# Hydrotope-based river flow simulation in a Swiss Alpine Catchment accounting for Topographic, Micro-climatic and Landuse Controls

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**Abstract:** An application of the Precipitation Runoff Modelling System (PRMS) based on the concept of Hydrological Response Units (HRUs) is presented for hydrological modelling of an alpine catchment. This is the Aare River catchment upstream of the Lake Thun, in the Bernese Oberland Region, Switzerland, which is characterised by large glacierised areas. Accounting for these areas required to develop further the original PRMS, which was rarely used in alpine regions. Particular attention was devoted to the analysis of the temporal and spatial distribution of temperature and rainfall within the catchment. The derivation of distributed model's parameters was based on an extensive database of catchment characteristics available for the region, thereby including a 25 m resolution Digital Elevation Model (DEM), and digital maps of geotechnical properties, soil and landuse. The encouraging results in spite of the highly complex catchment morphology underline the importance of the availability of spatially distributed data to be used for HRUs identification and parameterisation. Such availability allowed transferring the parameter set from one subcatchment to another without significant loss of model efficiency. However, as expected, the model was strongly sensitive to the parameters describing the runoff generation processes (retention capacity of the unsaturated storage, snowmelt infiltration capacity) and the routing of water in subsurface and groundwater reservoirs. This is due to the intrinsic variability of these parameters, but may be enhanced by the general lack of specific distributed data that could be used to improve calibration. Accordingly, the study concludes about the evident need for enlarging data availability in relation to subsurface and groundwater processes, or, alternatively, in fostering the development of robust parameter calibration methods, which rely on data that are generally available.

**Keywords:** hydrotopes; alpine catchment; topographic effects; PRMS

## 1 INTRODUCTION

In May 1999 a major flood event occurred in Switzerland affecting most regions of the northern part of the Alps. This event was caused by incessant heavy rainfall, preceded by a considerable snowmelt over a large area of the region, particularly in the Aare basin (in the Bernese Alps), due to a particularly mild weather conditions at the end of an extremely snow-rich winter. As a consequence, the water level of Lake Brienz and, even more markedly of Lake Thun rose far above the maximum levels ever reached before. Because of the complexity of the regulation of the lakes in relation to the downstream flood conveyance capacity, it is of interest understanding the dynamics of the event and investigating the long-term vulnerability of the basin to similar circumstances.

Furthermore, the basin is highly complex in terms of topography, geology, climatology, and pedology. Snow accumulation in winter and snowmelt in spring and early summer represent a significant component of the hydrologic cycle and play an important role in generating floods. However, due to the snow-fed regime of the river and to the retention effects of the regulated lakes, only large water volumes can generate flooding. Therefore, only long-duration rainfall events have to be considered critical.

The investigation of all of these aspects requires the availability of a tool that allows a robust simulation of the hydrological processes, which are responsible for the onset of major floods. In this paper, a continuous model for three subcatchments contributing to the mentioned lakes is presented. Some developments of the original formulation of the model are illustrated in order to account for peculiarities of the alpine environment. A preliminary set of results is illustrated, and the adequacy of the PRMS to represent the response of alpine catchments is also discussed.

## 2 STUDY AREA DESCRIPTION

The Aare river basin at Thun drains an area of about 2500 km$^2$, with an elevation range from less than 500 m a.s.l. near Thun to more than 4000 m a.s.l. It can be subdivided into 4 main subcatchments, 2 flowing into Lake Brienz and 2 more downstream into Lake Thun. The basins show a different topography, climate and, consequently, hydrological regime. One of them, the upper Aare catchment (upstream of Lake Brienz) is highly influenced by hydropower activities and is not further considered at the present stage of the investigation within this paper.

The basin has a humid alpine climate with a pronounced precipitation peak in summer and a secondary peak in December. The mean annual precipitation ranges from about 1300 mm in the valley to more than 3000 mm in the vicinity of the water divide. The average annual temperature at an elevation of 1600 m a.s.l. is 3.6 °C with a monthly minimum temperature of –2.6 °C in February and an average monthly maximum temperature of 11.2 °C in July.

The main characteristics of the subbasins are summarised in Table 1, showing the wide elevation range and the amount of glacierised area, resulting in different runoff regime types.

**Table 1.** Catchment characteristics

| Catchment | Simme | Kander | Lütschine |
|---|---|---|---|
| Area [km$^2$] | 564 | 520 | 379 |
| Elevation [m a.s.l.] | 762-2764 | 746-3553 | 657-3818 |
| Forest [%] | 25.0 | 17.1 | 17.7 |
| Glacier [%] | 2.0 | 7.5 | 16.7 |
| Rocks [%] | 9.7 | 25.1 | 27.6 |
| Flow regime type[1] | nival de transition | b-glacio nival | a-glacio nival |
| # of raingauges | 4 | 6 | 5 |
| elevation range of raingauges | 622-960 | 760-1710 | 574-2061 |
| # of temp. stations | 2 | 1 | 4 |
| elevation range of temp. stations | 890-1085 | 1355 | 574-3572 |
| # of HRUs | 89 | 132 | 152 |

[1] For further details on flow regimes refer to Aschwanden [1986].

## 3 THE PRMS MODEL

The PRMS (Precipitation Runoff Modeling System) was developed by the U.S. Geological Survey [Leavesley et al., 1983] to analyse the effects of precipitation, climate, and landuse on streamflow. It has been widely used in the U.S. [see e.g. Leavesley and Stannard, 1995] in middle altitude regions, but only few applications are known in European catchments [e.g. Flügel, 1997; Mehlhorn, 1998] and even less in alpine environments [Brendecke et al., 1985].

The PRMS is a deterministic, distributed, and process-oriented model using both physical laws and conceptual relationships to describe the processes. Daily precipitation and minimum and maximum daily temperature drive the processes of evaporation, transpiration, infiltration, snowfall, snowmelt, and sublimation. This is not a limitation in the specific case of the Aare basin, because the daily time step is consistent with the basin response and further allows the use of a relatively comprehensive climatic database, also enabling to neglect the explicit representation of flow routing.

However, the PRMS model was chosen because of its intrinsic ability to account for such heterogeneity of catchment physical properties. This is achieved by means of a basin description based on hydrotopes (originally denoted to as *Hydrological Response Units*, and henceforth referred to as HRUs), which are used to partition the basin into homogeneous units on the basis of elevation, slope, aspect, land use, soil type and geology. These not contiguous hydrologically similar areas (HRU) have a unique set of physical-parameter values and a water-energy balance is computed during each time step for each HRU.

The PRMS conceptualises the basin as a series of reservoirs and streamflow is obtained by summing up the various reservoir contributions (surface runoff, subsurface and groundwater flow). Many of the equations used in the model require coefficients that can be directly estimated from known or measurable basin characteristics. A few empirical parameter values, however, have to be estimated only by calibration to observed data. These parameters are primarily associated with subsurface and groundwater reservoirs and snowpack-energy computations.

### 3.1 Model Implementation

A careful analysis of the upper Aare basin suggested that two main aspects were expected to be critical for a successful modelling. These are, primarily, the presence in the region of extended glacierised areas (particularly in the Lütschine river basin) and, secondly, the predominant role of the topographic controls (e.g. aspect, slope, valley orientation) in determining local scale phenomena, which often affect the quality and the further regionalisation of the measured climatological data.

#### *3.1.1 Time-series Data Set*

Daily precipitation and maximum and minimum air temperature data series were compiled for 13 meteorological stations, as well as daily streamflow data for 3 runoff gauging stations. Different sets of calibration and independent validation periods were selected according to the availability, the consistency, and the quality of the data set (see § 3.3). Daily shortwave radiation required for snowmelt computation and for evapotranspiration assessment was estimated using air temperature, precipitation and potential solar radiation data.

### *3.1.2 Development of the Ice-melt Module*

During preliminary model runs, the PRMS simulation for the Lütschine basin showed indeed an evident and constant underestimation of the summer runoff component, when the winter snow cover completely disappeared, and glacier melt, which is neglected by the standard version of the model, became the main source of runoff generation. Therefore, a glacier module was developed on the basis of a modified degree-day procedure and implemented as a new module in the original PRMS code. Specifically, a distributed temperature index model, first developed by Hock [1999], was adopted. This includes a radiation index in terms of potential direct solar radiation, which is used to correct the original index model formulation, without additional data requirements besides air temperature. This allowed to capture the spatial variation in melt due to local variability of energy fluxes, which control the melting process of glacier.

### *3.1.3 Delineation of Physical Basin Characteristics*

The different subbasins were partitioned into "homogenous" HRUs by overlaying different layers using a GIS. Data layers included near-surface geology, soil suitability, landuse, vegetation, slope, aspect and elevation zones maps. Area, mean elevation and aspect were first directly computed from the DEM layer, and many of the values assigned to HRU parameters related to land-use or vegetation cover were derived from various GIS data layers.

For the annual water balance as a whole, precipitation and evapotranspiration play the key roles. In humid climates (as in our case), evapotranspiration is mainly driven by the water deficit of the atmosphere and the type of vegetation, since water deficit in the soil practically does not occur. Therefore, temperature and radiation are very important and they are strongly dependent on elevation and aspect. Hence, elevation and aspect, derived from a DEM, were first considered in delineating the HRUs.

For the short-term runoff production (i.e. floods), soil, near-surface geology, landuse and vegetation type are recognised to be the key variables, besides the snow. These properties mainly define the infiltration behaviour. In this respect a digital map of infiltration characteristics derived from digital maps of landuse, soil characteristics and geotechnics was used [Pfaundler, 2001]. The infiltration characteristics were based on the process description according to the U.S. Soil Conservation Service (SCS) for the so-called Curve Numbers [SCS, 1973]. The resulting number of HRUs for each subbasin is shown in Table 1.

## 3.2 Model Parameterisation

In order to preserve the spatial variability of the basin characteristics, PRMS parameters are both lumped and distributed. Many of these refer to topographic and physiographic properties and were directly derived from the DEM. Others are related to temperature and precipitation distribution and therefore allow considering microscale effects.

An example of these is given in § 3.2.1. Lumped parameters provide conversely a value of a catchment characteristic averaged over the entire basin. The main lumped parameters in the PRMS are related to potential evapotranspiration, subsurface flow, groundwater flow, snow, and snowmelt processes. Potential evapotranspiration was estimated in this case by means of the Hamon [1961] method from minimum and maximum air temperature data and the related parameters were considered constant within the basin. In consideration of available data a lumped parameterisation was also chosen to characterise the reservoirs that simulate the water balance in the catchment, in spite of the theoretical possibility offered by the PRMS of defining a distributed parameterisation. The soil water balance is accordingly described by a *Soil Storage Reservoir*, which is divided into a upper zone representing the recharge zone and a lower zone, representing the percolation component. A single *Groundwater Reservoir* was conversely defined for each subbasin. The *Subsurface Flow*, is computed by means of two conceptual reservoir-routing systems, simulating respectively the storage of shallow hillslopes and the storage of deep valley bottoms. Two parameters control the rate of the flow as a nonlinear function of storage volume in the reservoir. Finally, the storage capacity of glacierised HRUs was also simulated by means of an additional subsurface reservoir with a negligible seepage rate from the reservoir to the groundwater reservoir.

### *3.2.1 Microclimate Effects*

Precipitation and temperature data corrections were introduced to account for spatial variability and regional effects.

*Precipitation data adjustment*. Because the HRUs can be theoretically not contiguous the rainfall input to each of them cannot be simply based on the assignment of the value observed at the nearest precipitation gauge. Hence, an adjustment for each HRU was made, mainly applying a correction factor accounting for the elevation range between the standard basin-representative rain gauge (defined as the Thiessen-averaged rainfall over a specific subcatchment) and a particular HRU. A more general basinwide adjustment was additionally applied to each subbasin in the final calibration to accommodate the water balance.

*Temperature adjustment (lapse rates).* To account for the air temperature difference between the elevation of the climatological station and the mean elevation of the HRU, minimum and maximum air temperature lapse rates were included as PRMS parameter input, on the basis of data from 8 climate stations of the entire catchment (Figure 1). Some stations had to be excluded from the beginning because of regional or microclimatic anomalies. Temperature gradient varies during the seasons and exhibit a relatively small variation range for the daily minimum temperature $T_{min}$, and a considerably higher one for the daily maximum temperature $T_{max}$ (see Figure 1), whereas the variability is generally lower during the winter months. However, the differences in the monthly temperature gradients observed for the different subcatchments were small, thus allowing the use of a single average gradient for the entire catchment applied to the reference station selected for each subcatchment.

## 3.3 Model Calibration and Validation

Many of the initial values of the PRMS parameters could be set from values found in literature or derived from precedent studies [Laenen and Risley, 1997; Mehlhorn, 1998]. In order to account for a homogeneous procedure across different subbasins, further calibration of the model was undertaken accordingly to the following steps:

1. The PRMS evapotranspiration related parameters were calibrated in order to match the estimates of actual evapotranspiration losses derived from a previous detailed study [Menzel, 1997].
2. Precipitation records were adjusted for each HRU accounting for mean elevation and topographic effects and matching the monthly water balance through comparison of the measured and computed runoff volumes.
3. The parameters relevant to the different storages were then estimated by analysing the shape of the recession limbs;
4. Finally, the flood governing parameters, such as maximum infiltration rates, and minimum and maximum contributing areas were calibrated focusing on the shape of discharge peaks.

Two sets of independent records of streamflows were used for calibration (5 to 7 years, depending on the subcatchment) and validation (6 to 7 years). A summary of the results is reported in Table 2, showing the coefficient of determination ($R^2$) ranging from 0.72 to 0.86 for the calibration period and from 0.67 to 0.85 for the validation one.

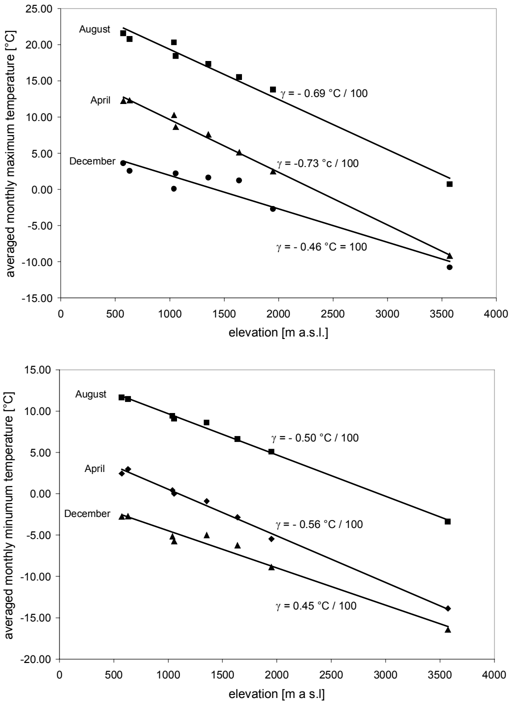

**Figure 1.** Maximum (above) and minimum (below) temperature monthly lapse rates.

Figure 2 shows the observed and simulated discharge for the Simme basin for the validation year 1987-88, denoting a few temporal shifts that may depend from the lack of an explicit routing module. Figure 2 shows also the separation of different flow components. Such separation, typical for streams in the Bernese region, which is dominated by low precipitation intensities occurring on predominantly forested areas that have loosely compacted soils and forest litter, suggested the importance of the model components that simulate the subsurface flows and the basin storage mechanisms. For this reason an exploration of the parameter space was carried as described in the next paragraph.

**Table 2.** Summary of the simulation results

| Basin | Runoff [mm] | | Coefficient of Determination | | Nash-Sutcliffe Efficiency | |
|---|---|---|---|---|---|---|
| | Obs. | Calc. | Calib. | Valid. | Calib. | Valid. |
| Simme | 1135 | 1137 | 0.72 | 0.67 | 0.66 | 0.52 |
| Kander | 1308 | 1401 | 0.86 | 0.83 | 0.70 | 0.77 |
| Lütschine | 1793 | 1617 | 0.83 | 0.85 | 0.73 | 0.81 |

### *3.3.1 Parameter Space Exploration*

A parameter space exploration was carried out aiming at identifying the most sensitive parameters, the modification of which significantly affects the performance of the model. This parameters should be further investigated by means of a sensitivity analysis. The influence of topographic characteristics was not considered at this stage, since it was already accounted for in the HRUs identification step. It was accordingly found that some of the PRMS parameters provide a major control of the model performance. These are:

- the monthly air temperature coefficients, which are the most sensitive parameters for the evapotranspiration;
- the correction factors for liquid and solid precipitation, which are the most important parameters in determining the water balance;

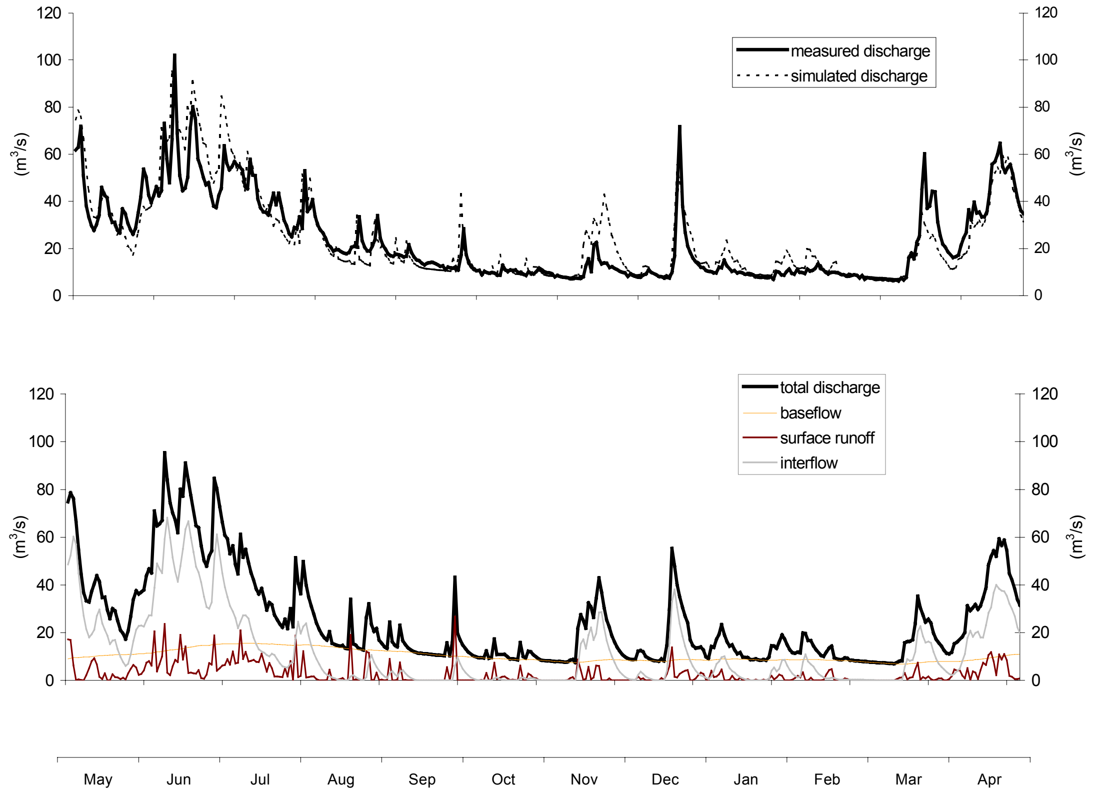

**Figure 2. Simulation results for the Simme basin (validation year 1987-88)**

- the coefficients governing the recharge from the subsurface into the groundwater reservoir; and the routing coefficients for the subsurface and the groundwater reservoirs, which are the critical parameters for partitioning water flows into the different storage components;
- some of the infiltration parameters, which are the most relevant controls of flood events, and more specifically the fraction of effective impervious area, the minimum and maximum contributing areas, and the maximum daily snowmelt infiltration capacity into the soil, which were detected as very sensitive.

### *3.3.2 Regionalisation of Parameter Sets*

Although satisfactory results were obtained from the validation runs, the storage capacities of the subsurface reservoirs remain critical parameters, mainly because of the lack of data for appropriate calibration. Because such lack is a general problem, it is appropriate to test whether the physically-oriented conceptualisation of the model can lead to a robust parameterisation,. This is investigated by using the parameter set obtained from the calibration for the Simme basin to model the Kander and Lütschine streamflows, and subsequently by comparing the simulated streamflows with those computed using the parameter set individually estimated for the two basins. The outcome of this investigation for the Lütschine basin showed that the model is relatively robust, being capable of reproducing most of the patterns of the annual hydrograph, thereby including volumes, low flows, seasonality, and peak timing. This suggests that a transfer of the parameters between two similar catchments is possible to the extent allowed by the physically-oriented character of the model and by the availability of distributed catchment properties. However, the presence of some unexplained process variance also suggests that some significant differences in the two parameter sets remain. A detailed analysis of the parameter space revealed, as intuitively expected, that such differences are essentially related to the subsurface and groundwater storage modules (Table 3), whereas most of the other parameters could be considered constant for all the subcatchments. An obvious conclusion in this respect is the need for improving the availability of basin data that form the basis for parameterising the subsurface and groundwater model components.

**Table 3.** Comparison of the most sensitive parameter values among different catchments

| Parameter | Simme | Kander | Lütschine |
|---|---|---|---|
| Rock subsurface reservoir storage [mm] | 20 | 20 | 10 |
| Glacier subsurf. reservoir storage [mm] | 10 | 10 | 5 |
| Holding capacity of recharge zone [mm] | 20 | 28 | 20 |
| Recharge rate from hillslope subsurface to groundwater reservoir [mm/d] | 0.2 | 0.2 | 0.02 |
| Recharge rate from valley bottom subsurface to groundwater reservoir [mm/d] | 0.2 | 0.1 | 0.02 |
| Recharge rate from glacier subsurface to groundwater reservoir [mm/d] | - | 0.002 | 0.002 |
| Maximum daily recharge from soil moisture excess to groundwater reservoir [mm/d] | 2.5 | 2.5 | 0.5 |
| Max. density of snowpack [g/cm$^3$] | 0.65 | 0.40 | 0.40 |
| Free-water-holding capacity of snowpack as % of total snowpack equivalent | 0.086 | 0.005 | 0.005 |

## 4 SUMMARY AND CONCLUSIONS

The use of the PRMS model in an alpine environment for continuous streamflow simulation was presented. A specific glacier melt module based on an improved degree-day-approach was developed and implemented in order to make the model suitable also for glacierised alpine regions. A considerable focus was put on the GIS-based identification of the hydrotopes, highlighting how the availability of detailed distributed information lead to a robust parameter estimation. It was also shown how the orographic complexity requires a careful evaluation of the spatial distribution of climatic variables and parameters due to microclimate localised effects. For instance, the common assumption of using a single temperature lapse rate was found to be inappropriate.

The suitability and the robustness of the model for the alpine environment was assessed by analysing the sensitivity of the model to the transfer of parameters between two different subcatchments, and showed that this is reasonable in presence of extensive data that allow for a physically-oriented calibration of the conceptual model schemes.

In order to reduce the risk of overparameterisation, the parameter space was first explored. However it must be observed that lack of adequate data did not allow to account for parameter uncertainty. An effort should be therefore spent in providing additional information for the subsurface and groundwater components and in linking the available distributed data with a physically consistent parameterisation of the storage modules of the PRMS.

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