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Integrated System for Water Resources Assessment - A Tool for Optimised Operation of Hydroelectric Power Plants

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Abstract

A JAVA based tool consisting of two snow-hydrological models for the simulation of snow distribution and snowmelt runoff, combined with a database management system and geographic information system is described. Its real-time application for stream flow forecasting and snow monitoring in spring 1999 is documented.

1 Introduction

In February 1999, heavy snowfall occurred in the Swiss Alps and adjacent areas, not only causing severe avalanches in different locations, but also leading to high flooding potential. In May 1999, large amounts of snow were still stocked in an elevation range between 1000m and 2000m a.m.s.l. An increase in air temperature shifted the 0°C line to elevations above 3000m, causing a release of melt water equivalent to as much as 50mm rainfall per day. In combination with extended rainfall over a period of several days, this snowmelt contributed to severe flooding not only in the Canton of Bern, but in larger parts of Switzerland.

However, despite such risks and problems, water is also one of the most important natural resources, used for drinking, irrigation, transportation and energy generation. Especially in alpine areas, the seasonal snow cover serves as an important reservoir for water supply. Together with the topographical conditions, allowing for the design of large artificial reservoir lakes, there are favourable conditions for hydroelectric power generation. In Austria, more than 90% of the total energy production is generated by hydropower; in Switzerland the proportion is 56% (in 1998). With such figures, the ongoing opening of the electricity market in Europe calls for efficient use of water resources and energy production.

Information on the water stocked as seasonal snow cover, as well as short-term forecasts of the river flow, are therefore not only required for flood warnings, but

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can also provide important data for optimised management of hydropower plants. In the case of small reservoirs, prediction of the water inflow can help provide sufficient capacity and thus avoid overspill during the major snowmelt period. For larger reservoirs, short-term forecasts are less important than information on the water reserve stored as snow. Data on the snow distribution permit estimation of the expected snowmelt water inflow during the melt season and thus water consumption up to a minimum left in the reservoirs.

This paper presents a decision support system that provides such information and can be used for both flood warning and hydropower plant management. Its core consists of a snow regionalisation model for determining the snow distribution and a model for runoff forecasting based on the daily computed snowmelt.

2 Design of the Decision Support System

The concept behind the decision support system is to have a combined set of tools, allowing snow distribution maps and hydrographs to be derived for a specific stream gauge. The overall system consists of three major parts: the database management system (DBMS) for central data management, a geographic information system (GIS) for visualisation and spatial data analysis and the SnowModel software for computing snow distribution and snowmelt runoff (Figure 1).

The DBMS contains all required data from meteorological stations and snow gauges as well as the attribute tables for the GIS. A JDBC driver it required to allow the JAVA based SnowModel software to connect to the database. The GIS is used to visualise the simulation statistics for each reference snow gauge and to display the computed snow maps. Any software can be used as long as it allows the user to connect to a database in order to link the attribute tables. It should also be able to read raster data in the GridAscii format as defined by ArcInfo™.

For the applications described below, an MS-Access™ database was installed using the ODBC-JDBC bridge for data exchange. ArcView™ was used as the GIS, likewise linked to the DBMS via an ODBC connection.

2.1 SnowModel Architecture

The SnowModel software defines the core application for simulating the snow pack and snowmelt runoff. It consists of four modules, each of which is responsible for a specific task (Figure 2). The DATA module is used for internal data management and can be accessed from all the other modules. It stores meteorological and snow data required as model input, spatial data like snow maps and digital elevation data, and the simulation results. The MODEL module, taking its input from, and writing its output to the DATA module, contains the simulation models for snow pack and snowmelt runoff simulation. The concept of the simulation models is described in more detail in section 3. The DATABASE module provides connection to the DBMS via JDBC. It permits all required data to be downloaded into the DATA module and the simulation results to be uploaded for visualisation within the GIS. Finally, the DISPLAY module provides some basic visualisation tools for plotting time series data or displaying snow distribution maps.

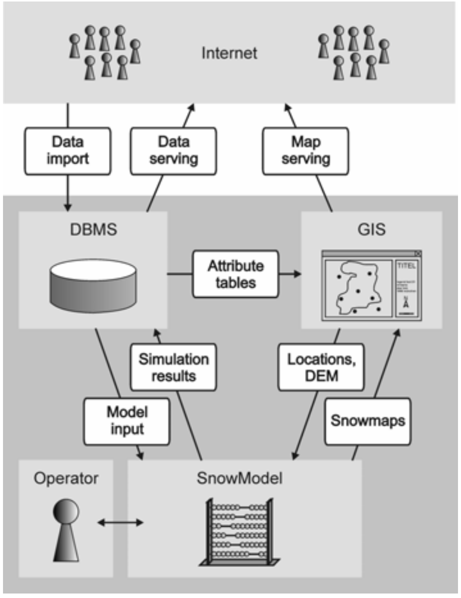

Figure 1: The decision support system consists of a database management system, a GIS and the simulation model. Data import, as well as display of the simulation results, is possible via the Internet.

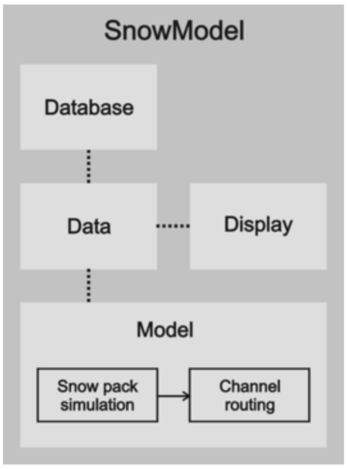

Figure 2: The SnowModel software is defined by several modules for data management, database connection and display features. The computation itself is carried out within the MODEL module.

2.2 Data Exchange

Data can be imported via FTP or written directly into the database if the local security concept allows for Internet access to the DBMS. The model reads the data from the database, but can, however, also import data through an ASCII interface. The spatial data such as snow maps can be read and exported in the GridAscii format defined by ArcInfo™. Attributes of the meteorological stations and snow gauges are accessed via the DBMS. The resulting snow distribution maps and hydrographs can be published over the Internet, using standard software solutions for GIS and DBMS. E-mail and FTP transfer are integrated in the software package and allow quick delivery of the simulation or forecast results.

2.3 User Interface

A command line interpreter is used as interface between the operator and the software. It provides a set of commands for loading and visualising data, executing simulations and calibrating the model parameters. It is possible to combine several commands in scripts using the same command syntax and, thus, to automate most of the routine processes. Some of the functionality is available via graphical user interfaces (GUI), but full access to all program facilities is currently available only through the command line interpreter.

2.4 Implementation

The program is implemented in JAVA based on the JDK 1.2. It uses only standard Java2™ classes, with exception of the *JClass.chart* package provided by the KL Group and the JDBC-ODBC bridge provided by Sun.

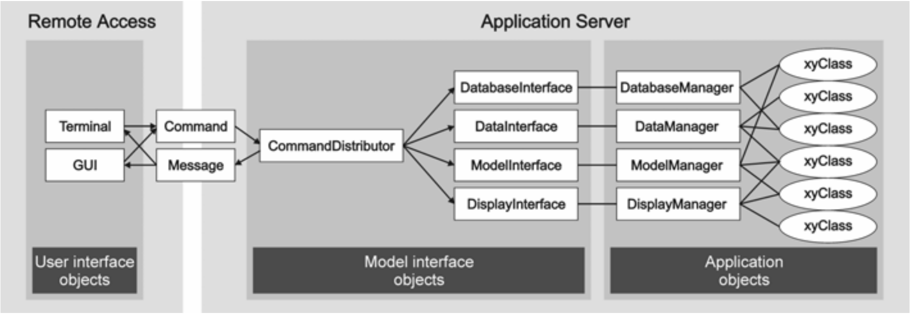

Figure 3:
Internal architecture of the SnowModel software. The program can be subdivided into remote access classes for direct user interaction and application classes on the server side. The model interface objects parse the commands whereas the application objects provide methods to carry out the tasks requested by the user.

The architecture is displayed in Figure 3. It is defined by user interface objects for direct user interaction, which can be located on a remote computer. Two classes *Command* and *Message* are used for data exchange and the *CommandDistributor* class dispatches the command to one of the command interface classes. The only function of the command interfaces is to parse the commands and call the respective methods of the manager classes, providing the required arguments. The manager classes themselves carry out the requested tasks, supported by a number of subsequent classes for data access, snow pack simulation, plotting, etc.

Figure 4 displays the main contents of the manager classes. Two classes are defined for the computation task within the model manager: *SnowpackModel* for simulating accumulation and melt of the snow pack, and *SnowmeltRouting* for calculating the channel routing. The algorithms behind these classes are described in section 3. Three collection classes available within the data manager control a number of data stations, snow maps and simulation targets. Each of these classes provides convenient methods to access single elements like a specific snow gauge or snow map. The display manager defines two classes, *Plot* for plotting time series data (based on the *JClass.chart* class collection provided by the KL Group) and *Gridpaint* for visualising spatial data like snow maps.

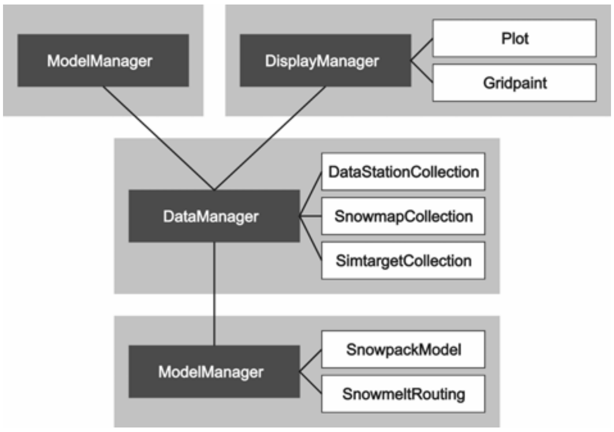

Figure 4:
Manager classes of the SnowModel software. The data manager contains collection classes for data stations, snow maps and simulation targets. The model manager accesses two additional classes, *SnowpackModel* for the snow pack simulation and *SnowmeltRouting* for channel routing. The display manager contains further classes for plotting time series data and displaying snow maps.

In order to increase system performance and to enable the user to start analysing the results while the computation is still running, a multi threading technique is applied. A one-year simulation of a grid of 110x70 cells for 51 meteorological stations and 43 snow gauges requires a processing time of approximately 120 seconds on an Athlon 750 PC with 256MB RAM.

3 Concept of the Simulation Models

As mentioned above, the simulation of the snow accumulation and snowmelt required to derive snow distribution maps and the channel routing are carried out within different classes of the SnowModel software. The snowmelt calculated for each grid cell by the snow pack model is required as input for the routing algorithm.

3.1 Snow Pack Model

In order to derive snow distribution maps on a daily basis, a simple snow pack model for calculating snow accumulation and snowmelt is applied to a spatial grid with a cell size of 1x1km^2. A digital elevation model (DEM) with respective spatial resolution provides data on the topographical conditions.

3.1.1 Data Requirements and Model Input Preparation

Several meteorological stations provide the required temperature and precipitation data. These data are interpolated to the reference grid and then used as input variables driving the model. The snow pack model requires only air temperature and precipitation as daily input variables. They are interpolated for each grid cell or snow gauge according to their coordinates and elevation before being used as model input. For precipitation an elevation-independent inverse-distance interpolation is used, whereas air temperature is first normalised to elevation before being interpolated by a first order inverse-distance approach. The normalisation to elevation is reversed, again based on the temperature lapse rate. The lapse rate is calculated for each location depending on the temperature data of the surrounding meteorological stations, fitting a linear regression of temperature versus elevation. A number of reference stations can be defined to be used for model validation or calibration. The snow pack simulation is carried out for each reference snow gauge's location and for all grid cells independently.

Snow depth and snow water equivalent measurements must be available for the model calibration. During the calibration process, these data are directly compared with the simulation results for each respective station. Snow maps – for example derived from satellite data – are used as additional and very important information for the calibration process. NOAA-AVHRR data provide frequent observations of the snow cover and have sufficient spatial resolution for the application presented here (1.1km). In Switzerland, snow maps from NOAA-AVHRR data are available every 5-8 days on average. The satellite has a nominal repetition cycle of less than one day, but cloud cover can hinder the observation of the snow cover extent. The procedure for deriving snow maps from satellite data that has been applied for the applications documented below is described by Voigt et al. (1999).

In addition to the variable model input, some static data have to be provided. As mentioned above, the digital elevation model is required as a representation of the topography, with a spatial resolution large enough to ignore the interaction between two adjacent grid cells by processes such as snow drift, etc. A radiation grid derived from the DEM has to be provided in order to take into account the influence of slope and aspect on the snowmelt process. It can be computed using the "hillshade" function available within many software packages.

3.1.2 Model Description

The snow pack model, which is used for the calculation of snow accumulation and snowmelt at specific locations, such as the snow gauges or the grid cells, is based on the degree-day approach. In addition to air temperature as indicator for snowmelt, a radiation correction is applied to adjust the snowmelt to the topographic conditions. The daily variable values, the parameters and the model state are listed in Table 1.

Variables	Temperature, precipitation (rainfall and snowfall), new snow density, potential snowmelt, real snowmelt, melt water flow
Parameters	Upper and lower precipitation threshold temperature, metamorphosis, maximum dry snow density, melt correction for negative temperatures, radiation correction, minimum and maximum degree-day factor, increase of degree-day factor with melt and time, critical snow pack density
Model state	Snow depth, snow water equivalent, liquid water content, degree-day factor, cold content

Table 1:
Variables, parameters and model state definition for the snow pack model.

The model described here is a strong simplification of reality. However, for the desired temporal and spatial scale, a more detailed approach would not necessarily provide improved results (Vehviläinen 1991).

Precipitation

The precipitation segment defines the precipitation type and properties. The type, either rain or snow, is determined via an upper and lower threshold temperature. With an air temperature below the lower or above the upper threshold, precipitation is assumed to be purely snow or rain, respectively. If the air temperature lies between the two thresholds, the precipitation is calculated as snow-rain mixture, with the proportions linearly interpolated. In the case of snowfall, the temperature of the new snow is assumed to be equal to the air temperature. It is required to calculate the new snow density. Since new snow increases the albedo of the snow surface, the degree-day factor is adjusted depending on the amount of new snow.

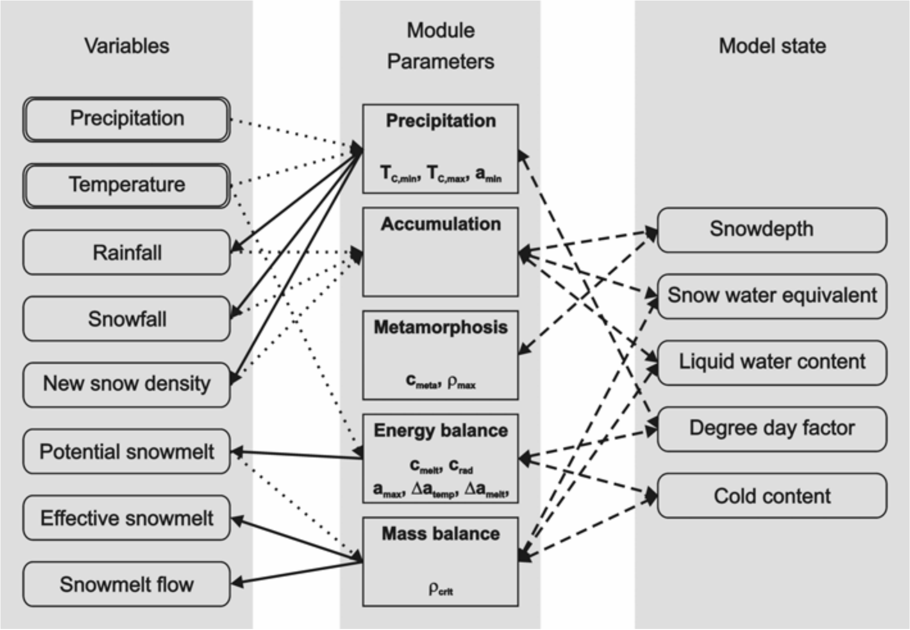

Figure 5: Variable, parameters and model state as they are used by the five segments of the snow pack model. Double-lined boxes indicate predefined input variables. Dotted arrows display input for the modules, solid arrows represent calculation results and dashed arrows indicate model state values, which are required as input and modified during the computation. ($T_{C,min/max}$ = lower and upper precipitation threshold temperature, $a_{min/max}$ = minimum and maximum of the degree-day factor, $\Delta a_{temp/melt}$ = time and snowmelt dependent increase of the degree-day factor, c_{meta}/ρ_{max} = metamorphosis parameter defining speed and boundary of dry snow compaction, cmelt/rad coefficients for snowmelt at negative temperatures and radiation correction, ρ_{crit} = critical snow pack density snow compaction computation)

Snow Accumulation and Metamorphosis

The snow accumulation segment adds the newly fallen snow to the snow pack. If precipitation occurred as rainfall, the liquid water content is increased respectively. The snow depth is increased according to the previously computed density of the new snow, taking into account the snow compaction of the underlying snow pack due to the weight of the new snow.

An exponential decrease of snow depth with time is applied to simulate the metamorphosis of the snow pack due to aging. Two parameters are used to define the speed of snow metamorphosis and the maximum density the dry snow can attain.

Cold Content

Within the segment for the cold content computation, the potential snowmelt is calculated as energy input into the snow pack. Only air temperature is used as input for the melt computation. However, a radiation correction allows the degree-day factor to be adjusted according to slope and aspect.

The calculated energy flux is positive if the air temperature is above the average temperature of the snow pack, and negative if it lies below the snow temperature. The energy flux at temperatures below 0°C is reduced by a constant factor, because in this case other processes dominate over the sensible heat flux.

The degree-day factor as the key parameter for the snowmelt computation is assumed to increase with time and potential melt, taking into account the ageing of the snow surface and the re-crystallisation of the snow due to energy input.

Snowmelt and Melt Flow

The potential snowmelt is used as the single input for the simulation of the mass balance of the snow pack. If the energy influx suffices to raise the average temperature of the snow pack to 0°C, all remaining energy is used for snowmelt. The resulting melt water is added to the liquid water content of the snow pack. The snow compaction procedure, as suggested by Bertler 1966 and used for many other models, is applied to take into account the water retention capabilities and the snow compaction due to newly available liquid water. If a critical snow pack density is exceeded, the liquid water will drain and melt flow occurs.

3.1.3 Calibration for Optimised Simulation

In order to provide an optimised representation of the real snow distribution, the snow pack model can be calibrated based on data from various snow gauges and snow cover maps derived from satellite data. The calibration process does not aim to find the best fit of simulated snow depth for single snow gauges, but tries to compensate for general over- or underestimation of the snow amount. Thus, calibration with similar tendency is applied to larger areas of several hundred square kilometres, represented by so-called calibration centres. The calibration is not defined on a daily basis but for periods of specific length between 20 days and two months. Four parameters, which are explained in Table 2, can be applied for calibration.

Parameter	Symbol	Comment
Threshold temperature	ΔT_C	With a time step of one day and only the average temperature available, it can happen that snowfall occurs at unexpectedly high or low temperatures. This cali-

		bration parameter permits adjustments to be made for such events.
Degree-day factor	Δa	It can happen that the automatically computed degree-day factor does not sufficiently represent the snowmelt conditions. In these cases, the factor can be modified by this parameter.
Precipitation correction	c_P	Precipitation gauges tend to underestimate the real precipitation – especially snowfall can exceed the measured data by up to 30-40%. This correction factor is meant to account for this effect.
Snow density correction	c_ρ	If snow water equivalent data are available, they can help assess the simulated snow density. If it becomes evident that snow density is generally over- or underestimated, it can be corrected via this parameter.

Table 2:
Calibration parameters for optimised simulation of the snow distribution.

3.2 Snowmelt Runoff Routing

The runoff routing model used for calculating the stream flow, resulting from the snowmelt simulation described above, is based on the widely used Snowmelt Runoff Model (SRM), first described by Martinec (1975). Since it is documented in detail by Martinec et al. (1998), it is only briefly described here.

A single non-linear storage as a combined retention-translation model is applied in order to transform the snowmelt into stream flow at a specific stream gauge (equation 1).

$$Q_n = \left(1 - k_n\right) \cdot R_n + k \cdot Q_{n-1} \qquad (1)$$

R_n defines the snowmelt available at the time step n. It is calculated based on the snow pack model results for each grid cell, including a time lag according to the distance of each cell to the location of the stream gauge. A stream flow dependent recession coefficient k is defined by two parameters as described in equation 2.

$$k_n = X \cdot Q_n^{-Y} \qquad (2)$$

Stream flow data can be used to validate the simulations and to update the model where accurate estimations are required – for real-time forecasting, for example.

4 Application

Two applications provided the motivation to develop the tools described here. Short-term stream flow forecasts for the Inn basin were carried out within the frame of the European research project HYDALP, which aimed to develop and implement methods to incorporate earth observation data into hydrological modelling (Rott et al. 1999). The simulation of the snow distribution for the Canton of Bern was part of a monitoring programme that was initiated after the intense snowfall events of February 1999, in order to set up an early warning system for flooding and geomorphological hazards (Mani 2000).

4.1 Short-term Stream Flow Forecasts for the Inn

In Spring 1999, real-time stream flow forecasts were issued for the stream gauge Tarasp at the Inn river (Kleindienst et al. 2000a). It defines a basin of approximately 1640km^2 in size, with an elevation ranging between 1000m and 4000m a.m.s.l. The Engadiner Kraftwerke AG uses large amounts of the available water for energy production and is thus interested in stream flow forecasts to improve water resource management.

At the time of this application, the stream flow simulations were carried out by a separate program as described by Kleindienst et al. (1999). The data processing, forecast simulation and dissemination of the results were fully automated except for the integration of stream flow correction data, which were received daily by fax and thus had to be entered manually. Meteorological data and forecast data from the mesoscale weather forecast model "Swiss Model" (provided by MeteoSwiss) were transferred via FTP, the processing was initiated by time controlled batch jobs. Figure 6 shows the results of a re-calculation comparing the stream flow forecast based on the meteorological forecast data with the simulation based on the observed temperature and precipitation data.

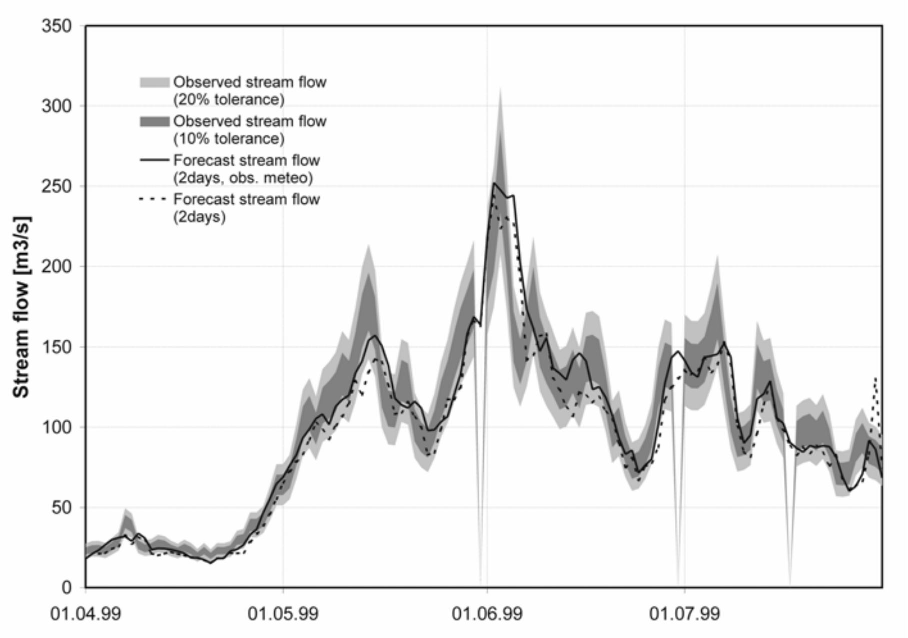

Figure 6: Simulated forecast for the stream gauge Inn-Tarasp for a 2-day period using forecast and observed meteorological data (no observed stream flow data are available for 31 May, 30 June and 17 July). The observed stream flow is shown with a 10% and 20% error tolerance (Kleindienst 2000a).

4.2 Simulation of the Snow Distribution for the Canton of Bern

The heavy snowfall during February 1999 mentioned in the introduction led to the formation of an expert group in order to set up an early warning instrument for flooding and geomorphological hazards. Knowledge of the snow distribution in the alpine environment was one of the key requirements for assessing the situation. For three months, weekly simulations were computed based on the weather forecasts issued specifically for this project. Hydrological simulations and the final assessment were carried out by a local geo-science consulting company.

Figure 7 shows the simulated snow distribution for 25 April 1999. Comparing the computed snow-covered area with the observations based on satellite data shows only a few errors for a small number of grid cells. Validating the simulation results for all dates with available satellite data leads to an average accuracy of 93% of all relevant grid cells, with 3.5% over- and underestimation, respectively (Kleindienst et al. 2000b).

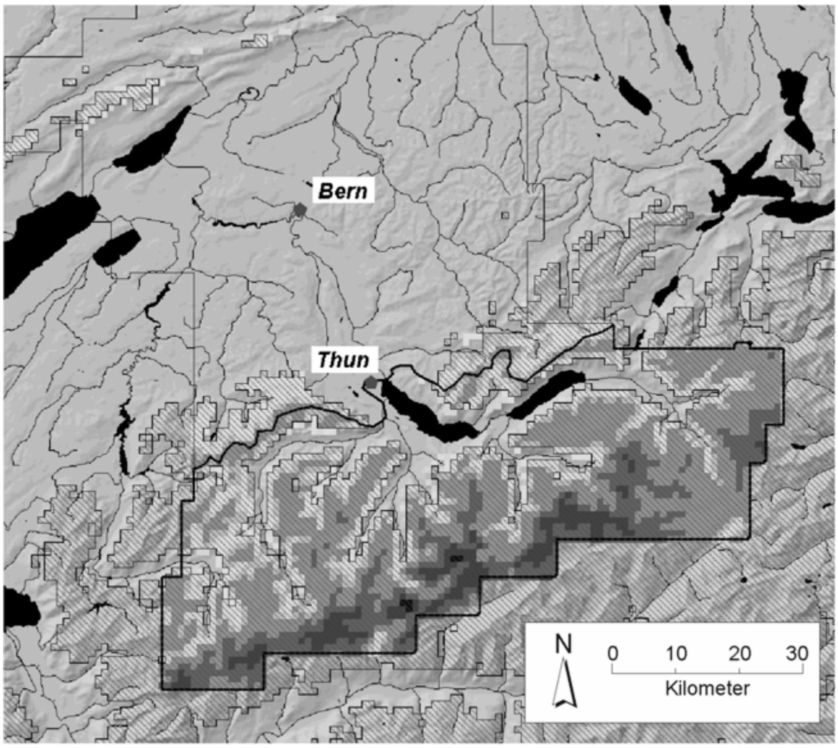

Figure 7 –Snow distribution within the Canton of Bern (25 Apr. 1999). The grey areas indicate different snow depth whereas the semi-transparent area defines the snow covered-area as observed by the NOAA-AVHRR satellite sensor. (Modified after Kleindienst et al. 2000b)

5 Conclusion and Outlook

The SnowModel software described in this paper, in combination with a database management system and a geographic information system, is a useful tool for water resources assessment. The overall decision support system can provide guidelines for optimised water management. The development of the software in JAVA allows for platform independent application. Modern computers together with new versions of the JAVA runtime environment help to reduce the execution time to only a few minutes, depending on the size of the simulation area as well as the number meteorological stations and snow gauges. Additional future applications in different areas might help to automate the calibration process independent of user interaction.

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