Catalogue of the models used in MOPEX 2004/2005

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Abstract A description of each of the 15 models used in MOPEX (the Model Parameter Experiment), as reported at the MOPEX workshops in 2004 and 2005, is provided. The following models are included: AFFDEF, GR4H, GR4J, HBV, HYDROTEL, IHACRES, MODSPA, MORDOR, NOAH, RRMT, SAC-SMA, SMAR, SWAP, SWB and VIC. Each is described systematically by the original author(s) with details of where the model was first published and of its subsequent use.

Key words AFFDEF; GR4H; GR4J; HBV; HYDROTEL; IHACRES; MODSPA; MORDOR; NOAH; RRMT; SAC-SMA; SMAR; SWAP; SWB; VIC

INTRODUCTION

It is common for most scientific publications to present the materials and methods used to reach a certain conclusion. Evidently, a special issue on a model intercomparison exercise should abide by the same rule. Given the large number of contributions and the relatively short length of the articles, the editors sought for a standardized presentation of all the models, fifteen in total. Our main objective was to help readers make their way through the "jungle" of hydrological models used throughout this publication. An electronic form was sent out to all the authors. The form had three sections: (1) general information about the model (name, acronym, creation date …); (2) model description both in terms of structure and parameterization; (3) references.

The fifteen models presented in this catalogue are: AFFDEF, GR4H, GR4J, HBV, HYDROTEL, IHACRES, MODSPA, MORDOR, NOAH, RRMT, SAC-SMA, SMAR, SWAP, SWB and VIC. Each model structure is described by its authors to ensure the accuracy of the information and avoid all misinterpretation possibilities. For the same reason, the forms are reproduced without modification or editing. Readers who require additional information about a given model are advised to consult the corresponding references or to contact the model developers directly.

AFFDEF

GENERAL INFORMATION

Model acronym: AFFDEF
Model full name: —
Authors first publication: Brath, A., Montanari, A. & Moretti, G. (2002) On the use of simulation techniques for the estimation of peak river flows. Proceedings of the International Conference on Flood Estimation, Berna, 6–8 March 2002, Rep II-17, 587–599, CHR/KHR, International Commission for the Hydrology of the Rhine basin, Lelystad, The Netherlands.
Original application domaine: Flow simulation and applications; assessment of the effect of the anthropogenic influence on the hydrological cycle; hydrological applications where long simulation runs of river flows are needed at different locations of the catchment; prediction in ungauged basin.
Type: Spatially-distributed, continuously (in time) simulating rainfall–runoff model
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MODEL DESCRIPTION

Brief model description The main characteristic of AFFDEF is that long simulation runs can be performed with short time steps in limited computational times. The model is robust and thus applicable to a wide spectrum of real world case studies.

AFFDEF is raster-based. It takes as input the Digital Elevation Model (DEM) of the basin in raster form, as a rectangular matrix covering the whole basin. The cells of the DEM can be of any size. It also needs input rainfall and temperature data collected at an arbitrary number of thermometers and raingauges. Many of the hydrological processes involved in the rainfall–runoff transformation have been schematized by using conceptual approaches. The simulation can be carried out for a single event as well as in continuous time. In the first case, the Curve Number (CN) method is used to separate between surface and sub surface flows. In the case of continuous simulations, a more complex schematization of the rainfall–runoff transformation has been implemented, which also accounts for the interception and evapotranspiration. The model computes the local contribution to the surface runoff by applying a modified CN method. In order to compute the soil storativity, one must provide the matrix of the CN numbers for any given DEM cell. The local contribution to the surface runoff and the groundwater flows are transferred to the basin outlet by using a Muskingum-Cunge model with variable parameters, which are determined on the basis of the “matched diffusivity” concept. Distinction between the hillslope and network channel is based on the concept of the constant critical support area. Some of the model parameters have a well defined physical meaning and can be estimated on the basis of *in situ* surveys; the remainder have to be optimized by calibration on the basis of some historical hydro-metereological records.

Since a number of conceptual schemes were used in modelling the rainfall–runoff transformation, AFFDEF cannot be considered physically-based in the strict sense. Although it can be used for any kind of basin, it should be noted that AFFDEF only uses a simplified solution to model the contribution of groundwater flows. Therefore it is best suited for basins where the runoff production is mainly due to infiltration excess.

The model code, written in Fortran programming language, provides a user friendly and ready to use tool that runs on a personal computer, on a classic DOS platform. A routine for performing automatic calibration that makes use of the SCE-UA algorithm is included in the code.

Main hydrological processes Interception of rainfall by the vegetation cover; computation of the local rainfall (Thiessen polygons or the inverse squared distance interpolation method); evapotranspiration of the intercepted precipitation and from the soil; distinction between surface and sub-surface flow and computation of the local runoff response; and infiltration and formation of groundwater flow.

Rainfall–runoff module The distinction between surface and sub-surface flow is based on a modified version of the CN method. Conceptual schemes are used to model the interaction between soil, vegetation and atmosphere.

Transfer function Surface and groundwater flow are propagated towards the basin outlet by applying the Muskingum-Cunge model with variable parameters.

Groundwater/percolation module The formation of the groundwater flow is based on the excess infiltration scheme.

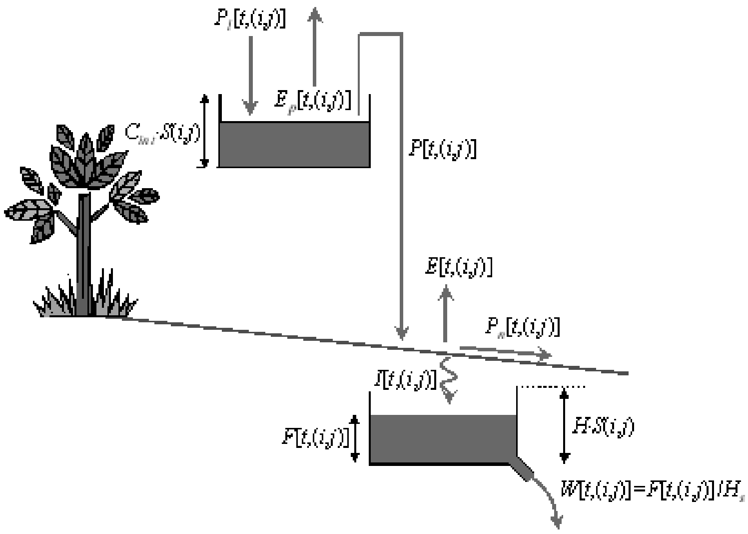

Fig. 1 Schematic representation of AFFDEF model structure.

Additional components None

Model applications In Brath *et al.* (2004), AFFDEF was applied to the Reno River Basin in Italy to assess its reliability when calibrated using data sets of increasing length. Overall, the results indicate that the best out-of-sample performances are obtained by calibrating the model with minimum periods of three months. Brath *et al.* (2002) used the model for estimating the flood frequency distribution of the Samoggia River basin, located in northern Italy. The model proved to be robust in the simulation of the observed flood frequency distribution, even if only short historical rainfall, temperature and river flow records were available for model calibration. An example of the success of the model in investigating the effects of land use change on flood flows may be found in Brath *et al.* (2003, 2006).

AFFDEF was applied for the prediction in ungauged basins to the Upper Neckar catchment, located in western Germany (Das *et al.*, 2006), and to the Riarbero Torrent (north of Italy, Moretti & Montanari, 2003).

Schematic representation of model structure (Fig. 1)

$P_l[t,(i,j)]$: rainfall depth at time t for the cell of coordinates (i,j)

$P[t,(i,j)]$: rainfall that reaches the ground at time t for the cell of coordinates (i,j)

$P_n[t,(i,j)]$: surface runoff at time t for the cell of coordinates (i,j)

$I[t,(i,j)]$: infiltrated water at time t for the cell of coordinates (i,j)

$F[t,(i,j)]$: water content of the infiltration reservoir at time t located in the cell of coordinates (i,j)

$W[t,(i,j)]$: outflow from the infiltrated reservoir at time t located in the cell of coordinates (i,j)

$E[t,(i,j)]$: effective evapotranspiration from the soil at time t for the cell of coordinates (i,j)

$E_P[t,(i,j)]$: evapotranspiration from the intercepted water at time t for the cell of coordinates (i,j)

$S[t,(i,j)]$: soil storativity according to the CN method for the cell of coordinates (i,j)

C_{int}: multiplying parameter for the interception reservoir capacity

H: multiplying parameter for the infiltration reservoir capacity

H_S: bottom discharge parameter for the infiltration reservoir capacity

DATA REQUIREMENTS; PARAMETERIZATION

Input data The input meteorological data consists of both observed precipitation (rainfall depths) and air temperature, at the same time step. The input topography data are required as a grid based Digital Elevation Model (DEM), which is given in raster format.

To characterize the spatial pattern of the infiltration capacity the Curve Number (CN) parameters associated to each DEM cell must be provided in input. Finally, a matrix is used to represent the spatial variability of the roughness on the hillslope for the overland flow. According to land use, different classes of roughness may be determined and a value for the Strickler coefficient is assigned to each class.

Overall model parameters

Parameter	Dimension and symbol	Method of estimation
Channel width/height ratio for the hillslope	w_v (dimensionless)	Calibrated
Strickler coefficients for the N-classes of roughness on the hillslope	k_{sv}(i), i=1,N ($m^{1/3}s^{-1}$)	Estimated
Channel width/height ratio for the channel network	w_r (dimensionless)	Estimated
Maximum and minimum Strickler roughness for the channel network	k^0_{sr} , k^1_{sr} ($m^{1/3}s^{-1}$)	Estimated
Value of the Curve Number for each cell	CN (dimensionless)	Estimated
Constant critical source area	A_0 (km^2)	Estimated
Saturated hydraulic conductivity	K_{sat} (m s^{-1})	Calibrated
Width of the rectangular cross section of the sub-surface water flow	B_P^{sub} (m)	Calibrated
Bottom discharge parameter for the infiltration reservoir capacity	H_S (s)	Calibrated
Multiplying parameter for the infiltration reservoir capacity	H (dimensionless)	Calibrated
Multiplying parameter for the interception reservoir capacity	C_{int} (dimensionless)	Calibrated

The values of some parameters, namely A_0, k^0_{sr}, k^1_{sr} and w_r, and the values of the Strickler coefficients for the different classes of roughness on the hillslope, can be estimated by physical reasoning or *in situ* measurements ("estimated" in the Table above). In particular, the value of A_0 is usually identified by comparing the river network determined by the model with a topography map of the catchment showing the natural flow paths. As an initial estimate one may set $A_0 = 0.5$ km^2. A first trial value for k^0_{sr}, k^1_{sr} and w_r along the river network can be derived from the analysis of the river network geometry. The parameter C_{int} is not well correlated with the other parameters, but can be calibrated separately by comparing observed values of the runoff coefficient with estimates derived by simulating sufficiently long records of synthetic river flows. The remaining parameters ("calibrated" in the Table above) can be calibrated manually with a trial and error procedure by comparing observed and simulated hydrographs.

Sensitivity analysis results In the sensitivity analysis carried out in Brath *et al.* (2004) it was found that certain input parameters had a more direct effect on the model outputs than others did. For example, the parameters of the surface Muskingum model (w_v, k_{sv}, w_r, k^0_{sr}, k^1_{sr}) mainly affect peak flow timing and somewhat affect hydrograph shape and peak flow magnitude. The parameters that refer to hillslopes (w_v, k_{sv}) have a more significant influence on the simulated river flows than the river network parameters, especially if A_0 is not small. The infiltration reservoir parameters H and H_s have a large effect on peak flow magnitude. Finally, the parameter H_s and those of the sub-surface Muskingum model (K_{sat}, B_P^{sub}) have an effect on the recessing limb of the hydrograph.

Calibrated parameters (See Table above)

Calibration procedure-algorithm Manual calibration based on the trial and error method; automatic calibration by means of the Shuffled Complex Evolution global optimization algorithm (implemented in AFFDEF code). The user must select the parameters to be automatically calibrated, and define their lower and upper bounds. The automatic calibration procedure, using a least square objective function, results in a better agreement between observed and simulated flows.

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Moretti, G. & Montanari, A. (2006) AFFDEF: a spatially distributed grid based rainfall–runoff model for continuous time simulations of river discharge. *Environ. Modelling Software* (in press).

GR4H

GENERAL INFORMATION

Model acronym: GR4H
Model full name: modèle du Génie Rural à 4 paramètres Horaire
Authors-first publication: Mathevet (2005) Which rainfall–runoff model at the hourly time-step? Empirical development and intercomparison of rainfall–runoff models on a large sample of watersheds, PhD thesis, ENGREF, Paris, France (in French).
Original application domain: Flow simulation and application such as flood estimation, flood forecasting for headwater basins.
Type: Lumped
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MODEL DESCRIPTION

Brief model description The GR4H model is an hourly lumped rainfall–runoff model, derived from the GR4J model (Perrin *et al.*, 2003). Its structure is similar to that of many conceptual type models (i.e. based on interconnected storages). However it was developed following an empirical approach, i.e. without *a priori* ideas on the rainfall–runoff transformation at the watershed scale. Moreover, the structure was developed by trying to find the more efficient formulation on a large sample of watersheds with hourly data, covering a wide range of hydro-climatic conditions. The model has two storages, four parameters to calibrate: two for the production function and two for the routing function. Full mathematical details are provided by Mathevet (2005). The GR4H structure is close to the GR4J structure, but is typically more efficient at the hourly time-step and thus dedicated to reactive watersheds. It has also been shown that GR4H was at least as efficient as GR4J at the daily time-step.

Main hydrological processes The model has no *a priori* physical underpinning. It includes a production function and a routing function.

Rainfall–runoff module The production function is based on: an interception phase using an interception store with zero capacity (potential evapotranspiration directly acts on input rainfall); a soil moisture accounting store (SMA) to determine (i) the part of raw rainfall that will become effective rainfall and (ii) the actual evapotranspiration; and a water-exchange function that can simulate import or export from/to the subterranean outside of the catchment. It acts on the two flow components simulated by the routing module.

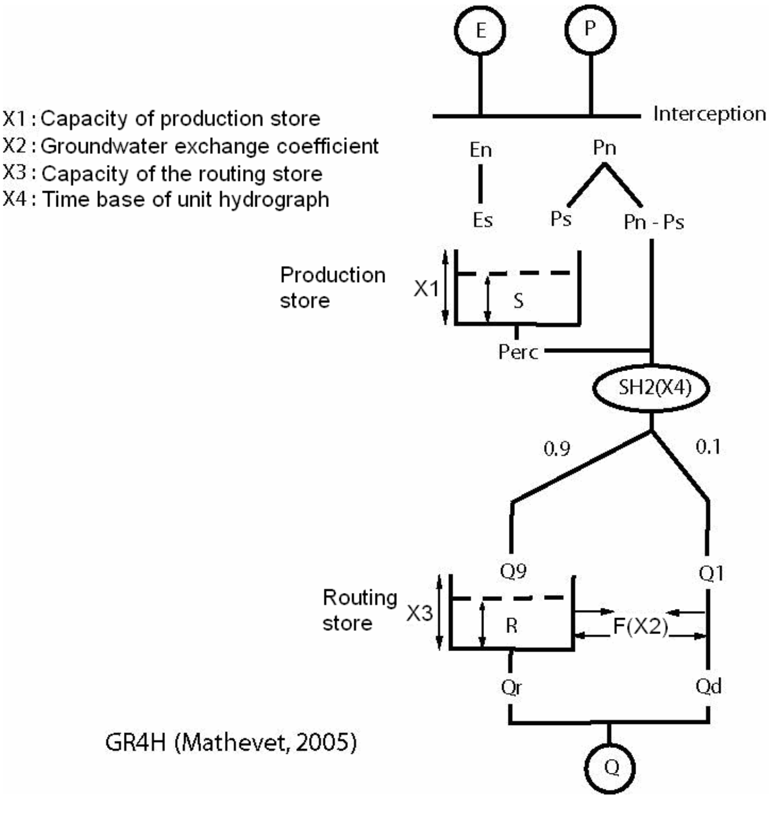
The difference between GR4J and GR4H in the production function is the percolation rate.

Transfer function The routing function is based on: a percolation from the SMA store; a constant volumetric split of effective rainfall into direct flow component (10%) and an indirect flow component (90%); one unit hydrograph (UH) for the direct and indirect flow components; a nonlinear routing store that transfers the indirect flow component; the difference between GR4J and GR4H in the routing function is the use of only one UH, with a smooth shape.

Groundwater/percolation module Interactions with groundwater are accounted for via the two model stores and the water exchange function.

Model applications The model was applied on more than 300 watersheds worldwide (Mathevet, 2005), covering a wide range of hydro-climatic conditions (semiarid, Mediterranean, oceanic, temperate, mountainous and continental) and of watershed area (from 0.5 km^2 to 5000 km^2). Watersheds were located in France, the USA, Australia, Slovenia and Spain.

Schematic representation of model structure



DATA REQUIREMENTS; PARAMETERIZATION

Input data The only inputs are: hourly potential evapotranspiration (PE) time series, derived from the disaggregation of the long-term average regime curve (i.e. the same PE curve is used every year); hourly rainfall time series. Rainfall is an estimate of area rainfall, e.g. calculated each day as an average on all available raingauges.

The model simulates flow time series. Observed hourly flow time series are required for model calibration and evaluation.

Overall model parameters The model has four free parameters:
$x1$: maximum capacity of the production store,
$x2$: groundwater exchange coefficient,
$x3$: one-day-ahead maximum capacity of the routing store,
$x4$: time base of unit hydrograph UH2.

Sensitivity analysis results An empirical sensitivity analysis of the model structure was performed by Mathevet (2005).

Calibrated parameters All four parameters are calibrated.

Calibration procedure-algorithm Given the low number of parameters, model errors, climatic variability, input and output variables uncertainties, the model can be calibrated by a simple direct search algorithm. The "step-by-step" optimization algorithm developed at Cemagref was found to be effective and efficient enough to successfully calibrate the model. It is a local search procedure (Edijatno *et al.*, 1999), that starts from a default parameter set, that is usually the media parameter of the parameter distribution obtained after the optimization of the model over a large sample of watersheds. Then, the optimization search step-by-step, or by trial and error, in the parameter space establishes the direction that improves the objective function the most. During the search, the search step is progressively reduced to refine the location of the optimum. The use of a progressively detailed search step allows the algorithm to locate the region of the optimum, with a low probability of getting trapped in a local optimum. Then, once the region of the optimum is located and no objective function improvement is achieved, the search step is reduced. The search stops when the search step is below a given threshold, i.e. when one considers that the optimum was located precisely enough. This method was tested in several studies and used to optimize parameter sets of thousands of watersheds. A comparative study with global search algorithms (SCE-UA and a Genetic Algorithm) showed that this method was able to optimise four to ten free parameters models, as successfully as global search algorithms.

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Mathevet, T. (2005) Which rainfall–runoff model at the hourly time-step? Empirical development and intercomparison of rainfall–runoff models on a large sample of watersheds, PhD Thesis, ENGREF, Paris, France (in French).

Perrin, C., Michel, C. & Andréassian, V. (2003) Improvement of a parsimonious model for streamflow simulation. *J. Hydrol.* **279**(1–4), 275–289.

GR4J

GENERAL INFORMATION

Model acronym: GR4J
Model full name: modèle du Génie Rural à 4 paramètres Journalier
Authors first publication: Edijatno *et al.* (1999) Mise au point d'un modèle élémentaire pluie-débit au pas de temps journalier. PhD Thesis, University Louis Pasteur/ENGEES, Strasbourg, France.
Original application domain: Flow simulation and applications such as flood estimation, flood forecasting (Yang, 1993; Yang & Michel, 2000; Tangara, 2005), drought forecasting, design of water regulation structures, detection of anthropogenic influence over the hydrological cycle.
Type: Lumped
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MODEL DESCRIPTION

Brief model description The GR4J model is a daily lumped continuous rainfall–runoff model. Its structure is similar to that of many conceptual type models (i.e. built using storages). However, it was developed following an empirical approach, i.e. without *a priori* ideas on the rainfall–runoff transformation, but trying to find the model structure that performs best on a large set of hydro-climatic conditions. The model has four parameters to calibrate. Full mathematical details are provided by Perrin *et al.* (2003).

Main hydrological processes The model has no *a priori* physical underpinning. It includes a production module and a routing module.

Rainfall–runoff module The model production module is based on:
(a) an interception phase using an interception store with zero capacity (potential evapotranspiration directly acts on input rainfall);
(b) a soil moisture accounting (SMA) store to determine: (i) the part of raw rainfall that will become effective rainfall; and (ii) the actual evapotranspiration;
(c) a water-exchange function that can simulate import or export of water from/to the subterranean outside of the catchment. It acts on the two flow components simulated by the transfer module.

Transfer function The transfer production module is based on:
(a) a percolation from the SMA store;
(b) a constant volumetric split of effective rainfall into a direct flow component (10%) and an indirect flow component (90%);

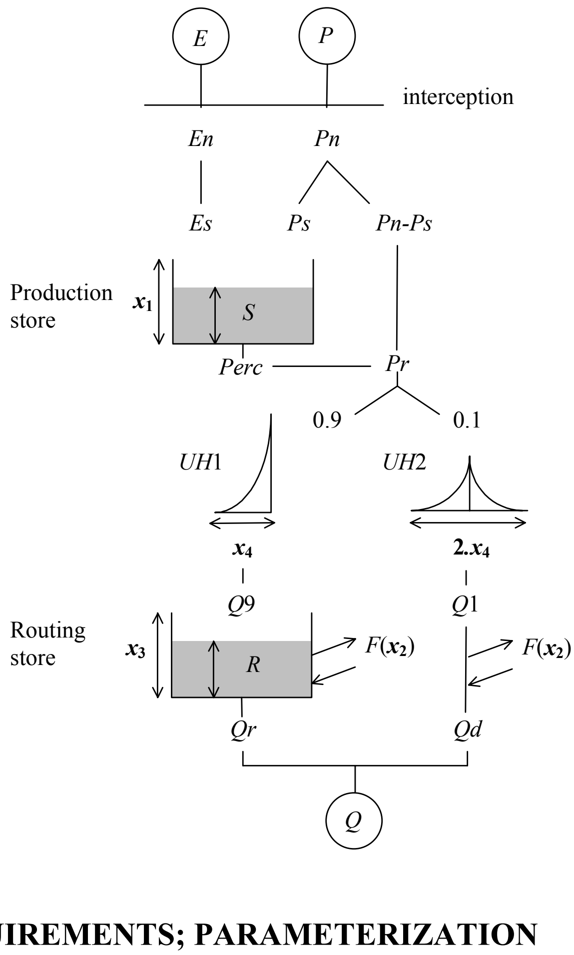
(c) two unit hydrographs (UH), each one acting on one flow component;
(d) a nonlinear routing store that routes the indirect flow component.

Groundwater/percolation module Interactions with groundwater are accounted for via the two model stores and the water-exchange term.

Additional components An optional snowmelt module was proposed by Makhlouf (1994).

Model applications The model was applied on more than 1000 catchments worldwide. The model was intensively tested and compared to other models in: France (Edijatno *et al.*, 1999; Perrin, 2000; Oudin, 2004; Mathevet, 2005), the UK (Perrin & Littlewood, 2000), Slovenia (Mathevet, 2005), the USA (Perrin, 2000; Oudin, 2004; Mathevet, 2005), Australia (Perrin, 2000; Oudin, 2004; Mathevet, 2005), Mexico (Rojas-Serna, 2005), Brazil (Perrin, 2000; Oudin, 2004; Mathevet, 2005), the Ivory Coast (Servat & Dezetter, 1991, 1992; Perrin, 2000).

Schematic representation of model structure



DATA REQUIREMENTS; PARAMETERIZATION

Input data The only inputs are daily potential evapotranspiration (PE) time series PE can be a long-term average regime curve, i.e. the same PE curve is used every year; and daily rainfall time series. Rainfall is an estimate of areal rainfall, e.g. calculated each day as an average on all the available raingauges.

The model simulates daily flow time series. Observed daily flow time series are required for model calibration and evaluation.

Overall model parameters The model has four free parameters:

$x1$ maximum capacity of the production store (mm),
$x2$ groundwater exchange coefficient (mm),
$x3$ one-day-ahead maximum capacity of the routing store (mm),
$x4$ time base of unit hydrograph UH1 (days).

Sensitivity analysis results Several structural sensitivity analyses were performed during PhD research projects (Edijatno, 1991; Nascimento, 1995; Perrin, 2000; Mathevet, 2005). Sensitivity analyses to model inputs were performed by Oudin (2004), Oudin *et al.* (2004, 2005) and Andréassian *et al.* (2001, 2004a,b). Uncertainty analyses were also carried out by Yang & Parent (1996) and Kuczera & Parent (1998).

Calibrated parameters All four model parameters are calibrated.

Calibration procedure-algorithm Given the low number of parameters, the model can be calibrated using any calibration approach. The step-by-step optimization algorithm developed at Cemagref was found to be effective and efficient to calibrate the model.

It is a local gradient search procedure (Edijatno *et al.*, 1999). The optimization starts from a default parameter set that is the average of parameter sets obtained from a large number of gauged watersheds. Then the optimization procedure searches step by step in the parameter space for the direction that improves the objective function the most. During the search, the search step progressively reduces to refine the location of the optimum. The search stops when the search step is below a given threshold, i.e. when one considers that the optimum was located precisely enough. This method was tested in several studies and showed good performances for models having up to eight parameters to calibrate (Nascimento, 1995; Perrin, 2000; Mathevet, 2005).

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HBV

GENERAL INFORMATION

Model acronym: HBV
Model full name: HBV hydrological model
Authors first publication: Bergström, S. & Forsman, A. (1973). Development of a conceptual deterministic rainfall–runoff model. *Nordic Hydrology* **4**, 147–170.
Original application domaine: streamflow simulation and hydrological forecasting
Type: Semi-distributed conceptual model
Contact: Sten Bergström
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MODEL DESCRIPTION

Brief model description The HBV model consists of three main components; subroutines for snow accumulation and melt, subroutines for soil moisture accounting and response, and river routing subroutines. It uses sub-basins as primary hydrological units and an area-elevation distribution and a crude classification of land use. The sub-basin option is used in geographically or climatologically heterogeneous basins or in the presence of large lakes.

Main hydrological processes Snow accumulation and snowmelt; soil moisture accounting; response function; river and lake routing.

Rainfall/runoff module A variable source-area concept based on a soil moisture accounting routine.

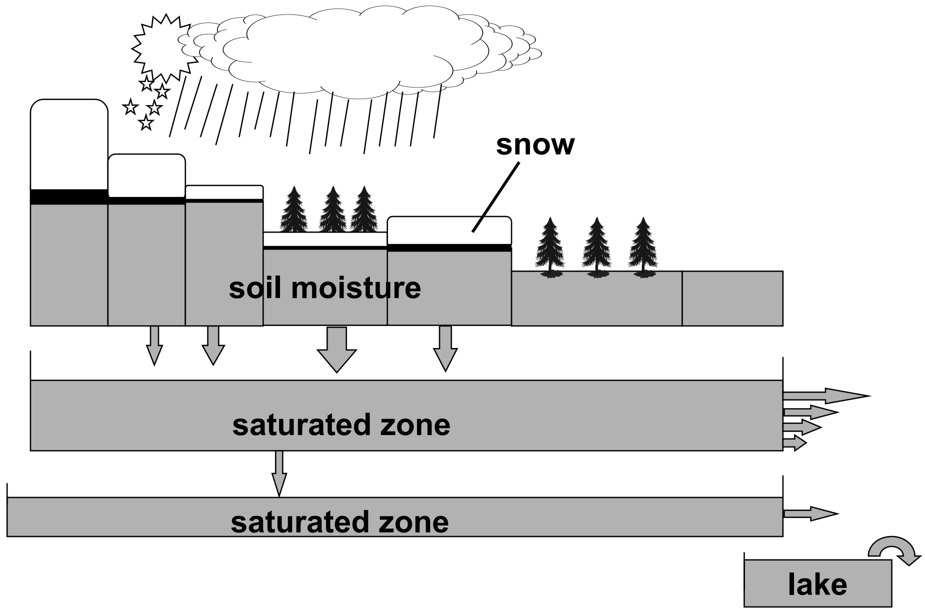
Transfer function A set of boxes representing the saturated zone with variable drainage depending on storage. River routing and explicit routing through lakes based on storage discharge relationships.

Groundwater/percolation module All excess water from the soil moisture accounting routine will enter the saturated (groundwater) zones. Water will leave the upper saturated zone either as runoff via rivers or as deep percolation to a lower saturated zone. Water from the lower saturated zone will eventually drain into rivers as well.

Additional components The HBV model has been developed to meet the needs of the environmental sector. Initially acidification was the main focus, but later nonpoint source pollution and transport of nutrients from land to sea became a major field of application.

Model applications The HBV model is a standard tool for runoff simulations and flood forecasting in Sweden, Norway and Finland. The model has been applied in more than 50 countries all over the world. Some of these applications are made by modified versions of the model developed in, for example, Norway, Finland, Germany and Switzerland (Bergström, 1995). More recently, the HBV model has been used extensively for analyses related to the impacts of global warming on water resources and hydropower production (Andréasson *et al.*, 2004).

Schematic representation of model structure



DATA REQUIREMENTS; PARAMETERIZATION

Input data Input variables to the HBV model are normally 24-hourly values of precipitation and air temperature and some estimate of potential evapotranspiration, which can either be daily or of lower resolution in time. A version of the model with hourly resolution in time is also available.

Overall model parameters Depending on the choice of the modeller and version of the model the number of parameters to calibrate are normally 2–4 in the snow routine, 3 in the soil moisture routine and 4–5 in the response function. In addition there are two general input correction factors, which should be used with some caution.

These are the most basic parameters used in calibration of the HBV-96 model version, which is standard for most Swedish applications (Lindström *et al.*, 1997):

General input corrections SFCF, snowfall correction factor; RFCF, rainfall correction factor.

Snow accumulation and snowmelt CFMAX, degree-day melt factor; TT, threshold temperature.

Soil moisture accounting FC, maximum soil moisture storage; LP, limit for potential evapotranspiration; BETA, exponent in the runoff generation equation.

Response function PERC, recharge of lower saturated zone; K, recession parameter; K4, recession parameter; ALFA, empirical coefficient.

Calibrated parameters Normally all the parameters above are the subject of calibration. However, the *general input corrections* are used restrictively.

Calibration procedure-algorithm Automatic calibration according to Lindström (1997).

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Arheimer, B. (2005) Evaluation of water quantity and quality modelling in ungauged European basins. In: *Predictions in Ungauged Basins: Promises and Progress* (ed. by M. Sivapalan, T. Wagener, S. Uhlenbrook, E. Zehe, V. Lakshmi, X. Liang, Y. Tachikawa & P. Kumar), 99–107. IAHS Publ. 303. IAHS Press, Wallingford, UK.

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HYDROTEL

GENERAL INFORMATION

Model acronym: HYDROTEL
Model full name: HYDROTEL
Authors first publication: Fortin *et al.* (1995) Fortin, J. P., Moussa, R., Bocquillon, C. & 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**(1), 97–124 (in French), Fortin *et al.* (2001a, 2001b) (in English).
Original application domain: Streamflow simulation
Type: Distributed
Contact: Alain Rousseau
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MODEL DESCRIPTION

Brief model description HYDROTEL is a distributed hydrological model compatible with remote sensing and GIS data. For each subprocess of the water cycle, HYDROTEL offers the possibility of choosing among various sub-models depending on available data. Thus, when the necessary data are available, it is possible to choose more accurate sub-models based on physical processes. Otherwise, more conceptual sub-models compatible with the available data may have to be chosen. This allows application of HYDROTEL to a wide variety of problems.

With the exception of river routing, computations are performed independently on a number of relatively homogenous hydrological units (RHHU) chosen so as to take into account the spatial variability of topography, land use, soil types and meteorological variables within a basin. Runoff from each RHHU is used to estimate lateral flow conditions for a hydraulic model which takes care of river routing. Computations associated with river routing are performed on each modelled river reach, starting with the most upstream ones and going down in a cascade through the river network to the outlet of the basin. Consequently, HYDROTEL can provide simulated flows at the downstream end of each river reach and not only at the outlet of the basin.

Main hydrological processes Six hydrological processes are simulated by HYDROTEL: interpolation of meteorological data; accumulation and melt of snow cover; potential evapotranspiration; vertical water budget; surface and sub-surface runoff; river routing.

Rainfall/runoff module Overland flow can be triggered by infiltration excess and saturation excess. The vertical water budget is computed by solving the Richards equation on three tilted layers of soil to take into account the local slope.

Transfer function Runoff is routed to the stream network using a geomorphological unit hydrograph. Kinematic wave and diffusive wave methods are available for river routing with assumed or measured channel cross-section, slope and length.

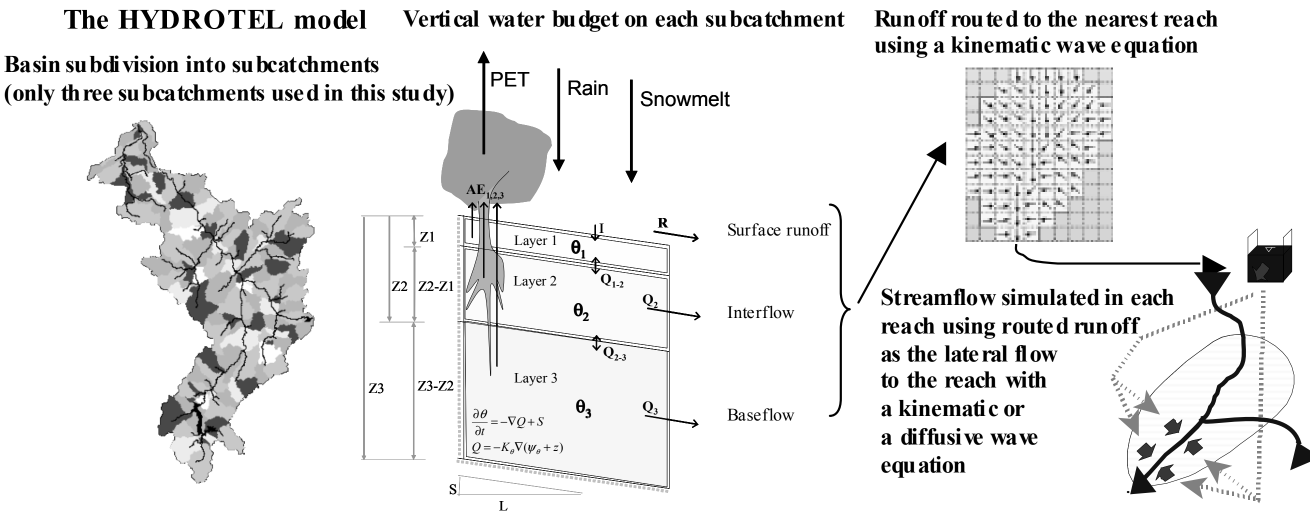
Groundwater/percolation module Exponential decay controlled by a recession coefficient.

Additional components Snow accumulation and melt are simulated using an energy budget approach, with radiation estimated from temperature. Different algorithms are available to estimate evapotranspiration, all taking into account the leaf area index and rooting depth of the vegetation.

Model applications Used operationally for streamflow forecasting in Québec for snowmelt- and rainfall-driven events for basins having a temperate climate with snowy winters, relatively low elevations (up to 1000m), and sizes varying from a few hundred square kilometres to over twenty thousand square kilometres (Turcotte *et al.*, 2004).

Embedded within a decision-support system used for integrated watershed management, including which can be used to simulate land use and water use effects on water quantity and quality (Lavigne *et al.*, 2004).

Schematic representation of model structure



DATA REQUIREMENTS; AND PARAMETERIZATION

Input data

Physiographic information *Required*: digital elevation model, leaf area index map, root depth map, soil type map, soil properties for each soil type (hydraulic conductivity, matrix potential, and water content at saturation, field capacity and wilting point). *Suggested*: vectorized river network. *Optional*: length, slope and width of river reaches, vegetation height, albedo.

Hydrometeorological observations *Required*: temperature and precipitation observations (daily or hourly). *Optional*: streamflow, water level, snow water equivalent, snow depth, wind speed, relative humidity, hours of sunshine, snow water equivalent.

Overall model parameters HYDROTEL has a total of 24 parameters which are subject to calibration. They can either be constant over the watershed, constant over groups of computational units, or fully distributed.

Interpolation of meteorological data Three parameters: vertical gradient of precipitation; vertical gradient of temperature; temperature threshold for separating rain and snow.

Accumulation and melt of snow cover Nine parameters: snow-soil melt rate; maximum density of the snowpack; snowpack densification rate coefficient; snow melting rate at the snow–air interface in coniferous forests, deciduous forests and open areas (three parameters); temperature threshold for snowmelt in coniferous forests, deciduous forests and open areas (three parameters).

Potential evapotranspiration One parameter: multiplicative optimization coefficient for adjusting PET.

Vertical water budget Five parameters: depth of each soil layer (three parameters); coefficient affecting the efficiency of transpiration; recession coefficient for base flow.

Surface and sub-surface runoff Four parameters: Manning's N runoff coefficients for forested areas, unresolved lakes, and open areas (three parameters); reference precipitation excess for the estimation of the geomorphological unit hydrograph.

River routing Two parameters: Manning's N runoff coefficient for the channel bed; multiplicative optimization coefficient for the width of assumed cross-sections.

Sensitivity analysis results All parameters are sensitive, but on different time scales.

Sensitivity on an annual time-scale Seven parameters: vertical gradient of precipitation; multiplicative optimization coefficient for adjusting PET; depth of each soil layer (three parameters); coefficient affecting the efficiency of transpiration; recession coefficient for base flow.

Sensitivity on a seasonal time-scale 11 parameters: vertical gradient of temperature; temperature threshold for separating rain and snow; snow-soil melt rate; maximum density of the snowpack; snowpack densification rate coefficient; snow melting rate at the snow-air interface in coniferous forests, deciduous forests and open areas (three parameters); temperature threshold for snowmelt in coniferous forests, deciduous forests and open areas (three parameters).

Sensitivity on the scale of the concentration time of the basin Six parameters; Manning's N runoff coefficients for forested areas, unresolved lakes, and open areas (three parameters); reference precipitation excess for the estimation of the geomorphological unit hydrograph; Manning' N runoff coefficient for the channel bed; multiplicative optimization coefficient for the width of assumed cross-sections.

Calibrated parameters All parameters can potentially be calibrated, but 17 are typically calibrated.

Accumulation and melt of snow cover Seven parameters: snow-soil melt rate; snow melting rate at the snow-air interface in coniferous forests, deciduous forests and open areas (three parameters); temperature threshold for snowmelt in coniferous forests, deciduous forests and open areas (three parameters).

Calibration procedure-algorithm Snow accumulation and melt parameters can be calibrated using snow observations (Turcotte *et al.*, 2005). Calibration of the remaining parameters can be performed using a process-oriented, multiple-objective calibration strategy accounting for model structure (Turcotte *et al.*, 2003).

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Turcotte, R., Lacombe, P., Dimnik C. & Villeneuve J. -P. (2004). Prévision hydrologique distribuée pour la gestion des barrages publics du Québec. *Rev. can. génie civ./Can. J. Civ. Engng* **31**(2), 308–320.

Turcotte, R., Fortin, L.-G., Fortin, J.-P., Fortin, V. & Villeneuve, J. -P. (2005) Operational analysis of the spatial distribution and the temporal evolution of the snowpack water equivalent in southern Québec. *Nordic Hydrology* (submitted).

IHACRES

GENERAL INFORMATION

Model acronym: IHACRES (PC-IHACRES is downloadable from http://www.ceh.ac.uk/ and http://www.wmo.int/web/homs/projects/homsp1.html (WMO HOMS Component K22.2.11); IHACRES Classic Plus is downloadable from http://www.toolkit.net.au/ihacres.)

Model full name: Identification of unit hydrographs and component flows from rainfall, evaporation and streamflow data

Authors first publication: Jakeman, A. J., Littlewood, I. G. & Whitehead, P. G. (1990) Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. *J. Hydrol.* **117**, 275–300.

Original application domain: Continuous flow simulation; unit hydrograph identification; hydrograph separation; catchment characterization; environmental change impact assessments.

Type: Spatially lumped

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Integrated Catchment Assessment and Management Centre, and Department of Mathematics, Australian National University, Canberra, Australia
Email: barry.croke@anu.edu.au.

MODEL DESCRIPTION

Brief model description A (nonlinear) loss module converts rainfall to effective rainfall, followed by a (linear) unit hydrograph module to convert effective rainfall to streamflow.

Main hydrological processes Conversion of catchment-scale rainfall to effective rainfall (i.e. the portion of rainfall that eventually leaves the catchment as streamflow) is based on a catchment wetness index; unit hydrograph routing of effective rainfall to streamflow at the catchment outlet.

Rainfall/runoff module Hybrid conceptual-metric.

Transfer function Unit hydrograph represented by a time-domain rational transfer function in the backwards shift operator, z^{-1}.

Groundwater/percolation module None (explicitly).

Additional components None (but additional snowmelt modules have been developed and applied for IHACRES modelling).

Model applications Many, please see References for a small selection.

Schematic representation of model structure (Fig. 1)

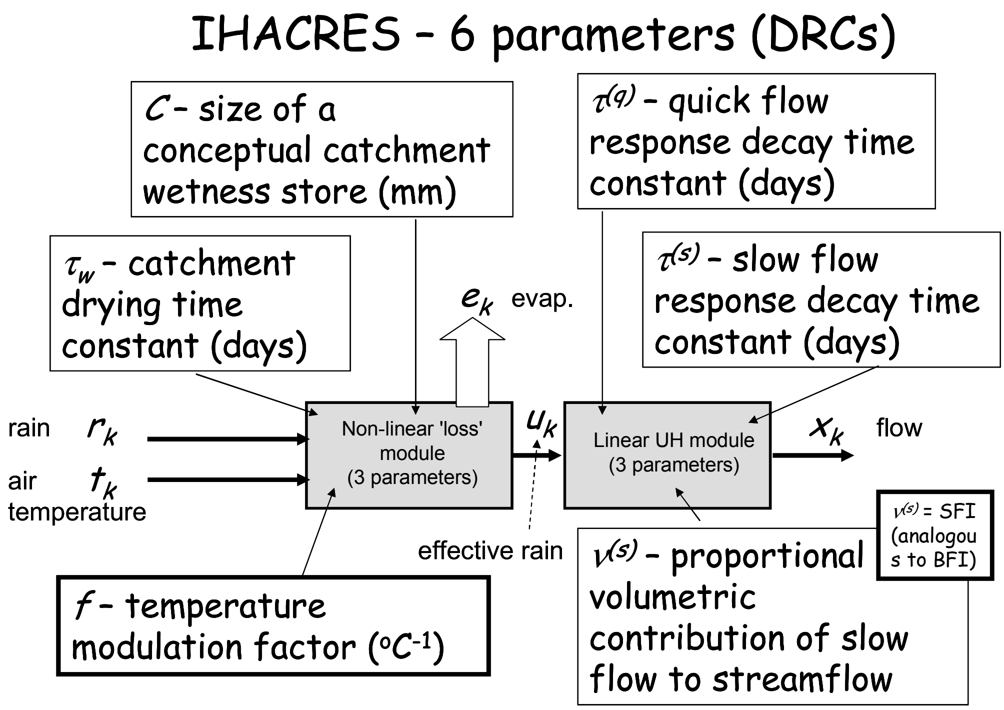

Fig. 1 Schematic representation of IHACRES model structure.

DATA REQUIREMENTS; PARAMETERIZATION

Input data Time series of rainfall, streamflow and air temperature. Apart from catchment area, no other data/information is required.

Overall model parameters See Fig. 1.

Sensitivity analysis results See literature.

Calibrated parameters See literature.

Calibration procedure-algorithm Usually six parameters. Loss module: Software-assisted, semi-automatic, grid-search for two of the three parameters in search of coincidentally high Nash-Sutcliffe efficiency for modelled streamflow and low "average relative parameter error" for the UH module. The third loss module parameter is calculated to give a water balance between effective rainfall and observed flow over the suitably chosen calibration period. The three UH module parameters are automatically identified using an advanced time series analysis technique. See Jakeman *et al.* (1990) for procedural details for initial calibration of the six parameters. The operator can use other model-fit statistics provided by IHACRES to help select a "best" model. In some cases, additional inspection of flow duration curves for observed and modelled flows can help the operator to adjust the loss module parameters in order to select a model "fit-for-purpose" (Littlewood *et al.*, 2003).

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Jakeman, A. J., Hornberger, G. M., Littlewood, I. G., Whitehead, P. G., Harvey, J. W. & Bencala, K. E. (1992) A systematic approach to modelling the dynamic linkage of climate, physical catchment descriptors and hydrologic response components. *Mathematics and Computers in Simulation* **33**, 359–366.

Jakeman A. J. & Hornberger, G. M. (1993) How much complexity is warranted in a rainfall–runoff model? *Water Resour. Res.* **29**(8), 2637–2649.

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MODSPA

GENERAL INFORMATION

Model acronym: ModSpa
Model full name: Modèle Spatialisé
Authors first publication Moussa, R. (1993) Modélisation hydrologique spatialisée et système d'information géographique. *La Houille Blanche* **5**, 293–301.
Original application domain: Streamflow simulation, flood prediction, water budget simulation, water resources management.
Type: Distributed
Contact: Roger Moussa
Institut National de la Recherche Agronomique (INRA), Laboratoire d'étude des Interactions entre Sol, Agrosystème et Hydrosystème, UMR LISAH ENSA-INRA-IRD, 2 Place Pierre Viala, 34060 Montpellier Cedex 1, France
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MODEL DESCRIPTION

Brief model description In ModSpa, Digital Elevation Models are used in order to subdivide the catchment into right-banks, left-banks or source/head subcatchments and to extract the channel network (Fig. 1(a)). Each subcatchment is linked to only one reach of the tree-like channel network. Over each subcatchment, the vertical water budget is computed using a two-layer model (Fig. 1(b)). The first layer, denoted "soil-reservoir", represents the upper soil layer where surface runoff, infiltration, interflow, percolation and evapotranspiration occur. The second layer, named the "aquifer-reservoir", represents the aquifer where the base flow occurs. Three state variables are calculated as a function of the time: the regulating function f which separates rainfall into surface runoff and infiltration, the level S in the soil-reservoir and the level S_b in the aquifer-reservoir. Then, a transfer function, based on the diffusive wave equation, is used to route flows on each subcatchment (surface runoff, interflow and base flow) and then through the channel network.

Main hydrological processes Surface runoff, infiltration, interflow, percolation, evapotranspiration, base flow, transfer function on subcatchments, transfer function in the channel network.

Rainfall–runoff module Infiltration/runoff is modelled using a two-layer reservoir model.

Transfer function The kinematic wave or a unit hydrograph on subcatchments, the diffusive wave on the channel network.

Groundwater/percolation module A simple reservoir characterized by a recession curve.

Additional components No additional components.

Model applications Simulation of streamflow on each reach of the channel network, calculation of the terms of the water budget, applications on catchments in humid, temperate and arid regions.

Application on the Gardon d'Anduze basin located in the Cévennes Mediterranean mountains southern France (daily and hourly time steps).

Schematic representation of model structure (Fig. 1)

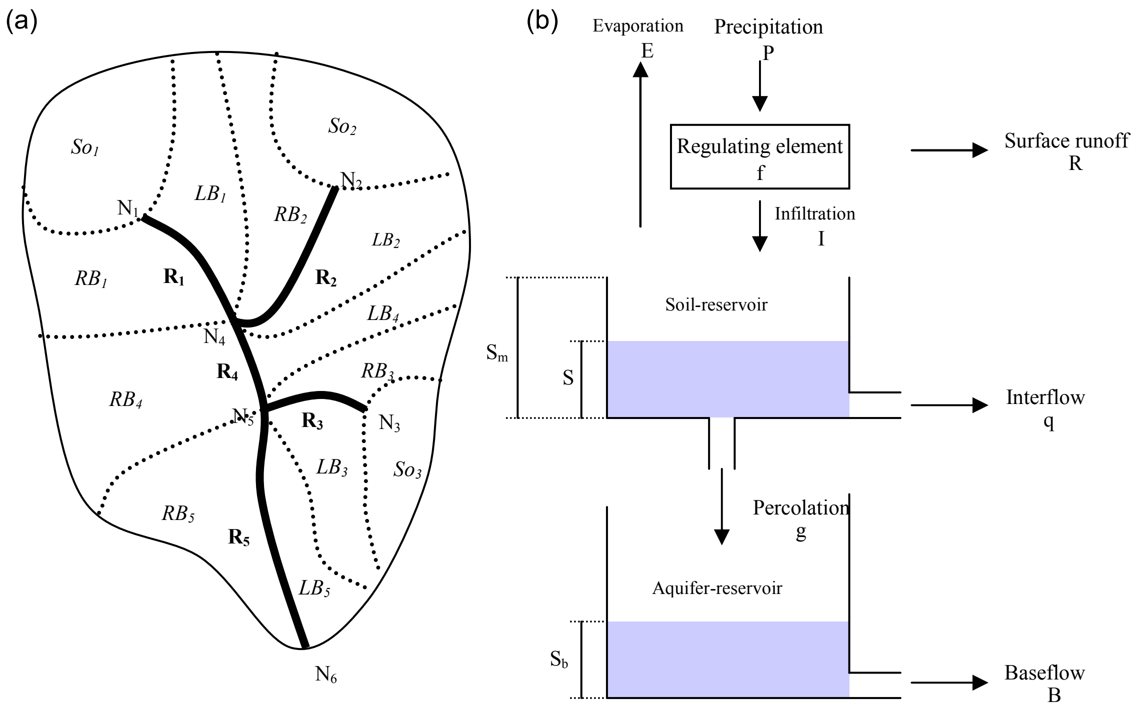

Fig. 1 ModSpa structure. (a) Representation of the basin topology in ModSpa: Channel network encoding: nodes (N_i), reaches (R_i in bold) and subcatchments (right-bank RB_i, left-bank LB_i and source basin So_i in italic). (b) Schematic structure of the vertical water budget in ModSpa.

DATA REQUIREMENTS; PARAMETERIZATION

Input data

(1) Topological structure of the basin calculated from the DEM: tree-like channel network, upstream and downstream nodes of each reach, links between subcatchments and reaches.

(2) On each subcatchment: (a) hydrometeorlogical data: rainfall and potential evapotranspiration; (b) geographical data from DEM: area, slope, distance to the reach; (c) soil hydrodynamic properties: hydraulic conductivity at natural saturation, soil-reservoir depth, the maximum value of the hydraulic conductivity; (d) leaf area index.

(3) On each reach: length, slope.

Overall model parameters

(1) On each subcatchment: the total storage of the soil-reservoir (S_m); the hydraulic conductivity at natural saturation of the soil (K_s); the maximum value of the hydraulic conductivity of the soil ($K_{max} = \alpha.K_s$ with α a parameter); the Leaf Area Index (LAI); a constant k representing the recession curve of the aquifer-reservoir; the celerity (C_u) on the subcatchment; the diffusivity (D_u) on each subcatchment.
(2) On each reach: the celerity (C_r); the diffusivity (D_r); sensitivity analysis results: the infiltration/runoff is sensitive to K_s, α, and S_m; the base flow is sensitive to k; the evapotranspiration is sensitive to LAI; the transfer function is sensitive to C_r and C_u.

Calibrated parameters Seven parameters are calibrated: α and k are considered similar for all subcatchments; C_u considered similar on all subcatchments; C_r is considered similar on all reaches; CK_s, CLAI and CS_m are three positive coefficients used as multiplication coefficients respectively of the *a priori* estimated K_s, LAI and S_m on each subcatchment.

Calibration procedure-algorithm Trial and error method.

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MORDOR

GENERAL INFORMATION

Model acronym: MORDOR
Model full name: Modèle à Réservoirs de Détermination Objective du Ruissellement
Authors first publication: Garçon, R. (1996) Prévision opérationnelle des apports de la Durance à Serre-Ponçon à l'aide du modèle MORDOR (*Operational inflow forecasting of the Durance River at Serre Ponçon using the MORDOR model*). *La Houille Blanche* **5**, 71–76.
Original application domain: Flow simulation and applications such as stochastic flood estimation, flood forecasting, long-term water resources forecasting, drought forecasting, reservoir inflow forecasting, snowpack water equivalent forecasting, design of water regulation structures, river temperature and sediment delivery forecasting.
Type: Lumped
Contact: E. Paquet, R. Garçon, J. Gailhard & T. Mathevet
EDF–DTG, Service CADE, 21, avenue de l'Europe, BP 41 38040 GRENOBLE 9, France
Email: thibault.mathevet@edf.fr

MODEL DESCRIPTION

Brief model description The MORDOR model is an hourly to daily lumped continuous rainfall–runoff model, developed since the 1990s by the French energy producer (EDF). The model development philosophy was close to the one of the HBV model. Its structure is similar to that of many conceptual type models (i.e. built using different interconnected storages) and composed of three main components: a snow accumulation and melt function, a production function (soil moisture accounting type) and a routing function. The whole model structure, with the snow component, is quite complex: it has five reservoirs and up to 23 free parameters to calibrate.

Main hydrological processes The model has no *a priori* physical underpinning. It includes a snow accumulation and melt function, a production function and a routing function.

Rainfall–runoff module The production function is based on: an evaporation function that determines the potential evaporation as a function of the actual temperature; a rainfall excess/soil moisture accounting store that determines: (a) the part of raw rainfall that will contribute to direct runoff; and (b) a part of the actual evapotranspiration; an evaporating reservoir, filled by a part of the indirect runoff component, that contributes to the actual evaporation.

Transfer function The transfer function is based on: an intermediate store that determines the split between (a) direct runoff, (b) indirect runoff and (c) percolation to a deep store; a deep store that determines a base flow component; an evaporating store, filled by a part of the indirect runoff component; a unit hydrograph (UH), based on a

Weibull law, that determines the routing of the total runoff (sum of the direct, indirect and baseflow components).

Additional components An optional snow accumulation and melt module is used. This module uses the hypsometric function of the basin to determine the actual part of the rainfall that is accumulated as snow. Then a melt function, based on a refined degree-day formulation, determines the part of the accumulated snow that contributes to (a) direct runoff or (b) baseflow.

Model applications The main application of the MORDOR model is in the hydro-meteorological operational forecasting centres of EDF-DTG. Models are mainly used to perform short term (sub-daily to daily) and mid term (weekly) streamflow and reservoir inflow forecasting, up to long-term snowmelt and reservoir inflow probabilistic forecasting. Models are coupled with quantitative forecasts and historical meteorological database. MORDOR models are currently used for operational forecasting on about 30 French watersheds (Fig. 1). MORDOR models are also used for general hydrological studies and for extreme flood probability studies.

MORDOR models have been developed and tested under various hydro-meteorological conditions in different countries over the world (Bolivia, Gabon, French Guyana, Laos, Honduras) for engineering applications.

A model intercomparison study (Mathevet, 2005), based on the assessment of 20 rainfall–runoff models, tested on a sample of 313 watersheds at the daily and hourly time-step, have shown that versions of the MORDOR model (with six and ten free parameters) were among the more efficient and robust rainfall–runoff model structures.

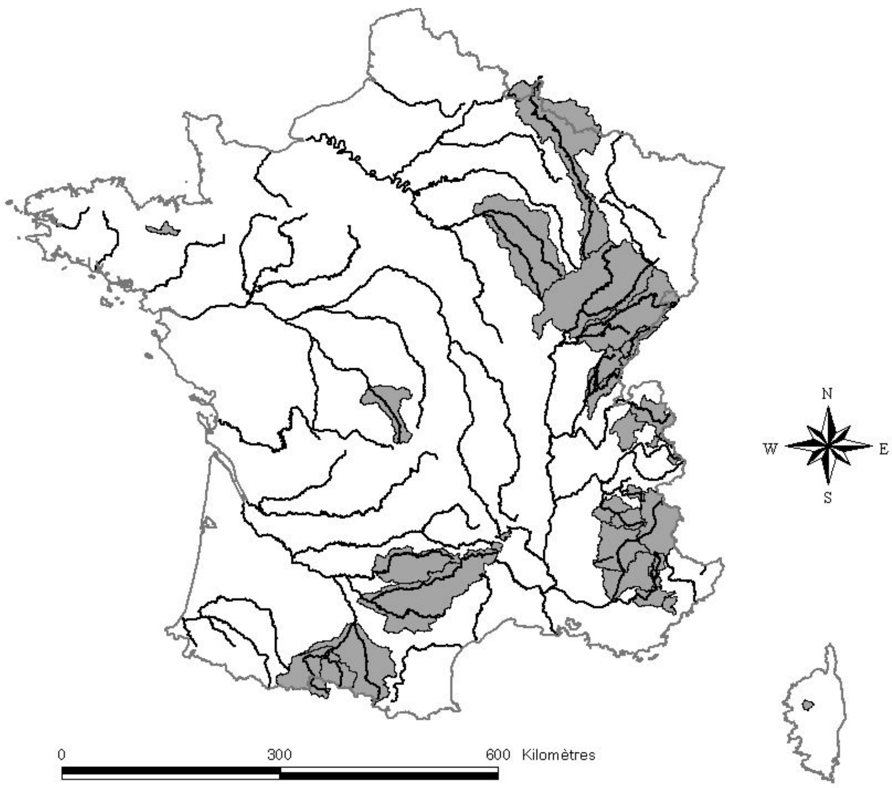

Fig. 1 Watersheds (in grey) where MORDOR models are used for hydrological forecasts.

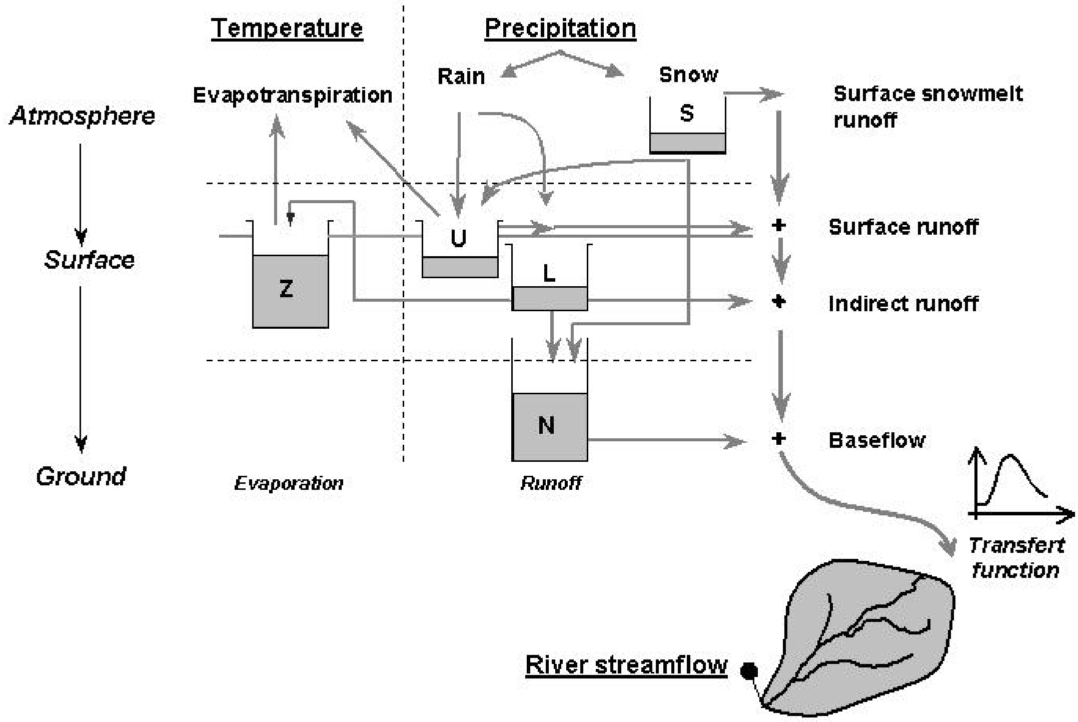

Fig. 2 Schematic representation of the MORDOR model.

Schematic representation of model structure See Fig. 2.

DATA REQUIREMENTS; PARAMETERIZATION

Input data The only inputs are: daily mean air temperature; daily rainfall time series (rainfall is an estimate of areal rainfall, e.g. calculated each day as weighted average on all the available raingauges); the hypsometric curve of the watershed. The model simulates daily flow time series, and daily snow accumulation and snowmelt. Observed daily flow time series are required for model calibration and evaluation.

Overall model parameters The model has up to 23 free parameters: 11 free parameters for the snow module: three for snow accumulation and eight for snow melt; two free parameters for the computation of the potential evapotranspiration; four free parameters for the production function; four free parameters for the routing function; two free parameters for the unit hydrograph (Weibull law).

Sensitivity analysis results The main sensitivity analysis was performed by Mathevet (2005) during research for a PhD. This work was done on a simplified MORDOR model structure, without the snowmelt module and using potential evapotranspiration input, instead of temperature input. This modified structure had ten free parameters. An empirical sensitivity analysis was performed on a sample of 313 watersheds, at the hourly time-step. Within the framework of this sensitivity analysis, the performance of 35 modified structures, with five to ten free parameters, was assessed. Results showed that the structure of the MORDOR model could be simplified and that a six free parameters structure could lead to the same mean model performance over the watershed sample, with a better robustness. This modified structure has not been tested yet in operational conditions.

Calibrated parameters All 23 model parameters are calibrated.

Calibration procedure-algorithm Given the high number of free parameters, the optimization algorithm is based on a global search strategy, using a classical genetic algorithm. This genetic algorithm is based on the generation of parameter vectors by mutations (random change made on a parameter) and crossovers (exchange of corresponding parameter between two vectors). The selection of the best parameter vectors is based on an objective function, such as the Nash-Sutcliffe criterion. This method was compared to the SCE-UA (Duan *et al.*, 1992) and the "step-by-step" (Edijatno *et al.*, 1999) optimization algorithm, on a sample of 313 watersheds at the hourly time-step (Mathevet, 2005). Results showed that this method was able to find parameter sets that have the same level of efficiency, compared to the one found by the two other methods. However, this method requires 3–30 times more objective function evaluations to converge to an optimal parameter set. To calibrate free parameters it is possible to choose among several objective function. Studies have shown that an objective functions based on the Nash-Sutcliffe criterion and the balance error or the streamflow distribution error yield more robust parameter vectors than the use of the Nash-Sutcliffe criterion only.

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

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Garçon, R. (1999) Modèle global pluie-débit pour la prévision et la prédétermination des crues (Overall rain-flow model for flood forecasting and pre-determination). *La Houille Blanche*, **7–8**, 88–95.

Mathevet, T. (2005) Which rainfall–runoff model at the hourly time-step? Empirical development and intercomparison of rainfall–runoff models on a large sample of watersheds. PhD Thesis, ENGREF, Paris, France (in French).

Paquet, E. & Garçon, R. (2002) Caprices du climat et de l'hydrologie en Haute-Durance: nos prévisions d'apports plurimensuels sont-elles encore fiables? (Climate and hydrology vagaries in Haute-Durance: are our several-month supply predictions still reliable?). *La Houille Blanche*, **8**, 62–68.

Paquet, E. (2003) Evolution du modèle hydrologique MORDOR: modélisation du stock nival à différentes altitudes (Improvement of the MORDOR model: toward the modelling of the snowpack distribution in function of the altitude). Société Hydrotechnique de France, section Glaciologie–Nivologie, 12/03/2003, Grenoble, France.

NOAH

GENERAL INFORMATION

Model acronym: Noah LSM
Model full name: Noah Land-Surface Model
Authors first publication: Chen, F., Mitchell, K., Schaake, J., Xue, Y., Pan, H., Koren, V., Duan, Q., Ek, M. & Betts, A. (1996) Modeling of land-surface evaporation by four schemes and comparison with FIFE observations. *J. Geophys. Res.* **101**, 7251–7268.
Original application domain: River and flood forecasting
Type: Lumped
Contact: kenneth.mitchell@noaa.gov

MODEL DESCRIPTION

Brief model description Noah LSM is a land surface model. It has been implemented operationally in the National Center for Environmental Prediction Eta model, a numerical weather prediction model. Noah LSM accounts for energy and water balance. The energy and water balance equations are defined over a single column, with no lateral exchange. Numerical schemes are used to solve the 1-D diffusion type energy and water balance dynamics.

Main hydrological processes Surface runoff when the precipitation exceeds infiltration capacity; baseflow from the bottom of the column; evapotranspiration from canopy, soil columns; energy fluxes; snow processes.

Rainfall–runoff module Richards equation

Transfer function Unit hydrograph

Groundwater/percolation module Darcy

Additional components No erosion and nutrients. Snow is represented by a full energy balance model.

Model applications Numerical weather prediction

Schematic representation of model structure See Fig. 1.

DATA REQUIREMENTS; PARAMETERIZATION

Input data Precipitation, air temperature, specific humidity, surface pressure, incoming short-wave solar radiation, incoming long-wave radiation, wind speed—vertical component, wind speed–horizontal component.

Overall model parameters There are many parameters that are determined using look-up tables based on soil and vegetation classifications.

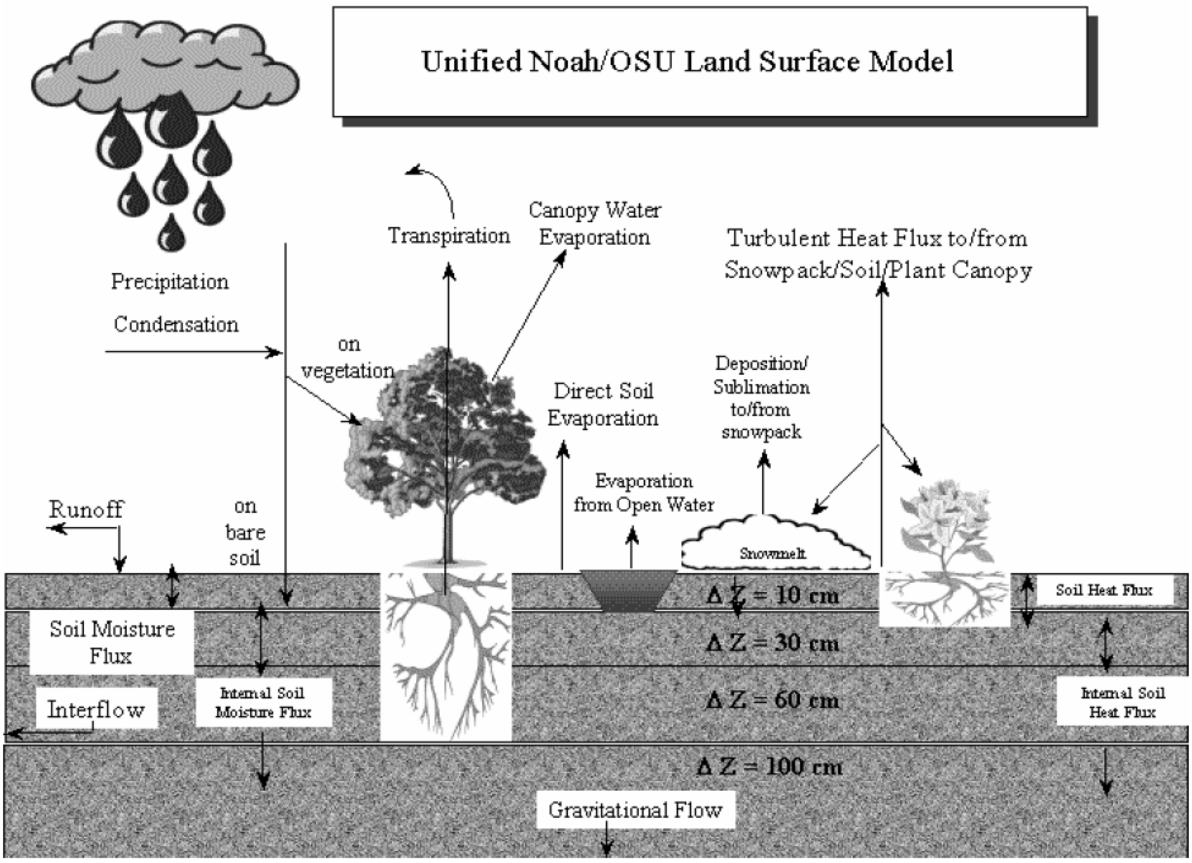

Fig. 1 Schematic representation of NOAH model structure.

Sensitivity analysis results No systematic sensitivity study was performed. Only the parameters considered to be sensitive in terms of runoff generation are considered for optimization.

Calibrated parameters BEXP, Brooke-Corey soil depletion curve exponent; DKSAT, Saturated hydraulic conductivity; DWSAT, Saturated soil matric potential; SMCMAX, Soil porosity; SMCREF, Soil field capacity; SMCWLT, Soil wilting point; KDT, Infiltration parameter–time scale factor.

Calibration procedure-algorithm SCE-UA

RRMT

GENERAL INFORMATION

Model acronym: RRMT
Model full name: Rainfall–Runoff Modeling Toolbox
Authors first publication: Wagener, T., Boyle, D. P., Lees, M. J., Wheater, H. S., Gupta, H. V. & Sorooshian, S. (2001). A framework for development and application of hydrological models. *Hydrol. Earth System Sci.* **5**(1), 13–26.
Original application domaine: Development and application of parsimonious rainfall–runoff models
Type: Lumped
Contact: Thorsten Wagener
Department of Civil and Environmental Engineering, 226B Sackett Building, The Pennsylvania State University, University Park, Pennsylvania 16802, USA
Email: thorsten@engr.psu.edu
Web site: http://www.engr.psu.edu/ce/divisions/hydro/wagener/index.html

MODEL DESCRIPTION

Brief model description A Rainfall–Runoff Modelling Toolbox (RRMT) has been developed within the scope of a model regionalization project to produce parsimonious, lumped model structures with a high level of parameter identifiability. Such identifiability is crucial if relationships between the model parameters representing the system and catchment characteristics (e.g. dominant soil types, land use, etc.) are to be established. RRMT is a modular framework that allows its user to implement different model structures to find a suitable balance between model performance and parameter identifiability. Model structures that can be implemented are lumped, relatively simple (in terms of number of parameters), and of metric (empirical), conceptual or hybrid metric-conceptual type. All structures consist of a moisture accounting and a routing module.

Main hydrological processes Depending on module chosen.

Rainfall–runoff module Empirical and conceptual soil moisture accounting structures. The choice is basically unlimited due to the modular structure of the framework.

Transfer function Both nonlinear and linear transfer functions are available. These include instrumental variable approach (after Peter Young), threshold structures, linear and nonlinear reservoirs, etc.

Groundwater/percolation module Depending on module chosen.

Additional components A snowmelt module is in preparation.

Model applications See References.

Schematic representation of model structure See Fig. 1.

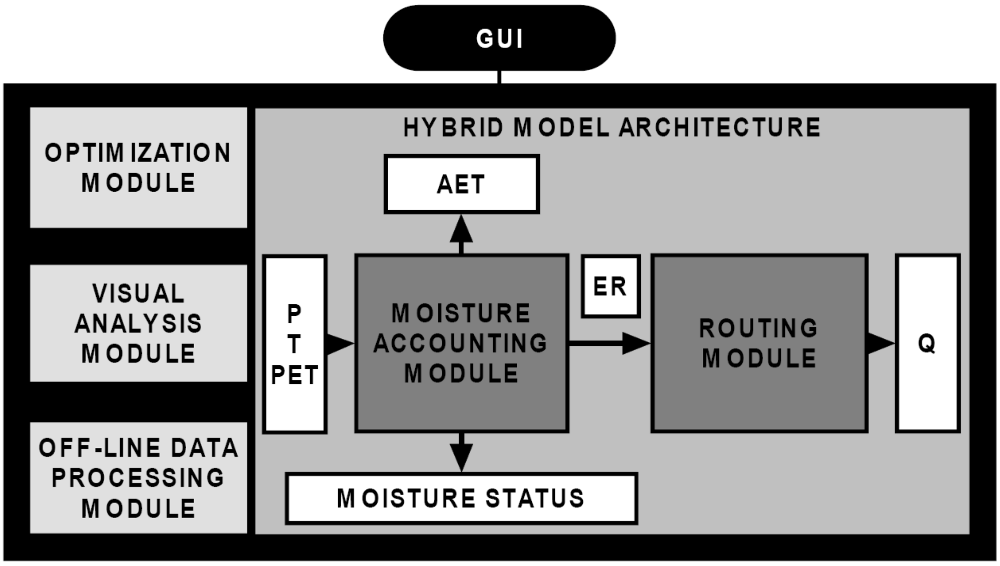

Fig. 1 Schematic representation of RRMT model structure.

DATA REQUIREMENTS; PARAMETERIZATION

Input data Rainfall/precipitation, temperature or potential evapotranspiration (depending on module chosen)

Overall model parameters Depending on module chosen

Sensitivity analysis results Depending on module chosen

Calibrated parameters Depending on module chosen

Calibration procedure-algorithm Currently: Monte Carlo Sampling, Latin Hypercube Sampling, Shuffled Complex Evolution Algorithm, Metropolis Algorithm

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Wheater, H. S., McIntyre, N. & Wagener, T. (2006) Calibration, uncertainty and regional analysis of conceptual rainfall–runoff models. In: *Hydrologic Modelling in Arid Regions* (ed. by H. S. Wheater, S. Sorooshian & K. D. Sharma). Cambridge University Press, Cambridge, UK (in press).

SAC-SMA

GENERAL INFORMATION

Model acronym: SAC-SMA
Model full name: Sacramento Soil Moisture Accounting model
Authors-first publication: Burnash, R. J., Ferral, R. L. & McGuire, R. A. (1973) A generalized streamflow simulation system conceptual modeling for digital computers, Technical Report. Joint Federal and State River Forecast Center, US National Weather Service and State of California Department of Water Resources.
Original application domain: River and flood forecasting
Type: Lumped
Contact: Michael Smith
Hydrology Laboratory, NOAA/NWS Office of Hydrologic Development,
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MODEL DESCRIPTION

Brief model description SAC-SMA is a conceptual rainfall–runoff model that simulates runoff response from a watershed, given precipitation and potential evapotranspiration input data. The runoff is consequently converted into streamflow through a unit hydrograph. The model is made up of six water storages, including two in the upper zone and three in the lower zone. The remaining water storage represents the water accumulated over the impervious area from partial saturation. There are 16 model parameters and six state variables. The key function is the percolation equation which determines how water percolates from the upper zone to the lower zone.

Main hydrological processes Direct runoff over impervious area; surface runoff when the upper zone is fully saturated; interflow from upper zone free water storage; primary and supplemental baseflow from the lower zone free water storages; evapotranspiration from all water storages.

Rainfall–runoff module Double storage/reservoir

Transfer function Unit hydrograph

Groundwater/percolation module Storage/reservoir model

Additional components No erosion and nutrients. Snow is represented in a separate model.

Model applications River and flood forecasting, water resources management, climate changes, etc.

Schematic representation of model structure See Fig. 1.

DATA REQUIREMENTS; PARAMETERIZATION

Input data Precipitation and potential evapotranspiration.

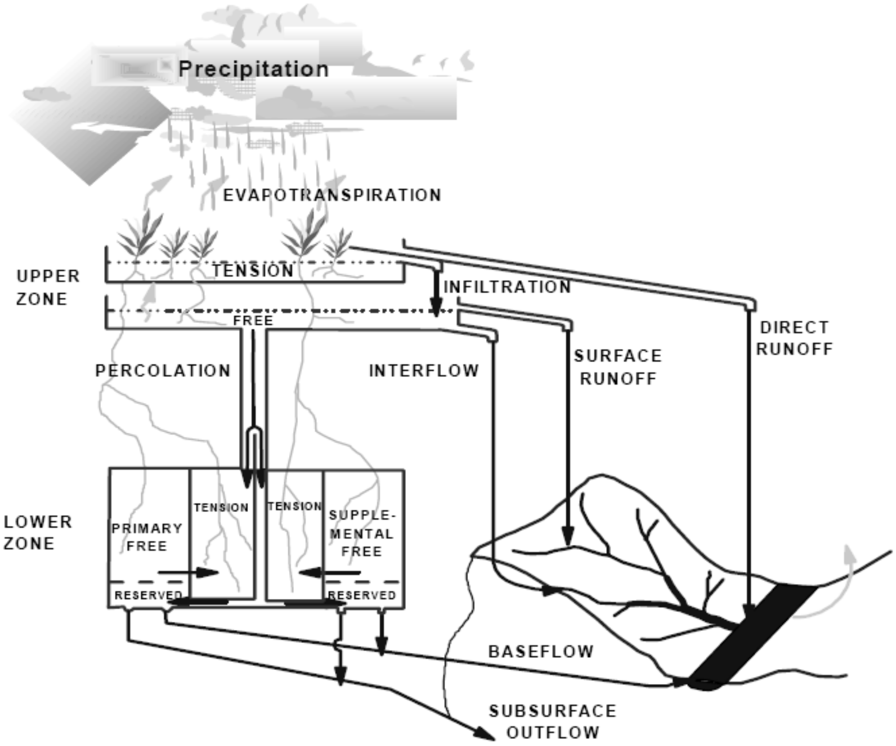

Fig. 1 Schematic representation of SAC-SMA model structure.

Overall model parameters UZTWM, Upper zone tension water storage capacity (mm); UZFWM, Upper zone free water storage capacity (mm); LZTWM, Lower zone tension water storage capacity (mm); LZFPM, Lower zone primary free water storage capacity (mm); LZFSM, Lower zone supplemental free water storage capacity (mm); ADIMP, Additional impervious area (fraction, unitless); UZK, Upper zone free water depletion coefficient (L day^{-1}); LZPK, Lower zone primary free water depletion coefficient (L day^{-1}); LZSK, Lower zone primary free water depletion coefficient (L day^{-1}); PCTIM, Percentage of impervious area (fraction, unitless); ZPERC, Percolation parameter–scaling; REXP, Percolation parameter–exponent; PFREE, Parameter controlling partition of percolated into free water storages and tension water storage; RSERV, Fraction of water not available for runoff or evapotranspiration; RIVA, Parameter controlling riparian water loss; SIDE, Fraction of water lost from river bed.

Sensitivity analysis results The model has 16 parameters, 13 of which are tuneable and included in the calibration.

Calibrated parameters UZTWM, UZFWM, LZTWM, LZFPM, LZFSM, ADIMP, UZK, LZPK, LZSK, PCTIM, ZPERC, REXP, PFREE

Calibration procedure-algorithm SCE-UA

REFERENCES

Burnash, R. J. C., Ferrell, R. L. & McGuire, R. A. (1973) A generalized streamflow simulation system. Jt. Fed.-State River Forecast Center, Sacramento, California, USA.

Burnash, R. J. C. (1995) The NWS River Forecast System—catchment modeling In: *Computer Models of Watershed Hydrology* (ed. by V. P. Singh), 311–366. Water Resources Publications, Highlands Ranch, Colorado, USA.

SMAR

GENERAL INFORMATION

Model acronym: SMAR
Model full name: Soil Moisture Accounting and Routing
Authors first publication: O'Connor, K. M, Goswami, M., Liang, G. C., Kachroo, R. K. & Shamseldin, A. Y. (2001) The development of the Galway Real-Time River Flow Forecasting System (GFFS). In: *Sustainable Use of Land and Water* (Proc. 19th European Regional Conference of the International Commission on Irrigation and Drainage, 4–8 June, Brno and Prague, Czech Republic) (available on CD).
Original application domain: Streamflow simulation and forecasting
Type: Lumped
Contact: Kieran Michael O'Connor
Department of Engineering Hydrology, National University of Ireland, Galway, Galway, Ireland
Telephone: +353 91 492213

MODEL DESCRIPTION

Brief model description The Soil Moisture Accounting and Routing (SMAR) model is a simple lumped conceptual rainfall–evaporation–runoff model.

In the SMAR model, the catchment is visualized as being composed of a set of horizontal soil layers, each of which may contain water up to a maximum depth of 25 mm (for daily data) except for the last (i.e. bottom) layer which may have a maximum depth <25 mm. The total combined water storage depth of these layers is a parameter (Z) of the model.

The evaporation input E to the model, when multiplied by a parameter T (<1), is converted to the estimate of the "potential evaporation demand rate (PE)", expressed as a depth.

Evaporation is considered to occur from the layers only when there is no rainfall or when the rainfall depth R is insufficient to satisfy the PE (= $T \times E$). Any evaporation from the first layer occurs at the full PE rate. On the depletion of the water depth in the first layer, any evaporation from the second layer occurs at the PE rate multiplied by the parameter C (<1). On the depletion of the water depth of the second layer, any subsequent evaporation from the third layer occurs at rate of C^2 and so on. Such evaporation would continue until either the storage of all the layers was depleted or the potential evaporation demand rate (PE) was accounted for.

When rainfall (R) exceeds the PE, runoff is generated. A fraction H' of the excess rainfall X (= $R - PE$) contributes to the generated runoff by producing the direct runoff component r_1. H' is given by $H' = H \times (W_{act}/W_{cap})$ where W_{act} is the total available water depth in the layers, W_{cap} is the maximum combined depth of all layers and H ($0 < H' < H$), which is a parameter of the model, is the constant of proportionality.

Any remainder of the excess rainfall X, after subtraction of r_1, which exceeds the maximum infiltration capacity Y, also contributes to the generated runoff as r_2. The remaining rainfall, after subtraction of r_1 and r_2, replenishes each soil layer in turn beginning from the first (i.e. top) layer downwards until either the rainfall is exhausted or all layers are full. Any still-remaining surplus is further divided into two fractions by a weight parameter G, the first fraction being the groundwater runoff component r_g and the second being the subsurface runoff component r_3. r_3 is added to r_1 and r_2 to produce the total generated surface runoff r_s. This r_s is routed through a two-parameter distribution function. Provision of three 2-parameter distribution function options are available, namely: the classic Negative Binomial distribution, the gamma distribution (Nash-cascade) model, and the Inverse Gaussian distribution, the Nash-cascade involving the shape parameter n and the lag parameter nK being that used in this study.

Main hydrological processes In the structure of the SMAR model, the main hydrological processes are grouped in two distinct complementary components. The first is the nonlinear water balance (soil moisture accounting procedure) component that keeps account of the balance between rainfall, evaporation, runoff and soil storage using a number of empirical and assumed functions which are physically plausible or at least physically inspired. The second is the routing component which simulates the attenuation and the diffusive effects of the catchment by routing through linear time invariant storage systems the different generated runoff components which are the outputs from the water balance part.

Rainfall–runoff module Lumped conceptual

Transfer function Either of three 2-parameter distribution functions, namely, the classic gamma distribution (Nash-cascade) model, its discrete counterpart—the Negative Binomial distribution, and the sharp-peaked Inverse Gaussian distribution.

Groundwater/percolation module Linear reservoir

Additional components None

Model applications Flow simulation, lead-time flow forecasting. The model is versatile, and has been used for flow modelling in catchments all over the world, covering a wide range of climatic types. Recent applications involve catchments from Ireland, France, India, China, Kenya, Bangladesh and Nepal (see References).

Schematic representation of model structure See Fig. 1.

DATA REQUIREMENTS; PARAMETERIZATION

Input data Observed rainfall, evaporation and discharge for flow simulation, Observed rainfall and evaporation over the forecast lead-times for flow forecasting.

Overall model parameters The version of the SMAR model used in this study has nine parameters. Five of these, namely T, H, Y, Z and C, control the overall operation of the water-budget component, one is a weighting parameter G for groundwater routing, and three are routing parameters, namely N, NK and Kg.

Sensitivity analysis results Normally Z is insensitive. The degree of sensitivity of the other eight parameters depends on the catchment system being modelled.

Calibrated parameters Some of the nine parameters of the model may be fixed at appropriately chosen values while the values of the rest are usually estimated

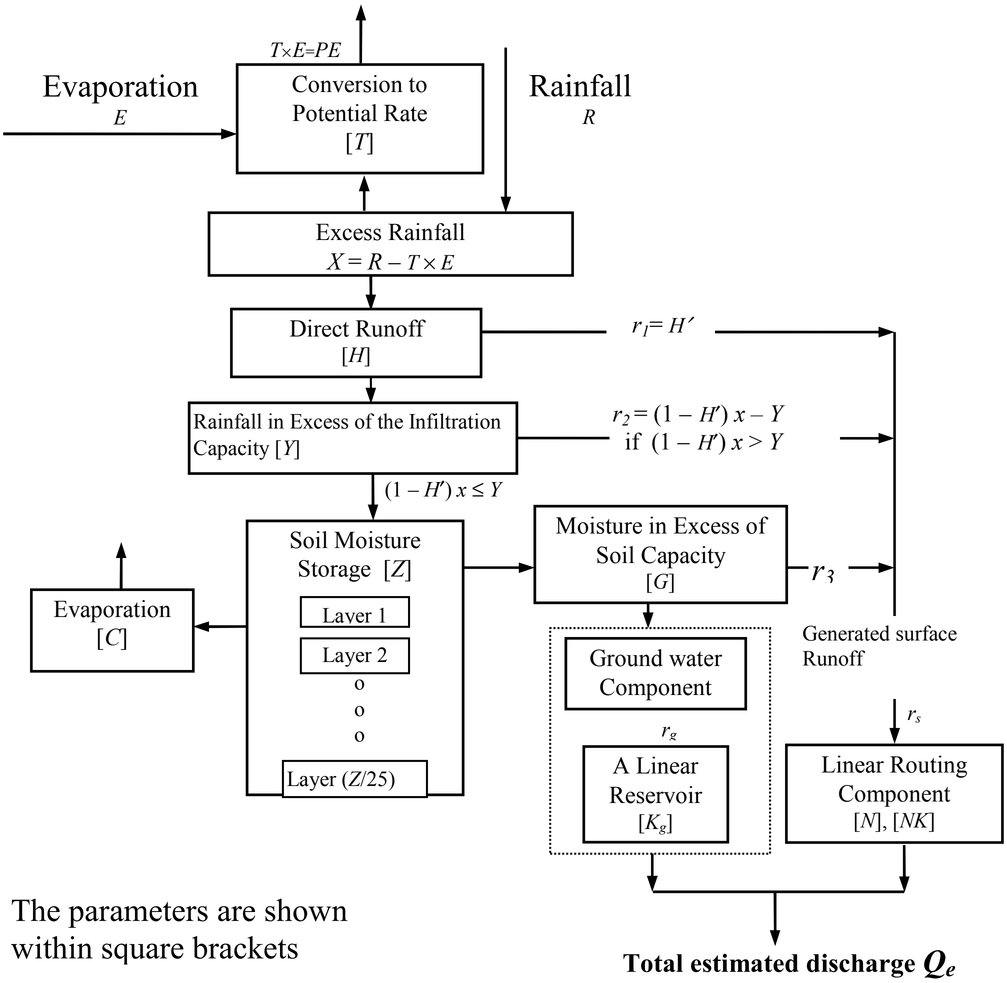

Fig. 1 Schematic representation of SMAR model structure.

empirically by optimization to minimize the selected measure of error between the observed and the model estimated discharges. All nine parameters may also be calibrated simultaneously.

Calibration procedure-algorithm Provision of five automatic optimization procedures/methods has been made. These methods are the Simplex search algorithm, the Rosenbrock direct search method, the Particle Swarm Optimization method, the Simulated Annealing method, and the Shuffled Complex Evolution algorithm. These may be used either individually or sequentially for model calibration.

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SWAP

GENERAL INFORMATION

Model acronym: SWAP
Model full name: Soil Water–Atmosphere–Plants
Authors first publication: Gusev, Ye. M. & Nasonova, O. N. (1998) The Land Surface Parameterization scheme SWAP: description and partial validation. *Global Planetary Change* **19**(1–4), 63–86.
Original application domain: Simulation of the components of energy and water balance, surface and subsurface state variables, evapotranspiration components.
Type: Land surface model
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MODEL DESCRIPTION

The SWAP model is a physically based land-surface model describing heat and water exchange between the land surface and the atmosphere throughout a year at different scales (from local to global) and oriented towards use of atmospheric forcings from the lowest atmospheric layer of GCMs or from any reference height. The main distinctive feature of SWAP is the combination of physically-based treatment of the main processes and the rationality of modelling technique used. The latter is provided by application of analytical methods (contrary to the usual practice of application of numerical ones) to solve the systems of equations and by a relatively small number of model parameters. This allows us to avoid many problems associated with solving the numerical equations (such as instability, great consumption of computer resources and calculational time, and so on) and parameter estimation.

Application of analytical methods has led to the non-traditional structure of SWAP. Thus, in SWAP, a calendar year is divided into the warm and cold seasons. For each season, a separate submodel was developed, then these two submodels were linked into one general model, named SWAP. The cold-season model is used only in the case of the fulfilment of, at least, one of the following conditions: (1) the mean daily air temperature is below 0°C continuously during several days (here, not less than 7 days); (2) the land surface is covered by snow; (3) the soil freezing depth is greater than zero. Otherwise, the warm-season submodel is used.

Main hydrological processes (1) interception of rainfall/snowfall by the canopy; (2) evapotranspiration (including transpiration by plants, soil/snow evaporation, evaporation of intercepted precipitation); (3) formation of snowpack on the ground and on the trees' crowns (including snow accumulation, snow evaporation, snowmelt, water yield of snow cover, refreezing of melt water); (4) formation of surface runoff; (5) formation of drainage; (6) water infiltration into a soil; (7) water exchange between soil layers; (8) interaction between soil water and groundwater.

Rainfall–runoff module Surface runoff in based on Hortonian mechanism (when precipitation rate exceeds infiltration rate).

Transfer function When runoff is simulated, the next problem is to transform it for simulating streamflow at the catchment (or calculational grid cell) outlet. For such a transformation we use an approach based on application of the concept of the 2-D kinematic wave.

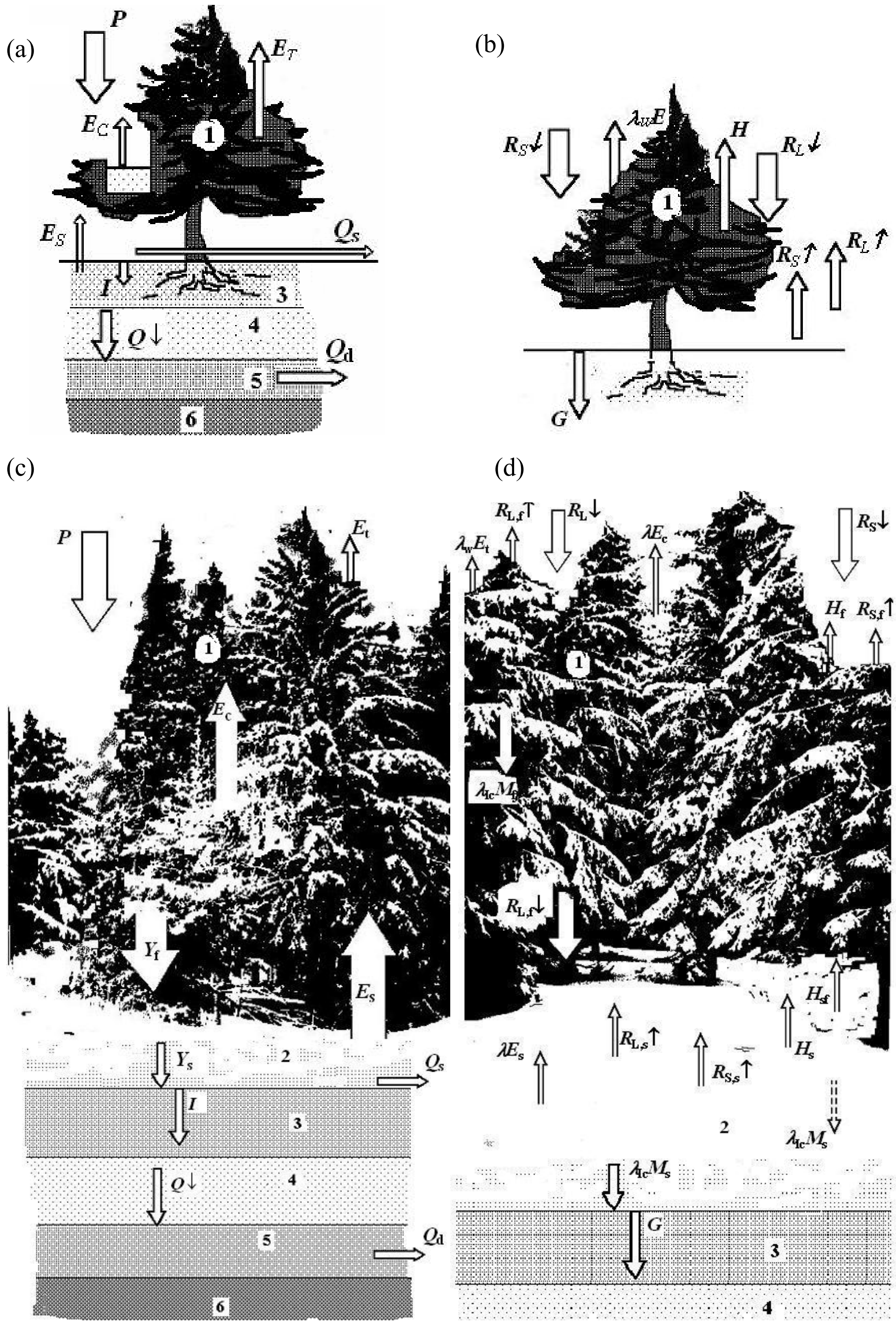
Groundwater/percolation module For parameterization of subsurface runoff the concept of saturation excess is used. Modelling the dynamics of the water table.

Additional components Snowpack formation on the ground and on trees' crowns; formation of energy balance; formation of the dynamics of soil freezing and thawing depths.

Model applications See Table below.

Purpose	Location	Climate	Reference
Participation in the international PILPS phase 2a experiment	The Netherlands (Cabauw)	Moderate maritime	Chen *et.al*., 1997; Gusev & Nasonova, 1998; Qu *et al*., 1998
Participation in the international PILPS phase 2c experiment	USA (Red-Arkansas River basin)	Subtropical (ranges from arid and semiarid in the west to humid in the east)	Wood *et al*.,1998; Lohmann *et al*., 1998; Liang *et al*., 1998; Gusev & Nasonova 2000
Participation in the international PILPS phase 2d experiment	Russia (Valdai, the Usadievskiy catchment)	Moderate continental	Gusev & Nasonova, 2000; Schlosser *et al*., 2000; Slater *et al*., 2001; Luo *et al*., 2003
Participation in the international PILPS phase 2e experiment	Sweden, Finland (Torne-Kalix River basin)	Moderate (transient from oceanic to continental), excessively humid	Bowling *et al*., 2003; Nijssen *et al*., 2003
Participation in the international Rhone AGG project	France (Rhone River basin)	Mediterranean, maritime-continental, alpine	Boone *et al*., 2004
Participation in the international SnowMIP project	France (Col de Porte), Switzerland (Weissfluhjoch)	Moderate highland	Etchevers *et al*., 2002, 2004
Participation in the international SnowMIP project	Canada (Goose Bay)	Moderate monsoon	Etchevers *et al*., 2002, 2004
Participation in the international SnowMIP project	USA (Sleepers River)	Moderate, sufficiently wet	Etchevers *et al*., 2002, 2004
Participation in the international MOPEX project	USA (12 MOPEX river basins)	Climate ranges from subtropical to moderate, from semi-arid to humid	Duan *et al*., 2006
Participation in the international PILPS-C1 experiment	The Netherlands (Loobos)	Moderate maritime	http://www.pilpsc1.cnrs-gif.fr/
Participation in the international PILPS San Pedro experiment	USA	Subtropical, semi-arid	http://ceefs2.cee.edu/PILPS-SanPedro/PILPS_SanPedro_prelim_v1.pdf
Simulation of soil water content in different ecosystems	Russia (the Kursk region, Petrinka)	Moderate continental	Gusev & Nasonova, 1998
Simulation of runoff from small catchment and river basin	Russia (Valdai, the Tayozhnyi catchment, the Polomet River basin)	Moderate continental	Gusev & Nasonova, 2002; Gusev, Nasonova & Busarova 2003
Simulation of runoff from small catchmets under permafrost and highland conditions	Russia (Kolyma River basin)	Sub arctic continental	Gusev & Nasonova, 2004; Gusev, Nasonova & Dzhogan, 2006
Simulation of the radiation and heat fluxes	USA (Oklahoma)	Subtropical, semi-arid	Gusev, Nasonova & Mohanty, 2004
Participation in the GSWP-2 Project	Globally	All	http://www.iges.org/gswp/

Schematic representation of model structure See opposite. Notation in Figure: representation of water ((a), (c)) and heat ((b), (d)) exchange processes in the natural ecosystem by the SWAP model for summer ((a), (b)) and winter ((c), (d)) seasons.



1, vegetation; 2, snow (on the ground and vegetation); 3, the first soil layer (root zone); 4, the second soil layer; 5, groundwater; 6, impermeable layer. Symbols are described in the list following.

List of symbols to schematic representation of model structure:

E	evaporation rate(kg m^{-2} s^{-1})
E_c	rate of evaporation of precipitation intercepted by a canopy (kg m^{-2} s^{-1})
E_s	evaporation rate from surface of soil or snow (kg m^{-2} s^{-1})
E_t	transpiration rate (kg m^{-2} s^{-1})
G	ground heat flux (W m^{-2})
H	sensible heat flux (W m^{-2})
H_f	sensible heat flux from the trees crowns to the atmosphere (W m^{-2})
H_s	sensible heat exchange between the forest floor and the atmosphere (W m^{-2})
H_{sf}	sensible heat exchange between the forest floor and forest crowns (W m^{-2})
I	infiltration rate (kg m^{-2} s^{-1})
M_s	the rate of melting snow on the ground (kg m^{-2} s^{-1})
M_f	the rate of melting snow on the trees' crowns (kg m^{-2} s^{-1})
P	precipitation rate (kg m^{-2} s^{-1})
Q	water exchange between soil and ground water (kg m^{-2} s^{-1})
Q_d	drainage (kg m^{-2} s^{-1})
Q_s	surface runoff (kg m^{-2} s^{-1})
$R_L\downarrow$	downward longwave radiation (W m^{-2})
$R_{L,f}\downarrow$	longwave emission by the trees crowns toward the forest floor (W m^{-2})
$R_{L,f}\uparrow$	upward longwave radiation emitted by trees' crowns (W m^{-2})
$R_{L,s}\uparrow$	upward longwave radiation from the forest floor (W m^{-2})
$R_S\downarrow$	downward shortwave radiation (W m^{-2})
$R_{S,f}\uparrow$	shortwave radiation reflected by trees' crowns (W m^{-2})
$R_{S,s}\uparrow$	shortwave radiation reflected by forest floor (W m^{-2})
Y_f	the rate of water yield of snow cover on trees' crowns (kg m^{-2} s^{-1})
λ =	$\lambda_W + \lambda_{Ic}$ (J kg^{-1})
λ_W	latent heat of vaporization of water (J kg^{-1})
λ_{Ic}	heat of ice fusion (J kg^{-1})

DATA REQUIREMENTS; PARAMETERIZATION

Input data

Forcing data incoming longwave and shortwave radiation, air temperature and air humidity, surface air pressure, wind speed, precipitation.

Overall model parameters See Table opposite

Sensitivity analysis results k_0, saturated hydraulic conductivity, (soil); h_{root}, root zone depth, (vegetation); W_{sat}, porosity, (soil); W_{fc}, water content at the field capacity, (soil); W_{wp}, water content at the plant wilting point, (soil); h_{soil}, the mean depth to the upper impermeable layer, (soil); α_{sn}, "Deep snow" albedo (snow); α_{vg}, Snow-free albedo of vegetation, (vegetation); $\alpha_{vg,sn}$, Albedo of vegetation with intercepted snow on crowns, (vegetation); LAI, SAI, leaf and steam area index (vegetation).

Calibrated parameters Usually we do not calibrate parameters. In the MOPEX experiment (Duan *et al.*, 2006) we have calibrated only one parameter (k_0).

Calibration procedure-algorithm In the MOPEX experiment, manual calibration was used.

Parameters	Symbol
Soil parameters	
Soil water content at the plant wilting point	W_{wp}
Soil water content at the field capacity	W_{fc}
Soil porosity	W_{sat}
Hydraulic conductivity at saturation	k_0
Matric potential of soil water at saturation	ϕ_0
"B" parameter of Clapp and Hornberger	B
Constant soil temperature at the depth where seasonal temperature variations are damped out (°C)	$\tilde{t}$
Snow cover parameters	
"Deep snow" albedo	α_{sn}
Roughness length of snow (m)	z_{0sn}
Vegetation parameters	
Depth of the soil root zone	h_{root}
Snow-free albedo of vegetation	α_{vg}
Albedo of vegetation with intercepted snow on crowns	$\alpha_{vg,sn}$
Effective linear leaf size (m)	l
Interception capacity of vegetation for liquid precipitation (m)	W_{cmax}
Interception capacity of vegetation for solid precipitation (m)	$S_{ch,max}$
Leaf area index	LAI
Stem area index	SAI
Roughness lenght of vegetation (m)	z_{0vg}
Zero plane displacement height (m)	d_0
Parameter β_v for the calculation of transpiration	β_v
Extinction coefficient	η
Other parameters	
The length of the catchment in the direction of mean slope (m)	Δx
The mean slope of watershed ($^0/_{00}$)	i_x
Effective Manning roughness coefficient ($m^{-1/3}$ c)	n
Mean depth from the surface to the impermeable layer (m)	h_{soil}

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SWB

GENERAL INFORMATION

Model acronym: SWB
Model full name: Simple Water Balance model
Authors-first publication: Schaake, J. C., Koren, V. I., Duan, Q. Y., Mitchell, K. & Chen, F. (1996) Simple water balance model for estimating runoff at different spatial and temporal scales. *J. Geophys. Res*. **101**(D3), 7461–7475.
Original application domain: River and flood forecasting
Type: Lumped
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MODEL DESCRIPTION

Brief model description SWB is a conceptual rainfall–runoff model that simulates runoff response from a watershed, given precipitation and potential evapotranspiration input data. The runoff is consequently converted into streamflow through a unit hydrograph. The model has two water storages, with a thin top layer and a thick lower layer. The top layer serves as an interception storage and only evapotranspiration occurs in the upper layer. Both runoff and evapotranspiration occur in the lower zone. There are five model parameters and two state variables.

Main hydrological processes Surface runoff when the precipitation exceeds infiltration capacity; baseflow from the lower water storages; evapotranspiration from all water storages.

Rainfall–runoff module Double storage/reservoir

Transfer function Unit hydrograph

Groundwater/percolation module Not included

Additional components No erosion and nutrients. Snow is represented in a separate model.

Model applications River and flood forecasting, water resources management, climate changes, etc.

DATA REQUIREMENTS; PARAMETERIZATION

Input data Precipitation and potential evapotranspiration

Overall model parameters DMAX, the max soil moisture deficit of bottom layer, in mm; KG, the potential subsurface flow, in mm day^{-1}; ALPSM, the bottom layer part which produces subsurface flow; ALPRT, the upper layer deficit proportion; KDT, the time scale factor.

Sensitivity analysis results The model has five parameters; all are included in the calibration.

Calibrated parameters Five parameters: DMAX, KG, ALPSM, ALPRT, KDT

Calibration procedure-algorithm SCE-UA

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VIC

GENERAL INFORMATION

Model acronym: VIC
Model full name: Variable Infiltration Capacity Macroscale Hydrologic Model
Authors first publication: Liang *et al.* (1994) A Simple hydrologically based model of land surface water and energy fluxes for GSMs. *J. Geophys. Res*. **99**(D7), 14 415–14 428.
Original application domaine: Streamflow simulation and hydrological forecasting
Type: semi-distributed land hydrological model
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MODEL DESCRIPTION

Brief model description VIC is a macroscale hydrological model that solves full water and energy balances, originally developed by Xu Liang at the University of Washington, USA. VIC is a research model and in its various forms it has been applied to many watersheds including the Columbia River, the Ohio River, the Arkansas-Red Rivers, and the Upper Mississippi Rivers, river basins in China, as well as being applied globally.

Main hydrological processes Soil moisture calculation; surface and subsurface runoff; evaporation; river routing.

Rainfall/runoff module A variable infiltration capacity concept based on soil moisture.

Transfer function The drainage is driven by gravity.

Groundwater/percolation module subsurface runoff follows the Arno model conceptualization.

Additional components Snowmelt module

Model applications See Reference list

Schematic representation of model structure See Fig. 1.

DATA REQUIREMENTS; PARAMETERIZATION

Input data Time series of rainfall, air temperature.

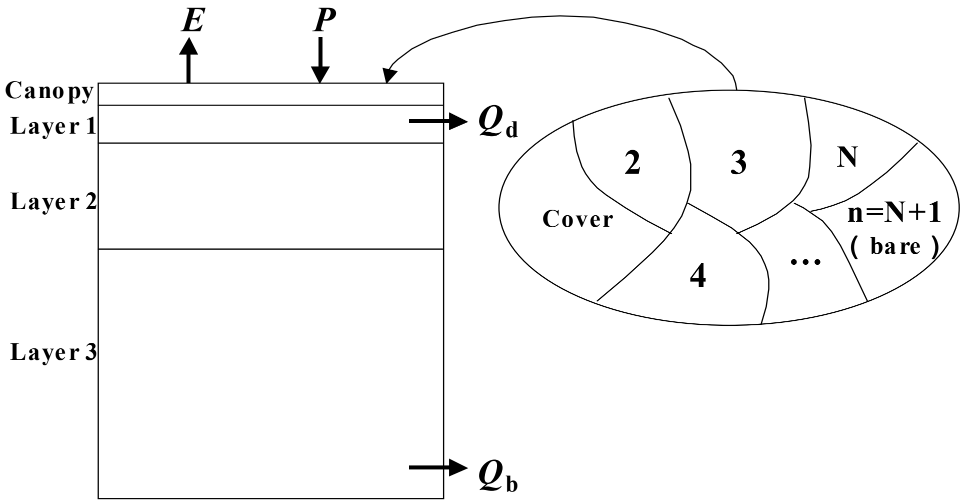

Fig. 1 Schematic representation of VIC model structure.

Overall model parameters

Parameter		Estimating method
Vegetation parameter	Architectural resistance Albedo Minimum stoma resistance Leaf area index Roughness length Zero-plane displacement	Literature
Soil parameter	Porosity Saturated soil potential Saturated hydraulic conductivity Exponent of unsaturated hydraulic conductivity curve Bulk density	Literature
	Exponent of variable infiltration capacity curve Three soil layer thicknesses Maximum velocity of baseflow Fraction of maximum baseflow Fraction of maximum soil moisture content of the third layer	Manual calibration

Sensitivity analysis results

Calibrated parameters Exponent of variable infiltration capacity curve; three soil layer thicknesses; maximum velocity of baseflow; fraction of maximum baseflow; fraction of maximum soil moisture content of the third layer.

Calibration procedure-algorithm During the calibration process, the infiltration parameter (*b*) and the depths of the three soil layers (d_1, d_2, d_3), which were treated as the primary calibration parameters, were changed to a uniform set of values in a given climate and large river basin zone. Calibrations were performed according to the following procedure: (a) set the estimated values for the depths of the three soil layers (d_1, d_2 and d_3), commonly with deeper depths for arid and semiarid regions and lower depths for humid regions; (b) calibrate the ARNO model parameters (D_m, D_s and W_s) so as to fit the low flow; (c) adjust the infiltration parameter b to match the observed flow peaks, with a higher value to increase the peak and a lower value to decrease the peak; (d) make a fine adjustment on these parameters to get the best simulation results. Consequently, after calibration the texture-based soil hydraulic parameters (k_s and θ_s) varied spatially, while b, d_i (i = 1, 2, 3), D_m, D_s and W_s were constant within each region. Generally, the thickness of the second soil layer was increased to allow for more storage. The calibrated infiltration parameter (b) tended to be smallest in the arid climates, in an effort to reduce runoff production.

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