Simulation of Snowpack and Discharge in an Alpine Karst Basin

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Abstract Many conceptual runoff models are well able to simulate daily discharge based on a rather modest data input (e.g. daily values of air temperature and precipitation) provided that calibration via discharge is possible. The underlying assumption is that no considerable losses or gains of water take place via subterranean pathways. This study reports on the application of an operationally used conceptual runoff model in a 96 km\textsuperscript{2} Swiss alpine watershed known to exhibit a complex karst-related hydrological behaviour. Three additional model parameters are introduced, one taking into account aspect-dependent snow melt, and two parameters controlling karst-related water losses. The values of these additional parameters are derived externally, and optimal values of the remaining parameters are achieved by a manual calibration procedure on the basis of discharge. A plausible complete water balance and satisfactory snow storage simulations are achieved by means of this extended model. It can be concluded that a rather simple conceptual model can be applied in karst basins under the assumption that certain intermediate model results can be optimized and verified with the aid of additional measurements apart from the standard hydrometeorological network.

INTRODUCTION

In the literature we find many examples of successful applications of rather simple conceptual precipitation-runoff models in a wide range of physiographic and climatological regions to calculate discharge (see for instance Bergström, 1992; Rango, 1992). One important prerequisite in all these cases is that the model can be calibrated based on reliable discharge measurements. If one is interested not only in discharge, but also in the assessment of all major components of the water balance, it is furthermore important to deal with basins that experience no considerable losses or gains of water via subterranean pathways. Generally, the calibration procedure needs to be applied for every basin separately and may be quite labour-intensive, as one can usually not rely
on conclusive relationships between parameter values and basin characteristics (see for instance Braun & Renner, 1992).

It may be necessary, however, to assess the spatial and temporal variation of the water balance components in a basin that is known to exhibit a complex hydrological behaviour due to well-developed karst features. In these cases, calibration of model parameters poses a special challenge to the hydrologist. This contribution describes a possible way to achieve a model calibration even under these difficult conditions.

METHODS AND DATA USED

The HBV-ETH runoff model

The precipitation-runoff model used in this study is based on the HBV model as developed for Scandinavian basins by Bergström & Forsman (1973) and applied in Switzerland by Jensen (1983). A more detailed snow- and glaciemelt subroutine was added (Braun & Lang, 1986; Braun & Aellen, 1990), and the necessary changes for its application as reported here were done by Hottelet (1991). In particular, these are the introduction of an aspect-dependent melt function (controlled by the model parameter REXP) and of karst-related losses (model parameters k3 and k4). Furthermore, the calculation of potential evapotranspiration ET was changed over previous applications: the seasonal variation is now described by a sinusoidal function with its maximum value (ETMAX) at the end of July and its minimum (ET = 0) at the end of January in accordance with findings by Gronowski (1992). The model calculates daily discharge and various intermediate results such as the water-equivalent of the snowpack at various elevations, for example. The general structure of the HBV-ETH model is given in Fig. 1, and a description of the most important model parameters are given in Braun et al. (1993).

The upper Thur basin

The 96 km² alpine head watershed of Thur River is situated in Northeastern Switzerland (Fig. 2). In the upper regions reaching up to 2500 m asl (Säntis peak) about 60% of annual precipitation falls as snow. As limestone is predominant, widespread karst-hydrological features such as dolines and caverns cause large water gains and losses. Detailed investigations using dye tracer experiments allowed the delineation of a subterranean watershed with an area of 12 km² feeding the upper Thur basin (Leibundgut & Attinger, 1988), and karst-hydrological connections between various points of the watershed and the Rinquelle lying outside the watershed (Rieg & Leibundgut, 1992). Latest
field experiments also revealed sub-lacustric water losses into Walensee situated South of the Thur basin (Mühlstein et al., 1992).

**Hydrometeorological data**

As input the HBV-ETH model requires daily values of air temperature (T) and precipitation (P), and the stations of the Swiss Meteorological Institute (SMA) used in this analysis are given in Fig. 2. Discharge data are taken from the gauging station Stein/Iltishag operated by the Swiss Hydrologic and Geologic Survey (LHG). Apart from these operationally measured data additional measurements were available to calibrate selected model parameters under the specific situation as given above: snow-water-equivalent data measured every two weeks at the Schwägalp station (1300 m asl, Northern slope of the Säntis
mountain, operated by the Department of Geography ETH and VAW, Swiss Federal Institute of Technology, Zurich) and short records of discharge of the Rinquelle measured by the Institute of Physical Geography, Albert-Ludwigs-Universität Freiburg.
Calibration procedure

A manual, rather labour-intensive calibration procedure of model parameters was employed using the Nash & Sutcliffe (1972) efficiency criterion and the difference of measured and simulated discharge. This procedure is described in more detail in Braun & Renner (1992) and was chosen to allow the first author to gain a thorough experience of the sensitivity and interdependence of model parameters. More recently, an automatic calibration procedure was developed for this model by Harlin (1991), and it would be worthwhile to compare calibration results using this procedure in a future study. The five years 1975/76 to 1979/80 were used for calibration, and the years 1980/81 to 1983/84 and 1989/90 served as verification.

Stage I In a first step, the optimal value of newly introduced parameter $k_3$ describing the fast response karst losses was externally derived by comparison of simulated and measured discharge of Rinquelle, assuming that all fast-response karst losses pass through this spring (Fig. 3). Furthermore, the parameter REXP controlling aspect-dependent snowmelt was externally derived by comparisons of observed and simulated snow cover melt out in the North- and South-facing slopes at various elevations. This first attempt yielded good discharge simulations, but a systematic underestimation of snow cover storage resulted in comparison to the measured values at Schwägalp (discussion further below).

Stage II After the unsatisfactory overall results of the first stage an additional parameter $k_4$ controlling karst losses was introduced. This second

Fig. 3 Schematic diagram of the two stages for the calibration of the newly introduced model parameters.
kind was assumed to have a rather slow response to rain and snowmelt inputs, and therefore was built in as outflow from the lower zone storage (see Fig. 1). No quantitative measurements of this kind of karst losses are available, but the existence of sub-lacustric wells in the Walensee situated about one km South of the Churfirsten peaks was proven by tracer experiments. Therefore it was assumed that the measured values of snowpack storage at Schwägalp reflected the "true" water input due to snowfall, and the snowfall correction factor SCF was externally derived in such a way as to yield acceptable snowpack simulations at an elevation of 1300 m asl in North-facing slopes (discussion

Fig. 4 Comparison of the water-equivalent as simulated (1300 m a.s.l, North-facing slopes) and measured (Schwägalp, 1300 m asl) after the first stage of the study.
further below). After that, the parameter $k_4$ was set to the value 0.013 which causes a minimal difference between measured and simulated discharge over the total calibration period, and acceptable results of both snowpack and discharge resulted.

RESULTS

Verification of snowpack simulations: first stage

Without the consideration of slow karst losses a systematic underestimation of simulated snowpack resulted in all years considered in comparison to the measured values of Schwägalp (Fig. 4). This result was unsatisfactory, as one of the reasons to undertake this study was the simulation of the spatial and temporal variation of snowmelt input to the hydrological system in the Northern slopes of Churfirsten, and therefore the second stage of analysis was necessary as described above.

Verification of snowpack simulations: second stage

Figure 5 shows the same comparison of simulated and measured snowpack after the second stage of the analysis, where the snowfall correction parameter SCF was set to 1.5 so as to yield acceptable snowpack simulations during the calibration phase. In most cases the simulations are acceptable over a wide range of snow accumulation conditions (strong accumulation in 1981/82, very poor accumulation in 1989/90.

Simulations of évapotranspiration, snow storage, discharge and karst losses

As an example, the meteorological data and various simulations for the year 1979/80 are shown (Fig. 6). This year experienced the second highest precipitation and discharge values of the ten years investigated, and snow storage on Northern slopes amounted to about 500 mm in March and April at 1300 m asl which was about average. The seasonal variation of simulated potential évapotranspiration is shown in the upper part of Fig. 6. The degree-day factor to calculate snowmelt varied between 2.5 and 4.4 mm °C$^{-1}$ day$^{-1}$ for the aspect class East/West/horizontal, and these values were multiplied by the parameter $REXP = 1.5$ for Southern slopes and divided by the same value of $REXP$ for Northern slopes. Simulated and measured snow-water-equivalent at elevation 1300 m and Northern aspect correspond very well, as this was one of the criteria that needed to be fulfilled when calibrating the snowfall correction factor SCF. Similar curves of snow storage are also generated for slopes with Southern aspect and for the aspect class East/West/horizontal.
Fig. 5 Comparison of the water-equivalent as simulated (1300 m asl, North-facing slopes) and measured (Schwägalp, 1300 m asl) after the second stage of the study.

The Nash & Sutcliffe efficiency criterion $R^2$ of the discharge simulation amounted to 0.78 for this year. Total measured discharge amounted to 1690 mm, while the simulated total is about 60 mm or 3.5% too low. In respect to the simulated fast karst losses (outflow of the Rinquelle) one can see that the maximal value is about $14 \text{ m}^3 \text{s}^{-1}$ on the 7 November 1979, and that the karst spring runs dry over several and extended periods of time. Slow karst discharge on the other hand takes on rather constant values between about 0.2 and $1 \text{ m}^3 \text{s}^{-1}$. 
Assessment of the complete water balance

Table 1 and Fig. 7 summarize the various water balance components for all ten years considered. For the calculation of basin precipitation an optimal value for
### Table 1
Calculated water balance components for the upper Thur basin for each of the ten years investigated (units: mm a\(^{-1}\)).

- (a) hydrological year
- (b) basin precipitation (P)
- (c) evapotranspiration (ET)
- (d) change of snow storage (\(\Delta S_{\text{snow}}\))
- (e) change of water storage in the ground (\(\Delta S_{\text{ground}}\))
- (f) calculated karst losses (Q\(_{\text{karst}}\))
- (g) calculated discharge (Q)

<table>
<thead>
<tr>
<th>Year</th>
<th>P</th>
<th>ET</th>
<th>(\Delta S_{\text{snow}})</th>
<th>(\Delta S_{\text{ground}})</th>
<th>Q(_{\text{karst}})</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975/76</td>
<td>1938</td>
<td>659</td>
<td>0</td>
<td>-23</td>
<td>296</td>
<td>157</td>
</tr>
<tr>
<td>1976/77</td>
<td>2574</td>
<td>658</td>
<td>0</td>
<td>-27</td>
<td>504</td>
<td>182</td>
</tr>
<tr>
<td>1977/78</td>
<td>2901</td>
<td>660</td>
<td>11</td>
<td>48</td>
<td>582</td>
<td>177</td>
</tr>
<tr>
<td>1978/79</td>
<td>2388</td>
<td>659</td>
<td>-11</td>
<td>-3</td>
<td>437</td>
<td>169</td>
</tr>
<tr>
<td>1979/80</td>
<td>3113</td>
<td>659</td>
<td>0</td>
<td>-38</td>
<td>667</td>
<td>196</td>
</tr>
<tr>
<td>1980/81</td>
<td>2853</td>
<td>660</td>
<td>3</td>
<td>86</td>
<td>553</td>
<td>175</td>
</tr>
<tr>
<td>1981/82</td>
<td>3155</td>
<td>658</td>
<td>-3</td>
<td>-11</td>
<td>662</td>
<td>191</td>
</tr>
<tr>
<td>1982/83</td>
<td>2537</td>
<td>659</td>
<td>0</td>
<td>-57</td>
<td>495</td>
<td>194</td>
</tr>
<tr>
<td>1983/84</td>
<td>2765</td>
<td>658</td>
<td>4</td>
<td>37</td>
<td>551</td>
<td>166</td>
</tr>
<tr>
<td>1989/90</td>
<td>2397</td>
<td>658</td>
<td>0</td>
<td>-13</td>
<td>418</td>
<td>196</td>
</tr>
<tr>
<td>Mean</td>
<td>2660</td>
<td>660</td>
<td>0</td>
<td>0</td>
<td>520</td>
<td>180</td>
</tr>
</tbody>
</table>

The correction factor of rainfall RCF = 1.4 was found, and for snowfall SCF = 1.5 as mentioned above. Annual basin precipitation varies between about 1940 and 3150 mm a\(^{-1}\) with a mean value of 2660 mm a\(^{-1}\). This value agrees fairly well with a recent map of corrected precipitation as evaluated by Kirchhofer & Sevruk (1992), where a basin precipitation of about 2450 mm a\(^{-1}\) is indicated. Discharge of the Thur river varies between 850 and about 1660 mm a\(^{-1}\) with a mean value of 1300, which is almost 50% of basin precipitation. Calculated evapotranspiration takes on potential values at all times and therefore remains constant from year to year at about 660 mm a\(^{-1}\) or 25% of basin precipitation. This result is in accordance with measurements of evapotranspiration in the Rietholzbach research basin located some 25 km Northwest of the upper Thur basin (Schädler, 1982). While snow storage

\[
P = Q + ET + \Delta S_{\text{snow}} + \Delta S_{\text{ground}} + Q_{\text{karst}}
\]

**Fig. 7** Mean water balance components over 10 years in respect to basin precipitation for the upper Thur basin as assessed by the HBV-ETH model.
changes from year to year are negligible, changes of water storage in the
ground may take on values up to about 90 mm, which points out the need for
proper initial values of these storage terms. Fast karst losses vary between
about 300 and 670 mm a\(^{-1}\), while the slow karst losses lie between about 160
and 200 mm a\(^{-1}\). Over all years considered karst losses amount to 700 mm a\(^{-1}\)
or more than 50% of total discharge measured at the Thur gauging station
Stein/Iltishag.

**SUMMARY AND CONCLUSIONS**

This study shows that some structural changes of an operational
precipitation-runoff model were necessary so that it could be applied to a basin
exhibiting a complex karst-related hydrologic behaviour. The extended version
of this conceptual runoff model calculates all major components of the water
balance including discharge and snow storage on a daily time-step based on
daily values of air temperature and precipitation as input variables. This model
now can serve as a tool to assess also certain aspects of water quality, which
was the initial task to be solved. For the calibration of model parameters
additional measurements apart from the standard hydrometeorological network
are necessary. In this study measurements of discharge of a major karst spring
allowed the external derivation of the parameter controlling fast response karst
losses, and snow-water-equivalent data assisted the modellers in calibrating
snowfall-related precipitation input. Furthermore, detailed dye-tracer
experiments allowed the delineation of a subterranean watershed feeding the
upper Thur basin. It can be concluded that a rather simple conceptual model
can be applied in karst basins under the assumption that the main
karst-hydrological connections are known and that certain intermediate model
results can be optimized and verified with the aid of additional measurements
not provided by the hydrometeorological services.

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