A pragmatic simulation of karst spring discharge with semi-distributed models. Advantages and limits for assessing the effect of climate change

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Abstract: A hydrological semi-distributed model for simulating karst springs discharge is presented and applied to the Flims case study (Graubünden) and the Milandrine underground river (Jura). This model used for flood prediction and management in river basins has been adapted to karst flow and springs. The model takes into account snowmelt, glacier melt, soil infiltration, evapotranspiration as well as flood routing in surface rivers, sinkholes, and fast and slow flows in underground reservoirs. The Flims karst system is composed of three springs at three different levels: Lag Tiert, Tunnel spring and Pulté spring. In 2002, flows in the system were disturbed by the drilling of a highway tunnel. After a long work of development the model is now able to simulate the discharge rate of these three springs. It allows us to evaluate the effect of the tunnel drilling and the potential effect of the climate change. The first results for the Milandrine River are not as good as the ones of Flims because the simulation of the recharge through the soil and of complex storage processes in the cave conduits is not very easy with the selected approach.

Introduction

The SWISSKARST project (www.swisskarst.ch) aims at setting up a specific approach and a series of tools for improving the sustainable management of karst ground-water systems. The main part of the project is dedicated to document all main karst hydrogeological systems of Switzerland (See Malard et al, this volume). One part of the project is dedicated to develop a pragmatic way for modeling the relation between recharge (snow and rain) and discharge (at karst springs). This modeling is also applied to assess the future evolution of karst ground-water resources within the next decades related to the climate change. Five main karst systems (Flims, Milandre, Areuse, Hölloch and Montana region) have been selected to test and improve various modeling approaches.

In this short note, a conceptual semi-distributed model is presented and applied to the Flims test-site. It is also briefly compared to an application on the Milandre test-site. The applied model takes into account snowmelt, glacier melt, infiltration, surface runoff and flood routing in rivers (Hamdi et al. 2005, Jordan, 2007, Dubois, 2005). Dual porosity in karst is represented by a reservoir which takes into account fast and slow flow components. Lakes can be simulated by a dam object with overflowing capabilities. The numerous hydrological parameters have to be adjusted according to the knowledge and the reality of the field work. A robust calibration process is needed to avoid errors. The model used in this study, named Routing System 3.0 (Dubois, 2005), was originally developed for surface hydrology. It was adapted to karst systems with the help of e-dric, a hydrologist engineer office developing this software.

In the first example the model was used to simulate the response of the Flims karst system to recharge events. The same model was also used to simulate the level of the Cauma Lake, which is largely fed from the karst system. In a second step the model was applied to the Milandre case-study. The comparison shows that application was much easier and more precise in the alpine case than in the tabular Jura in northwestern Switzerland.

The Flims and Milandre test-sites

The present paper focuses mainly on the Flims test-site (Fig. 1), a very special region considering the huge rock-slide which occurred 9'500 years BP (Deplazes et al., 2007). This mass, broadly composed of carbonate rocks, overlies highly karstified rock layers from the Jurassic to Cretaceous as well as some Permian rocks overlapped by the famous Glarus overthrust. Karst springs occur at different altitudes along the rockslide mass (Lag Tiert and Tunnel springs) and within the Rockslide mass (Pulté spring). These three main springs are hydraulically interconnected through a network of karst conduits. The stream coming out of the highest overflow spring (Pulté) feeds the Cauma Lake located in a downstream porous aquifer.

The catchment area of this karst system is located between 1400 and 3000 m a.s.l. and is partially drained by the Laaxerbach stream. 19 km^2 are covered by creta-ceous limestone and 6 km^2 by impermeable Permian rocks (allogenic).

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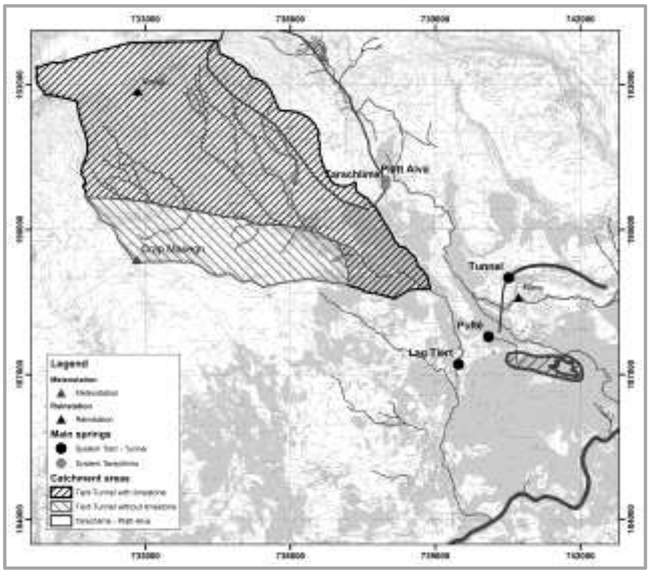

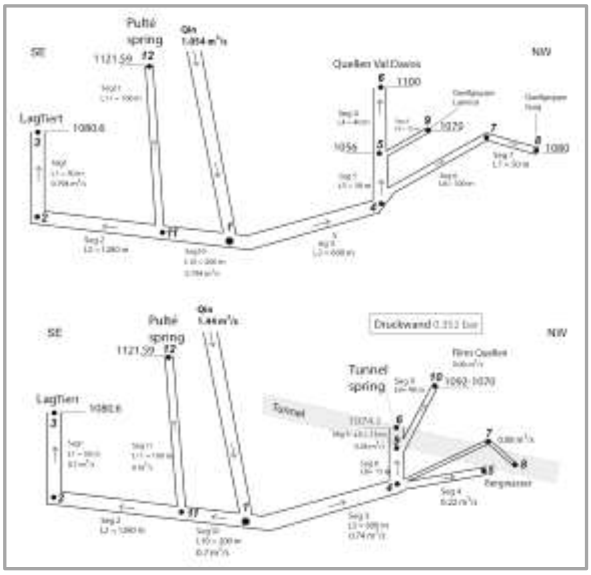

Fig. 1a: Location of the catchment area and the three springs of the Tiert Tunnel karst system. Cauma Lake is located ESE from Pulté spring.

Fig. 1b: Schematic representation of the Flims Tiert-Tunnel karstic network before drilling of the tunnel (top right) and after the tunnel construction (bottom-right).

In 2002, the drilling of a road tunnel under the Flims village crossed a 1 meter karst conduit with a flow rate up to 1 m^3/s. The lowering of the saturated level in the karst aquifer led to the dewatering of the overlying springs in Flims village. The very sensitive balance in the network was modified, triggering a lowering of the flow rate in the Lag Tiert and Pulté Spring, and increasing the flow rate in the Tunnel itself.

Hydraulic experiments proved the relation between the tunnel and the springs. A pipe-flow model (JEANNIN, 1996, ISSKA 2009) based on the length, diameter and roughness of the pipes made it possible to quantify hydraulic heads and flow rates at various points of the system (Fig. 1b).

The Milandre test-site is located in Northern Switzerland in the front part of the Jura Mountains. The catchment area expands over a limestone plateau at an elevation of about 500 m. a.s.l. Recharge is completely autogenic, percolating through a soil with a thickness ranging from 30 cm to 3 m. Nearly 1/3 of the catchment is forested, 1/3 is pastured and 1/3 is cultivated.

Hydrological model

In mountainous regions, the presence of glaciers and snow has a strong influence on the hydrological response of the springs. In such regions, the melt processes are temperature-driven. For this reason, the elevation of the sub-catchments is an important parameter. Moreover, typical deep valleys in such regions are characterized by variable and local precipitations. An appropriate model discretization which allows taking into account the spatial distribution of the precipitations during floods is necessary.

In this context, a conceptual semi-distributed hydrological model was developed, which takes into account these morphological and meteorological characteristics (HAMDI et al., 2005). The catchment area is divided in sub-catchment with specific morphological and hydrological characteristics. Every sub-catchment is subdivided into elevation bands in order to account for temperature-driven processes. The elevation bands can be either glacier or non-glacier areas. The modeling concept is presented in Figure 2 with the example of one sub-catchment composed of a non-glacier and another glacier elevation band. Every non-glacier elevation band

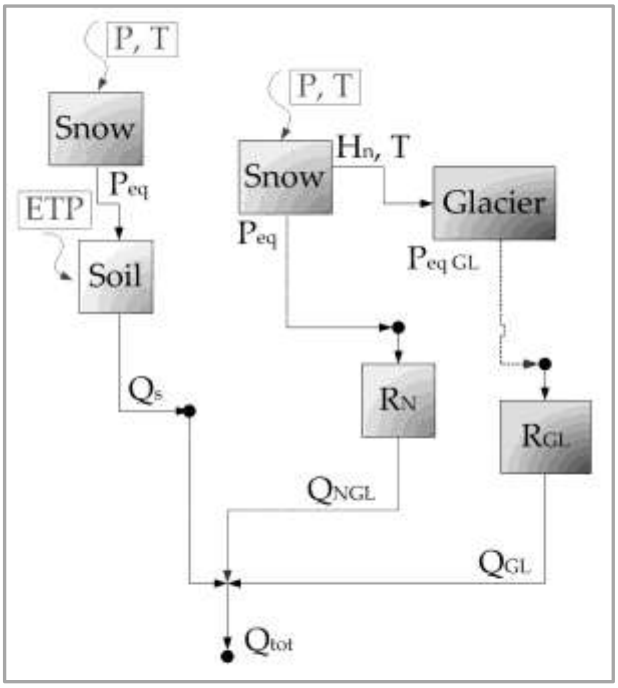

Fig. 2: Description of the hydrological modelling concept. Example of a sub-catchment with one non-glacier and one glacier elevation band (JORDAN et al. 2006).

is composed of a snowpack model and a soil infiltration and runoff model with serial connections. Based on temperature (T) and precipitation (P), the snowpack model simulates the time evolution of the snow pack (accumulation and melt) and produces an equivalent precipitation (Peq) used as input for the soil infiltration and runoff model. This model also takes into account the potential evapotranspiration (ETP) calculated with the Turc formula. The resulting discharge (Q_s) is transferred to the sub-catchment outlet. A snowpack model creates an equivalent precipitation (P_{eq}) which is transferred to a linear reservoir (RN) and finally to the catchment outlet (Q_{NGL}). The glacier melt model creates a glacier melt discharge only when the simulated snowpack is zero (H_n=0). The glacier melt discharge (P_{eqGL}) is then transferred into a linear reservoir (R_{GL}) and the resulting discharge (Q_{GL}) to the catchment outlet. The final discharge at the sub-catchment outlet (Q_{tot}) is the sum of these three contributions.

In order to apply such model to karst systems, some concepts of karst hydrogeology have to be considered. Karst aquifers are characterized by high permeability conduit network embedded in a low permeability fissured limestone matrix. The concentrated discharge of karst systems at springs is a direct consequence of this structure. Depending on local hydrodynamic conditions, conduits can be dry, partially filled or pressurized (DE ROOIJ & PERROCHET, 2006). Our first approach, represented in figure 1b, consists in a simplified pipe-flow model without matrix contribution.

Results

Using a dataset covering four years of discharge measurements at the Pulté, Lag Tiert and Tunnel springs (Fig. 3), it was possible to calibrate the model in order to reach good and realistic parameters. Figure 3 shows that the annual discharge is guided by snow melting with high flow rates from April to October. The first challenge for all models is to simulate infiltration. By dividing the catchment area in altitude bands RS3.0 manages efficiently this process.

The calibration of the model was quite successful and a reasonable fit between observed curves and simulations could be obtained for all three springs. Figure 4 shows the curve for only one of the springs.

After the calibration procedure, a validation of the model is essential. The application of the model to 2010 and 2011 dataset showed that the discharge of the three springs is well reproduced with the initial calibrated parameters (Fig. 4).

The model was then used to simulate past discharges in order to evaluate the effect of the tunnel to the respective spring discharge rates.

The model was then used for the assessment of future climate change on the system. Various climate scenarios (CH2011, 2011) have been introduced in the input time series of the model. This enabled us to assess the regime of the karst springs in 2085. At his date the small glacier, which is now present in the catchment area will have disappeared and the regime will have moved from a nivo-glacial to a nival type. This will reduce the duration of the winter drought. A summer drought period will progressively appear, but it will be clearly "softer" than the actual winter drought (shorter and less dry).

Simulations (Fig. 5) also show that the discharge rate will significantly decrease when the glacier will have completely disappeared. The water shortage at the Pulté spring due to absence of the glacier will reduce the discharge by about 30%. This will have serious consequences on the level of the Cauma Lake.

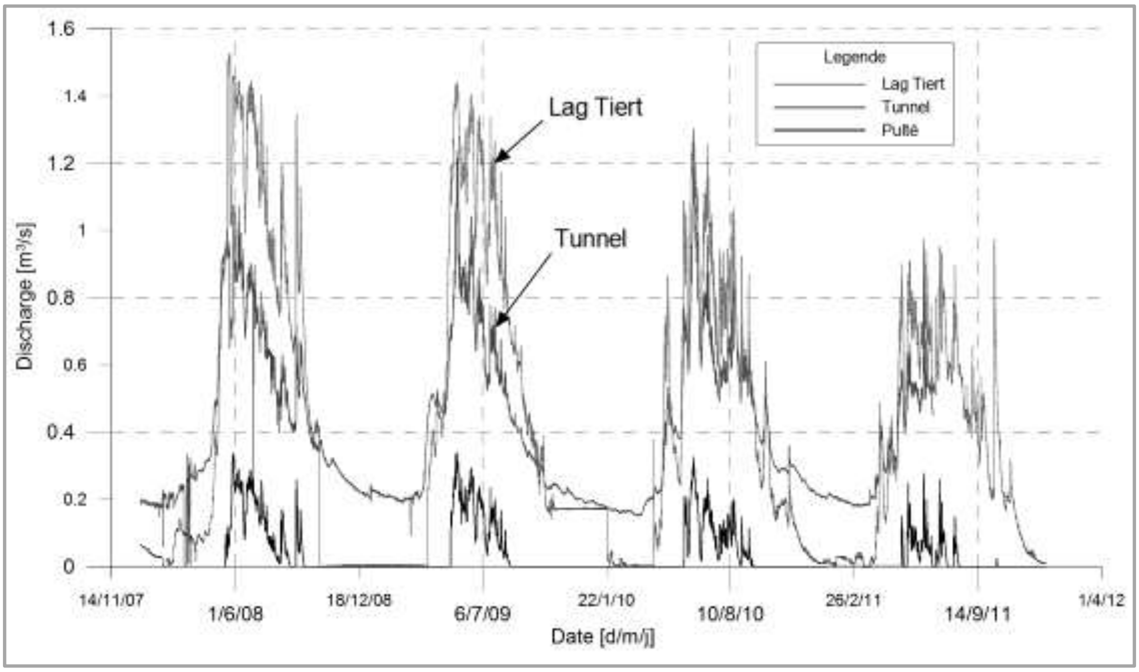

Fig. 3: Discharge measurements over a four years period at the Pulté, Lag Tiert and Tunnel springs. Some measurement problems are visible on the Lag Tiert discharge rate curve.

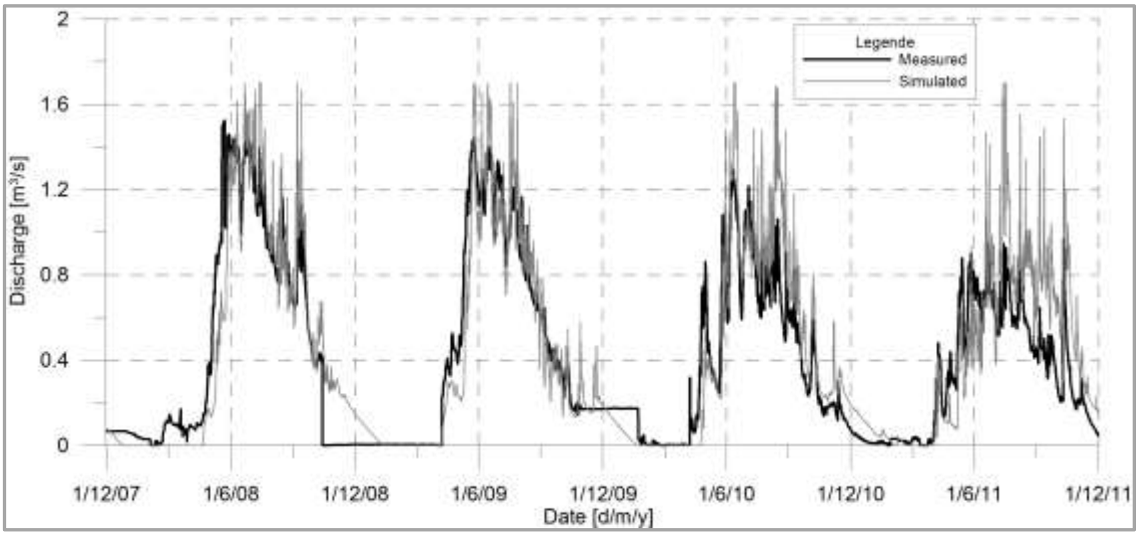

Fig. 4: Discharge observations and measurements for the Tiert spring. Simulated peaks flows are often too high.

Conclusion

Simulations over a four-year-period of data measurements in the Flims test site provided results with Nash coefficients ranging between 0.7 and 0.9.

This simulation was used for assessing climate change. The assessment showed that the flow regime of the spring in 2085 should move from a nivo-glacial to a nival type, with a less marked drought in winter and a low water period in late summer. This summer drought should be less extreme than today's winter drought. The discharge rate of the springs will also be reduced by about 30% after the glacier will have completely disappeared. The model was also successfully used in order to simulate the level of the Cauma Lake and to assess the effect of a tunnel construction on the level of the lake (WEBER et al 2011).

Model application was quite quick and precise in the Flims region (alpine context). It was also applied for the simulation of recharge-discharge relationships in the Milandre case-study (Fig. 6). The calibration of the model was difficult and remained imprecise so far. The main reason is that the effect of contrasted vegetation and soil covers plays a much more significant role in the Milandre case than in alpine systems.

In Flims most of the variations are related to snow-melt, which is quite predictable using temperature. Taking into account more complicated formulas or more variables (type of vegetation, vegetation growth, type of soil) doesn't improve significantly the results because of the topographic situation with a wide range of altitudes. A good geographic distribution and quality of input data (mainly snow cover and temperature) is much more important.

The effect of climate change is therefore more difficult to predict in lowland areas such as Milandre. Unfortunately, the effect of climate change could be much more dramatic than in alpine systems. Further efforts are thus required for making more reliable predictions.

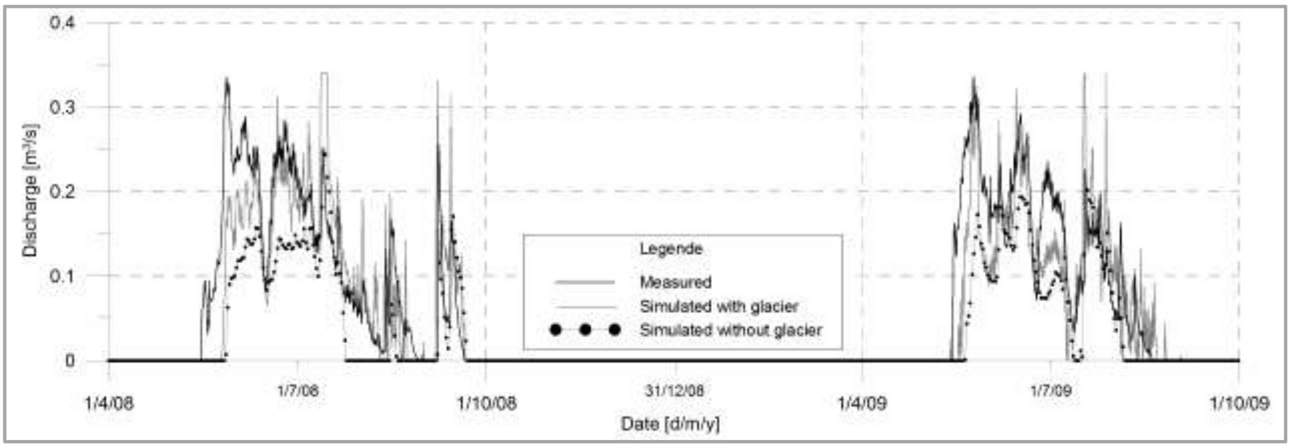

Fig 5: Simulation of the Pulté spring discharge with and without glacier. The annual volume decrease due to glacier death is about 30%.

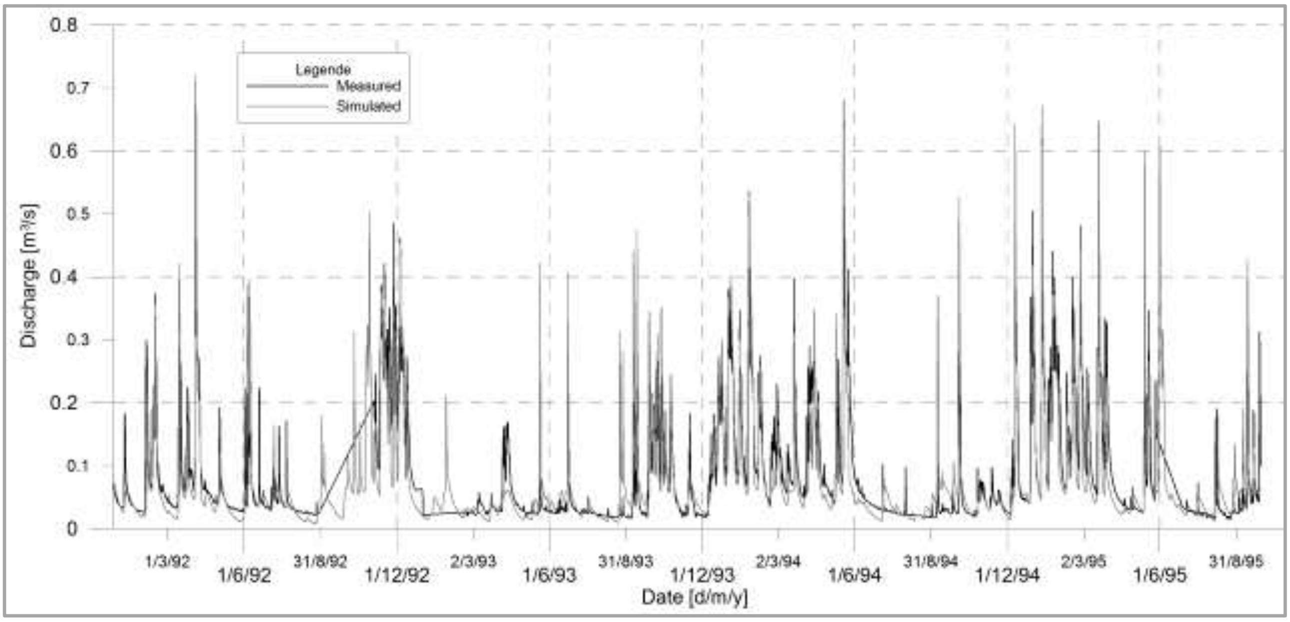

Fig 6: Simulation of the Milandrine discharge rate (grey). Result is globally acceptable, but some aspects are not well simulated (drop, peaks, storage).

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