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Experience from applications of the HBV hydrological model from the perspective of prediction in ungauged basins

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Abstract Since its introduction in the 1970s the HBV hydrological model has been applied in more than 50 countries and it is now a standard tool for hydrologists in the Nordic area. It has appeared in many shapes and for a great number of applications. Many of these are in basins with poor data coverage or even ungauged basins. The latter is, for example, the case in the nationwide hydrological mappings carried out in Finland, Norway and Sweden. It has also been used in many river basins where uncalibrated output from a hydrological model is the only realistic option due to shortage of data. These results are produced in a rather pragmatic way, with generalized parameter values, but they are much better than nothing. Ungauged simulations have opened new possibilities in hydrological modelling. In Sweden the total transport of nutrient to the Baltic Sea could be simulated and the step from limited basin studies of impacts of climate change to nationwide assessment was made possible. The paper reviews the history of the HBV model with the focus on discussion of prediction in ungauged basins.

Key words hydrological modelling; prediction in ungauged basins

INTRODUCTION

The first computer based hydrological models appeared in the late 1960s and since then numerous models have been developed for various purposes. Surprisingly good results were obtained by rather simple models. This simplicity was a necessity due to the limited data that were normally available. As the models had some physical background, but subroutines based on a lot of empiricism, they were often referred to as conceptual models. Examples of conceptual hydrological models from the 1970s are the Canadian UBC model (Quick & Pipes, 1976), the Danish NAM model (Nielsen & Hansen, 1973), the Japanese TANK model (Sugawara, 1979), the Swiss-American SRM model (Rango & Martinec, 1979) and two models from the USA: the SSARR model (US Army Corps of Engineers, 1976) and the NWSRFS (Anderson, 1973). Examples of more recent models are the British TOPMODEL (Beven & Kirkby, 1979) the Chinese Xinanjiang model (Zhao, 1992), the Danish MIKE-SHE (Refsgaard & Storm, 1995), the Italian ARNO model (Todini, 1996) and the American VIC model (Liang & Lettenmaier, 1994). An overview of some of the best known hydrological models can be found in the work by Singh (1995).

Most hydrological models need calibration to perform well. But the calibration option is not always there and today at least three situations can be identified with reference to the calibration and application of hydrological models:

(a) applications within the range of model calibration;
(b) applications outside the range of model calibration;
(c) applications without model calibration.

Model applications within the range of calibration are, for example, conventional runoff simulations which may be used to fill in gaps in runoff records or short and long term hydrological forecasting and water balance studies. While most applications within the range of model calibration are quite straightforward and can be done with a high degree of confidence, the use of conceptual models outside the range of calibration is more controversial. This may mean that the model is run on data which are more extreme than those during the period of calibration, e.g. floods, or that input data are from a climate that is not stable. Nevertheless, it is sometimes necessary, when no other reliable methods are at hand. Examples where models regularly are used this way are simulations of design floods for dam safety analysis and studies of the effects of climate change or changing land use on river runoff.

Maybe the most demanding type of application of a hydrological model is to use it without any calibration at all. This is referred to as prediction in ungauged basins, PUB. Although it is often stated that the conventional conceptual model is unsuitable for this role, due to its calibration needs, this is now an everyday type of application. It appears that the need for information about water resources is so strong that model limitations have to be accepted. The information provided by a conceptual hydrological model with a standard set of parameter values is accepted because it is better than no information at all. When the development of the HBV hydrological model started its was intended solely for runoff simulation within or, at least, not far outside its range of calibration. Today it is being used outside its range of calibration and for prediction in ungauged basins as well.

THE HISTORY OF THE HBV MODEL

The history of the HBV hydrological model dates back to 1972 (Bergström & Forsman, 1973). Its development was very much inspired by the strategy suggested by Nash & Sutcliffe (1970). Their work is usually referred to because of the introduction of a criterion of model performance, the R^2-value, but its most important message is a plea for a realistic attitude to model complexity. They realized the risk of overparameterization if the model structure was allowed to grow in complexity, although the term *parameter interaction* was more often used than *overparameterization*. A commonly used tool for analysis of parameter interaction was mapping of the error function, and it is here the R^2-value came into use. If the topography of the error function was not distinct enough the model simply had too many degrees of freedom. This technique, as illustrated in Fig. 1, was an important tool in the early development of the HBV model.

The strategy used for the development of the HBV model can thus be summarized as follows:

(a) The model must be based on a sound physical description but must not be so complex that it has a higher data demand than can be met by our standard climatological and hydrological networks.
(b) The number of free model parameters (used for calibration) shall be kept to a minimum.

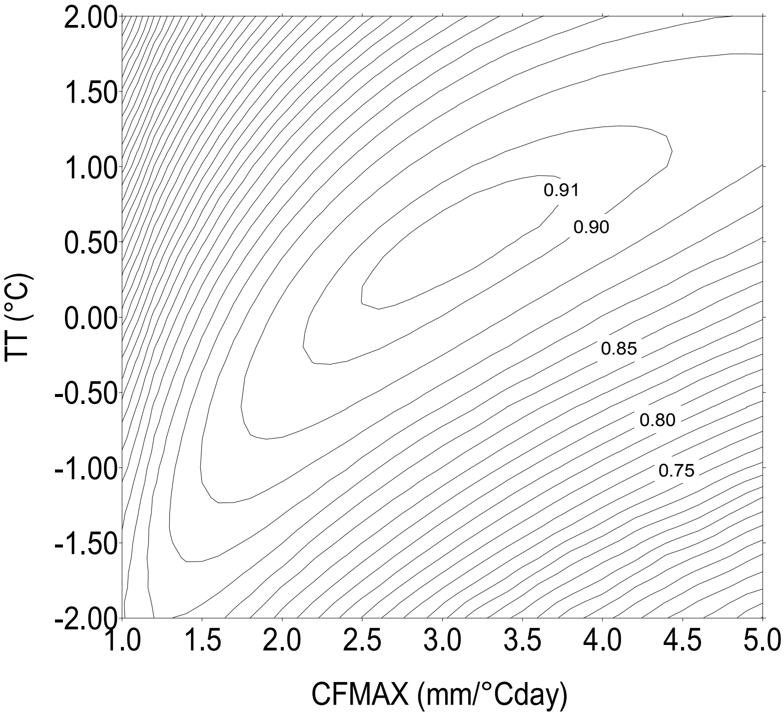

Fig. 1 Example of mapping of the topography of the error function of the two parameters, TT and CFMAX, in the snow routine of the HBV model. In this case the distinct maximum confirms that both parameters contribute to the model performance. The error function is R^2 as suggested by Nash & Sutcliffe (1970).

(c) The performance of the model must be controlled by observations from a period independent of the calibration process.
(d) It must be easy to understand and to use the model.

In the 1970s and 1980s a number of well controlled model intercomparisons were carried out. Of great importance for the development of the HBV model was the intercomparison organized by the World Meteorological Organization (WMO, 1986). From the conclusions of that project the following is worth citation: "*On the basis of available information, it was not possible to rank tested models or classes of models in order of performance. The complexity of the structure of the models could not be related to the quality of the simulation results.*" (WMO, 1986, page 35). These results meant a lot as they confirmed the experience gained during the early development of the HBV model. When trying to improve results by introducing more complexity, we soon reached a point where this increased complexity simply could not be justified by improved performance. When introducing too many parameters the calibration of the model became like manoeuvring a car with individuals steering each of its four wheels.

The first successful run with the HBV hydrological model was carried out in 1972 (Fig. 2, Bergström & Forsman, 1973,) and a routine for snow accumulation and melt was introduced in 1975 (Bergström, 1975). So far the model was lumped, even though area-elevation zoning was introduced in its snow routine. Since then it has been improved in small steps during its more than 30 years of existence, but its initial basic structure remains the same. The most robust part is probably its soil moisture accounting, which has proved very versatile in applications all over the world. Today

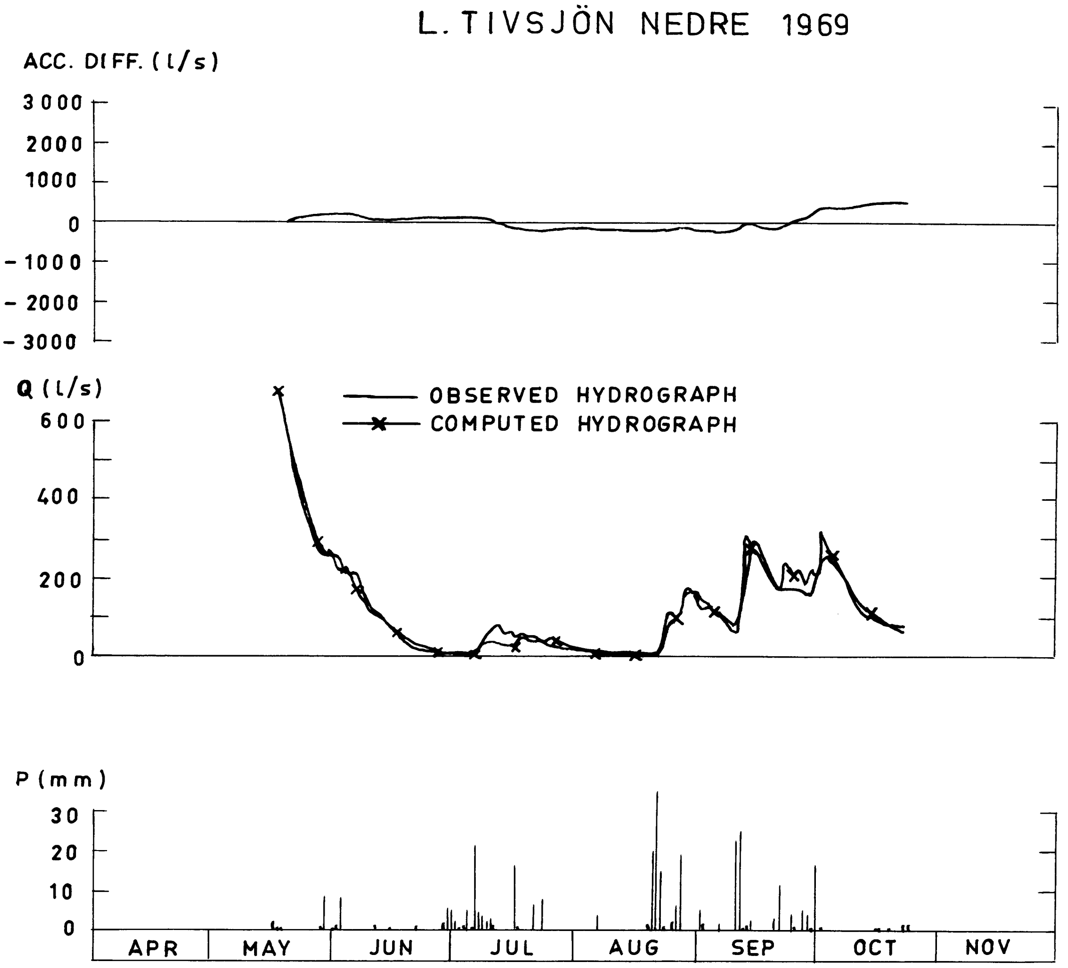

Fig. 2 The very first successful run by the HBV model in 1972. The catchment is the Lilla Tivsjön research basin in northern Sweden, with an area of 13 km^2 (from Bergström & Forsman, 1973).

the HBV model has developed from being a forecasting model to become a more general tool in many types of applications, whenever there is a need to transform meteorological observations into runoff. Even though the model has not undergone any dramatic changes, its scope of application has widened substantially over the years.

The recent HBV model is best characterized as a semi-distributed conceptual model (Lindström *et al.*, 1997). Like most hydrological models it consists of three main components: subroutines for snow accumulation and melt, subroutines for soil moisture accounting and response and river routing subroutines. It uses sub-basins as primary hydrological units and an area-elevation distribution and a crude classification of land use. The sub-basin option is used in geographically or climatologically heterogeneous basins or in the presence of large lakes. Depending on the choice of the modeller and model version the number of parameters to calibrate are normally 2–4 in the snow routine, 3 in the soil moisture routine and 4–5 in the response function.

Input variables to the HBV model are normally 24-hourly values of precipitation and air temperature and some estimate of potential evapotranspiration, which can either be daily or of lower resolution in time. A version of the model with hourly resolution in time is also available. The model has been applied to a wide range of scales, from small research basins less than 1 km^2 in size up to the continental scale representing of the whole land area of 1 729 000 km^2 draining into the Baltic Sea (Graham, 2004).

Applications of the HBV model

Over time the HBV model became very popular and it is now a standard tool for runoff simulations in Sweden, Norway and Finland. The number of applications outside the Nordic region is also growing and it has been applied in more than 50 countries all over the world. Some of these applications are made by modified model versions of the model developed in, for example, Norway, Finland, Germany and Switzerland.

The HBV model is nowadays applied within the range of model calibration, outside this range and even without calibration, in a PUB mode. This development has to a great degree been driven by demands. In Scandinavia hydrological models came into operational use for flood warning and forecasts of the inflow to the reservoirs of the hydropower systems in the mid 1970s. In 1990 new guidelines on design flood determination were adopted, which meant a new role for the HBV model, as it became part of the design procedure (Flödeskommittén, 1990; Bergström *et al.*, 1992; Norstedt *et al.*, 1992). This also meant that model results extrapolated outside the range of model calibration were trusted as the basis for design of Sweden's high hazard dams.

Starting from the 1990s the growing concern about the risks of climate change stimulated the use of hydrological models as tools for analysis of impacts on water resources. The HBV soon came into use for this purpose in the Nordic countries (Vehviläinen & Lohvansuu, 1991; Saelthun *et al.*, 1998; Bergström *et al.*, 2001). These are other examples of use of the HBV model outside its range of calibration. Still others were when the HBV model was used for analyses of the effects of deforestation based on empirical experience of its parameter values (Brandt *et al.*, 1988) and a study of the effects of drainage of wetlands, based on an improved version of the HBV model with a more realistic description of runoff generation, was carried out by Johansson & Seuna (1994).

From the 1980s and onwards the HBV model has also been developed to meet the needs of the environmental sector. Initially acidification was in focus (Bergström *et al.*, 1985b), but later nonpoint source pollution and transport of nutrients from land to sea became a major field of application (Arheimer & Brandt, 1998; Andersson *et al.*, 2003). This development was driven by a growing concern about eutrophication of the Baltic Sea and a need for analysis tools for counter measures. Later on the needs of the environmental sector were to become a major motivation for starting to use HBV without calibration.

Ungauged basins

Prediction in ungauged basins (PUB) is the ultimate goal of many hydrological modellers. But it has long been argued that a simple conceptual model like HBV would lack potential in this respect, due to problems in the identification of its empirical coefficients (parameters). Nevertheless, this was a type of application that started already in the early 1990s in Sweden (Johansson, 1992). The reason was obvious. There was a need for assessments of river flow at an arbitrary point and it is not realistic to believe that we can meet that demand by means of measurements. There was also a need for retrospective simulations in cases where water chemistry had been observed, but simultaneous runoff records were lacking. The development towards prediction in ungauged basins was thus mainly driven by the environmental sector, which needed runoff data to estimate the transport of nutrients based on observations of their concentrations.

It was realized that there were basically three possible ways of estimating runoff in rivers without data. The first was to simply use information from neighbouring rivers through statistical methods. The second option was to get so much experience with a conceptual model that we can map the optimum values of its parameters, or relate them to catchment characteristics. The third was to use a model that is so physically correct that it does not need calibration at all. The first option had been used for a long time at the Swedish Meteorological and Hydrological Institute and the use of a conceptual hydrological model was considered to be a realistic supplement to that method. It was, however, not considered realistic to introduce the physically correct modelling option, simply because there was no such model available. And anyhow, such a model would not be feasible due to the lack of proper and unbiased input data.

A first nationwide mapping of applications of the HBV model did not show a discouraging variability of its parameter values (Bergström, 1990) and subsequent evaluations of blind tests also looked promising (Johansson, 1992). One additional finding, which helped stabilize the variations in parameter values, was the break-out of major lakes in the model structure. This was shown to give more stable recession coefficients (Bergström *et al.*, 1985a). The introduction of a method for regional model calibration was also a great help (see, for example, Lindström *et al.*, 2005). This generated regional standard sets of parameter values, which could easily be used for basins in between the gauged ones. The key to success in ungauged prediction with standard parameter values is to keep the number of such parameters as low as possible. The new release of the HBV-96 model helped a bit further along that route as it reduced the complexity of the response function of the model by one empirical parameter (Lindström *et al.*, 1997). Finally it was found that the success in ungauged prediction is strongly dependent on a consistent database of meteorological input to the hydrological model. Such a database was developed for Sweden by Johansson (2002).

Attempts to relate model parameters to catchment characteristics were also carried out. The idea was that clear relationships would help the assessing of parameter values from the physiographic setting in the basin. The studies did, however, show that most optimum model parameters of this conceptual model were relatively insensitive to catchments characteristics. The most significant signal came from lakes and vegetation cover (Johansson, 1994). The difficulty of relating the empirical parameter values of the HBV model to physiographic conditions was later confirmed by Arheimer (2005) in a European evaluation of the model’s ability to predict both water quality and quantity in ungauged basins.

So in the end the pragmatic solution to the problem of PUB turned out to be to rely upon empirical experience from the vast number of HBV applications and to supplement these with regional model calibrations. This made it possible to carry out nationwide application with complete areal coverage and thus a new era in hydrological modelling could start. HBV model-based national hydrological maps are now available for Sweden. They are based on model simulations in some 1000 basins, after calibration of the model to runoff records available at almost 400 sites (Figs 3 and 4). Similar work has been carried out in Norway and Finland. The database behind these maps has opened the possibility to assess the total load of nutrients from Sweden to the Baltic Sea and to carry out nationwide vulnerability studies of the impacts of climate change on water resources among many other applications (Andréasson *et al.*, 2004).

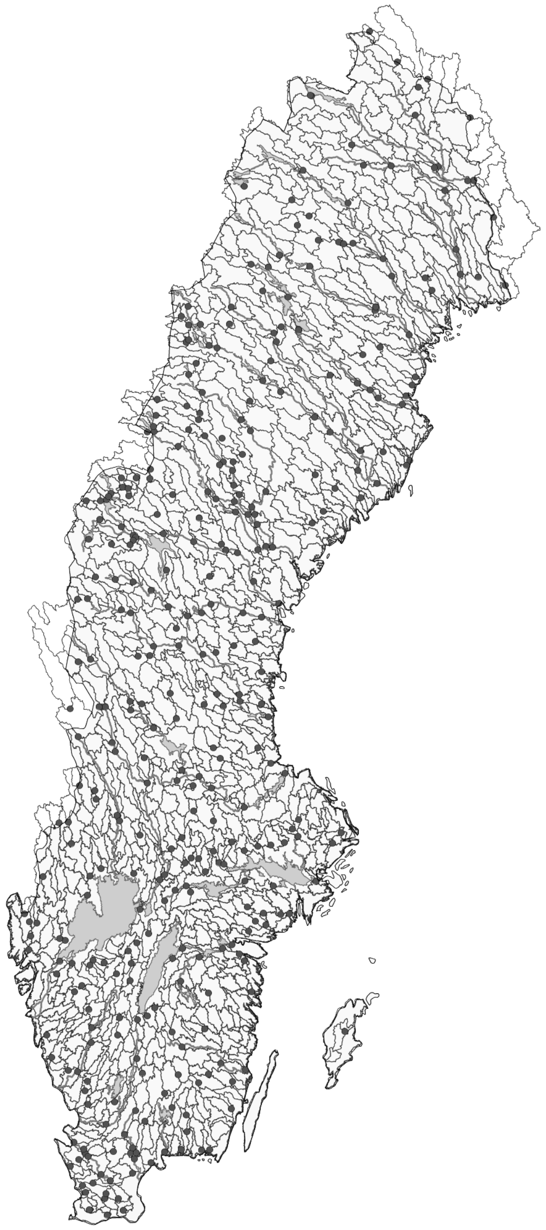

Fig. 3 The runoff stations used (dots) for calibration of the HBV model and generalization of model parameters, and basins used for the ungauged simulations for production of nationwide runoff maps. The area of Sweden is around 450 000 km^2.

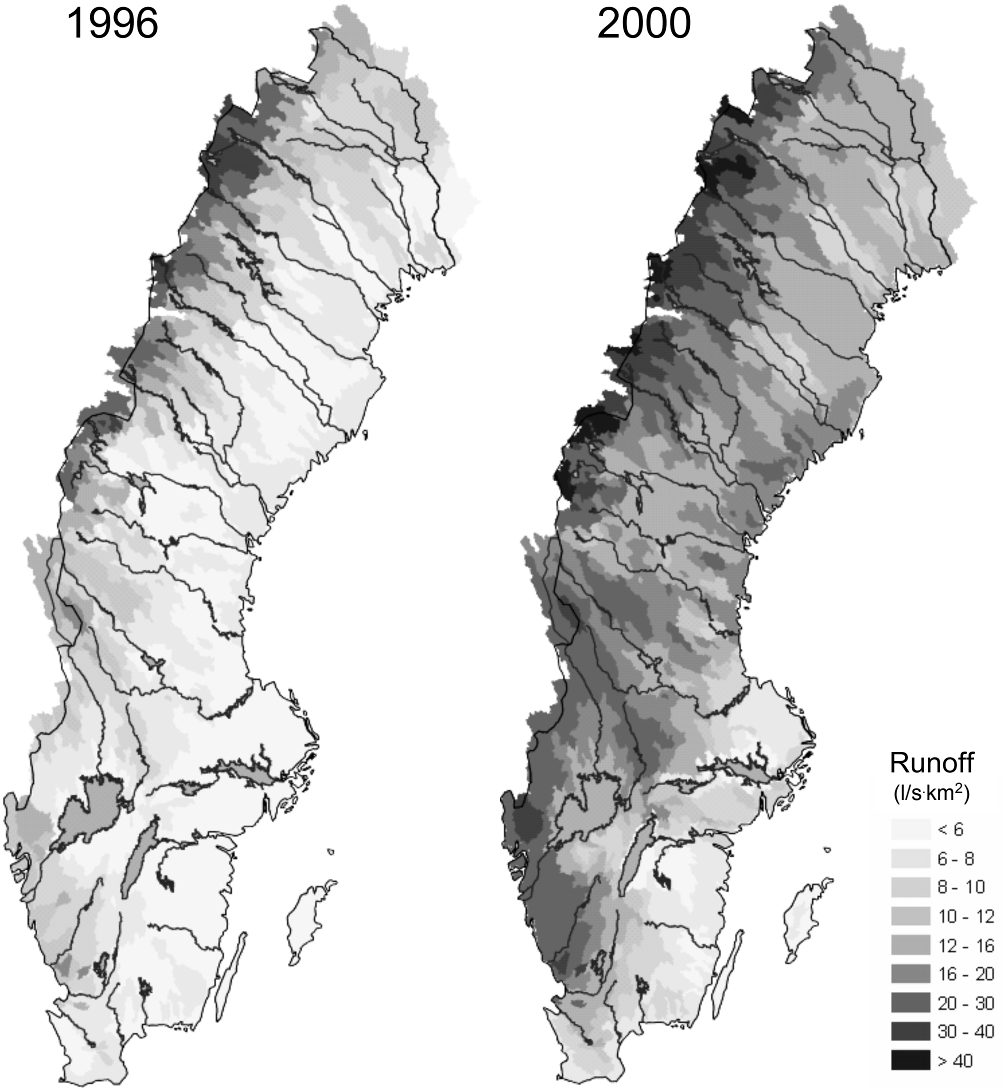

Fig. 4 These runoff maps of Sweden for a dry (1996) and a wet (2000) year are examples of products that can easily be generated by a database consisting of uncalibrated model runs with generalized parameter values in some 1000 basins.

DISCUSSION

Conceptual hydrological models have proved to be very cost-efficient tools for many water resources applications. Their best merits are that they are cheap compared to measurements and that they help us combine hydrometeorological information in a clever way. Thus we can make optimal use of regionally scattered runoff data and climatological records. Sometimes models are the only realistic way of obtaining runoff data. The main limitations are related to the need for model calibration and stationarity of the model in a non-stationary world.

The need for runoff data may sometimes force us to run the hydrological models without a complete calibration of their parameters. This can be done if a robust model structure with few empirical parameters is used. Values for these parameters can be set by calibration of the model to rivers in the neighbourhood or to rivers of similar character elsewhere. But we have to be aware that this is a compromise which yields data of lower quality than ordinary measurements. One important limitation is that the models need input data. Therefore the quality of the ungauged prediction has to be judged in the light of the quality of the data used for running the hydrological model.

The large number of applications of the HBV model in the world have proved that this relatively simple conceptual model is surprisingly general. The key processes seem to be described in a reasonable way. The model has the advantage of limited demand on data coverage and computer facilities, which makes it very versatile. However, generalization of optimum values of parameter values of a model like HBV is not trivial. Differences in climatological conditions in a basin are sometimes accounted for by the set up of the model structure in sub-models. These sub-models may have different parameter values. There also exist different versions of the HBV model and the different groups who apply it may have developed their own calibration practise. Further, the parameter values depend on the type of input data used, computational details in the model version and, to some degree, on the calibration skill of the user. All these factors have to be considered when trying to chose parameter values for the ungauged simulation. Thus the safest thing to do is to carry out a new regional calibration of a number of basins in the surrounding area of the point of interest.

CONCLUSIONS

The HBV model has found a multitude of applications that were hardly anticipated when the model was developed in 1972. Prediction of runoff in ungauged basins is probably one of the most demanding of these. Experience shows that a conceptual model of this type does have a potential for predictions under ungauged conditions, even though it is conceptual and requires calibration to obtain simulations of the highest quality. With *a priori* knowledge from generalized standard values of the parameter values it is possible to obtain added value by blind simulations. The proof is the widespread use of the HBV model under ungauged conditions today. However, it must not be forgotten that model simulations in the normal case are inferior to observations and that output from calibrated models is almost always more reliable than results from uncalibrated models. We also have to realize that the use of hydrological models without calibration means that we have to rely almost entirely upon information from input data. This requires a critical assessment of the climate database.

The application of the HBV model under ungauged conditions would have been improved further with a robust relationship between the physiographic conditions in the basin and the optimum values of the model's parameters. This is not easily obtained. The values of the parameters are affected by many other factors, like compensation for systematic errors in observations and compensating errors that most likely mask the possible signals from catchment characteristics.

The use of the HBV model with generalized model parameters has grown unexpectedly fast. In this process a database of model parameters developed from regional model calibration has been very important. Equally important is the access to a consistent database of meteorological data used as input to the model. These two factors have opened new possibilities for nationwide hydrological mapping and for many other aspects of large scale hydrological modelling and climate impact studies.

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