic index

$$\bar{q}_{\text{subsurface}} = \mathrm{e}^{-\lambda} \mathrm{e}^{-\frac{\bar{s}}{m}} \tag{4}$$

in which $\lambda = 1/A \int \ln(a/T_0 \tan\beta)\mathrm{d}A$ is average soil topographic index, $\bar{s} = -m \ln R - m\lambda$, is the average soil moisture deficit under λ.

Generalized power function decay of mean surface discharge is given as

$$\bar{q}_{\text{subsurface}} = T_0 \lambda^{-n} \left(1 - \frac{\bar{s}}{m}\right)^n \tag{5}$$

in which $\lambda = 1/A \int (a/\tan\beta)^{1/n}\mathrm{d}A$ is the average topographic index, and $\bar{s} = m[1 - (R/T_0)^{1/n}\lambda]$ is the average soil moisture deficit under λ. Using the soil topographic index

$$\bar{q}_{\text{subsurface}} = \lambda^{-n} \left(1 - \frac{\bar{s}}{m}\right)^n \tag{6}$$

in which $\lambda = 1/A \int (a/T_0 \tan\beta)^{1/n}\mathrm{d}A$ is average soil topographic index, $\bar{s} = m[1 - R^{1/n}\lambda]$ is the average soil moisture deficit under λ.

3.2. Simulation of overland flow

Saturation-excesses overland flow is generated when precipitation falls on a saturated area (Hornberger et al., 1998), so

$$q_{\text{overland}} = \frac{A_{\text{sat}}}{A} P \tag{7}$$

where A_{sat}/A is the fraction of the hillslope area that is saturated, and p $[L/T]$ is the throughfall or snowmelt rate.

Infiltration-excesses overland flow uses an infiltration rate, i identified by Beven (1984) as

$$i = \frac{dI}{dt} = \frac{\Delta\psi + Z}{\int_{z=0}^{z=z} \frac{dz}{K_z}} \tag{8}$$

in which I is the cumulative infiltration, K_z is the hydraulic conductivity at soil depth Z, and $\Delta\psi$ is effective wetting front suction. As illustrated by Beven (1984), for exponential decay: $K_z = K_0\ e^{-fz}$, and the above Eq. (8) becomes

$$i = \frac{K_0(\Delta\psi + z)}{\int_{z=0}^{z=z} e^{fz} dz} \tag{9}$$

Assuming at the ponding time t_p, the cumulative infiltration, I_p, has penetrated as a wetting front to a depth z_p, where $z_p = I_p/\Delta\theta$, and $\Delta\theta = (\theta_s - \theta_i)$ is the saturated soil moisture content minus the initial soil moisture content. Then, substitution in Eq. (9), given $i = r$ and $I_p = rt_p$, where r is infiltration rate before ponding, gives

$$r = \frac{dI}{dt} = \frac{\frac{1}{m} K_0(C + I_p)}{e^{I_p/m} - 1} \tag{10}$$

in which $f = \Delta\theta/m$, $C = \Delta\psi\Delta\theta$ is assumed a constant called the 'storage-suction factor', as explained by Beven (1984). After ponding, Eq. 10 continues to apply. Rewriting Eq. 10 in terms of I gives

$$\int_{I_p}^{I} \frac{e^{I_p/m} - 1}{C + I_p} dI = \frac{1}{m} K_0(t - t_p) \tag{11}$$

Eq. 11 can be integrated at known values t_p and I_p from Eq. 10 to get I at any time t after ponding (Beven,1984), given as

$$\frac{K_0}{m}(t - t_p) = -\left[\ln(I + C) - \frac{1}{e^{-C/m}} \ln(I + C) + \sum_{n=1}^{\infty} \frac{\left[-\frac{1}{m}(I + C)\right]^n}{n!n} - \lambda\right] \tag{12}$$

in which

$$\lambda = \ln(I_p + C) - \frac{1}{e^{-C/m}} \left[\ln(I_p + C) + \sum_{n=1}^{\infty} \frac{\left[-\frac{1}{m}(I_p + C)\right]^n}{n!n}\right] \tag{13}$$

A Newton–Raphson iterative procedure was used in OBJTOP to solve Eq. 12.

Power function decay of hydraulic conductivity is provided in OBJTOP for two cases. The basic equation for power function decay is given as, $K_z = K_0(1 - fz)^n$. OBJTOP presents two main transmissivity profiles as linear, where $n = 1$, and parabolic, where $n = 2$, to simulate infiltration excess overland flow.

In the case of linear decay, $n = 1$ and $K_z = K_0(1 - fz)$. Substitution of K_z into Eq. (8) gives:

$$i = \frac{dI}{dt} = \frac{-fK_0(\Delta\psi + z)}{\int_{z=0}^{z=z} (1 - fz)^{-1} dz} \tag{14}$$

Substituting $f = \Delta\theta/m$, $C = \Delta\psi\Delta\theta$, $z_p = I_p/\Delta\theta$ and given $i = r$ ($I_p = rt_p$) causes Eq. 14 to become:

$$r = \frac{dI}{dt} = \frac{-\frac{K_0}{m}(C + I_p)}{\ln(1 - I_p/m)} \tag{15}$$

After ponding begins, Eq. 15 becomes:

$$\int_{I_p}^{I} \frac{\ln(1 - I/m)}{C + I} dI = -\frac{K_0}{m}(t - t_p) \tag{16}$$

There is no explicit solution for Eq. 16. In OBJTOP, a numerical solution (the Simpson method) is used to approximate cumulative infiltration I at any time t after ponding.

In the case of parabolic decay, $n = 2$ and $K_z = K_0(1 - fz)^2$. Substituting this form for K_z into Eq. (8) gives:

$$i = \frac{dI}{dt} = \frac{-fK_0(\Delta\psi + z)}{\int_{z=0}^{z=z} (1 - fz)^{-2} dz} \tag{17}$$

Substituting $f = \Delta\theta/m$, $C = \Delta\psi\Delta\theta$, $z_p = I_p/\Delta\theta$ and the given infiltration rate $i = r$ ($I_p = rt_p$), into Eq. (17) creates Eq. (18):

$$r = \frac{dI}{dt} = \frac{K_0}{I_p}(C + I_p)(1 - I_p/m) \tag{18}$$

After ponding starts, Eq. 18 becomes.

$$\int_{I_p}^{I} \frac{I\,dI}{(C+I)(1-I/m)} = K_0(t-t_p) \tag{19}$$

A simple numerical solution is used to find I in Eq. 19 for any time t after ponding.

4. Design of OBJTOP

For any hydrological model design, there should be three essential parts: (1) a theory to describe hydrological processes; (2) a programming language to transform the abstract theory into model reality; (3) methodology and principles for the model design. As discussed above, the TOPOMODEL hydrological concept and the C++ programming language are used in the creation of OBJTOP, and more detailed methodology and principles for OBJTOP design are available in Wang et al. (2005). Reductionism is commonly used to study the hydrologic system because it efficiently highlights the individual process (parts). Besides studying things through dissection, interactions of process (parts) should be studied to take a wider view, attempting to understand the whole system by observing how process (parts) and their interactions form the global pattern. This work is novel by describing watershed run-off using an object-oriented approach. The C++ 'Inheritance' concept is used to study individual objects (or processes) at multiple levels while 'aggregation' is used to study the interactions of objects (or processes), thus creates a description of hydrologic processes in a direct, concise, and natural manner, distinct from hydrologic models implemented using procedural design and languages (Wang et al., 2005).

4.1. Conceptual watershed model of OBJTOP

In OBJTOP, class watershed contains the five subclasses of precipitation, vegetation, evapotranspiration, soil, and channel. These classes can be considered parts of a watershed. Class precipitation is divided into rainfall and snowmelt. Class soil is thought composed of four subclasses: surface (mainly for infiltration process), root zone, unsaturated zone and saturated zone. According to TOPMODEL concepts, topography exerts a dominant control on flow. In OBJTOP, topography is part of the soil and channel, so that it can exert influence on all the flow calculation. Fig. 1, using unified modeling language (UML), shows relationships for the above classes. The interactions among the above classes are shown in Fig. 2.

Class Rainfall and Snowmelt are components of class Precipitation (Fig. 1); i.e. Rainfall and Snowmelt are part of Precipitation and thus illustrate an aggregation relationship. However, rainfall and snowmelt can also be thought as examples of precipitation. The two classes share common characteristics of precipitation and thus represent a generalization relationship; class Precipitation is

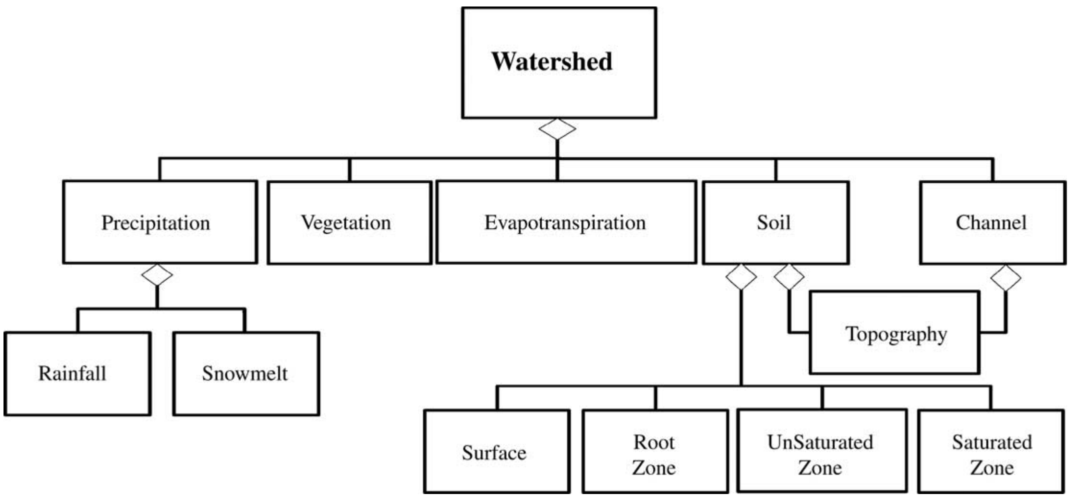

Fig. 1. Unified Modeling Language (UML) class diagram for Composition of class Watershed in OBJTOP. The diamonds indicate a 'part of' relationship, i.e. classes Rainfall and Snowmelt are a 'part of' the higher level class Precipitation.

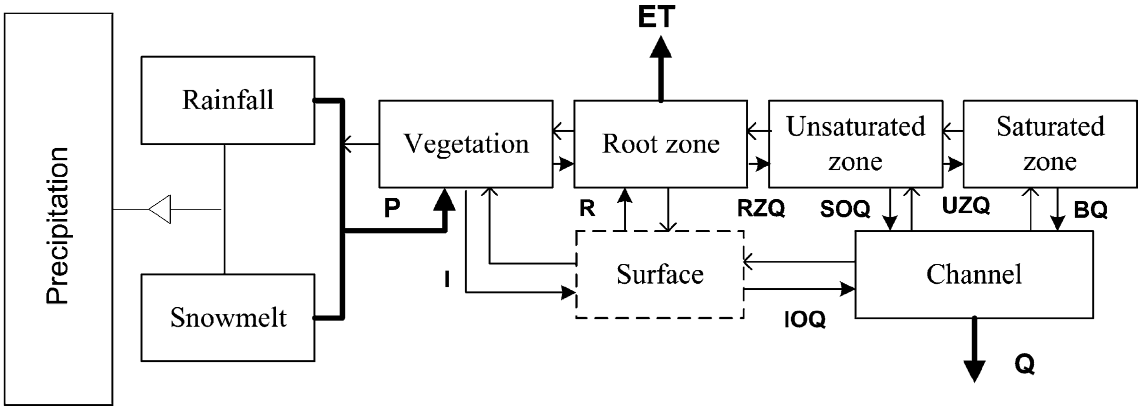

Fig. 2. Unified Modeling Language (UML) interaction diagram schematic illustrating interactions among OBJTOP classes. P indicates precipitation (snow melt or rainfall); ET is evapotranspiration from the root zone and Q is the total run-off from the watershed. I is through fall (precipitation after vegetation interception), R is recharge rate to the soil, IOQ is infiltration excess overland flow, RZQ is root zone flow, SOQ is saturation excess overland flow, UZQ is flow from unsaturated zone to saturated zone, and BQ is base flow. The symbols have meanings as follows: ——◁—— means inheritance (or generalization) and represents 'is a' relationship, i.e. rainfall or snow melt is a kind of precipitation. ——————> indicates association, i.e. class A asks class B to do something, ——————▶ indicates a flow of information from B to A. The combination of the two arrows indicates that class B provides data to class A under the request of A. The 'Surface' class simulates the infiltration process for infiltration excess overland flow. For saturation excess overland flow, the recharge rate R goes directly to the root zone after interception of precipitation by vegetation.

generalized from classes Rainfall and Snowmelt. There is no mechanism now in OBJTOP to simulate the snowmelt that will be incorporated in the future.

A similar relationship exists in the soil class. Classes surface, root zone, unsaturated zone, and saturated zone can be viewed as parts of soil. At the same time, the four classes share some common characteristics of soil, so the class Soil can be viewed as a generalization of the four classes. The two relationships among soil and its surface, root zone, unsaturated zone, and saturated zone are very useful and important and are reflected in the model design to simulate hydrological processes. The 'surface' class, shown in Fig. 2, is only designed to simulate surface infiltration processes for infiltration excess overland flow. For saturation excess overland flow, the recharge rate R directly gets to the root zone after vegetation interception. For additional explanation of OBJTOP classes, please refer to Wang et al. (2005).

5. Graphical user interface (GUI) design of OBJTOP

The GUI of OBJTOP was designed using visual C++ windows programming with MFC (Microsoft Foundation Class library for Windows programming). Multiple document/view architecture was used to build the GUI. Document and view work together to process the user's input and draw textual and graphical representations of the resulting data. The document class in OBJTOP was created to deal with data. It facilitates input of parameters, files, simulation schemes and other instructions from the user, as well as interacts with the underlying working engine for hydrological simulation. The document class manipulates and provides time series and spatial data input in a format suitable for the view class to generate varies graphical outputs.

The view class in OBJTOP was created to view simulation results as graphical outputs which include time series precipitation-run-off (total run-off, base flow, surface run-off, observed run-off and different combinations of the above run-off), topographic index (TI and STI) spatial pattern, fractional area of each TI/STI in the catchment, time series average water table of the catchment, time series water table of a specific location represented as a TI/STI value, and water table depth maps. The OBJTOP user not only can see the whole time series graphic output but also can select graphics in any time period for more detailed information.

OBJOTOP users benefit from the multiple document view structure, and can evoke any number of sub windows for simulation to compare results with different simulation schemes or parameters side by side in the same window. Features that the GUI was designed to facilitate include loading input files, modifying parameters, changing simulation schemes, displaying graphical outputs, evaluating and comparing model performance under different simulation schemes and parameters with the help of model calibration (three CRFs emphasizing different aspects of the simulation). The GUI is not designed for convenience only, but is an essential part of the model. Without the GUI, it would be difficult to fully use all the capabilities of the model, such as selecting a simulation scheme from the sixteen available options, examining the graphical outputs and comparing the calibration results instantly, which not only provides convenience but also increases modeling efficiency.

6. Test and application of OBJTOP

OBJTOP uses TOPMODEL theory, and there exists extensive literature on the applicability and robustness of this theory to simulate watershed hydrological response. In the objected oriented OBJTOP, with increased access to flexibly adjusting model assumptions, the model was tested for computational accuracy. This was tested using data from Slapton Wood catchment in the United Kingdom, which is included on Beven's TOPMODEL web page (http://www.es.lancs.ac.uk/hfdg/topmodel.html). The Slapton Wood catchment of Devon, UK is 0.94 km^2 in area, with 60% above 90 m, where the land is intensively farmed. The remaining area is permanent grassland and forest cover (Birkinshaw and Ewen, 2000). The soils are reported as 2 m deep, freely draining with a clay loam texture (Trudgill, 1983), and underlain by folded slates (Chappell and Franks, 1996).

OBJTOP's saturation excess overland flow mechanism was first used for simulation to ensure that OBJTOP output for the standard simulation scheme matched reported TOPMODEL output. Parameter values for OBJTOP were identical to those given by Beven, and exponential decay of conductivity was chosen. The time series run-off simulation outputs from OBJTOP were identical to the TOPMODEL generated values, which validated the internal computational structure of OBJTOP. The Nash-Sutcliffe criterion (CRF1) for the simulation was 0.81. To demonstrate model flexibility, an alternative simulation scheme of saturation excess overland flow with altered channel routing was applied for Slapton Wood, and obtained a CRF1 of 0.91, using manual calibration to obtain this distinct parameter set. Fig. 3 shows the simulated precipitation and run-off time series using saturation

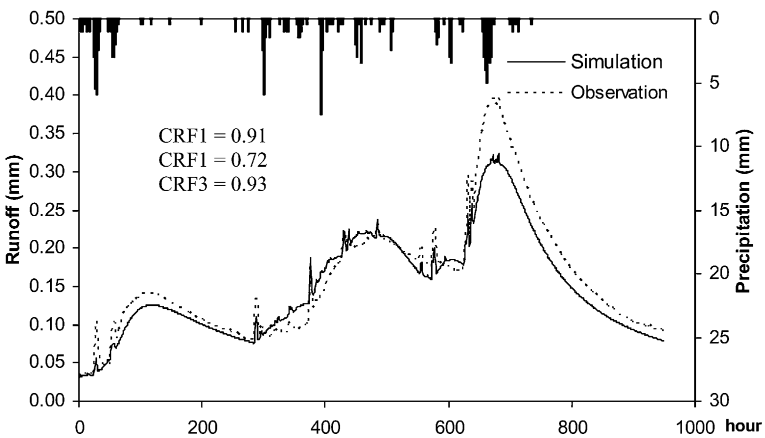

Fig. 3. Precipitation (mm) with observed and predicted run-off (mm) for Slapton Wood, UK with a 1 h time step for the 950 h time steps. Calibration is measured by the three criteria functions reported as CRF.

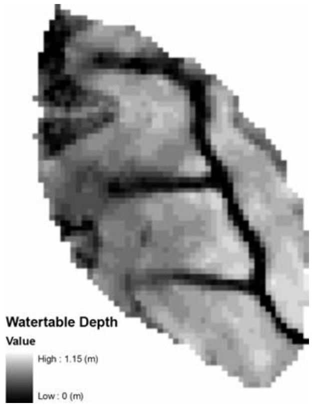

Fig. 4. Spatial water table depth (m) distribution for Slapton Wood, UK after 950 h of simulation, illustrating output options with OBJTOP.

excess overland flow with channel routing, revealing a good fit between observed and simulated records.

The calibrated results for the three simulation objective functions in Slapton Wood simulation were: CRF1 = 0.91, CRF2 = 0.72, CRF3 = 0.93. Fig. 4 is a watershed map of the water table distribution at 950 h into the simulation, and Fig. 5 is water table time series with catchment average TI (7.7), a high TI (15.0) and low TI (4.7). It can be seen that water table time series with a higher TI is closer to the ground, i.e. a shallow water table. The availability of moisture and hydrologic flowpath are critical factors for biogeochemical processes (Cirmo and McDonnell, 1997), such as nutrients and pollutants transport. Water table data with TIs in a catchment is useful for study of catchment biogeochemistry. Parameters used for the simulation of Slapton Wood are presented in Table 1.

OBJTOP was later, applied to the Ward Pound Ridge (WPR) sub-watershed to further illustrate the flexibility in adjusting model assumptions. This WPR application is in the New York City 967 km^2 Croton drinking water supply area that provides about 10% of NYC's water supply (Fig. 6). WPR has a mixed hardwood forest cover and a watershed area 0.376 km^2, underlain by igneous and metamorphic bedrock mantled by a discontinuous cover of till of variable thickness in upland areas, and alluvium, peat-muck, and outwash in the main valleys. Annual precipitation in this area is approximately 117 cm (Heisig, 1999). The WPR elevation data was retrieved for this study from low-altitude stereo-pair photography, generating a DTM with a spatial resolution of 2 m. Nearly 20% of the WPR catchment area has exposed bedrock, indicating that a combined infiltration and saturation excess overland flow mechanism should be selected, with hydraulic conductivity (K) adjusted for the bedrock. Further, the field investigation indicated that the K decayed with soil depth in a power function profile ($r^2 = 0.99$), thus the power function decay of K was used in the simulation instead of the traditional exponential K decay profile. WPR

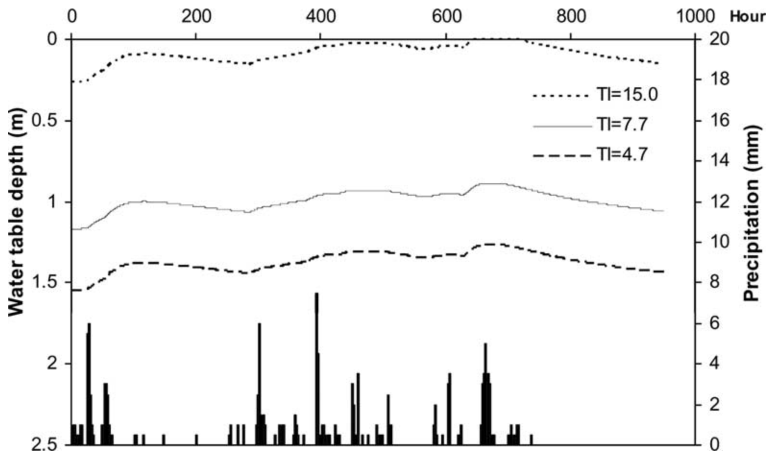

Fig. 5. Precipitation (mm) and water table depth (m) with three different Topographic Index (TI) values for Slapton Wood, UK catchment, with average TI = 7.7.

Table 1
OBJTOP model parameters used in Slapton Wood (SL), UK and the Ward Pound Ridge (WPR), NY calibration simulations

Parameter name	Slapton Wood	Ward Pound Ridge	Comment
NHRU	25	30	Number of HRU used for simulation
N	–	2.0	Exponent of power function decay
M	0.025	0.21	A scaling parameter
T_0 (m^2/h)	86.41	0.074	Saturated surface soil transmissivity
T_d (h)	198	20	Unsaturated zone time delay
MRZD (m)	0.005	0.052	Maximum root zone storage deficit
MCRV (m/h)	3600	660	Main channel routing velocity
ICRV (m/h)	3600	590	Internal channel routing velocity
ψ (m)	–	0.05	Wetting front suction factor
θ (%)	–	0.4	Wetted soil moisture content
K (m/h)	–	0.0011	Hydraulic conductivity

SL ran with saturation excess overland flow with channel routing using exponential decay, while WPR ran with infiltration and saturation excess overland flow with channel routing using power function decay.

data capture was guided by the US Environmental Protection Agency required and NYC Department of Environmental Protection approved Quality Assurance Project Plan. Fig. 7 shows the topographic index pattern generated using the parabolic TI = $(a/\tan \beta)^{2.0}$. Simulation was run at an hourly time step, and Fig. 8 shows the simulated and observed run-off between October 1, 2001 and March 4, 2002, a period selected

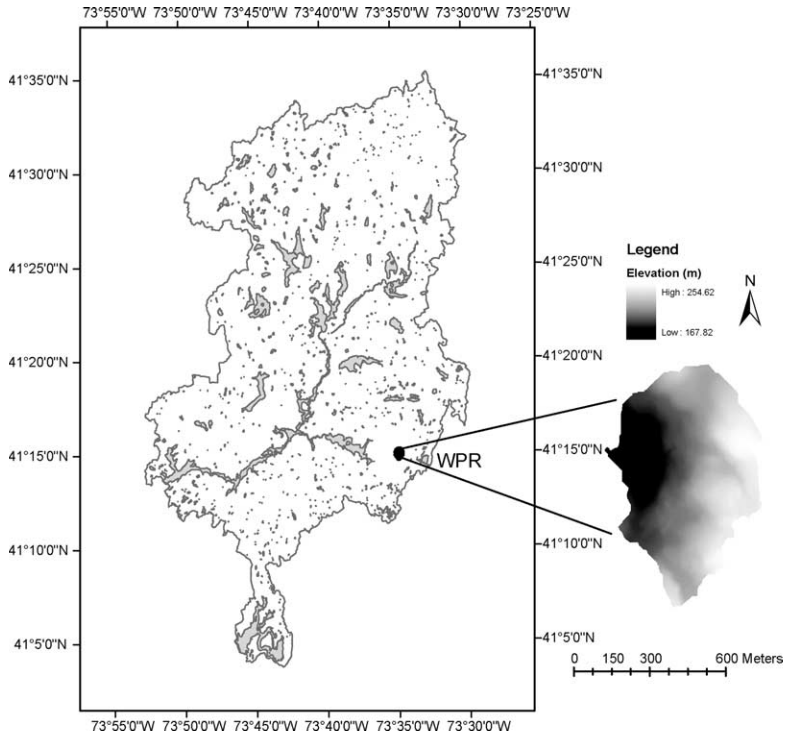

Fig. 6. The Ward Pound Ridge (WPR) watershed within the larger Croton watershed, and its location within New York State, showing waterbodies in the Croton watershed and elevation (m) for the WPR site.

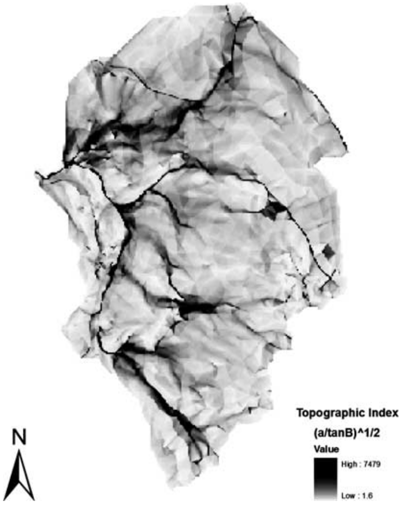

Fig. 7. Topographic index spatial pattern for Ward Pound Ridge using the power function, $n=2$, generated in OBJTOP.

for model calibration and bounded by data gaps due to field equipment failure. Peaks were the focus of the calibration, rather than baseflow, which is scattered due to the absence of snowmelt routines in OBJTOP. The calibration results for the three objective functions were: CRF1 = 0.92, CRF2 = 0.57, CRF3 = 0.81. Parameters used for the simulation of Ward Pound Ridge are presented in Table 1.

OBJTOP is computationally efficient, with run time dependent on the size of the DEM matrix, the number of simulated time steps, and the computer processor. The simulation time of hydrological processes in WPR for the October 2001 to March 2002 time period using hourly time step is about 4 s in a Pentium III (1.13 GHz processor) computer. Most of that time was spent on the calculation of topographic indices (TIs), where the matrix of 2 m DEM of WPR is 351×500. The simulation time is reduced to less than 1 s if TIs are available from previous model run(s) and not needed to recalculate. This provides efficiency for model calibration processes for selecting different options and parameters. TIs need to be recalculated if different K decay profiles (exponential or power function) are selected in simulations. In several seconds time, the user may then obtain one simulation result with various graphical, text outputs,

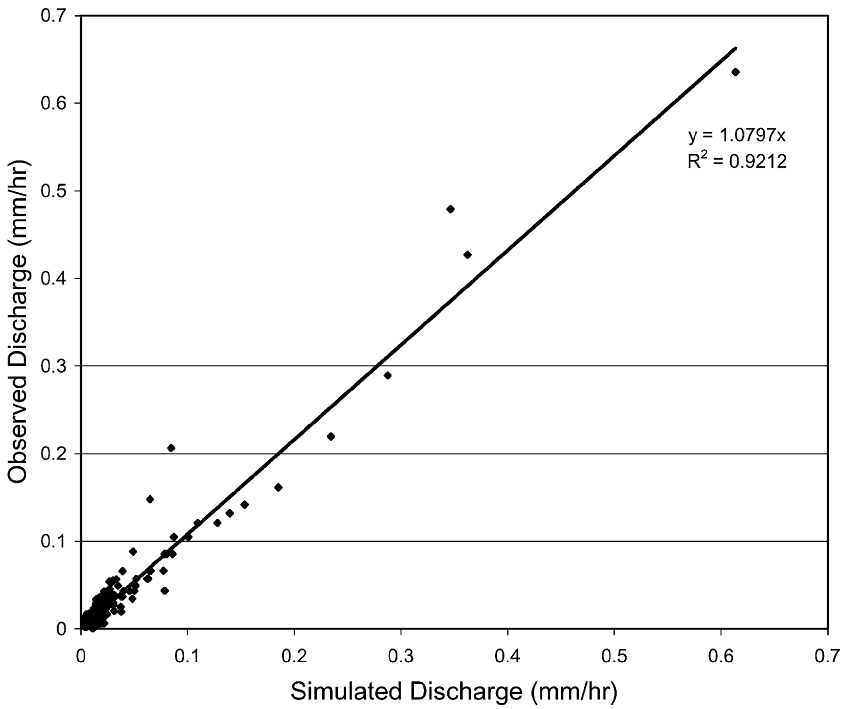

Fig. 8. Observed and predicted channel run-off (mm/h) from October 1, 2001 to March 4, 2002 for Ward Pound Ridge. Simulation used Δt equal to 1 h.

and three objective function values providing simulation evaluations. As to the model calibration, three parameters T_0, m and n (used for power function decay) are most sensitive to hydrograph output and should be calibrated first.

7. Discussion and conclusions

Simulation is central to much watershed hydrological assessment, and it depends on a model that captures the behavior of the study site. Unfortunately, model selection often requires the same detailed knowledge of the governing hydrological processes that is being sought. Traditionally, if the model assumptions do not fit the conditions of the study site, another model is selected or bad results ensue because of using an inappropriate model. OBJTOP, created with an object-oriented design methodology, provides a watershed hydrological model that incorporates a flexible array of assumptions about governing processes to increase utility in different watersheds with different conditions. The present version of OBJTOP has 16 simulation schemes suitable for different watershed conditions, which improves the model's capability in both simulation and calibration. OBJTOP is under further development for urban applications to increase model flexibility and power by providing more simulation schemes.

Nash and Sutcliffe (1970) presented a principle in model building that is adding parts to the model to increase model versatility is only acceptable if they substantially extend the range of model application, and increase the model accuracy, robustness. Consistent with this principle, OBJTOP was built to include hydraulic conductivity power or exponential function decay, channel or no channel routing, soil or standard topographic indices, and saturation or infiltration excess overland flow to extend the range of model application yet simple enough for implementation. Complexity was constrained with increasing simulation flexibility, and no individual simulation scheme is more complicated. Hydrologists can conceptually distinguish alternative run-off controls in their watershed, and then select between the model options to represent these processes in their simulation. Once processes are correctly captured, the goodness of fit obtained in calibrated runs are more likely to hold for validation, and theory is more readily tested. It is comparatively easier and more efficient to incorporate different mechanisms into one model using OOP method and C++ class templates as compared to using structured programming (Wang et al., 2005).

OBJTOP not only presents an incremental model for hydrological process simulation, but also presents a new methodology to describe natural processes using OOP. The 'inheritance' concept is used to simulate the 'is a' relationship and to study individual parts or process of a system at multiple levels. The 'aggregation' concept is used to simulate the 'part of' relationship and interactions of different parts or processes. OBJTOP represents an initial attempt to apply OOD and C++ in hydrological modeling, and some limitations have been identified. First, OBJTOP has not removed some original TOPMODEL assumptions. Humid and shallow soil conditions should still be met for a good and reasonable modeling result. Second, the application of OBJTOP is limited by its available simulation mechanisms, which, for example, currently does not include snowmelt and preferential flow. OOD's advantage, of course, is the ease in which additional simulation schemes are incorporated to extend the model. OBJTOP is now under extension to simulate sediment erosion and transportation, nutrients/pollutants behavior, human activities and management options.

Beven and Feyen (2002) posit there has been very little change for distributed hydrological models in the concepts on which the models are based and the ways in which they are calibrated and used since 1992. Despite this static condition, it remains unclear when and where to use various models (Singh and Woolhiser, 2002). OBJTOP, with its flexible simulation schemes, unique GUI design and data input and calibration structure, may bring some useful changes in hydrological modeling, and hopefully this can make hydrological modeling easier and more efficient.

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