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The Hydrological Modelling System PREVAH

Part I – Overview and Selected Applications

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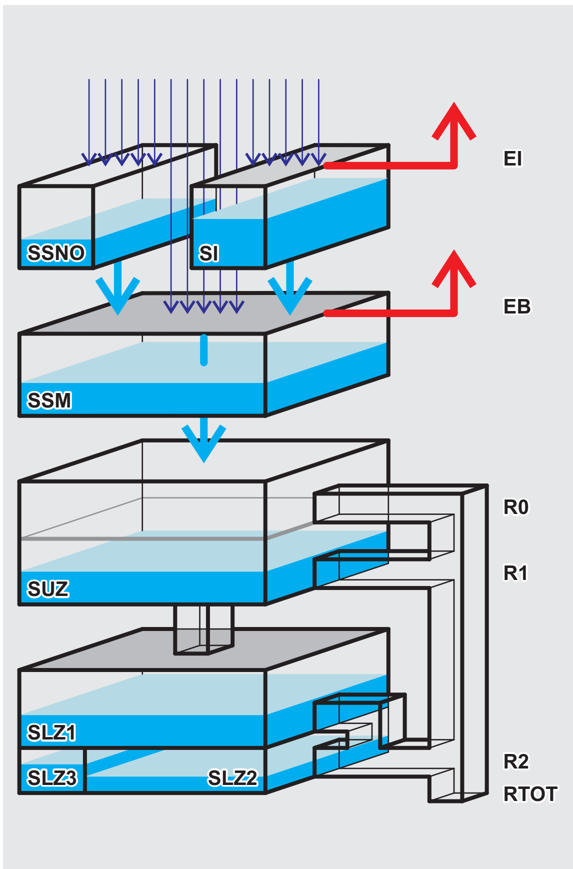

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This publication contains an overview of the hydrological modelling system PREVAH and selected application examples. It is Part I of the extensive PREVAH model documentation and is complemented by the physical model description (Part II), the user manual (Part III) and a sample PREVAH project (Part IV). Parts II, III and IV are available for download at http://www.hydrologie.unibe.ch/PREVAH.

Publication Part	**Part I**	**Part II**	**Part III**	**Part IV**
Contents	Overview and selected applications	Physical model description	User manual	Sample project and selected executables
Availability	Printed only	On-line only (pdf)	On-line only (pdf)	On-line only (zip)

The PREVAH modelling system is available for academic and research purposes exclusively. It must not be used commercially. Please read the "Terms of use" on page 3 of Part III or contact the authors for further inquiries: PREVAH@giub.unibe.ch.

Authors Daniel Viviroli[1], Joachim Gurtz[2] and Massimiliano Zappa[3]

[1] Institute of Geography, University of Berne (GIUB)
[2] Institute for Atmospheric and Climate Science, ETH Zurich (IACETH)
[3] Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf (WSL)

with contributions from Simon Jaun (IACETH) and Jan Schwanbeck (GIUB)

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The extensive physical model description, the user manual as well as a sample project (including selected components of the PREVAH modelling system) are available for download at http://www.hydrologie.unibe.ch/PREVAH.

1. Introduction

For a well-founded simulation of hydrological processes at catchment scale, physically congruous hydrological models are required, including their careful parameterisation, calibration and evaluation. In the past decade, spatially distributed modelling became an established tool for studying both components and possible changes of the hydrological cycle. The availability of geographic information systems (GISs) and digital elevation models (DEMs), the improved reliability, precision and resolution of meteorological and hydrological networks, combined with the availability of remotely sensed data, allowed the development and application of spatially distributed hydrological models within mountainous landscapes and their calibration and evaluation with respect to observed time series and spatial patterns of hydrometeorological variables.

Especially mountainous catchments are characterised by highly variable morphology, soil and vegetation types as well as by pronounced temporal and spatial variations of the climatic elements. 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. 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 distributed hydrological catchment modelling system PREVAH (Precipitation-Runoff-Evapotranspiration Hydrotope 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 conceptually oriented approach. With its modular set-up, the modelling system offers a model core as well as a large number of tools. The latter provide easy-to-use solutions for handling the large amounts of data involved in preprocessing and postprocessing tasks, model parameterisation, calibration and evaluation as well as visualisation of results.

This brochure presents a brief overview of the most important components of PREVAH, while a number of applications are selected to demonstrate its abilities. An extensive description of the physics underlying the model, the complete user manual as well as data of a sample catchment including selected PREVAH executables are available at http://www.hydrologie.unibe.ch/PREVAH.

2 Basics of the PREVAH modelling system

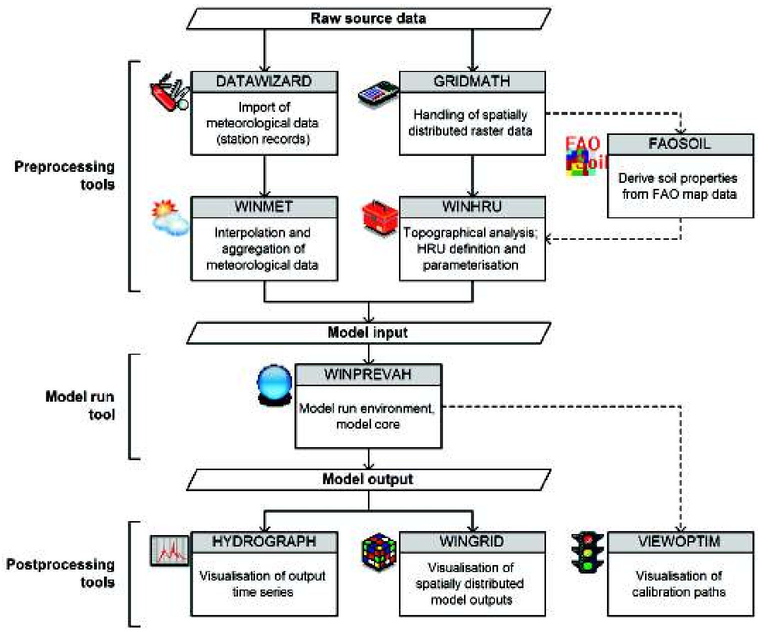
The hydrological modelling system PREVAH is a collection of user-friendly, tailor-made tools which have been developed in order to facilitate and speed up data preprocessing and postprocessing tasks involved in the operation of the semi-distributed hydrological model PREVAH (Precipitation-Runoff-Evapotranspiration HRU-related Model). PREVAH was originally intended to improve the understanding of the spatial and temporal variability of hydrological processes in catchments with complex topography. The spatial discretisation of PREVAH relies on the aggregation of gridded spatial information into clusters showing similar hydrological response, the hydrological response units (HRUs).

PREVAH is fed with standard meteorological variables with high temporal resolution. For its application, data on air temperature, precipitation, water vapour pressure, global radiation, wind speed and sunshine duration are required.

PREVAH relies to a high degree on conceptual representations of hydrological processes. It incorporates several sub-models, such as for snow accumulation and snowmelt, glacial melt, interception, soil water storage and depletion by evapotranspiration, runoff and baseflow generation as well as for discharge concentration and flood-routing.

This hydrological modelling system contains the following tools:

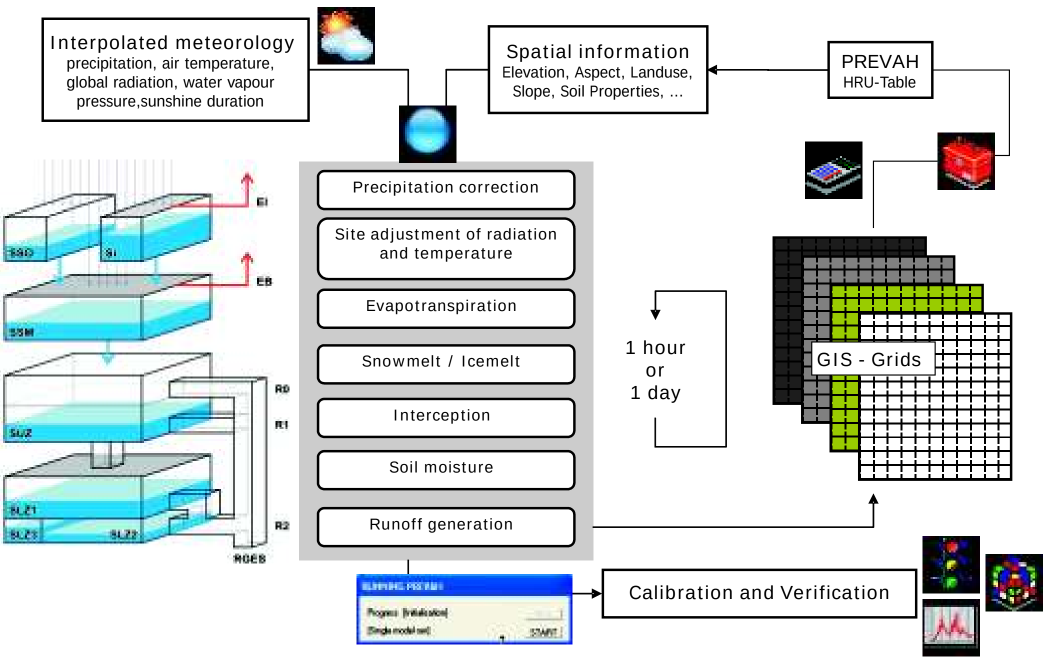
- GRIDMATH provides basic GIS functions. It has been specifically developed for managing spatially distributed data. Amongst other features, GRIDMATH allows for mathematical operations between raster data and for conversion of raster data into formats compatible with common commercial GIS and remote sensing applications.
- FAOSoil is used when information on soil properties is not available; this tool processes data from the FAO/UNESCO Soil Map of the World.
- WINHRU has been developed to generate all spatial information required for running PREVAH. WINHRU is able to delineate hydrological catchments and performs a detailed topographical analysis. Hydrological response units (HRUs) are created as specified by user-defined criteria, and the corresponding information is summarised in tables. By assimilating the information from these tables, PREVAH is able to "understand" the physiogeographical complexity of the catchment under investigation. WINHRU also generates a default control file for initialising PREVAH and its graphical user interface



Preprocessing and postprocessing tools of the PREVAH modelling system.

- DATAWIZARD assimilates and manages hydrometeorological data, which is an important prerequisite for the distributed hydrological modelling. In this way, DATAWIZARD provides a link between hydrometeorological raw data and the spatial interpolation tool WINMET. It is designed for the stepwise assimilation of raw meteorological information from a network of stations. A small database is created and maintained. Besides assimilation, DATAWIZARD is also able to verify hydrometeorological data.
- WINMET handles the spatial interpolation of the meteorological variables. This tool extracts the relevant hydrometeorological information from a database and creates elevation-dependent regressions of the variables analysed. Various approaches are available for the spatial interpolation of hydrometeorological data, such as elevation-dependent regression, Kriging and inverse distance weighting.
- WINPREVAH constitutes the PREVAH model core. It assimilates both spatial data and hydrometeorological information and simulates the complete hydrological cycle of a catchment. WINPREVAH is equipped with a monitored calibration routine which has been designed specifically for PREVAH and implements a number of objective efficiency scores. Furthermore, WINPREVAH is able to generate Monte Carlo simulations with random allocation of the most sensitive free model parameters; this enables estimation of parameter uncertainty.
- HYDROGRAPH draws time series of observed and modelled data and of modelled water balance components.
- WINGRID is used to visualise grid maps such as spatially distributed model outputs.
- VIEWOPTIM facilitates interpretation and assessment of a calibration procedure.
- Finally, the LAUNCHER toolbar provides one-click access to all components of the hydrological modelling system PREVAH.

WINPREVAH and its companion tools have been programmed in FORTRAN, the respective graphical user interfaces run on every Windows computer. The FORTRAN-based PREVAH model core is integrated in WINPREVAH but has also been compiled for application under MS-DOS, Unix and Linux.



Data flow to the core of the PREVAH modelling system.

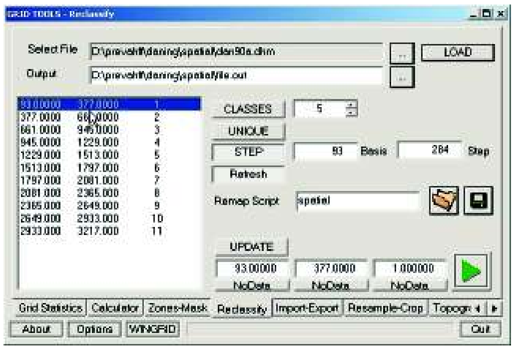
3 Preprocessing

3.1 Grid processing: GRIDMATH

Ease of management regarding digital representations of spatially distributed physiogeographical information is an important requirement for the development, parameterisation and initialisation of GIS-based spatially distributed hydrological models such as PREVAH. The GRIDMATH tool allows the user to manage spatially distributed data stored in grid format as required for using the PREVAH modelling system. The grid format of PREVAH is binary, while being structured similarly to the ASCII format used in ESRI GIS systems such as ArcMAP and Arc/INFO. GRIDMATH implements a number of operations with and between raster grids:

- Computation of statistical values
- Simple mathematical calculations
- Overlaying a grid mask to a grid
- Zonal statistics
- Reclassifying the data into categories (1)
- Importing grids from and exporting grids to other grid formats (2)
- Reducing the resolution of a grid (resample) (3)
- Reducing the size of a grid by cropping the borders (4)
- Conducting a topographical analysis of a digital elevation model according to Schulla and Jasper (2000) (5)

(1)



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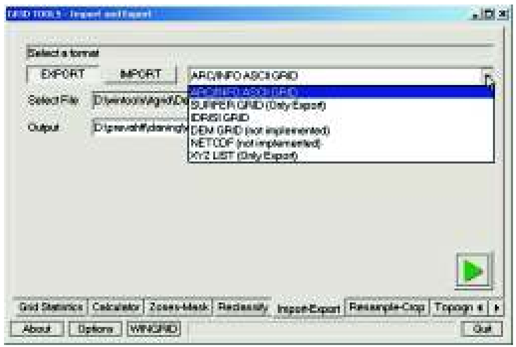

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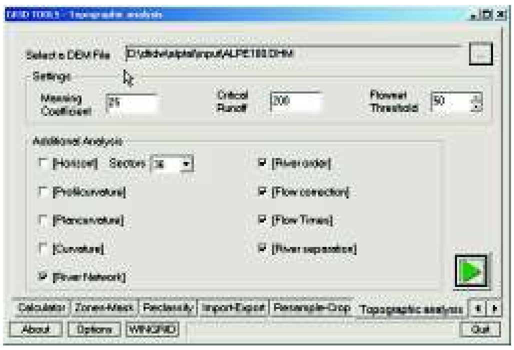
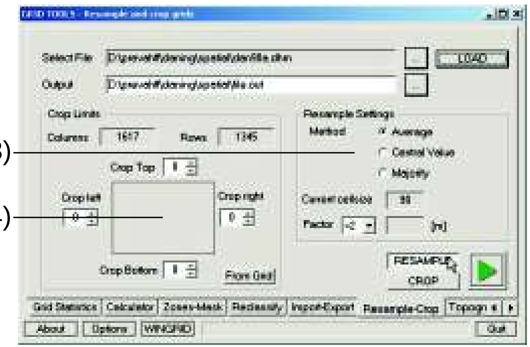


(3)

(4)



TEXT REFERENCES

- Export of maps to GIS: see Part III, Chapter A.4.6
- Binary format: see Part II, Chapter 3.2

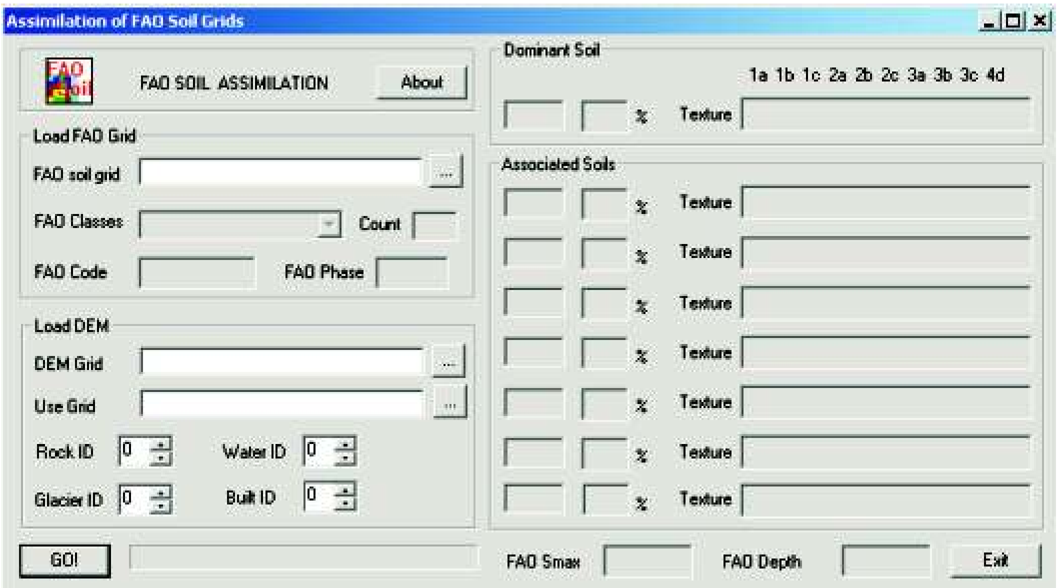
LITERATURE

Schulla J, Jasper K (2000): *Model Description WaSiM-ETH*. Zürich: Institute for Atmospheric and Climate Science, ETH Zürich.

3.2 Soil data assimilation: FAOSoil

The sound parameterisation of soil properties is essential for accurate water balance and runoff simulations. The most important parameters for PREVAH are soil depth and plant available field capacity. These two soil properties are required to estimate how much water is available for evapotranspiration. In general, the information for deriving soil depth, hydraulic conductivity and field capacity is obtained from local soil maps. If no such information is available, it may be possible to process information from the FAO/UNESCO Soil Map of the World. The FAOSoil tool allows for the parameterisation of soil property grids from information on the spatial distribution of FAO soil classes within the investigated domain. The FAO soil classes can be generated from the Digital Soil Map of the World (http://www.fao.org/ag/agl/agll/dsmw.htm). The Digital Soil Map of the World consists of the following map sheets: Africa, North America, Central America, Europe, Central and Northeast Asia, Far East, Southeast Asia, and Oceania. Data on all the continental surface areas are provided by FAO upon request.

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. It is assumed that the deepest soils and the soils with highest plant available field capacity are located at lower altitudes and in flat areas of the domain. Additional restrictions depend on land use. Shallow soil should be assigned to grid cells representing water bodies, rocky areas, urban areas and glaciers. For the use of FAOSoil, the following spatially distributed data are required: digital elevation model, land use map, and a map with information on the FAO classes.



The graphical user interface of FAOSoil.

LITERATURE

FAO-UNESCO (1988): Soil Map Of World, Revised Legend. World Soil Resources Report 60. Rome: FAO.

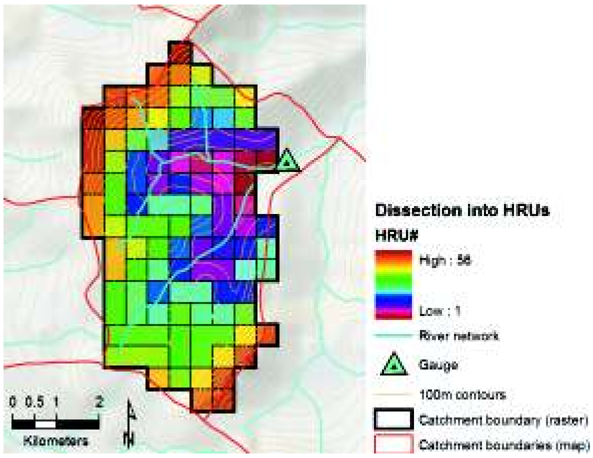
Sonderegger C (2004): Rainfall/Runoff Modelling of a Sub-Catchment of the Yangtze in China. Diploma Thesis at the ETH and University Zürich.

3.3 Spatial discretisation: WINHRU

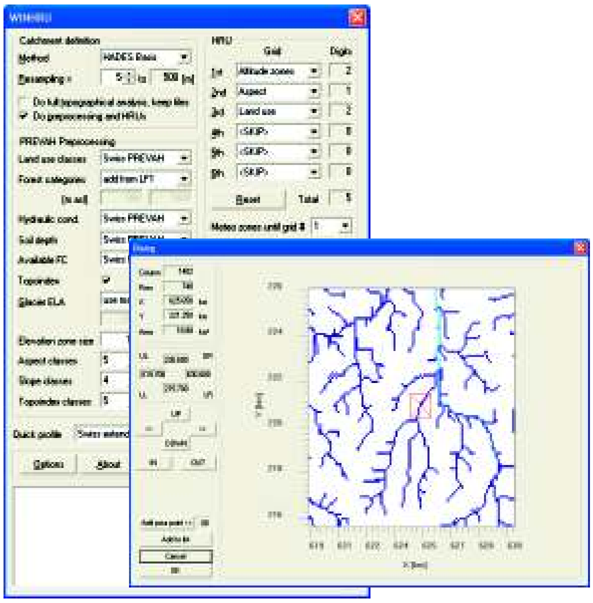
Instead of a uniform raster-cell resolution, PREVAH uses the concept of hydrological response units (HRUs) by default. This means aggregating spatially distributed grid cells according to a set of structural and statistical characteristics. The goal is to aggregate cells with similar and homogeneous hydrological response. Consequently, the criteria applied for differentiation are related to the processes that most significantly influence runoff generation and evapotranspiration (e.g. elevation, land use, aspect). Essentially, this concept corresponds to a dynamical spatial resolution: the higher the spatial variability of soil, land surface and topographical characteristics, the lower the average size of the HRU.

WINHRU is the PREVAH modelling system's comprehensive tool for efficient aggregation of hydrological response units (HRUs). 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 maps such as from the Hydrological Atlas of Switzerland or from any other GIS-formatted file. A total of 12 criteria are available to differentiate the HRUs, of which a maximum of 6 may be used at a time. Required input data include raster-formatted files for elevation, land use and soil properties; they may be complemented with extra information layers regarding, for example, geology or hydrogeology. Once all other settings such as resolution, number of altitude zones, etc. have been defined, preprocessing takes but a few moments to complete and results in an HRU properties table, a grid map of HRU identifiers and a PREVAH control file – all that is needed in terms of physiographical information to run PREVAH.

While this tool, by default, is set up for application in Switzerland, it can be easily used for other regions of the world as well. The input raster data required for this are created with additional tools such as FAOSoil and GRIDMATH.



Example of HRU discretisation in a Swiss alpine catchment.



The graphical user interface of WINHRU used for aggregation of hydrological response units (HRUs).

TEXT REFERENCES

- Preprocessing, spatial data: see Part III, Chapter C
- Raster map display: see Part III, Chapter H
- Raster map processing: see Part III, Chapter A
- Sample preprocessing data: see Part IV (PREVAH project)

LITERATURE

Engel BA (1996): Methodologies for development of response units based on terrain, land cover and soils data. **Goodchild MF, ed.** *GIS and environmental modeling*. Fort Collins, CO, US: GIS World Books, p. 123–128.

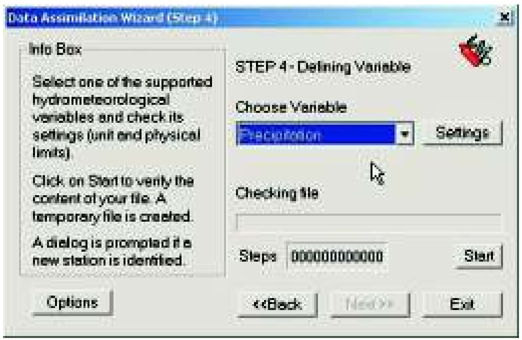
Flügel W-A (1997): Combining GIS with regional hydrological modelling using hydrologic response units (HRUs): An application from Germany. *Mathematics and Computers in Simulation* **43**:297–304.

Zappa M (1999): *Untersuchungen zur Aufbereitung unterschiedlicher Rauminformationen für die flächendifferezierte Einzugsgebietsmodellierung.* Diploma thesis, Department of Geography, ETH Zürich.

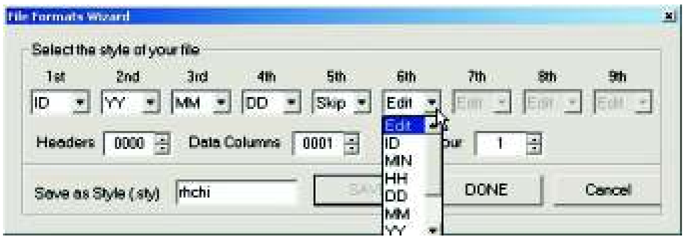
3.4 Meteorological data assimilation: DATAWIZARD

The assimilation and management of hydrometeorological data from a network of stations is crucial for the application of distributed hydrological models. DATAWIZARD is a tool allowing the assimilation and simple verification of hydrometeorological data; it provides a link to WINMET, the spatial interpolation tool of the hydrological modelling system PREVAH.

DATAWIZARD has been specifically developed to manage the hydrometeorological information required for running PREVAH. The software is designed for the stepwise assimilation of raw meteorological information available as ASCII tabular data. DATAWIZARD is able to process the following hydrometeorological variables: precipitation, air temperature, wind speed, global radiation, relative humidity, water vapour pressure, sunshine duration, runoff and two user-defined variables.

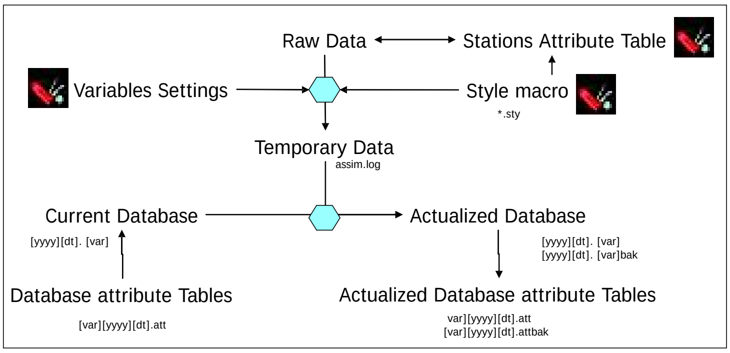


Check for data completeness.

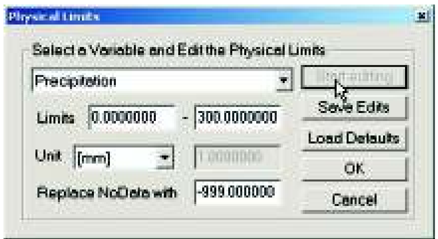


Definition of scripts for assimilation of ASCII tables.

Update station attributes.



Creation, management and update of a simple database.



Definition of physical limits.

TEXT REFERENCES

– Meteorological model input: see Part II, Chapter 3.4

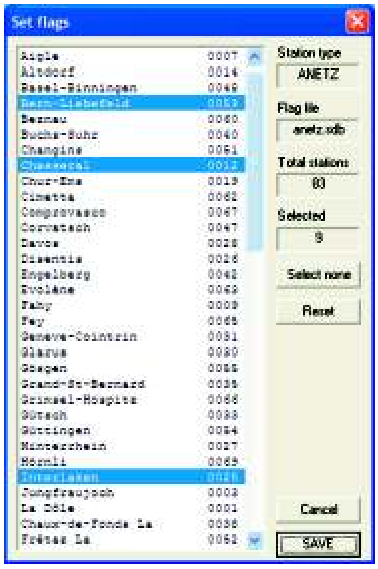
3.5 Meteorological data interpolation: WINMET

In PREVAH, the distributed hydrological modelling is based on observations of meteorological variables at different gauging stations. The stations used are located within or near the area under investigation. WINMET has been developed to interpolate meteorological information as required by PREVAH. Currently, WINMET integrates two versions. The Swiss version has been designed specifically for applications based upon the hydrometeorological data provided by the Swiss meteorological service. The international version is more generalised and has been designed to interact with DATAWIZARD.

WINMET extracts meteorological data from a database which is usually created and maintained by DATAWIZARD.

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

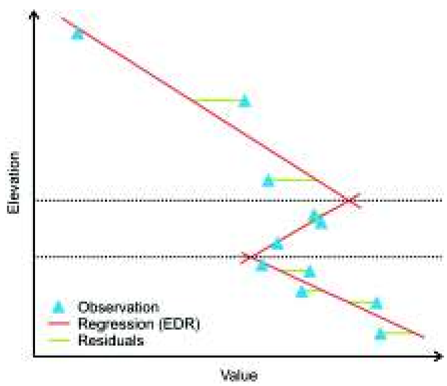
Compatibility with the current PREVAH modelling project is achieved by adopting the grids generated by WINHRU; this specifically concerns the digital elevation model, the basin watershed mask and a map of the relevant meteorological zones. Meteorological zones are generally defined according to sub-basins and 100-metre elevation bands. After interpolation, WINMET creates ASCII-formatted tables of meteorological data required to run PREVAH. An average interpolated value is provided for each time step and for each meteorological zone.



Selection of stations from a list.

The basic procedures adopted for the spatial and temporal interpolation of observed meteorological information are elevation-dependent regression (EDR), inverse distance weighting (IDW), Kriging and laps-rate (only for temperature data).

It is possible to combine EDR with Kriging or IDW, resulting in a procedure called detrended interpolation: For this, the residuals (difference between interpolated and observed values) of the EDR method are spatially interpolated with IDW or Kriging. By adding this interpolated residual map to the map interpolated with EDR, altitude biases in the station values are accounted for (see Garen and Marks, 2001).



Elevation-dependent regression.

TEXT REFERENCES

– Meteorological model input:
  see Part II, Chapter 3.4

LITERATURE

Garen DC, Marks D (2001): Spatial fields of meteorological input data including forest canopy corrections for an energy budget snow simulation model. **Dolman AJ, Halla J, Kavvas ML, Oki T, Pomeroy JW, eds.** *Soil-Vegetation-Atmosphere Transfer Schemes and Large Scale Hydrological Models.* IAHS publication **270**. Wallingford, UK: International Association of Hydrological Sciences, p. 349–353.

4. Running the model

4.1 Model input and free parameters: WINPREVAH (I)

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 behaviour of evapotranspiration. On the other hand, a PREVAH-grid-formatted map locates the individual HRU positions for spatially distributed output. Both inputs are generated by WINHRU.

2) Meteorological input for the altitude zones: After interpolation of the station values, the spatially distributed meteorological data are aggregated to altitude zones. An ASCII-formatted table lists these values for each time step. Details required include precipitation, temperature, wind speed, vapour pressure (or relative humidity), global radiation and sunshine duration. Station selection, interpolation and aggregation are handled by WINMET.

3) A control file containing all site-specific information required for modelling, e.g. number of HRUs and altitude zones, free model parameter values, initial storage contents, time step and application timeframe, output options, etc. An initial control file is generated by WINHRU, changes are made using WINPREVAH.

A number of free parameters are available to adjust PREVAH to the specific modelling site. Depending on module specifications (e.g. evapotranspiration modelling scheme), this number typically ranges between 14 and 19. These parameters can be subdivided into six groups:

1) Water balance adjustment: with PKOR and SNOKOR, precipitation input is adjusted in order to reduce the total volume error of the model as observed at the catchment outlet. Gauge error correction is already effected during preprocessing.

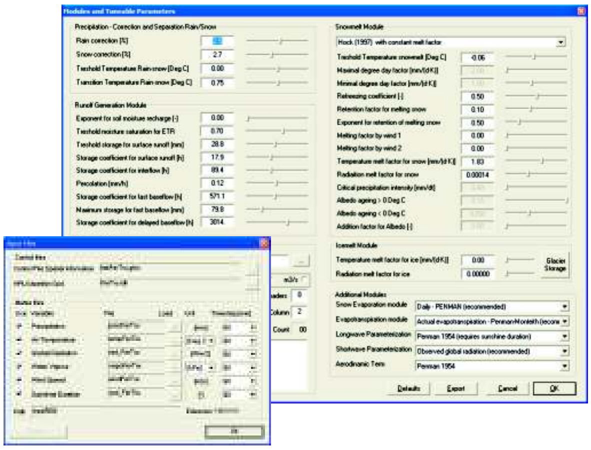
2) Differentiation of precipitation into liquid (rain) and solid (snow) fractions with the help of both threshold temperature (TGR) and temperature range (TTRANS).

3) Snowmelt module: threshold temperature for snowmelt (T0), temperature melt factor (TMFSNOW; if variable: TMFMIN and TMFMAX), radiation melt factor (RMFSNOW), coefficient for re-freezing (CRFR). Retention of meltwater in snow (SLIQMAX) is usually set to a fixed value of 10%.

4) Glacier module (if applicable): radiation and temperature melt factors (ICETMF and ICERMF). Additional parameters for storage and translation times in firn, snow and ice are available.

5) Soil moisture module: non-linearity parameter for infiltration as a function of actual soil moisture (BETA). Various other important characteristics (e.g. maximum soil moisture storage) are parameterised by PREVAH with the help of soil and land use parameters.

6) Runoff generation module: storage coefficients for fast and delayed runoff (K0H, K1H) and baseflow (CG1H, K2H), threshold for generation of fast runoff (SGR), threshold for fast baseflow storage (SLZ1MAX), percolation rate (PERC).



Parameter settings and meteorological input data dialog in WINPREVAH.

TEXT REFERENCES

- Model input, physiography: see Part II, Chapter 3
- Model input, meteorology: see Part II, Chapter 3.4
- Model structure, modules, parameters: see Part II, Chapter 2
- Calibration of free parameters: see Part II, Chapter 6

LITERATURE

Bergström S (1976): *Development and Application of a Conceptual Runoff Model for Scandinavian Catchments*. Bulletin Series A, **52**, University of Lund.

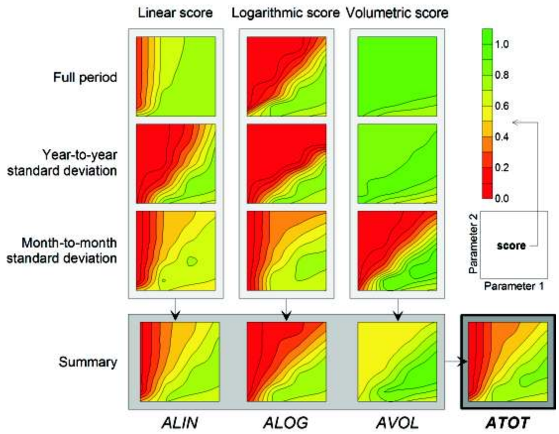
Gurtz J, Baltensweiler A, Lang H, Menzel L, Schulla J (1997): *Auswirkungen von klimatischen Variationen auf Wasserhaushalt und Abfluss im Flussgebiet des Rheins*. Projektschlussbericht im Rahmen des Nationalen Forschungsprogrammes "Klimaänderungen und Naturkatastrophen", NFP-31. Zürich: vdf Hochschulverlag.

4.2 Model calibration: WINPREVAH (II)

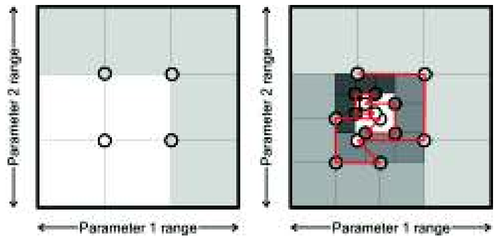
PREVAH contains a number of free parameters which are used to adjust the model to the conditions prevailing in a specific catchment. A suitable set of free model parameters is sought, maximising the extent to which the simulated and observed hydrographs correspond to each other. As an alternative to time-consuming and partially subjective trial-and-error calibration, PREVAH comprises an automatic calibration procedure.

Determining the model efficiency is essential for successful automatic calibration. Gauged data for runoff are usually the only measurement available to assess model efficiency. Consequently, it is of paramount importance to extract the maximum possible amount of information from a comparison of observed and simulated runoff. For this purpose, PREVAH combines three standard efficiency scores with three different temporal viewpoints: Linear and logarithmic Nash-Sutcliffe efficiency as well as the volumetric deviation are assessed over the entire calibration period and in their annual and monthly variations. Each of these 9 scores is mapped to a user-defined score range and then weighted to give a total score. The purpose of this procedure is to find a parameter set which not only achieves high efficiency scores, but also shows a high degree of stability and representativity.

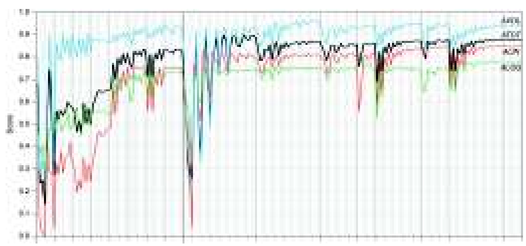
For establishing a suitable parameter set, the automatic calibration procedure uses an interactive search algorithm. First of all, the parameters to be calibrated have to be grouped in pairs of related parameters (e.g. storage coefficient for interflow and percolation). These pairs are then processed 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 is reached or until calibration improvements remain below a certain threshold.



A set of multi-objective efficiency scores is used to guide the automatic calibration procedure.



PREVAH's iterative calibration algorithm minimises computational cost.



Evolution of PREVAH summary scores during an automatic calibration.

TEXT REFERENCES

–Model calibration:
see Part II, Chapter 6
–Calibration visualiser:
see Part III, Chapter I

LITERATURE

Nash JE, Sutcliffe JV (1970): River flow forecasting through conceptual models: Part I – a discussion of principles. *Journal of Hydrology* **10**:282–290.

Viviroli D (2007): *Ein prozessorientiertes Modellsystem zur Ermittlung seltener Hochwasserabflüsse für ungemessene Einzugsgebiete der Schweiz.* Geographica Bernensia **G77**. Berne: Institute of Geography, University of Berne.

5 Postprocessing

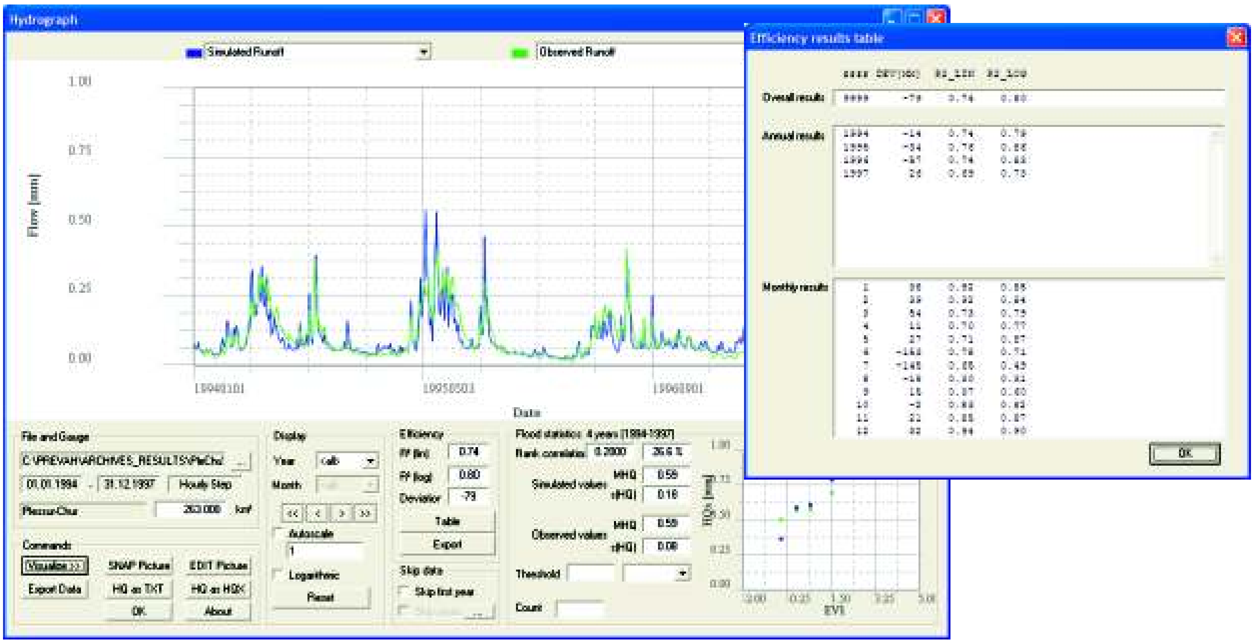
5.1 Hydrograph interpretation: HYDROGRAPH

PREVAH delivers its model output in the form of various ASCII-formatted text 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 and model storage contents.

Instead of interpreting these tables with commercial data-processing packages, the PREVAH postprocessing feature HYDROGRAPH may be used to quickly visualise and compare model and observation data. A corresponding PREVAH output control file (runoff data or model water balance data) is simply selected from the file open dialogue and visualised by pressing a button. Runoff data are easily screened by scrolling through years and months.

When displaying water balance data, two arbitrary variables may be compared with the help of a drop-down menu. Rates or fill levels of the following quantities are available: interpolated precipitation (with or without adjustment), snowmelt, ice melt, snow water equivalent, interception storage, plant available soil moisture storage, upper runoff generation storage (unsaturated zone), lower runoff generation storage (saturated zone), water balance components, evapotranspiration (potential and actual), interception evaporation, soil evapotranspiration, surface runoff, interflow, total baseflow (including its three sub-components) and total runoff.

Additionally, statistics on model efficiency and on flood estimation scores are available in the form of tables and graphs. Like the hydrograph itself, these can be exported to text or graphic files.



HYDROGRAPH display of observed and simulated runoff in hourly resolution and efficiency table.

TEXT REFERENCES

- Hydrograph interpretation: see Part III, Chapter G
- Efficiency scores: see Part III, Chapter F.4.9
- Sample output data: see Part IV (PREVAH project)

LITERATURE

Dyck S, Peschke G (1983): *Grundlagen der Hydrologie*. Berlin: Verlag für Bauwesen.

McCuen RH (1998): *Hydrologic Analysis and Design*. Upper Saddle River, NJ, US: Prentice Hall.

Nash JE, Sutcliffe JV (1970): River flow forecasting through conceptual models: Part I – a discussion of principles. *Journal of Hydrology* **10**:282–290.

Postprocessing

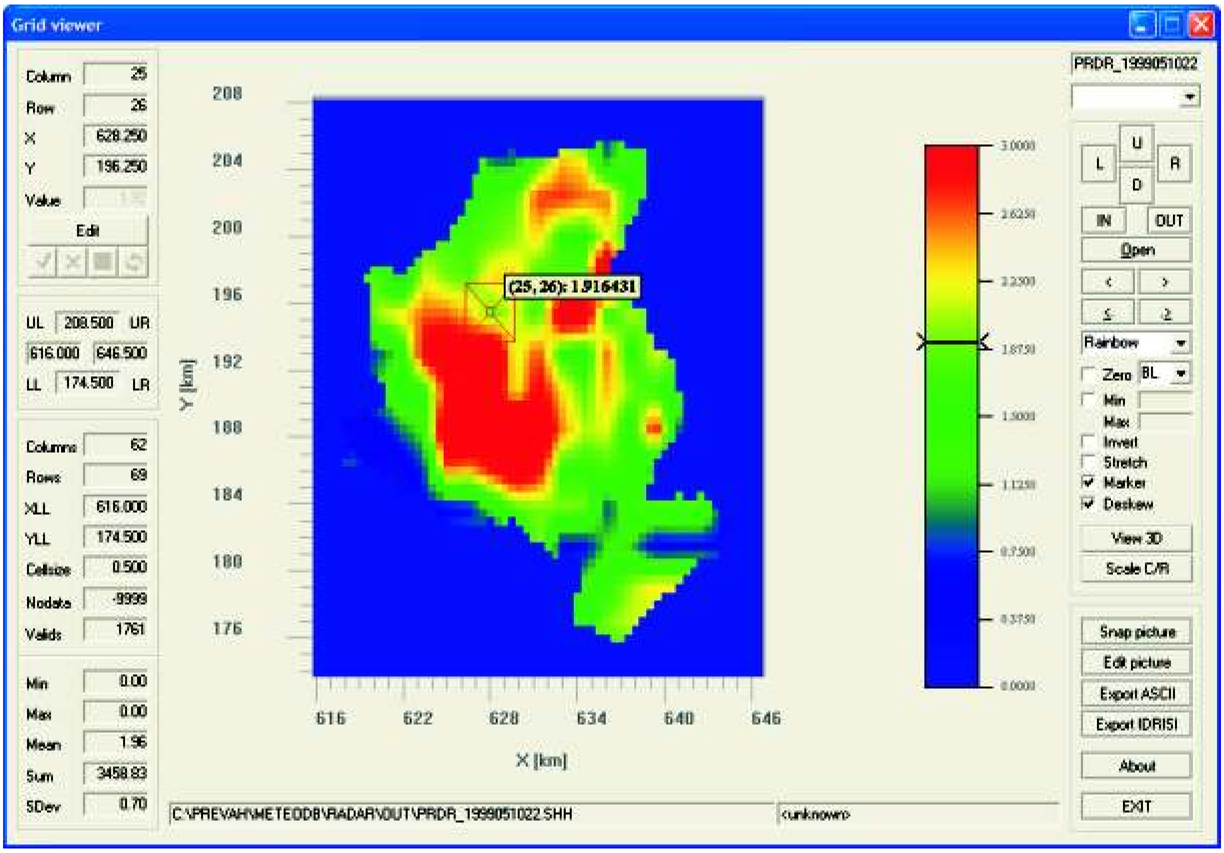
5.2 Raster map display: WINGRID

PREVAH implements a binary file format for saving maps to grid raster files. It is used for all preprocessing inputs (see WINHRU and WINMET) as well as for all spatially distributed model outputs. These files are easily re-formatted for use with commercial GIS and image-processing packages.

PREVAH offers straightforward tools to work with the raster files, in particular for displaying (WINGRID) and processing them (GRIDMATH).

WINGRID is used for quick visualisation, verification and interpretation of PREVAH raster data. It recognises and identifies 80 preprocessing and model file extensions and will handle any binary PREVAH grid map. Besides various display options (e.g. zoom, pan, scale, palette selection, 3D view), it also features a simple grid editor which can e.g. be used to modify preprocessing input data. The extent of the raster file is shown along with elementary data statistics.

PREVAH raster data are exported to ESRI ArcGIS and Clark Labs IDRISI import formats by simply pressing a button, while a built-in screen capture tool allows for the display to be exported to a graphic editor or to a word-processing software.



WINGRID main window with display of PREVAH raster data.

TEXT REFERENCES

−Raster map display:
see Part III, Chapter H

−Raster map processing:
see Part III, Chapter A

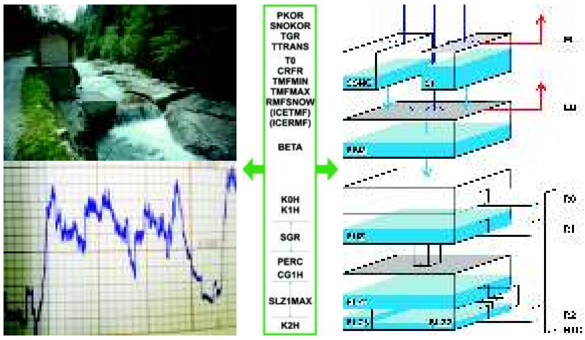
5.3 Calibration visualiser: VIEWOPTIM

Despite being an automatic procedure, PREVAH's iterative calibration needs to be supervised. For doing so, the modelling system contains a specific calibration visualiser tool: VIEWOPTIM.

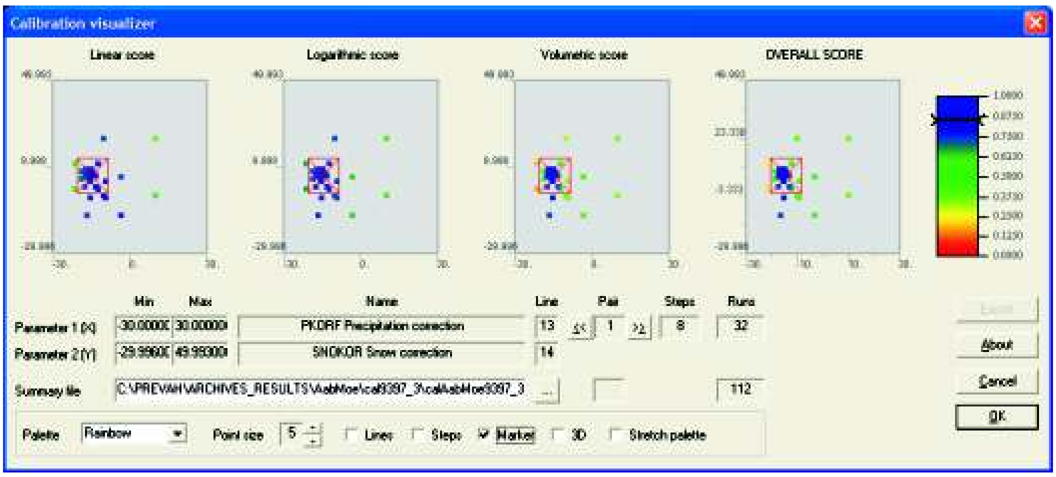
VIEWOPTIM enables the user to track the course of a calibration. As described above, PREVAH's calibration scheme treats parameters pair-wise. Consequently, VIEWOPTIM allows various efficiency scores to be displayed for two parameters at a time. This makes it possible to verify whether the iterative process resulted in an increase in efficiency stabilising at a high level. Problems such as parameters reaching the chosen calibration range are easily identified as well.

A number of display options extend the interpretation possibilities: For instance, showing the calibration path as a line or with colour markers clarifies the actual iterations computed by PREVAH, and a 3D display of the graphs enhances ease of interpretation.

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



Free parameters serve as interfaces between reality and the model. Calibration means finding model parameters which allow adequate simulation of the catchment in question.



After running PREVAH's automatic calibration algorithm, VIEWOPTIM is used to display various efficiency scores for the respective parameter pairs. This allows investigation of calibration plausibility and success.

TEXT REFERENCES

–Calibration procedure:
see Part II, Chapter 6

–Hydrograph interpretation:
see Part III, Chapter G

LITERATURE

Nash JE, Sutcliffe JV (1970): River flow forecasting through conceptual models: Part I – a discussion of principles. *Journal of Hydrology* **10**:282–290.

6 Selected Applications

6.1 High-resolution water balance for Switzerland

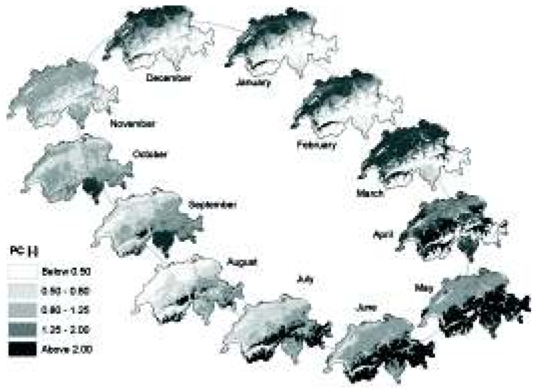
A simulation experiment with PREVAH involving the entire area of Switzerland has been completed. The experiment allowed the simulation of evapotranspiration and natural runoff generation for the 20-year period from 1981 to 2000. PREVAH was fed with daily meteorological data, while the spatial resolution was set to 500 × 500 m². The results were compared to previous data on the natural water balance of Switzerland (see Table).

To quantify the spatial and temporal dynamics and variability of the natural discharge regimes, monthly Pardé coefficients were computed (see Figure).

Typical alpine regimes show a distinct dependence on elevation as a direct consequence of the timing of the main snowmelt season and of rainfall. At higher elevations, the regimes are governed by both snowmelt (May to July) and, if glaciers are present, melt from the ablation area of alpine glaciers (July to September). Runoff generation from glacierised areas accounts for about 7% of the total runoff generation in Switzerland.

The results show that PREVAH is a reliable tool for detailed hydrological studies in alpine environments. The map of the natural runoff regime of the Swiss Alps allows for the analysis of both gauged and ungauged areas and opens many possibilities for studies dealing with the management of water resources.

Selected maps and analyses have been published in Version 2 of the Digital Atlas of Switzerland (http://www.atlasderschweiz.ch).



High-resolution spatial and temporal (monthly) dynamics of the computed Pardé coefficients for Switzerland, as an average for the 1981–2000 period. The monthly maps are arranged in clockwise order, starting with January (top right).

Climate Unit	P [mm·y^{-1}]	R [mm·y^{-1}]	ET [mm·y^{-1}]	DS [mm·y^{-1}]
Wallis	1573	1276	344	-47
Ticino	1955	1479	476	0
Alpine Rhine	1435	1060	387	-13
Engadin	1199	942	290	-33
Alpine Aare	1771	1347	461	-37
Prealps	1946	1505	448	-7
Jura	1403	806	597	0
East plains	1265	654	608	3
West plains	1282	657	621	4
Switzerland 1981-2000	1518	1044	487	-13
Switzerland [a] 1961-1980	*1481*	*961*	*513*	*7*
Switzerland [b] 1961-1990	*1458*	*991*	*469*	*-2*

[a] Schädler & Bigler (1992), [b] Schädler & Weingartner (2002)

Simulated mean annual water balance components (P = precipitation, ET = evapotranspiration, R = runoff, DS = storage change) within the 20-year period from 1981 to 2000. Estimations from other authors are indicated in italics.

TEXT REFERENCES

- Export of maps to GIS: see Part III, Chapter A
- Evapotranspiration: see Part II, Chapter 4.4
- Runoff generation: see Part II, Chapter 4.5

LITERATURE

Pfaundler M, Zappa M (2006): Die mittleren Abflüsse über die ganze Schweiz – Ein optimierter Datensatz im 500×500 m^2 Raster. *Wasser, Energie, Luft* **98**(4):291–298.

Schädler B, Weingartner R (2002): The components of the natural water balance 1961–1990. Hydrological Atlas of Switzerland, Plate 6.3. Berne: Federal Office for the Environment.

Zappa M (2002): *Multiple-Response Verification of a Distributed Hydrological Model at Different Spatial Scales.* Ph.D. Thesis **14895**, Institute for Atmospheric and Climate Science, ETH Zürich.

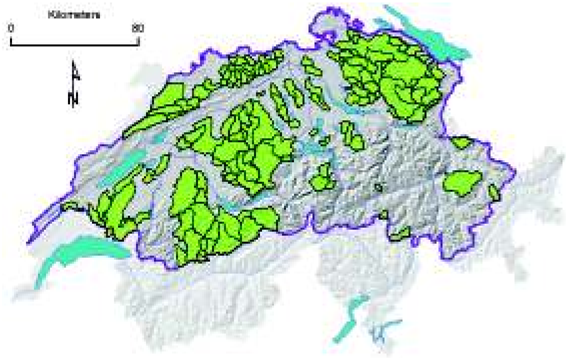
Applications

6.2 Flood estimation in ungauged catchments of Switzerland

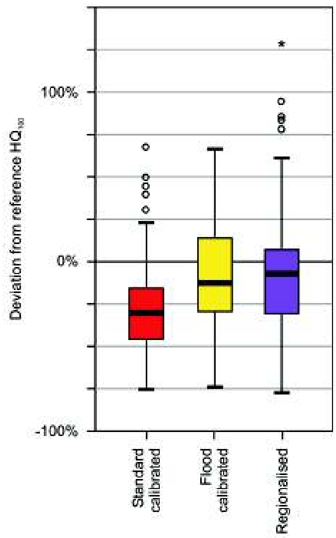
Successful flood protection requires sound estimations of floods of various return periods, a demand that is especially difficult to meet in ungauged catchments. Experience shows that the empirical methods used today still carry large errors. Therefore, the approach of deterministic long-term modelling is now adopted in Switzerland, using the hydrological modelling system PREVAH to simulate the discharge of a 20-year period in hourly resolution. These simulations are then analysed conventionally by means of extreme value statistics, resulting in estimations for peak discharge and flood discharge volume.

In order to enable the free model parameters to be determined in catchments without gauge records and therefore without any possibility for calibration, a regionalisation module was developed (Viviroli, 2007). This was based on 140 mesoscale Swiss catchments (approx. 20–1000 km²) which were successfully calibrated using the semi-automatic calibration scheme included in PREVAH. Additional flood-sensitive scores were used to tweak modelled peak runoff values (Viviroli, 2007). Regionalisation of the free model parameters was then obtained through a combination of three approaches: Nearest Neighbour uses a number of most similar catchments as donors for model parameters, Kriging performs an interpolation of parameters in space and Regression establishes relations between model parameters and independent catchment attributes.

Results show that this approach of long-term simulation is indeed able to produce plausible flood estimations for ungauged Swiss catchments. For a 100-year return period flood, the median error from 49 regionalised test catchments with long-term gauge data is only -7%, while the error for half of these catchments ranges between -30% and +8%. This approach adds significant information to the already existing methods and is suitable to complement and extend flood estimation procedures used in Switzerland today.



140 mesoscale catchments in northern-alpine Switzerland successfully calibrated for application of PREVAH.



Deviation in extrapolated HQ_{100} from reference, shown for standard and flood calibrated as well as for regionalised parameter sets. The box plot refers to data from 49 representative test catchments with long-term gauge data.

TEXT REFERENCES

–Model calibration procedure: see Part II, Chapter 6

LITERATURE

Viviroli D (2007): *Ein prozessorientiertes Modellsystem zur Ermittlung seltener Hochwasserabflüsse für ungemessene Einzugsgebiete der Schweiz.* Geographica Bernensia **G77**. Berne: Institute of Geography, University of Berne.

6.3 Analysis of the August 2005 flood in Switzerland

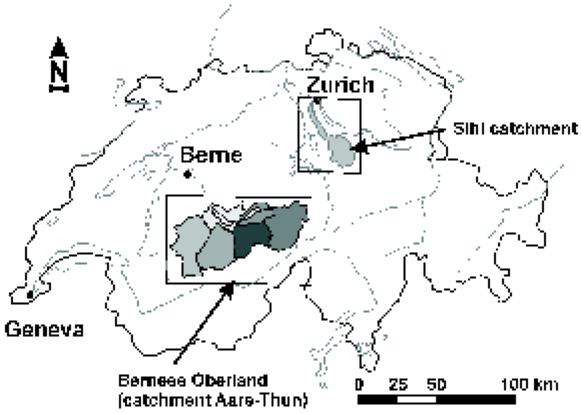
In August 2005, a severe rainfall event caused flood damage in the Swiss northern-alpine region, with a damage total of about 3 billion Swiss Francs. This devastating event once more showed the vulnerability of structures built close to rivers and lakes. An adequate knowledge of flood risk therefore constitutes the most important prerequisite to minimise or prevent future damage.

Using the PREVAH, the effects of several extreme advective rainfalls were analysed with regard to flood generation in two regions with complex topography. While the Bernese Oberland (i.e. the Aare River catchment as far as Thun) was directly affected by the August 2005 flood, the Sihl River catchment was investigated on account of highly flood-vulnerable infrastructure located in Zurich. For this modelling task, both catchments had to be divided into smaller sub-areas, of which some could be calibrated and others had to be regionalised before starting the investigation.

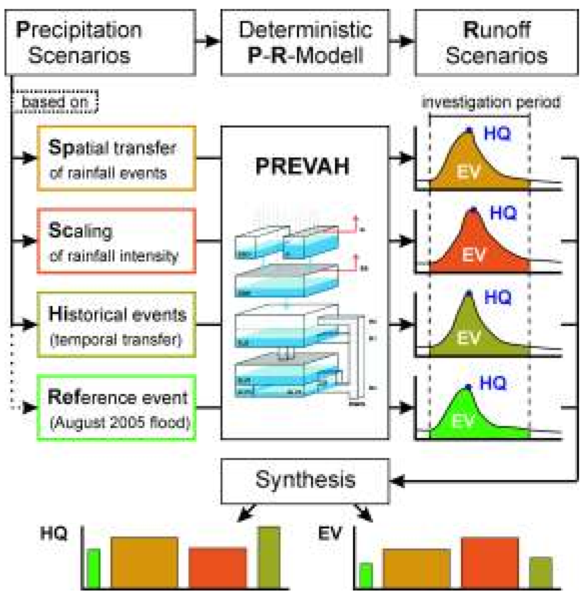
Extreme precipitation scenarios were designed on the basis of three methodologies: (1) Spatial transfer of precipitation events which have occurred outside of the catchment under investigation and were moved to different locations within the catchment; (2) Scaling of precipitation events due to modification of precipitation intensity while spatiotemporal distribution was retained unchanged; (3) Historical extreme precipitation events were temporally transferred and thus combined with different boundary conditions.

After transformation of precipitation scenarios into runoff, hydrographs (hourly resolution) are available for further analysis. Flood events more severe than the one of August 2005 have to be expected for both Sihl-Zurich and Aare-Thun catchments.

This analysis shows that model-based flood risk estimation complements statistical estimation methods, such as frequency analysis, as well as simpler deterministic approaches. However, the results call for prudential interpretation, because of uncertainties related to the input data on the one hand and the model system on the other hand.



Location of main catchments under investigation.



Flowchart showing the work flow: Generation of precipitation scenarios, which are transformed into hydrographs by PREVAH. Finally, summarisation by comparison of maximum peak-flow (HQ) and total flood discharge during the investigation period (EV).

TEXT REFERENCES

–Model calibration procedure: see Part II, Chapter 6

LITERATURE

Schwanbeck J, Viviroli D, Weingartner R: Modellgestützte Sensitivitätsanalysen. **Hegg C, Bezzola GR, eds.** *Ereignisanalyse Hochwasser 2005, Teil 2 – Analyse von Prozessen, Massnahmen und Gefahrengrundlagen.* Berne: Federal Office for the Environment, forthcoming.

Viviroli D (2007): *Ein prozessorientiertes Modellsystem zur Ermittlung seltener Hochwasserabflüsse für ungemessene Einzugsgebiete der Schweiz.* Geographica Bernensia **G77**. Berne: Institute of Geography, University of Berne.

Applications

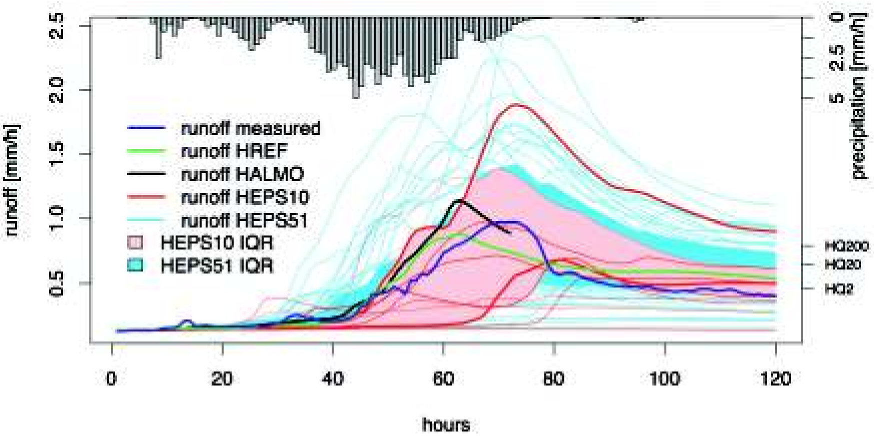
6.4 Ensemble flood forecasting for large Swiss catchments

In both meteorological and hydrological forecasting, long lead times are required for planning appropriate measures in the case of flood occurrences. This in turn is inherently connected with an increased uncertainty which cannot be accounted for by deterministic forecasts. An attractive way of addressing this issue is the use of probabilistic forecasts driven by meteorological ensemble prediction systems (EPSs), as the meteorological input is considered to represent a main source of uncertainty.

Several meteorological ensemble prediction systems are operationally available at the global scale, one of them being the ECMWF EPS with 51 members. The differences between the 51 forecasts forming the ensemble represent the initialisation uncertainty of the meteorological model. The output of the large-scale model is dynamically downscaled by means of a limited area model, the COSMO-LEPS (Marsigli et al., 2001). Owing to high computational time requirements, it is not feasible to downscale the full global ensemble in everyday operational applications and therefore only a subsample of 10 (16 since February 2006) representative ECMWF ensemble members selected by cluster analysis is processed. The full ensemble is available, though, for selected case studies. With regard to PREVAH, six parameters (temperature, precipitation, humidity, wind, sunshine duration, global radiation) from each member of this ensemble are used to drive the hydrological model with hourly time steps. A reference simulation (HREF) driven by meteorological observations serves to generate the initial conditions of PREVAH.

The figure shown, a hindcast from 20 August 2005 at the Hagneck gauge (Aare), illustrates what ideally would be expected from a probabilistic forecast system: The observed runoff is captured well by the interquartile range (IQR) of both the full (HEPS51) and the reduced ensemble (HEPS10). The HEPS10 IQR only slightly differs from the HEPS51 IQR, which indicates a proper representation of the full ensemble. The spread of the ensemble can also be interpreted as the uncertainty of a deterministic simulation, given that the deterministic and probabilistic runs are based on the same model chain.

Established in meteorological sciences and for operational meteorological forecasts, the ensemble approach is now increasingly applied to hydrological problems. Case studies of selected extreme flood events such as spring 1999, November 2002 (Verbunt et al., in press) and August 2005 have shown the suitability of such forecast systems to complement deterministic forecasts.



Hydrological hindcast, starting on 20 August 2005 at Hagneck gauge (Aare). HEPS10 (red) and HEPS51 (blue) are shown, with corresponding IQR and median; in addition, a deterministic simulation (HALMO: black, only 72 h), measured runoff (dark blue) and HREF (green). Spatially interpolated observed precipitation (catchment mean) plotted from top.

LITERATURE

Marsigli C, Montani A, Nerozzi F, Paccagnella T, Tibaldi S, Molteni F, Buizza R (2001): A Strategy for high-resolution ensemble prediction. II: Limited-area experiments in four Alpine flood events. *Quarterly Journal of the Royal Meteorological Society* **127**:2095-2115

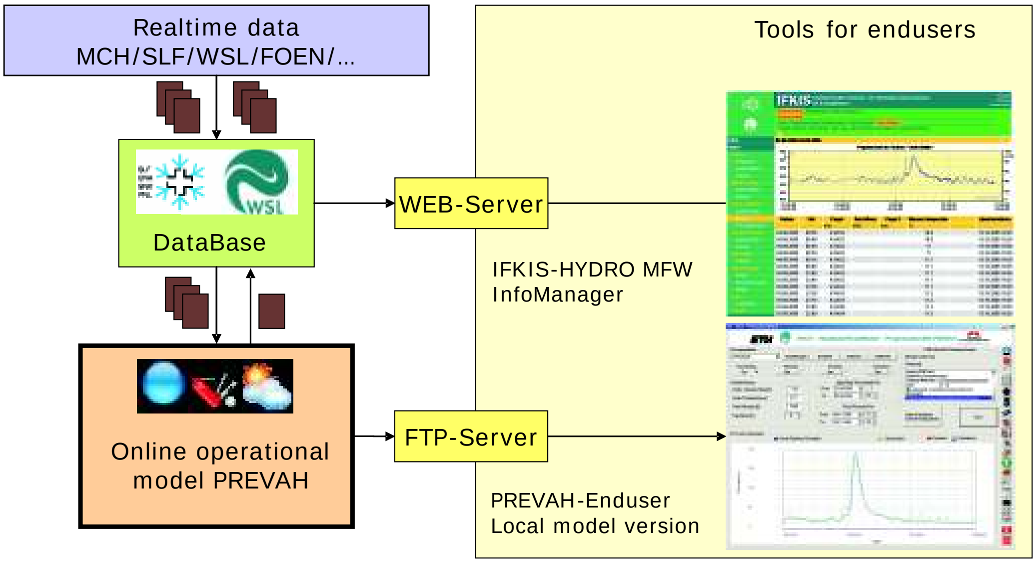
Verbunt M, Walser A, Gurtz J, Montani A, Schär C: Probabilistic flood forecasting with a limited-area ensemble prediction system: Selected case studies. *Journal of Hydrometeorology*, forthcoming.

6.5 Flood forecasting in the Canton of Glarus, Switzerland

In 2004, the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) and the Swiss Federal Institute for Snow and Avalanche Research (SLF) started developing an information and early warning system for hydrological hazards in small to medium-sized catchments (ranging from 1 to 500 km²). The system refers back to the successful experience with the Swiss avalanche warning system IFKIS (Bründl et al., 2004) and was therefore named IFKIS-Hydro. An operational version of PREVAH was developed (Zappa et al., 2006) as part of an information system delivering real time information; this allows decisions to be made on emergency measures in small mountainous catchments.

This operational version of PREVAH is embedded in a complex system ensuring the real time flow of the required meteorological information (see Figure). PREVAH obtains real-time data from a database operated at the SLF in Davos. This database integrates information from different observation networks: the Swissmetnet network of MeteoSwiss (MCH), the IMIS network of SLF/WSL, the hydrometric network of the Swiss Federal Office for the Environment (FOEN), and other local data sources. At the end of the operational model run, the results (precipitation, runoff, snow water equivalent, and others) are uploaded to a database and can be accessed via a web platform (INFO-MANAGER).

Furthermore, the metadata for running a 13-day simulation are uploaded to a dedicated FTP server. The end-user can access this server and use these data to make local model runs with a specific desktop version of PREVAH. This desktop version enables the end-user to prepare tailor-made forecasts and flood scenarios. The nowcasting system is currently implemented for the Linth basin up to the Mollis gauge (600 km²) in the Canton of Glarus (Central Switzerland).



Work flow of the forecast model PREVAH, as implemented in the Canton of Glarus for real time runoff nowcasting and forecasting. Screen shots of the IFKIS-Hydro web platform.

TEXT REFERENCES

–Data assimilation:
see Part II, Chapter 3.4
–Interpolation:
see Part II, Chapter 3.4.2

LITERATURE

Bründl M, Etter H.J, Steiniger M, Klinger C, Rhyner J, Ammann WJ (2004): IFKIS – a basis for managing avalanche risk in settlements and on roads in Switzerland. *Natural Hazards and Earth System Sciences* **4**:257–262.

Zappa M, Rhyner J, Gerber M, Egli L, Stöckli U, Hegg C (2006): IFKIS-HYDRO MountainFloodWatch – Eine endbenutzer-orientierte Plattform für Hochwasserwarnung. *Risikomanagement extremer hydrologischer Ereignisse*, Beiträge zum Tag der Hydrologie 2006, 22–23 März 2006. *Forum für Hydrologie und Wasserbewirtschaftung* **15**, Band 2, pp. 189–200.

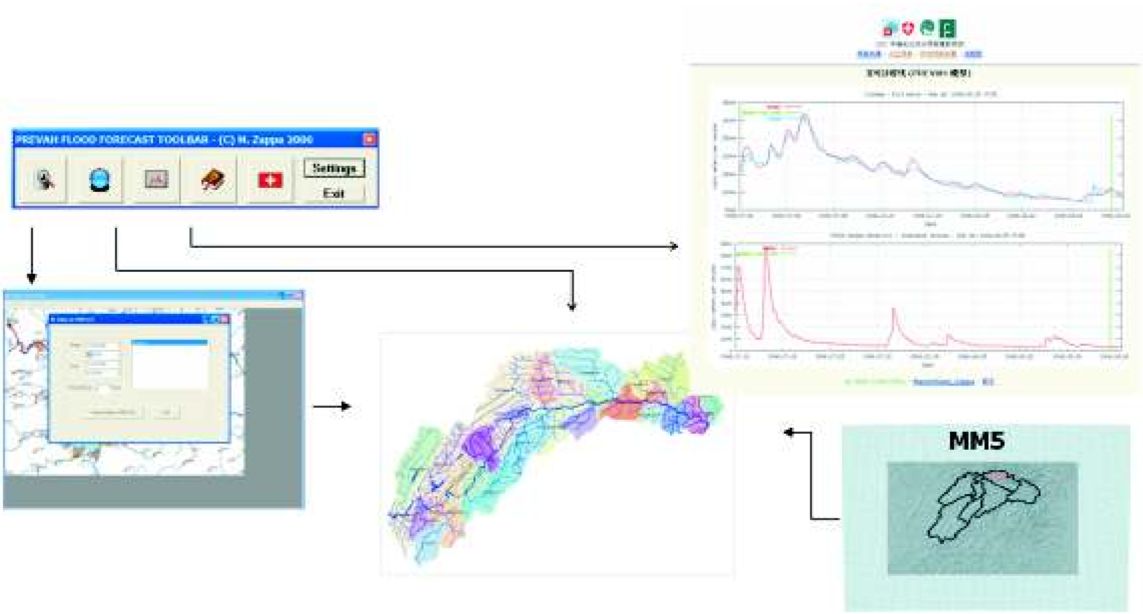
Applications

6.6 Flood forecasting for the Yangtze River, China

The Changjiang (Yangtze) is the largest river in the People's Republic of China, as well as one of the biggest in the world. In its catchment area, there are abundant rainfalls with uneven distribution in space and time. Floods mainly occur from April to October following rainstorms. Flooding disasters have been frequent.

PREVAH has been implemented as a flood forecasting model in the framework of the Changjiang Flood Forecasting Assistance Project (2003–2007). This project aims to enhance the flood-forecasting standard for the middle part of Changjiang River. The project is assisted by the Swiss government through the Swiss Agency for Development and Cooperation (SDC), and by the Changjiang Water Resources Commission (CWRC). A know-how and technology transfer from the Swiss partners to the CWRC collaborators has been completed. This includes training of CWRC staff in GIS, remote sensing and hydrological modelling, as well as the installation of a satellite receiving station together with the required computer hardware and image-processing and GIS software at CWRC in Wuhan (China).

PREVAH has been installed at CWRC for estimating discharge from poorly gauged contributing areas of the Three Gorges dam reservoir (56,000 km², about 15,000 km² larger than Switzerland). For operational forecasting, a set of 34 sub-basins has to be processed in a predefined order, from the upstream headwaters to the last sub-area, which includes the region close to Yichang city. The processing chain also includes automatic consideration of two inflows from large upstream basins: the Yangtze River, upstream from Chongqing (basin of 866,559 km²), and the Wulong River (basin of 83,035 km²). PREVAH is coupled in real time to the database of CWRC (data for nowcasting) and to the numerical weather prediction (NWP) model MM5, which provides operational 72-hour forecasts.



Work flow of the forecast model PREVAH, as implemented in the Three Gorges Area (PR China).

TEXT REFERENCES

−Data assimilation:
see Part II, Chapter 5

LITERATURE

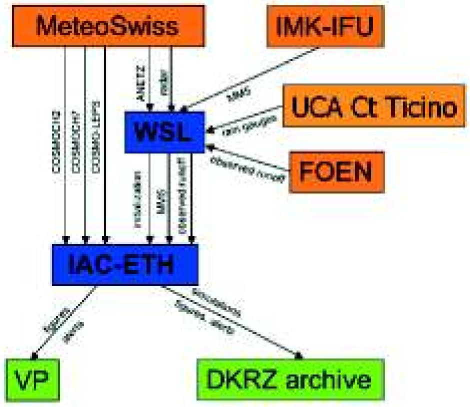
Zappa M, Werhahn J, Song Zhi Hong, Baumgartner MF, Gurtz J, Kunstmann H, Schädler B (2006): Vermittlung von Know-how zur Verbesserung der Hochwasservorhersage im Yangtze-Einzugsgebiet des Drei-Schluchten-Stausees (China). In „Risikomanagement extremer hydrologischer Ereignisse“, Beiträge zum Tag der Hydrologie 2006, 22–23 März 2006. *Forum für Hydrologie und Wasserbewirtschaftung* 15, Band 3, pp. 227–230.

6.7 Ensemble flood forecasting for MAP D-PHASE

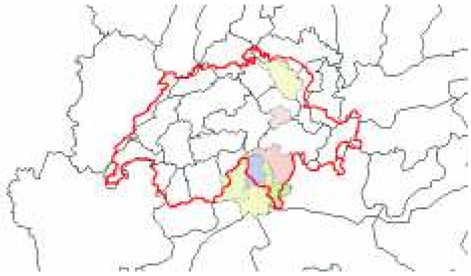
Appropriate dispositions in the case of flood occurrences require longer lead times in hydrological forecasting. This in turn implies an increased uncertainty which cannot be accounted for by a deterministic simulation. The operational use of (probabilistic) ensemble prediction systems (EPSs) to assess the level of uncertainty involved in forecasting precipitation is an established practice in the atmospheric modelling community. In contrast, most hydrological forecasts rely on input from deterministic atmospheric models or are driven by observations alone. Setting up an advanced hydrometeorological forecast system capable of transferring the probabilistic information and the related uncertainty from observations and atmospheric EPSs into the hydrological models used is one of the main goals of MAP D-PHASE (Demonstration of Probabilistic Hydrological and Atmospheric Simulation of Flood Events in the Alps). D-PHASE is an example of a research effort which aims to demonstrate the potential of EPSs for improving the quality of forecasting heavy precipitation and related (flash) flood events in the Alps.

Within MAP D-PHASE, PREVAH has been set up as a quasi-operational system for ensemble forecasts of river streamflow, covering the River Ticino catchment as a study area. The model is fed with data from an operational global atmospheric EPS (ECMWF) which is dynamically downscaled using a limited-area atmospheric EPS (COSMO-LEPS). From the 51 ECMWF/COSMO-LEPS ensemble members available, a sub-sample of 16 representative members is used to produce daily forecasts with a range of 120 h.

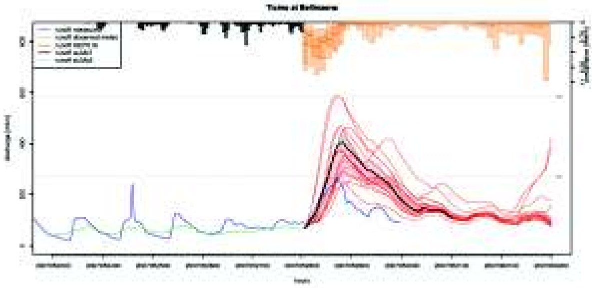
The application of this model framework in MAP D-PHASE aims at demonstrating the potential of hydrological EPSs while exploring their strengths and weaknesses. In order to provide reference values, PREVAH is also operated with three deterministic numerical weather prediction models (COSMO-7, COSMO-2 and MM5).



Data flow for running PREVAH on quasi-operational mode during MAP D-PHASE.



MAP D-PHASE PREVAH basins.



Operational ensemble streamflow forecasts for the Ticino basin as far as Bellinzona (May 2007).

LITERATURE

Ranzi R, Zappa M, Bacchi B (2007): Hydrological aspects of the Mesoscale Alpine Programme: findings from field experiments and simulations. *Quarterly Journal of the Royal Meteorological Society* **133**:867–880.

Verbunt M, Walser A, Gurtz J, Montani A, Schär C: Probabilistic flood forecasting with a limited-area ensemble prediction system: Selected case studies. *Journal of Hydrometeorology*, forthcoming.

Applications

7. Scientific papers and publications

Bründl M, Etter HJ, Steiniger M, Klinger C, Rhyner J, Ammann WJ (2004): IFKIS – a basis for managing avalanche risk in settlements and on roads in Switzerland. *Natural Hazards and Earth System Sciences* **4**:257–262.

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GEOGRAPHICA
BERNENSIA

Daniel Viviroli

Ein prozessorientiertes Modellsystem zur Ermittlung seltener Hochwasserabflüsse für ungemessene Einzugsgebiete der Schweiz

Weiterentwicklung und Anwendung des hydrologischen Modellsystems PREVAH

Für einen modernen, differenzierten Hochwasserschutz sind zuverlässige hydrologische Bemessungsgrundlagen von grosser Wichtigkeit. Gleichermassen heikel wie auch wichtig sind insbesondere Abschätzungen in Gebieten ohne Messungen des Abflusses. In der Praxis spielten dabei bisher vor allem empirische Schätzverfahren eine wichtige Rolle. Um methodisch und inhaltlich weitere Verbesserungen zu erzielen, wurde nun der Ansatz der kontinuierlichen Niederschlag-Abfluss-Modellierung für eine Anwendung in der Schweiz weiterentwickelt und praktisch umgesetzt. Unter Verwendung des konzeptuellen, prozessorientierten hydrologischen Modellsystems PREVAH (Precipitation-Runoff-Evapotranspiration Hydrotope Model) wird dabei der Abfluss eines Einzugsgebietes kontinuierlich in stündlicher Auflösung simuliert. PREVAH wurde für 140 mesoskalige Einzugsgebiete erfolgreich kalibriert, für ungemessene Gebiete können die Modellparameter über ein neu entwickeltes Regionalisierungsmodul bestimmt werden. Die Simulationen werden anschliessend extremwertstatistisch ausgewertet. Der vorgestellte Ansatz erlaubt es, die relevanten Hochwasserkenngrössen für beliebige Gebiete abzuleiten, wobei neben den Spitzenwertreihen auch die kompletten Abflussganglinien zur Verfügung stehen.

A Process-based Modelling System for Estimation of Rare Floods in Ungauged Swiss Catchments. Further Development and Application of the Hydrological Modelling System PREVAH

Reliable estimations for floods of various return periods are an indispensable prerequisite for successful flood protection. To elaborate such estimations for ungauged catchments is equally difficult as well as important. So far, empirical methods have mainly been used for this purpose. In order to make further progress in flood estimation, the approach of continuous precipitation-runoff-modelling is further developed and elaborated for practical application in Switzerland. For this, the conceptual process-oriented hydrological modelling system PREVAH (Precipitation-Runoff-Evapotranspiration Hydrotope Model) is used to simulate continuous discharge hydrographs in hourly resolution. While PREVAH was calibrated successfully for 140 meso-scale catchments, parameter values for ungauged catchments are derived with help of a newly developed regionalisation module. The simulations are subsequently analysed by means of extreme value statistics. With this approach, it is possible to derive the relevant flood estimations for an arbitrary catchment, while both peak flow series as well as complete discharge hydrographs are available.

(Text in German; Tables, Figures and Chapter abstracts in English)

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