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An introduction to the hydrological modelling system PREVAH and its pre- and post-processing-tools

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ABSTRACT

Spatially distributed modelling is an important instrument for studying the hydrological cycle, both concerning its present state as well as possible future changes in climate and land use. Results of such simulations are particularly relevant for the fields of water resources, natural hazards and hydropower. The semi-distributed hydrological modelling system PREVAH (PREecipitation-Runoff-EVApotranspiration HRU Model) implements a conceptual process-oriented approach and has been developed especially to suit conditions in mountainous environments with their highly variable environmental and climatic conditions.

This article presents an overview of the actual model core of PREVAH and introduces the various tools which have been developed for obtaining a comprehensive, user-friendly modelling system: DATAWIZARD for importing and managing hydrometeorological data, WINMET for pre-processing meteorological data, GRIDMATH for carrying out elementary raster data operations, FAOSOIL for processing FAO World Soil Map information, WINHRU for pre-processing spatial data and aggregating hydrological response units (HRU), WINPREVAH for operating the model, HYDROGRAPH for visualising hydrograph data and VIEWOPTIM for visualising the calibration procedure. The PREVAH components introduced here support a modelling task from pre-processing the data over the actual model calibration and validation to visualising and interpreting the results (post-processing). A brief overview of current PREVAH applications demonstrates the flexibility of the modelling system with examples that range from water balance modelling over flood estimation and flood forecasting to drought analysis in Switzerland, Austria, China, Russia and Sweden.

Software availability

Software name: PREVAH hydrological modelling system
Contact: prevah@giub.unibe.ch
Hardware requirements: Personal Computer
Software requirements: Windows 98/ME/NT/2000/XP/Vista
Coding language: Compaq Visual Fortran 6.6C
Availability: Sample project and extensive documentation at http://www.hydrologie.unibe.ch/PREVAH; for full version, contact authors via e-mail (see above)
Cost: Free for non-commercial academic research. Training courses are provided upon request

1. Introduction

In the past decade, spatially distributed modelling became an established tool for studying both components and possible changes of environmental systems. The hydrological cycle has great significance in these systems since it connects geology, ecology, atmosphere and society and involves basic sciences such as physics, chemistry and biology (Savenije, 2009). Furthermore, all of these aspects are integrated into a single response through runoff at the catchment's outlet. When the hydrological cycle is brought into focus, important fields for models are water resources in individual basins (e.g. Singh and Bengtsson, 2005; Christensen and Lettenmaier, 2007) and at global scale (e.g. Barnett et al., 2005; Viviroli et al., 2007a), natural hazards and extremes such as floods (e.g. Cameron et al., 2000; Lamb and Kay, 2004) and droughts (e.g. Zappa and Kan, 2007; García et al., 2008), hydropower (e.g. Bergström et al., 2001; Schaefli et al., 2007), and ecology (e.g. Zierl, 2001; Randin et al., 2006;

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Hannah et al., 2007). In order to understand the effects of changes in the system (e.g. climate, land use, population dynamics), it is of paramount importance to have models at hand which, through adequate representation of key processes, give the right answers for the right reasons under present conditions (Kirchner, 2006) and therefore provide reliable estimates for potential future conditions.

When we concentrate on hydrological processes at catchment scale, aforementioned adequacy calls for physically congruous hydrological models, including their careful parameterisation, calibration and evaluation (Gurtz et al., 2003; Refsgaard, 1997; Uhlenbrook and Leibundgut, 2002). Especially for mountainous catchments, simulation is a challenging task since the environment is characterised by highly variable morphology, soil and vegetation types as well as by pronounced temporal and spatial variations of the climatic elements (Klemeš, 1990; Gurtz et al., 1999; Weingartner et al., 2007). Depending on the location and elevation of a watershed, mountain discharge regimes are influenced by glacial melt, snowmelt, rainfall and their spatial and temporal superposition (Weingartner and Aschwanden, 1992). The quality of a hydrological simulation depends on the ability of the underlying model to describe and accurately represent the heterogeneity of such hydrological systems at the different spatial and temporal scales.

The semi-distributed hydrological catchment modelling system PREVAH (Precipitation-Runoff-Evapotranspiration HRU Model) has been developed to suit these conditions. Its main purpose is to describe the hydrological processes in mountain environments in their high spatial and temporal variability. With a view to keeping computational cost and complexity of process descriptions within reasonable bounds, PREVAH implements a conceptual, process-oriented approach.

In order to encourage its application, the actual model core of PREVAH (Gurtz et al., 1999, 2003) has been supplemented over the past few years by a large number of tools. These tools facilitate handling the large amounts of data involved in pre-processing and post-processing tasks, model parameterisation, calibration and evaluation as well as visualisation of results. This user-friendliness constitutes an important prerequisite for thorough and extensive modelling studies which are, for example, necessary for regionalisation, i.e. application of models in regions where calibration data are not available (Beven, 2007). Paired with the flexible modular structure, the easy applicability furthermore facilitates the incorporation of uncertainty and sensitivity frameworks (Beven and Freer, 2001; Campolongo et al., 2007; Refsgaard et al., 2007), identification of models or model components (Wagener and McIntyre, 2005; Bai et al., 2009), application of ensemble methodologies (Atger, 2004; Ahrens and Jaun, 2007; Roulin, 2007) as well as assimilation of novel data products such as soil moisture estimates from remote sensing (Vischel et al., 2008; Immerzeel and Droogers, 2008; Parajka et al., 2009) or radar-based precipitation estimates (Borga, 2002; Zhang et al., 2004; Kim et al., 2008; Germann et al., 2009).

After a short review of hydrological models and the position of PREVAH (Chapter 2), this article presents an overview of PREVAH's most important key features (Chapters 3 and 4) and describes the tools accompanying it (Chapter 5), altogether constituting a complete hydrological modelling system. An overview of selected applications demonstrates the abilities of PREVAH and the flexibility of its tools (Chapter 6). The presentation is completed with a discussion of PREVAH's strengths and limitations (Chapter 7) and an outlook (Chapter 8).

2. Development of hydrological modelling and position of PREVAH

Hydrological models are important tools for simulating the behaviour of catchments in space and time and provide important information to both scientists and policy makers. By means of mathematical equations, such models attempt to represent – in varying degree of detail – the complex interactions of water, energy and vegetation.

With the digital revolution which started in the 1960s it became possible to simulate different components of the hydrologic cycle and integrate them in a single model (Singh and Woolhiser, 2002). The first attempt in that direction was the pioneering Stanford Watershed model (Crawford and Linsley, 1966). Being a 'lumped' and process-oriented model, it represents entire landscape units as interconnected reservoirs for which hydrological fluxes and storage levels are computed and the mass balance is solved. Representatives of this model type are, among many others, the Sacramento Soil Moisture Accounting (SAC-SMA) model (Burnash et al., 1973; Burnash, 1995), the Hydrologiska Byråns Vattenbalansavdelning (HBV) model (Bergström, 1976; Lindström et al., 1997), the Tank model (Sugawara, 1967) or the Xinanjiang model (Zhao, 1977; Zhao and Liu, 1995). Spatially refined application of lumped models is achieved by sub-dividing a catchment into smaller landscape units or even raster grid cells. In spite of their strong conceptualisation, lumped models have proven to be robust and are therefore still very popular, particularly for flood forecasting and water resources planning and management. Moreover, they can cope with reasonable quantities of meteorological and physiogeographical input data and are therefore applicable in a wide range of environments.

A large number of more physically based and distributed modelling tools were devised since. An ambitious approach was pursued in the widely known Système Hydrologique Européen (SHE) (Abbott et al., 1986a,b) which follows the so-called Freeze–Harlan blueprint (Freeze and Harlan, 1969), thus departing from non-linear partial differential equations for different surface and subsurface processes. Another interesting concept is found in the popular TOPMODEL distributed simulation tool (Beven and Kirkby, 1979) which considers saturation excess to compute runoff formation; it is based on a topographic index which is calculated for each pixel. Interesting examples of recent developments of distributed models are the Water balance Simulation Model-ETH (WaSiM-ETH), a fully distributed model with a highly physical description of hydrological processes (Klok et al., 2001), the TOPographic Kinematic APproximation and Integration (TOPKAPI) model, a fully distributed and physically based hydrologic model (Liu and Todini, 2002), and the Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) model, an enhanced version of the two-dimensional, physically based model CASC2D which considers streamflow generation by both infiltration excess and saturation excess mechanisms, as well as exfiltration and groundwater discharge to streams (Downer et al., 2004). It would however be beyond the scope of this paper to deal in more depth with the large number of models available today. For a more comprehensive review, the reader is referred to Singh and Woolhiser (2002), Reggiani and Schellekens (2005), Singh and Frevert (2006) and Todini (2007).

PREVAH, in general, follows the HBV model structure and is process-oriented. The lumped formulation of the original HBV was however changed to semi-distributed by implementing hydrological response units (HRUs), which is a cost-efficient way of achieving spatially distributed results. Furthermore, PREVAH contains a number of improvements and extensions which concern the soil moisture accounting and evapotranspiration scheme, the interception module, the combined temperature-radiation modules for snow- and icemelt, distinct glacier storage modules for firn-, snow- and icemelt as well as a three-department groundwater module. These components are discussed in more detail in the following Chapter 3. A comparison against the fully distributed and more physically formulated WaSiM-ETH showed that PREVAH yields comparable results for both discharge and evapotranspiration in spite of its more conceptual processes representation. Differences were however found in the separation of runoff components which strongly depends on the formulation of the runoff generation modules (Gurtz et al., 2003).

The abovementioned improvements do not complicate application of PREVAH or significantly increase its data needs thanks to the comprehensive suite of tools (see Chapter 5). The model is therefore applicable in a wide range of geographic regions with reasonable effort.

3. Basics of the PREVAH model

3.1. Philosophy

PREVAH was originally intended to improve the understanding of the spatial and temporal variability of hydrological processes in catchments with complex topography. While aiming at a conceptual process-based representation of catchment hydrology, computational costs also had to be kept at a reasonable rate. At the same time, the model should be able to operate with data from a standard network of meteorological and hydrological stations (e.g. from a national hydrometeorological service) to ensure the application to a wide range of possible sites. Therefore, the widely known HBV model concept (Bergström, 1976; Lindström et al., 1997) was used as a basis and adopted with the semi-distributed approach of hydrological response units (HRUs; Ross et al., 1979; Gurtz et al., 1999).

Besides sub-models for interception (Menzel, 1997), soil water storage and depletion by evapotranspiration (Zappa and Gurtz, 2003), runoff and baseflow generation as well as for discharge concentration and flood-routing (Bergström, 1976), PREVAH also incorporates modules written specifically with view to representation of hydrological processes in mountainous areas, i.e. for snow accumulation and snowmelt (Zappa et al., 2003) as well as for glacial melt (Hock, 1999; Klok et al., 2001). The groundwater module was adopted from Schwarze et al. (1999) (see Gurtz et al., 2003). Fig. 1 shows the different modules with relevant inputs and outputs as well as the succession in which the modules are processed in the PREVAH model core. The internal time-step of PREVAH is always hourly. While this is at the same time the minimum temporary resolution, multiples are allowed for input and output (see also Chapter 5.1.2).

3.2. Tuneable model parameters

While some model parameterisations are assigned a priori through digital representations of the physiogeographical basin characteristics (see Sections 3.3 and 5.1.1) and relevant values from the literature (Thompson et al., 1981), a number of tuneable parameters need to be adjusted in PREVAH to the specific modelling site. Depending on module specifications (e.g. evapotranspiration modelling scheme or presence of glaciers within the investigated area), this number typically ranges between 14 and 19. These tuneable model parameters can be subdivided into six groups which are introduced below, following the model structure as to Fig. 2 from top to bottom.

3.2.1. Water balance adjustment

PKOR [%] and SNOKOR [%] are used to adjust the precipitation input in order to reduce the total discharge volume error of the model as observed at a catchment outlet. With this, a series of systematic errors in the modelling chain are addressed: (a) the wind-dependent gauge error correction (Sevruk, 1996); (b) spatial interpolation errors; (c) errors arising by the insufficient representativity of the available gauge networks; and (d) errors in the estimation of evapotranspiration. It has to be noted that in glaciated basins, adjustment of the water balance may also be achieved by increasing or diminishing ice melt rates; this increases markedly the number of suitable parameter combinations and therefore adds to the equifinality of the tuneable parameters (Beven, 2002; Stahl et al., 2008).

3.2.2. Discrimination between rain and snow

Precipitation is split into the liquid (rain) and solid (snow) fractions with the help of a threshold temperature (TGR [°C]). Additionally, a temperature range (TTRANS [°C]) is specified where a proportional mixing of rain and snow is assumed (linear relationship with 100% snow at TGR−TTRANS, 50% rain and 50% snow at TGR, 100% rain at TGR + TTRANS).

3.2.3. Snowmelt

Among different approaches implemented, the degree-day approach introduced by Hock (1999) is recommended for modelling snowmelt with PREVAH since it has proven highest efficiency in an in-depth comparison of four methods (including a physically based approach) for the spatially distributed simulation of snow hydrology at catchment scale (Zappa et al., 2003). Hock's approach incorporates a variable degree-day-factor which has a seasonal cycle between

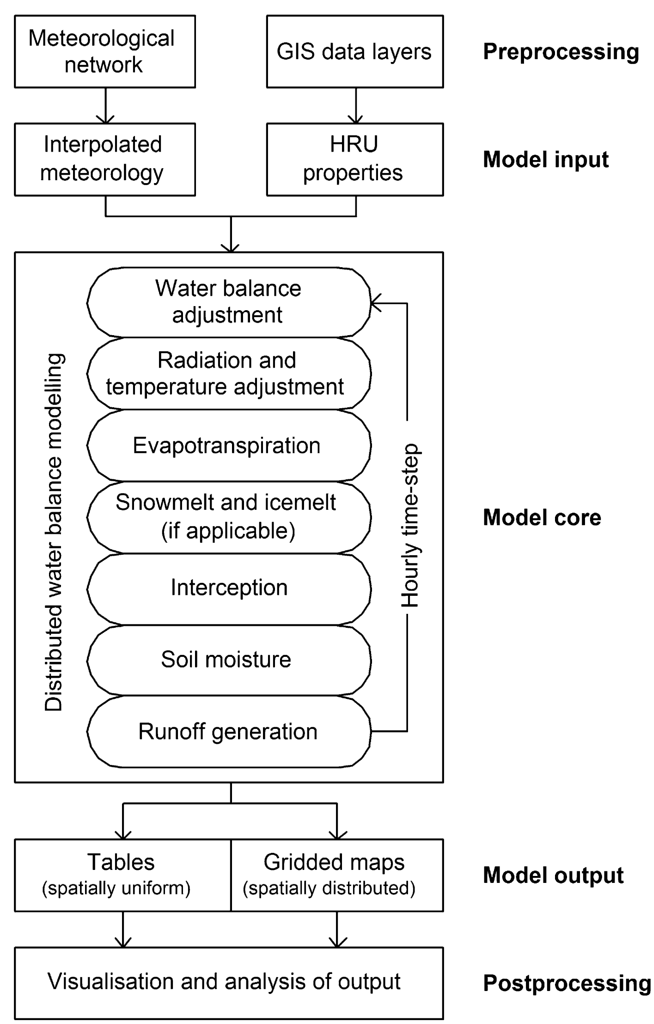

Fig. 1. Flow chart of data, modules and outputs for a PREVAH modelling task. For the corresponding tools see also Fig. 3.

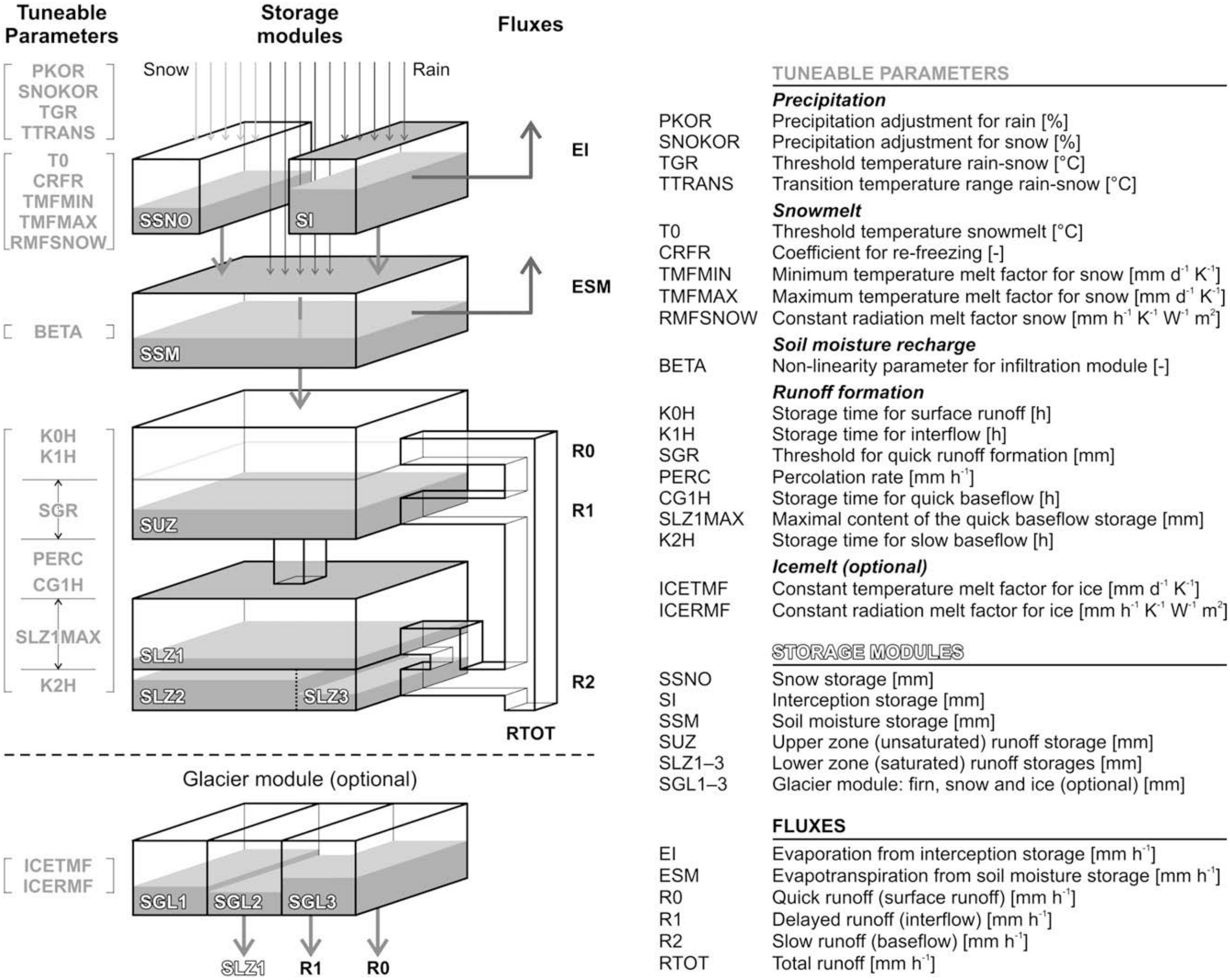

Fig. 2. Schematic of the PREVAH model structure with tuneable parameters, storage modules and hydrological fluxes.

TMFMIN [mm d^{-1} K^{-1}] and TMFMAX [mm d^{-1} K^{-1}]; snowmelt starts if the air temperature exceeds the threshold T0 [°C]. On the other hand, a radiation melt factor (RMFSNOW [mm h^{-1} K^{-1} W^{-1} m^2]) is combined with information on potential direct solar shortwave radiation. Retention of meltwater in snow is usually set to a fixed value of 10%, while re-freezing is controlled through a coefficient CRFR [–]. Further snowmelt modules have been implemented and are available to the user, e.g. the energy balance approach ESCIMO by Strasser et al. (2002) (see Zappa et al., 2003 for details)

3.2.4. Glaciers

If the catchment is glaciated, the glacier module is used, incorporating radiation and temperature melt factors for ice (ICETMF [mm d^{-1} K^{-1}] and ICERMF [mm h^{-1} K^{-1} W^{-1} m^2]; see Hock, 1999). Snowmelt on glaciers is treated with the variable degree-day-approach already used in the snowmelt module, with similar values each for TMFMIN and TMFMAX. The module contains separate storages for firn, snow and ice melt; while additional parameters for storage and translation times of these storages are available, they are usually set to default values (Klok et al., 2001; Koboltschnig et al., 2007).

3.2.5. Soil moisture

Here, the only tuneable parameter is the coefficient BETA [–] which controls infiltration as a function of actual soil moisture; the larger BETA, the more non-linear (delayed) the infiltration response to precipitation (Uhlenbrook, 1999). Various important soil characteristics (e.g. maximum soil moisture storage) are parameterised by PREVAH with the help of soil and land use parameters already during pre-processing (Gurtz et al., 1999; Viviroli et al., 2007b). Evapotranspiration, being a depletion term of soil moisture, is usually parameterised according to Penman (1948) and Monteith (1981) (see also Gurtz et al., 1999). This approach delivers a direct estimate for actual evapotranspiration, but demands detailed measurements of temperature, relative humidity, incoming global radiation, wind speed and sunshine duration. Alternatively, more simple approaches are available, such as the schemes developed by Hamon (1961), Turc (1961) or Wendling (1975) (see also Zappa and Gurtz, 2003).

3.2.6. Runoff generation

This module is based on the HBV model concept (Bergström, 1976; Lindström et al., 1997). Runoff generation in the soil's unsaturated zone is governed by storage times for surface runoff (K0H [h]) and interflow (K1H [h]). Baseflow is produced by the combination of two linear groundwater reservoirs (Schwarze et al., 1999) with a fast and a delayed component, defined by two distinct storage times (CG1H [h] and K2H [h]). A storage threshold (SGR [mm]) defines generation of surface runoff, while percolation rate (PERC [mm ΔT^{-1}]) and storage limit for the fast baseflow storage (SLZ1MAX [mm]) control the flux from the unsaturated to the saturated soil zone. Contrary to the original HBV being a lumped model, runoff generation has been adapted to a spatially distributed representation in PREVAH (see Gurtz et al., 1999, 2003).

3.3. Model input

Three types of input data are required to run PREVAH:

(1) Physiographical information for the hydrological response units (HRUs): on the one hand, this contains an ASCII-formatted table listing the physiographical properties of each HRU. These properties are used in PREVAH to parameterise various HRU properties, such as maximum storage contents and land surface characteristics (Viviroli et al., 2007b). On the other hand, a map locates the individual HRU positions for spatially distributed output. Both inputs are generated by PREVAH's pre-processing tool WINHRU (see Section 5.1.1).

(2) Meteorological input: PREVAH is fed with standard meteorological variables with high temporal resolution. Usually, this involves data on air temperature, precipitation, relative humidity (or water vapour pressure), global radiation, wind speed and sunshine duration in hourly or daily time-step. Following the semi-distributed model concept, these variables are provided as distinct average values for different altitude zones: after interpolation of the station values, the spatially distributed meteorological data are averaged to previously defined meteorological sub-areas. For small basins, these are usually coincident with 100 m elevation bands (Gurtz et al., 1999). For applications in larger river basins, further differentiation of the meteorological sub-areas (e.g. including both sub-basins and elevation bands) is recommended (Zappa, 2008). An ASCII-formatted table lists these values for each time-step. Station selection, interpolation and aggregation are handled by the WINMET tool (see Section 5.1.2).

(3) Control file: it contains the configuration of the tuneable model parameters which control the individual sub-models of PREVAH. Besides that, the control file contains all site-specific information required for modelling, e.g. the number of HRUs and altitude zones, initial storage contents, time-step and application timeframe, output options and calibration settings. Among further options, a built-in dialog for modifying the meteorological input with monthly factors is available which allows for representative climate change scenario analyses (Gurtz et al., 2005) by adopting the 'delta change method' (Hay et al., 2000).

4. Model calibration

As described above, PREVAH contains a number of tuneable parameters which are used to adjust the model to the conditions prevailing in a specific catchment. In practice, this means that the agreement between observed and simulated hydrographs has to be maximised by selecting a suitable set of such parameters. This is referred to as model calibration and is a key process in the application of hydrological models. Calibration is particularly difficult due to inherent limitations and uncertainties (input data, model structure, basin characteristics, process understanding and scaling issues), as a consequence of which a number of local optima exists rather than a global optimum. Model calibration is therefore a complex task and has received considerable attention over the years (for an overview see, e.g. Duan et al., 2003 and Gupta et al., 2005).

Initially, models were calibrated manually, which is time-consuming, partially subjective and only feasible by a trained and experienced user (Botterweg, 1995; Madsen et al., 2002). Therefore, automatic calibration procedures were devised. A first approach were so-called local search procedures which guide an initial parameter guess towards the direction of local improvement with an iterative strategy. This is achieved either by direct search, e.g. with the downhill simplex (Nelder and Mead, 1965), pattern search (Hooke and Jeeves, 1961), or rotating directions (Rosenbrock, 1960) algorithms or by gradient search, e.g. using the Gauss–Marquardt–Levenberg algorithm (as implemented, e.g. by Doherty, 2002). Because it was found that local search algorithms are unable to provide a reliable estimate of the global optimum, a variety of global search procedures were developed when more powerful computers became available. These global algorithms consider the entire feasible parameter space and iteratively evolve towards regions that show promising results. Popular examples are adaptive random sampling (Masri et al., 1980), simulated annealing (Aarts and Korst, 1989), controlled random search (Price, 1987) and the genetic algorithm (Goldberg, 1989). The shuffled complex evolution (SCE-UA) algorithm was later developed as a combination of local and global approaches (Duan et al., 1992).

PREVAH comprises an automatic objective calibration procedure which uses a straight-forward interactive global search algorithm (see Zappa and Kan, 2007; Viviroli, 2007). First of all, the parameters are grouped in pairs which relate to similar processes in order to consider common sensitivities. The grouping follows the model schematic from input treatment and melt processes over to fast and then slow components. With this, the most sensitive parameters are treated first. The parameter pairs are then processed consecutively: after dividing the parameter space into nine sections, the model is run for each of the four resulting intersection points. The four sections surrounding the point with the best model performance are retained, the other five discarded. In a next step, the remaining parameter space is processed similarly until a user-defined number of such iterations are reached or calibration improvements remain below a certain threshold. Since the parameters are treated pair-wise and not at once, multiple sequential runs of above parameter search algorithm are recommended (usually two to three runs) in order to allow all parameters to adjust to each other. The procedure can be repeated for different calibration periods and with additional configurations for specific portions of the hydrograph, e.g. with focus on flood peaks (Viviroli, 2007). This procedure is both transparent and cost-effective and was specifically developed for calibration of a large number of catchments by a single user (Viviroli, 2007).

Determining the model efficiency is essential for successful automatic calibration. Gauged data for runoff are usually the only measurement available to assess model efficiency, and they are compared to simulated runoff with help of an objective function. But particularly for complex models, using a single aggregate measure of model performance leads to the loss of information and therefore poor discriminative power (Wagener et al., 2001). Therefore, multiple-objective functions should be used to extract the maximum possible amount of information from the available data (Madsen, 2000; Seibert and McDonnell, 2002). One of the major strengths of PREVAH's calibration scheme is that it combines three standard efficiency scores with three different temporal ranges: Linear and logarithmic Nash–Sutcliffe efficiency (Nash and Sutcliffe, 1970) as well as the volumetric deviation are assessed over the entire calibration period and in their annual and monthly variations. This gives a set of nine objective functions which are mapped to a user-defined score range and then weighted to give a total score. While other search algorithms might find parameter sets with even higher efficiency scores, it was demonstrated by Viviroli (2007) that the parameter sets found by PREVAH's procedure show a high degree of stability and representativity for a large number of catchments with very varied properties.

5. Tools for pre-processing, model operation an post-processing

Setting up a model for a new catchment is often a time-consuming task which involves the extensive use of a geographic information systems (GIS) in order to create the necessary spatial information for running the model. Another obstacle to a quick application of models is the need to compile, process and interpolate data series from meteorological station networks. And finally, the interpretation of the model outputs (discharge hydrograph and further internal fluxes as well as state variables) usually requires extra software and is not as straight-forward as it would be desirable to verify the results. In the PREVAH modelling system, the tasks typically involved with pre-processing, running the model and post-processing are handled by adopting tailored tools with graphical user interface (GUI). On the one hand, this notably speeds up a modelling task, and on the other hand, specific (and often costly and complicated) extra software is not necessary. These components of the modelling system are introduced in the following paragraphs according to the order they will be used during a complete model application. Fig. 3 provides an overview of the tools in the usual workflow.

5.1. Pre-processing tools

5.1.1. Spatial pre-processing: WINHRU, GRIDMATH and FAOMAP

Two methods are most commonly adopted for the spatial discretisation of a watershed (Singh and Woolhiser, 2002): the grid-oriented approach and the response units approach. Grid-oriented hydrological models (Abbott et al., 1986a,b) assimilate the spatial information for cell-by-cell simulations from grids with a prescribed spacing. Response units based models (Ross et al., 1979; Flügel, 1995; Gurtz et al., 1999) rely on a physiographically oriented discretisation of the investigated domain into irregular-shaped hydrologically similar areas as determined by the ensemble of the soils, land surface and topographic characteristics. The necessary spatial information can be assimilated from a database consisting of a digital elevation model (DEM), a land use map and soil maps.

As mentioned above, PREVAH uses the concept of hydrological response units (HRUs) instead of a uniform raster-cell resolution. HRUs are clusters representing areas of the basin where similar hydrological behaviour is expected. In mountainous environments, it most advisable to assign to an HRU all the grid elements located in the same meteorological sub-unit (e.g. the same range of elevation), showing similar aspect, the same land-use classification and similar soil properties (Gurtz et al., 1999). In glaciated catchments, the equilibrium line of the glacier should also be considered in order to define whether grid cells are part of either the accumulation or the ablation area (Klok et al., 2001). The HRU-specific spatial information is stored in a table and assimilated by PREVAH during the model initialisation (see Figs. 1 and 3). The HRU size is smaller where the ensemble of soil, land surface and topographic characteristics shows higher spatial variability. Each HRU – and implicitly each grid cell – is finally provided with a set of parameters based on information derived from the DEM, from soil maps (plant-available soil field capacity, soil depth, hydraulic conductivity) and from digital maps of land-use and land surface characteristics. For determining evapotranspiration, additional canopy-specific parameter values are assigned a priori (e.g. albedo, rooting depth, interception storage capacity, vegetation height, leaf area index and minimum stomata resistance). Non-vegetated surfaces (snowpack, glaciers, rock, large water bodies and urban areas) are also parameterised a priori with specific parameterisations (Gurtz et al., 1999).

GRIDMATH provides elementary raster data GIS functions such as mathematical operations, overlaying and masking, zoning,

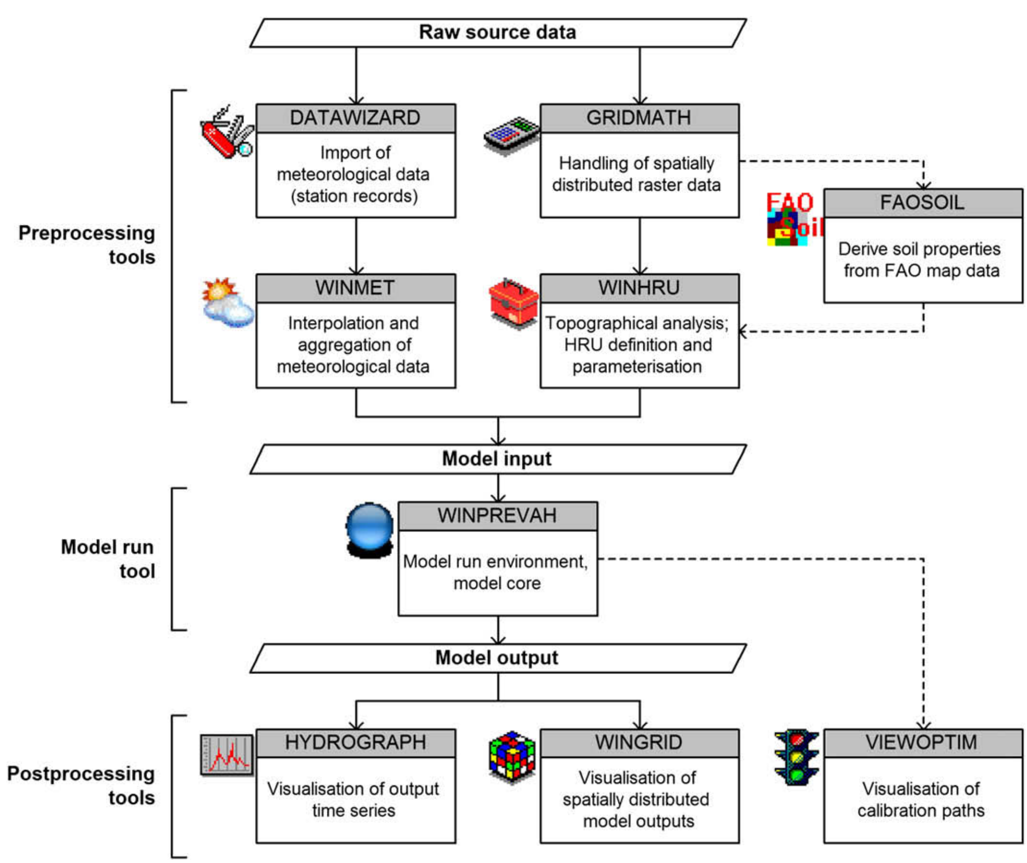

Fig. 3. PREVAH's pre-processing, model run and post-processing tools in their logical succession for a typical modelling task.

reclassifying, resampling, cropping and statistical analysis. PREVAH's internal proprietary raster data format is binary and structured similarly to the best-known ArcInfo ASCII format; it is used for all pre-processing inputs (see WINHRU, below and WINMET, Chapter 5.1.2) as well as for all spatially distributed model outputs. With import and export functions, GRIDMATH is able to link with commercial GIS and remote sensing applications.

WINHRU (Fig. 4) is a comprehensive tool for efficient clustering of hydrological response units (HRUs) and an essential pre-processing tool for PREVAH. First of all, the boundaries of a catchment have to be defined. Various methods are available for this: on the one hand, the boundaries may be derived from the digital elevation model's flow directions by either selecting a standard gauge location or by defining an arbitrary pour point. On the other hand, they may be transferred from any other GIS-formatted map file. For Switzerland, the catchment hierarchy of the Hydrological Atlas of Switzerland (Breinlinger et al., 1992) has been implemented additionally. To differentiate the actual HRUs, several criteria are available: sub-catchments, elevation bands, aspect, slope, land use, soil type, topographic index, glaciated area (Klok et al., 2001) and, if available, geology. The source data necessary for distinction of these criteria are read from raster-formatted files for elevation, land use and soil properties; for the elevation layer, a topographic

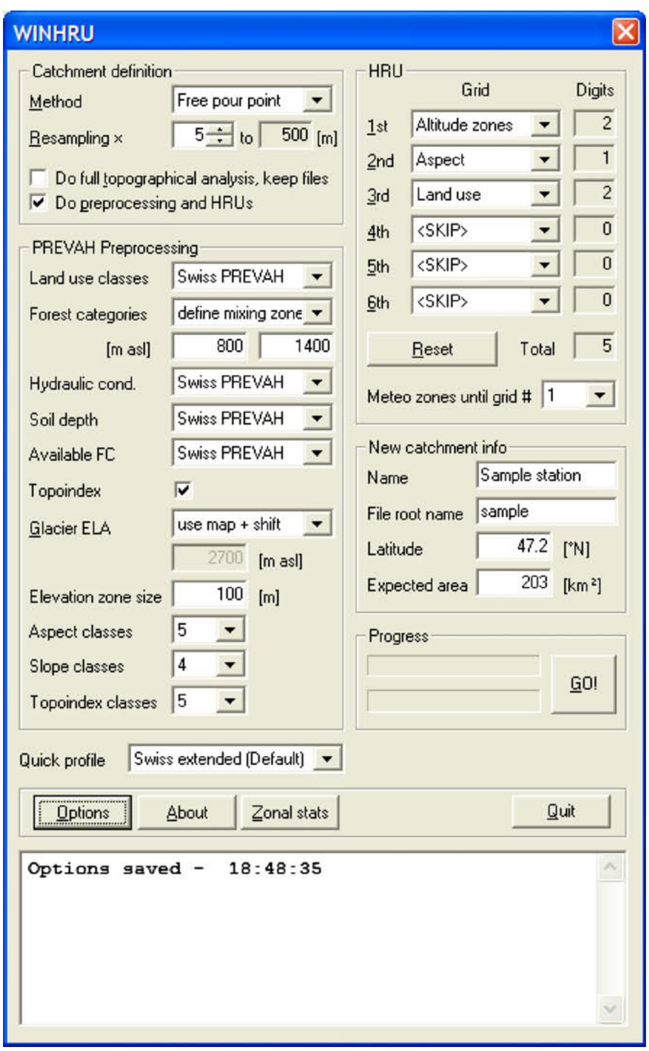

Fig. 4. WINHRU main dialog used for specifying aggregation of hydrological response units (HRUs) and pre-processing of physiographic data.

analysis (Binley and Beven, 1993) is performed to derive the required topography-related maps (e.g. aspect and slope). The data may be complemented with extra layers if desired (e.g. with hydrogeology maps). Once all other settings such as co-ordinate system (metric), resolution, number of altitude zones, etc. have been defined, WINHRU builds a HRU properties table and a distributed grid map of HRU identifiers and initialises the PREVAH control file with the necessary configuration. WINHRU requires only a few seconds for compiling a complete HRU dataset. For application of a model to an extensive number of sites (such as in Viviroli, 2007 for 140 catchments in Switzerland), this is an invaluable time saving. While this tool is by default set up for application in Switzerland, it may also be configured for processing information from other regions of the world (see Chapter 6). The input raster data required for this may be created and handled with the additional tools GRIDMATH and FAOSOIL.

One of the most difficult tasks is to determine values for soil depth and plant available field capacity which in turn are important to estimate how much water is available for evapotranspiration. For places where no local soil maps are available, these values are determined from soil classes contained in the FAO Soil Map of the World (FAO, 1988) with help of the FAOSOIL tool. A simple index based on slope elevation and land use is adopted in order to spatially disaggregate the soil properties according to soil depth and plant available field capacity classes in the different FAO soil units (Viviroli et al., 2007b). It is assumed that the deepest soils and the soils with highest plant available field capacity are located at lower altitudes and in flatter areas of the domain. Additional restrictions depend on land use. Shallow soils are assigned to grid cells representing water bodies, rocky areas, urban areas and glaciers.

5.1.2. Meteorological pre-processing: WINMET, DATAWIZARD

In PREVAH, the deterministic semi-distributed hydrological simulations rely on observations of meteorological variables at different gauging stations within or near the area under investigation. While the station data are interpolated on a spatial raster, they are passed on to PREVAH in form of ASCII-formatted tables which specify sums or averages of the respective variables for altitude bands with a pre-defined interval (usually 100 m vertical extent), the so-called meteorological zones. These data have to be processed for each time-step. The full system can be run with meteorological forcing in time-steps of 1, 2, 3, 4, 6, 8, 12 and 24 h. Furthermore, it is possible to operate PREVAH with hourly information for temperature, wind speed and precipitation and daily data for other variables such as global radiation and sunshine duration.

The pre-processing tool WINMET has been developed to select and interpolate the meteorological information as required by PREVAH. WINMET requires grids generated by WINHRU, namely a digital elevation model of the basin, a watershed mask and a map of the relevant meteorological sub-areas.

The selection of the meteorological stations to be used for interpolation is assisted with the help of a search radius; this preliminary choice is then evaluated and completed interactively.

The basic procedures adopted for the spatial and temporal interpolation of observed meteorological information are elevation-dependent regression (EDR), inverse distance weighting (IDW), Kriging (KRG) and a simple elevation lapse-rate (LPR, only for temperature data). It is possible to combine EDR with Kriging or IDW, resulting in a detrended interpolation: For this, the residuals (difference between interpolated and observed value) of the EDR method are spatially interpolated with IDW or Kriging. By adding this interpolated residual map to the map interpolated with EDR, interpolation biases at the station locations are adjusted spatially (see Garen and Marks, 2001). Our experiences concerning which spatial interpolation procedure to use for which meteorological variable are reported in Table 1.

For importing and managing hydrometeorological data from a station network, the DATAWIZARD tool is available. It provides a link to WINMET and processes all relevant meteorological variables (see Table 2), storing them in a simple ASCII database. Additionally, it includes a simple plausibility test for the data (Behrendt, 1992). Extensive checks for data plausibility and homogeneity should be carried out before processing the data with DATAWIZARD, however.

5.2. Model operation tool: WINPREVAH

The WINPREVAH tool is the graphic user interface of the actual PREVAH model core. It links both spatial data and hydrometeorological information (as generated during pre-processing) to the model physics and is the starting point for simulations of the complete hydrological cycle of a catchment.

Several sub-dialogs allow of editing all information relevant to control a model run. Most importantly, the user is able to directly access and alter the model parameters and select the module parameterisations (e.g. evapotranspiration scheme, snowmelt routine) (Fig. 5). Also details for model evaluation (efficiency scores, e.g. Nash and Sutcliffe, 1970) and degree of detail for the model output are easily changed.

WINPREVAH also controls the automatic calibration routine which has been designed specifically for PREVAH through a number of objective efficiency scores (cf. Chapter 3). Furthermore, WINPREVAH is able to infer Monte Carlo simulations with random allocation of the most sensitive tuneable model parameters; this enables estimation of parameter uncertainty (cf. Beven, 2001).

The flux rates and fill levels available for every time-step and for every HRU (i.e. spatially distributed) are listed in Table 3. These variables can also be stored in files which are used for re-initialisation of the model with prescribed initial conditions.

5.3. Post-processing tools

5.3.1. Hydrograph display: HYDROGRAPH

HYDROGRAPH draws time series of observed and modelled data and of modelled water balance components as simulated by PREVAH (Fig. 6). The original PREVAH model outputs come as various ASCII-formatted tables. Depending on the output type and the specifications chosen before running the model, these tables contain observed and modelled runoff data or comprehensive data from model inputs, modelled water fluxes, model storage contents and model outputs. Instead of interpreting these tables with commercial data processing packages, HYDROGRAPH quickly visualises and compares model and observation data. When displaying water balance data, two arbitrary variables may be compared with the help of a drop-down menu (cf. Table 3). When displaying observed and simulated runoff, an additional flood frequency statistics diagram is generated in a second plotting area. Additionally, statistics on model efficiency are available.

5.3.2. Raster map display: WINGRID

WINGRID is used to visualise raster maps such as spatially distributed model outputs which PREVAH generates from the HRU-related results (Fig. 7). As explained in Chapter 5.1.1, PREVAH implements a binary grid file format for raster maps. WINGRID is used for quick visualisation, verification and interpretation of these raster data. It will handle any binary PREVAH grid map and identify its contents on basis of 80 known file extensions which comprise all pre-processing and model operation outputs. Besides various display options, it also features a simple grid editor which can, e.g. be used to modify pre-processing input data. For export to ESRI ArcGIS and Clark Labs IDRISI, an export module to is available; further grid operations may be performed with GRIDMATH (see Chapter 5.1.1)

5.3.3. Calibration interpretation: VIEWOPTIM & DOTTYPLOT

VIEWOPTIM (Fig. 8) facilitates interpretation and assessment of a calibration conducted by PREVAH's built-in procedure. Despite being an automatic procedure, PREVAH's calibration needs to be supervised. More specifically, the results should always be examined by expert judgement to avoid non-optimal calibrations.

As described above, PREVAH's calibration scheme treats parameters pair-wise. Consequently, VIEWOPTIM allows various efficiency scores to be displayed for two parameters at a time. This makes it possible to verify whether the iterative process resulted in a steady increase in efficiency. Problems such as parameters approaching the limits of the chosen parameter space are easily identified as well.

In addition to verifying the calibration course with VIEWOPTIM, the calibration results should also be verified. This concerns verification of standard efficiency scores, comparison of simulated and observed discharge curves and ensuring the plausible behaviour of the model's conceptual storage modules. All of these tasks may be performed using HYDROGRAPH.

A companion tool to VIEWOPTIM is DOTTYPLOT, which is designed for displaying the log-files generated by WINPREVAH when inferring Monte Carlo simulations. The log-files can be adopted for estimating parameter uncertainty and to discriminate behavioural from non-behavioural parameter sets (see Bosshard and Zappa, 2008).

6. Selected applications

In Table 4, a number of selected successful applications of the modelling system PREVAH are presented. All of them were elaborated using the various tools introduced above and illustrate the flexibility of the system. Besides the 'classical' application for water balance investigations (Zappa and Pfaundler, 2008), the further examples demonstrate amongst other the potential of using PREVAH in flood estimation (Viviroli, 2007), flood forecasting (Zappa et al., 2008) and analysis of single flood events (Schwanbeck et al., 2008), including sensitivity analyses concerning model input and

Table 1
Suitable interpolation methods.

Variable	EDR + IDW	EDR	IDW	KRG	EDR + KRG	LPR + IDW	LPR + KRG
Precipitation	Careful	No	Yes	Yes	Careful	No	No
Air temperature	Yes	Careful	Careful	Careful	Yes	Yes	Yes
Global radiation	Yes	Careful	Yes	Yes	Yes	No	No
Wind speed	Yes	Careful	Careful	Careful	Yes	No	No
Sunshine duration	Yes	Careful	Yes	Yes	Yes	No	No
Relative humidity	Yes	Careful	Careful	Careful	Yes	No	No
Water vapour pressure	Yes	Careful	Careful	Careful	Yes	No	No

Abbreviations are explained in the text.

Table 2
Units conversion table for meteorological variables as supported by DATAWIZARD.

Variable	Abbrev.	Units supported
Precipitation	prec	**[mm]**, [$^1/_{10}$ mm]
Air temperature	tair	**[°C]**, [0.1 °C], [°F], [K]
Wind speed	wspd	**[m s^{-1}]**, [0.1 m s^{-1}]
Global radiation	radg	**[W m^{-2}]**, [J cm^{-2}]
Relative humidity	rhum	**[–]**, [%], [‰]
Water vapour pressure	vapo	**[hPa]**, [0.1 hPa]
Sunshine duration	sund	**[–]**, [min], [0.1 h], [h]
Runoff	runo	**[mm]**, [l s^{-1}], [m^3 s^{-1}]

The default units are marked bold.

parameter sets. With a recently developed regionalisation scheme (Viviroli, 2007), it is possible to estimate the tuneable model parameters for arbitrary meso-scale catchments in Switzerland without calibration.

Although the main focus of PREVAH applications is Switzerland, the modelling system or parts of it have also been used successfully in mountainous regions of Austria, China, Germany, Italy, Kenya, Kyrgyzstan, Russia, Sweden, the United States and Uzbekistan. A more extensive overview of applications is provided by Viviroli et al. (2007b).

7. Discussion of PREVAH's strengths and limitations

As already noted in Chapter 2, a large number of watershed models are available, and one or more models are found for almost any scientific or practical question. In order to place PREVAH within this context and provide a concise review of its strengths and limitations, the model is discussed below following a list of pervasive deficiencies of today's models which was conceived by Singh and Frevert (2006).

- *User-friendliness*: this is one of the major strengths of the non-commercial PREVAH. A number of tools with intuitive graphical user interface are available for all relevant steps from data collection over to pre-processing, calibration, operation and finally post-processing. Furthermore, the most important input and output data are easily imported in standard GIS or data processing programs. This should however not raise the expectation that working with PREVAH is similar to commercial GIS software.
- *Data requirements*: when operated with the detailed Penman–Monteith evapotranspiration scheme, PREVAH requires extensive meteorological input data at high temporal resolution. This is however not a limitation since more simple evapotranspiration formulae are readily available (see Chapter 3.2) and allow for application in regions where meteorological observations are scarce. The required physiogeographical data are ideally derived from regional or national maps, but they can also be aggregated from the FAO Soil Map of the World with specific tools (see Chapter 5.1.1).
- *Quantitative measures of reliability*: PREVAH's multi-objective score system addresses the problem of limited information availability with focus on calibration (see Chapter 4). Furthermore, objective functions have been devised and applied for testing the snow and soil moisture modules (Zappa and Gurtz, 2003; Zappa et al., 2003; Zappa, 2008). More sophisticated analyses of reliability and uncertainty (such as proposed, e.g. by Wagener et al., 2003) are however beyond the scope of PREVAH.
- *Clear statement of limitations and clear guidance as to the conditions for applicability*: the main limitations of PREVAH concern small catchments ($<$10 km^2). There, application of the model is currently not advisable due to the conceptual description of runoff processes, direct routing of HRU response to the catchment outlet and hourly time-stepping. Large

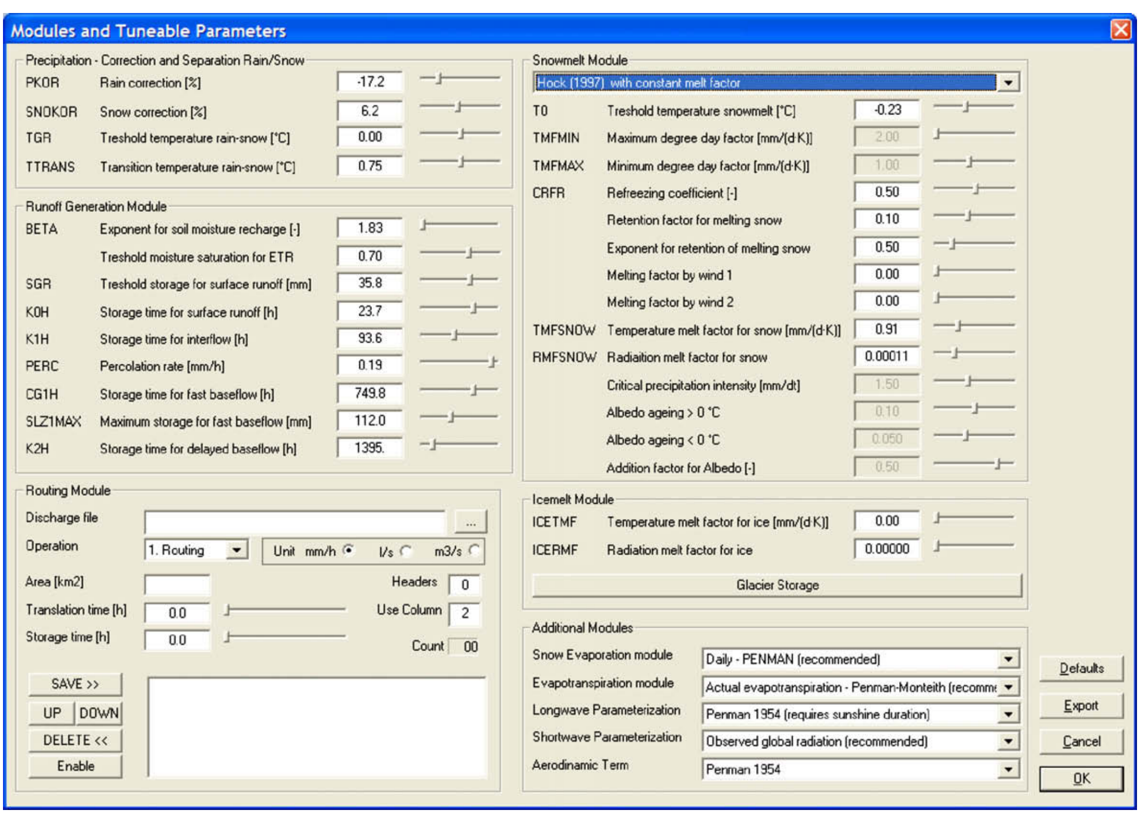

Fig. 5. WINPREVAH graphical user interface sub-dialog for editing parameter values and selection of module parameterisations.

Table 3
Flux rates and storage levels available from a PREVAH model run for each time-step (ΔT) and each raster cell.

Variable
Interpolated and adjusted precipitation [mm ΔT^{-1}]
Snowmelt [mm ΔT^{-1}]
Potential evapotranspiration [mm ΔT^{-1}]
Actual evapotranspiration [mm ΔT^{-1}]
Interception evaporation and snow evaporation [mm ΔT^{-1}]
Transpiration and soil evaporation [mm ΔT^{-1}]
Surface runoff [mm ΔT^{-1}]
Interflow [mm ΔT^{-1}]
Total baseflow [mm ΔT^{-1}]
Total runoff [mm ΔT^{-1}]
Snow water equivalent [mm]
Interception storage [mm]
Plant available soil moisture storage [mm]
Runoff generation storage (unsaturated zone) [mm]
Runoff generation storage (saturated zone) [mm]
Balance from previous time-step [mm ΔT^{-1}]
Ice melt [mm ΔT^{-1}]
Fast response baseflow [mm ΔT^{-1}]

catchments (>1000 km^2) should be composed of simulations of a number of sub-catchments which are linked by a suitable routing scheme (Verbunt et al., 2006; Schwanbeck et al., 2008; Bosshard and Zappa, 2008). Limitations also apply for arid and semi-arid regions for which PREVAH currently contains no specific process descriptions. Furthermore, the HRU structure is not optimal for land use change studies since any shift in land use distribution requires re-processing of the spatial data with WINHRU (e.g. Koboltschnig et al., 2007).

8. Summary and outlook

With PREVAH, a spatially distributed model is available for simulating the relevant components of the hydrological cycle with special focus on mountainous environments. The computational core of PREVAH has been steadily extended with new components and tools that allow of a user-friendly application of the model. Currently, PREVAH has grown into a fully functional modelling system able to manage all the tasks necessary for its application. Tools are available for the pre-processing, management and interpolation of the required meteorological information as well as for the transformation, parameterisation and pre-processing of the physiogeographical spatial information. An in-built automatic calibration routine significantly reduces the amount of user intervention that is usually required for tuning the model parameters, and Monte Carlo model runs can be started, e.g. in order to obtain estimates of parameter uncertainties. Finally, tools have been developed to visualise and interpret the various model outputs (grids, tables and outputs of the calibration module).

Thanks to the transparent data structure, the pre- and post-processing tools introduced here can be also adopted for modelling tasks using the WaSiM-ETH (Klok et al., 2001; Gurtz et al., 2003) and the Alpine3D models (Lehning et al., 2006).

Future developments are envisaged in various areas. With a view to better representation of flash floods in small catchments,

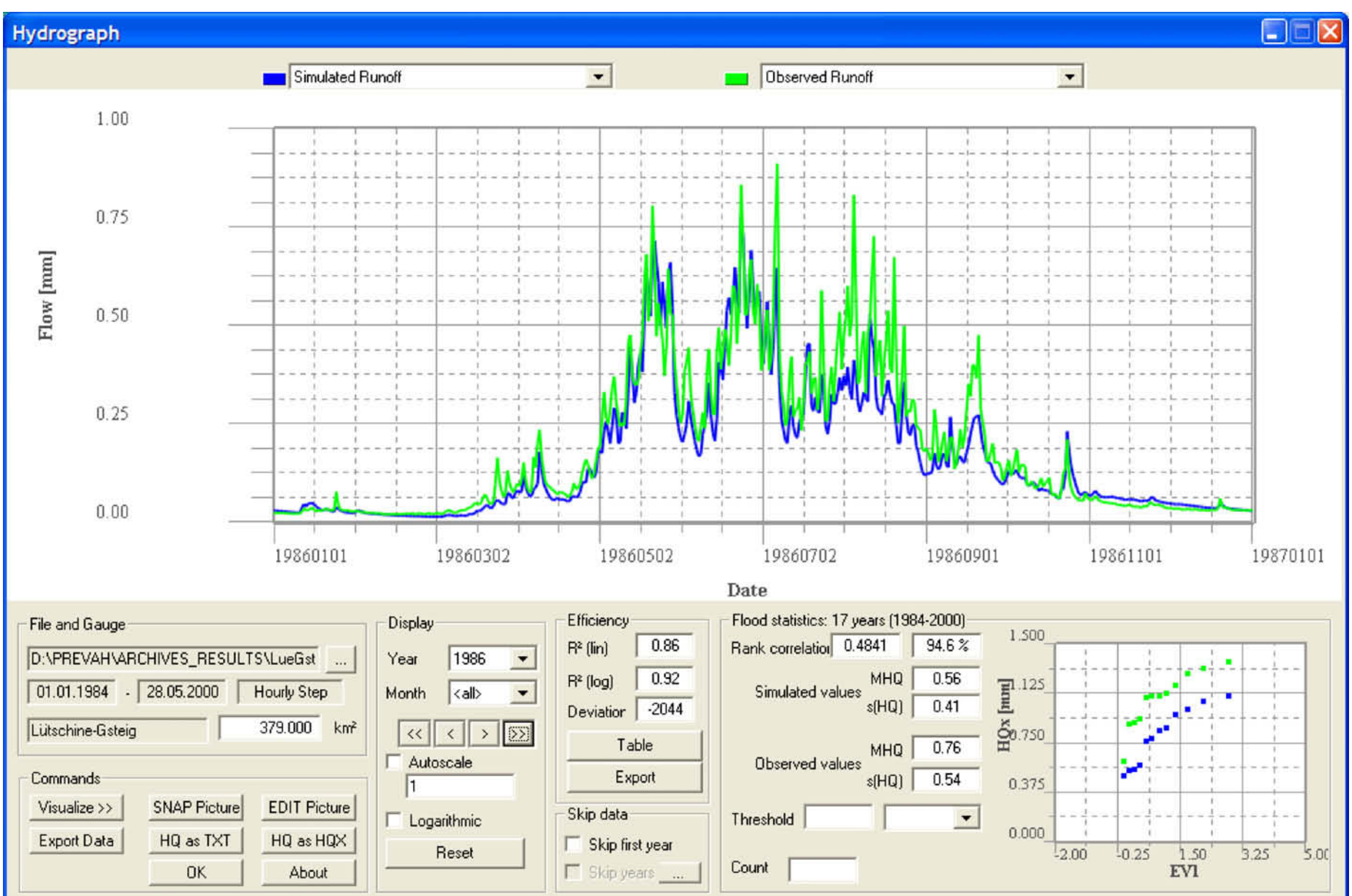

Fig. 6. HYDROGRAPH graphical user interface for visualisation and evaluation of complete model runs. While the present graph shows hourly observed and simulated data, HYDROGRAPH can also display flux rates and storage levels as computed by PREVAH (cf. Table 3). In the lower right of the window, flood statistics are displayed.

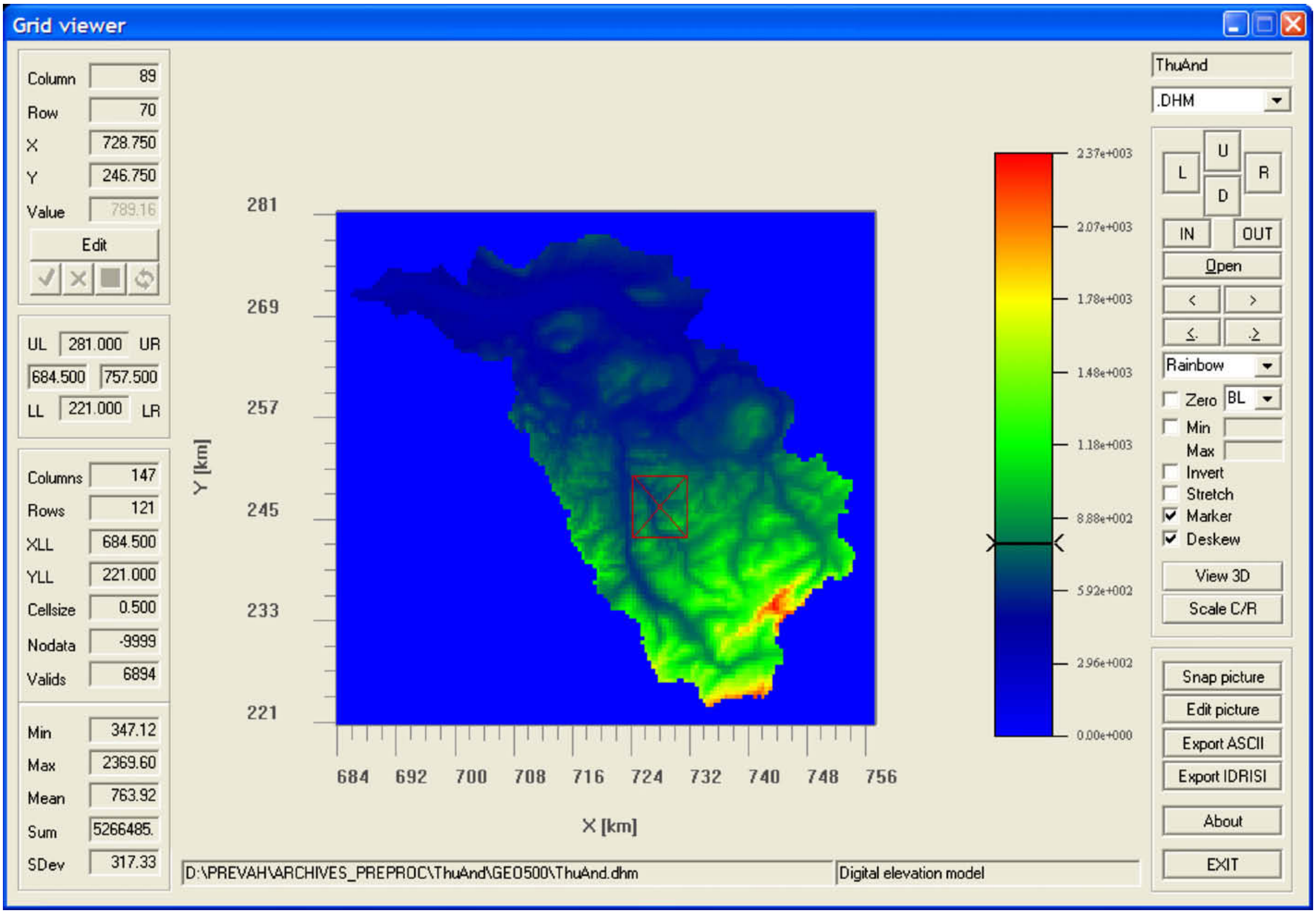

Fig. 7. WINGRID graphical user interface for visualising, exporting and editing spatially distributed (raster) model input or output.

it seems important to implement time-steps smaller than 1 h and consider more physically based runoff generation and soil modules (see, e.g. Schmocker-Fackel et al., 2007), an explicit routing of the HRU responses and spatially differentiated parameter sets. Following the experience gained from using PREVAH coupled with high resolution meteorological models, quantitative precipitation estimation from weather radar (Zappa et al., 2008) and land use change scenarios it is also planned to develop a fully distributed

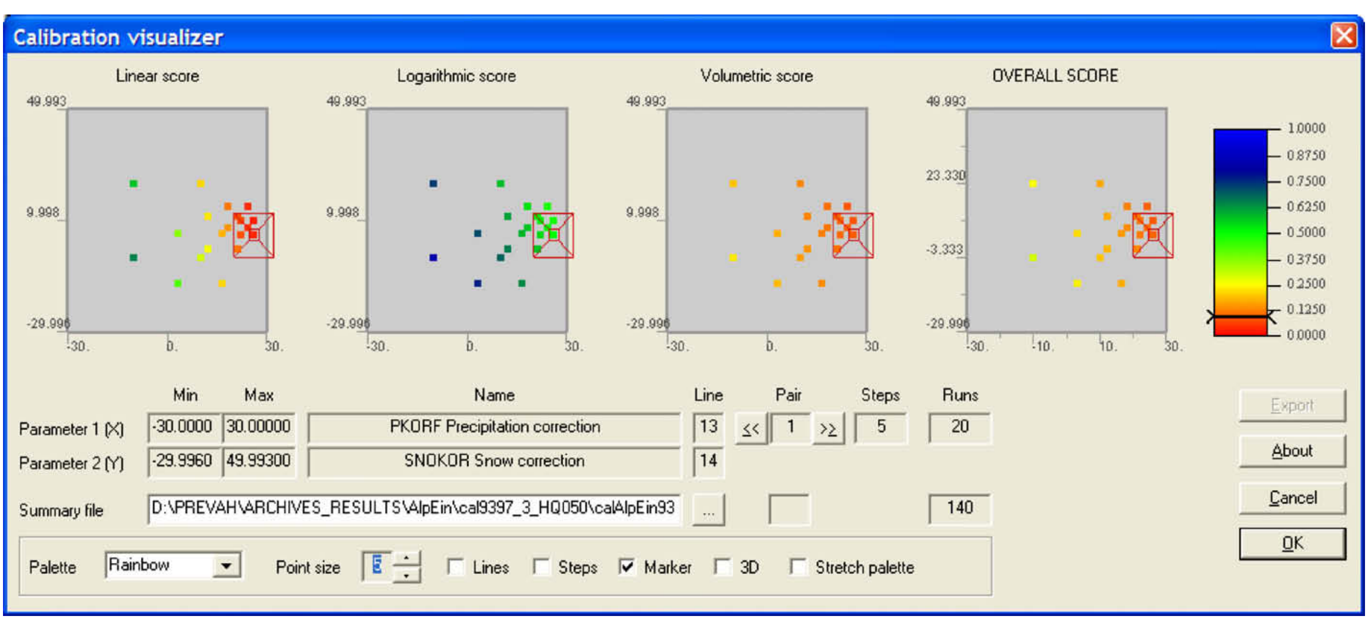

Fig. 8. VIEWOPTIM graphical user interface for visualising and verifying PREVAH calibration runs. For this, parameters are assessed pair-wise concerning their modelling efficiency.

Table 4
Selected application examples for the hydrological modelling system PREVAH.

Subject	Keywords and special features	Resolution (m^2)	Time-frame	Region	Publication(s)
Discharge regimes and spatially high-resolved water balance for Switzerland.	Water balance. Reconcilement with data from observing networks	500 × 500	Daily data, 1980–2000	Switzerland: entire area	Zappa and Pfaundler, 2008
Evaluation of climate change impacts on the water resources of the boreal forest at the Volga source.	Water balance; climate change scenarios. Coupling with GCM and RCM data[a]	500 × 500	Daily data, 1990–2000	Russia: Volga source area	Oltchev et al., 2002
Sensitivity of the simulated discharge to the extension of glaciated areas during extreme warm summers	Water balance; droughts. Use of WINHRU for two different land use maps (1979 and 2003)	30 × 30	Hourly data, 2002–2003	Austria: Goldbergkees glacier	Koboltschnig et al., 2007
Hydrological impacts of extreme summer heatwaves	Water balance; droughts. Hydrological model as supporting tool for interpretation of long-term observed time series	100 × 100	Hourly data, 1982–2005	Switzerland: 3 meso-scale basins	Zappa and Kan, 2007
Spatially distributed water balance of a glaciated mountainous catchment in Northern Sweden	Water balance; glaciers. Modelling in a high-mountain environment with sparse data	150 × 150	Hourly data, 1993–2005	Sweden: Mount Kebnekaise area	Hubacher, 2007
Flood estimation in ungauged meso-scale catchments of Switzerland using continuous simulation	Flood estimation; regionalisation. Parameter estimation for ungauged catchments using a combination of three regionalisation approaches	500 × 500	Hourly data, 1983–2003	Switzerland: 140 meso-scale test catchments	Viviroli, 2007
'Worst-case' analysis of the August 2005 flood event in Switzerland with various extreme precipitation scenarios	Flood estimation; precipitation scenarios. PREVAH outputs are coupled with a hydraulic model	500 × 500	Hourly data, 2005	Switzerland: Bernese Alps and eastern pre-alps	Schwanbeck et al., 2008
Flood forecasting for the Three Gorges area, Yangtse River, China (56,000 km^2, processed in 34 sub-basins)	Flood forecasting. DATAWIZARD, WINMET and WINPREVAH merged for operational model runs	630 × 630	Six-h data and NWP[b] forecasts	China: Yangtse River	Bosshard and Zappa, 2008
Operational ensemble runoff nowcasting and forecasting for selected basins during MAP D-PHASE[c]	Flood forecasting; ensembles. Use of ensemble radar data and ensemble meteorological forecasts	500 × 500	Hourly data and NWP[b] forecasts	Switzerland: selected meso-scale basins	Zappa et al., 2008
Analysis of severe flood events in the Swiss Rhine basin (processed in 26 sub-catchments)	Flood forecasting; ensembles. Hindcast with probabilistic approach	500 × 500	Hourly data and NWP[b] forecasts	Switzerland: Rhine basin	Verbunt et al., 2007; Jaun et al., 2008
Implementation in the IFKIS-HYDRO WEB Platform for operational runoff nowcasting and forecasting	Flood forecasting; nowcasting. Special end user version with data import from a FTP-Server	200 × 200	Hourly data, operational	Switzerland: Linth basin	Hegg et al., 2007

[a] RCM: regional climate model; GCM: general circulation model.
[b] NWP: numerical weather prediction model.
[c] MAP D-PHASE: meso-scale Alpine programme, demonstration of probabilistic hydrological and atmospheric simulation of flood events in the Alpine region.

version of PREVAH. This would allow for the implementation of new algorithms for runoff concentration and routing. Finally, algorithms for model updating such as Ensemble Kalman Filtering (Andreadis and Lettenmaier, 2005) or other tailored algorithms (Wöhling et al., 2006) should be implemented for improving the operational applicability of PREVAH.

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