Evaluation of water quantity and quality modelling in ungauged European basins

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Abstract The conceptual rainfall–runoff model HBV was evaluated for predictions in ungauged basins in Sweden and in selected basins across Europe. The paper mainly stresses the impact of model parameter estimation and meteorological input data. Daily simulations for 1000 sub-basins (of which 700 are ungauged) for the period 1961–2002 include all of Sweden, normally with a volume error <5%. When transferring the model to 18 European basins, it was concluded that modelling was normally trustworthy (i.e. R^2 > 0.7 and VE < 5%) if rainfall data was representative. The automatically calibrated parameter values could not easily be related to basin characteristics. However, blind-test simulations showed that *a priori* parameter values gave almost as good results as the calibrated model. This highlights the influence of the modeller's experience and knowledge on the results.

Key words blind tests; Europe; HBV model; parameter estimation; PUB; Sweden

INTRODUCTION

The International Association of Hydrological Sciences (IAHS) has initiated the decade for Prediction in Ungauged Basins (PUB): a research initiative with the aim of providing hydrological data where ground-based observations are missing. PUB is defined as predicting or forecasting the hydrological response of ungauged basins to climatic input, i.e. before it happens (Sivapalan *et al.*, 2003). An ungauged basin is one with inadequate data to estimate the hydrological variable of interest to the required accuracy.

For operational predictions in ungauged basins, one of the corner-stones of the Swedish national hydrological forecasting service is the synoptic water balance map (Bergström & Sundquist, 1983; Häggström *et al.*, 1996). The map is based on hydrological modelling for each of the synoptic meteorological stations in Sweden. *A priori* values of model parameters are used together with an ensemble of meteorological forecasts.

Long-term values and mapping of distributed water discharge from the entire Swedish surface to the sea has been requested by the environmental sector during the last 10 years. To achieve this Sweden is divided into 1000 sub-basins, which are modelled from the 1960s to present, using regional parameter values and a nationwide precipitation grid (Johansson, 2002). This model has been applied for nutrient load calculations (Arheimer, 2003) and in impact studies of hydrological consequences of climate change (Andréasson *et al.*, 2004). Nutrient load estimates from sources to the sea is needed for regular international reporting to marine commissions (e.g.

HELCOM and OSPARCOM). Climate change impact on the water resources is examined on behalf of the water power industry and physical planning sector.

This aim of the present study was to evaluate the Swedish model approach HBV (e.g. Bergström, 1976; Lindström *et al.*, 1997) for predictions in ungauged basins: (a) The uncertainty in the distributed national predictions that covers Sweden was analysed through independent monitoring sites and time-periods. (b) The possibility to use the model under various environmental conditions was evaluated by applying the model in 18 European basins (Fig. 1). An attempt was made to relate basin characteristics to model parameter values, which were estimated through automatic calibration. (c) The use of *a priori* parameter values, based on modeller's experiences, was evaluated by performing blind tests in three basins, considering both water quantity and quality.

Fig. 1. Location of the 18 European basins (circles) in 17 countries (flags).

MATERIAL AND METHODS

The water balance and discharge at the basin scale is estimated using the conceptual rainfall–runoff model HBV (Bergström, 1976; Lindström *et al.*, 1997), which makes daily calculations in coupled sub-basins along the river network. The HBV model consists of routines for snow melt and accumulation, soil moisture, runoff response and routing through lakes and streams. Detailed model information and equations can be found at www.smhi.se under Research and Hydrology. The driving variables are daily precipitation and temperature.

When applying the model to Sweden (about 450 000 km^2) driving variables were achieved from a national grid of 4 × 4 km (Johansson, 2002). The Swedish model includes about 1000 sub-basins, in the range 200–700 km^2. The model was calibrated regionally against measured time-series of water discharge from 230 gauging stations. The parameter values obtained in each region was used for all sub-basins in that region. Daily measurements for the period 1987–1997 were used for calibration while the total modelling period was 1961–2002. The evaluation of model performance was based on daily time-series covering the whole period, and in addition, another 130 independent gauging stations were included.

To test the transferability of the Swedish HBV concept, it was evaluated for 18 European basins that cover a wide range of the different hydro-meteorological conditions existing in Europe (Table 1). Most of the data was collected by local partners within the EuroHarp-project (www.euroharp.org). For some basins this database was extended with synoptic meteorological data to complete the precipitation time-series, and two additional German basins were included. The HBV model was calibrated automatically for each basin to find the optima of parameter values (Table 2)

Table 1 Some general characteristics of the 18 European basins (cf. Fig. 1).

Country	Basin size (km^2)	Landcover (%)		Relief (m.a.s.l.)	Average runoff (l s^{-1} km^{-2})	Average precip. (mm)	Average temp. (°C)
		Forest	Lakes				
Austria	2600	60	~0	395–1820	12	900	11
Check Republic	1200	30	2	320–765	6	650	8
Denmark	500	3	4	10–110	10	900	9
England	3300	4	1	5–680	16	900	10
Finland	1350	60	13	0–145	7	700	5
France	10500	20	2	0–310	6	750	13
Germany, Neckar	1400	40	~0	150–1250	12	800	9
Germany, Warnow	3100	20	4	10–150	4	550	9
Greece	2800	35	0	50–1900	14	1000	14
Hungary	3200	25	1	100–650	2	700	11
Ireland	10600	3	8	0–150	18	950	10
Italy	900	30	0	17–2000	12	1000	13
Lithuania	1200	30	0.5	30–130	5	600	7
Luxembourg	2600	30	0	210–540	11	900	9
Netherlands/Germany	2400	11	1.5	0–85	21	750	9
Norway	700	80	7	25–275	14	800	6
Spain	800	20	~0	4–500	9	550	17
Sweden	1900	45	3	0–200	13	700	7

Table 2. Model parameters tuned in the calibration of the HBV model in Europe. Complete equations are described in e.g. Bergström (1976), Lindström *et al.*(1997) and at www.smhi.se.

Rain and snow routine	Soil moisture and evaporation routine	Groundwater and river response
General precipitation correction factor (pcorr), Snowfall correction factor (sfcf), Rainfall correction factor (rfcf), Precipitation lapse rate (pcalt), Snowmelt rate (cfmax), Threshold temperature for snowmelt (tt), Threshold temperature for rain/snow fall (dttm)	Field capacity (fc), Soil variability parameter (beta), capillary transport (cflux), Limit for potential evapotranspiration (lp), Potential evapotranspiration factor (athorn)	Recession rate (khq), Recession non-linearity (alfa), Percolation (perc), Base flow recession (K4), Response transformation function (maxbas)

according to a parabolic method (Lindström, 1997). Attempts were then made to correlate these parameter values to easily available basin characteristics such as land use, topography, basin size, mean temperature and precipitation.

Model performance was evaluated by using the explained variance, R^2 (Nash & Sutcliffe, 1970) and accumulated relative volume error, *VE*, according to:

$$R^2 = \frac{\sum (Q_{rec} - Q_{\overline{rec}})^2 - \sum (Q_{comp} - Q_{rec})^2}{\sum (Q_{rec} - Q_{\overline{rec}})^2} \tag{1}$$

$$VE = \frac{\sum (Q_{comp} - Q_{rec})}{\sum Q_{rec}} \tag{2}$$

where, Q_{rec} is recorded values; $Q_{\overline{rec}}$ is average of recorded values; and Q_{comp} is modelled values.

Blind tests were performed to evaluate the model capability of predictions in ungauged basins. The model was applied to three basins without access to monitoring data, and thus, was run un-calibrated: relying only on *a priori* values. In this exercise the model's capability of predicting both water quantity and quality was evaluated. The nitrogen module (HBV-N) was used for estimating riverine nitrogen concentrations according to the Swedish TRK concept (Arheimer, 2003). After the "blind" model runs, the model was calibrated and the results were compared, according to the procedures of the EuroHarp project of the 5th EU framework programme (EVK1-CT-2001-00096).

RESULTS AND DISCUSSION

In the model evaluation for Swedish conditions, time-series of modelled water discharge were compared to observations at 307 sites. At 188 sites the volume error was <5%, 82 sites showed a volume error between 5 and 10%, and it was more than 10% at 37 sites. Hence, the model can be used for rather trustworthy distributed mapping of national water discharge. More than 100 independent time-series from different observation sites were used for validation of the nitrogen flow in Sweden. A general judgement, after visual inspection of these, is that transport and annual average concentrations show good correlation to measured values while daily concentration fluctuations were more difficult to capture.

When transferring the model to European basins, the HBV model gave reasonable accuracy compared to observed time-series, with R^2 above 0.7 and *VE* <5% (Fig. 2). However, a few basins showed poor results. The model did not capture the flow dynamics in the southernmost basins, e.g. Italy, Greece, and Spain, which resulted in low R^2 values. These basins have a quick rainfall–runoff response due to steep topography and absence of lakes, which made it difficult to capture the recessions after peak flows. In addition, these basins may have saturation excess mechanisms, which are not explicitly described in the HBV concept. The precipitation pattern may also be more intense and local and probably not fully included in the meteorological observations of rainfall data for the whole basin. For Greece, it was hypothesized that

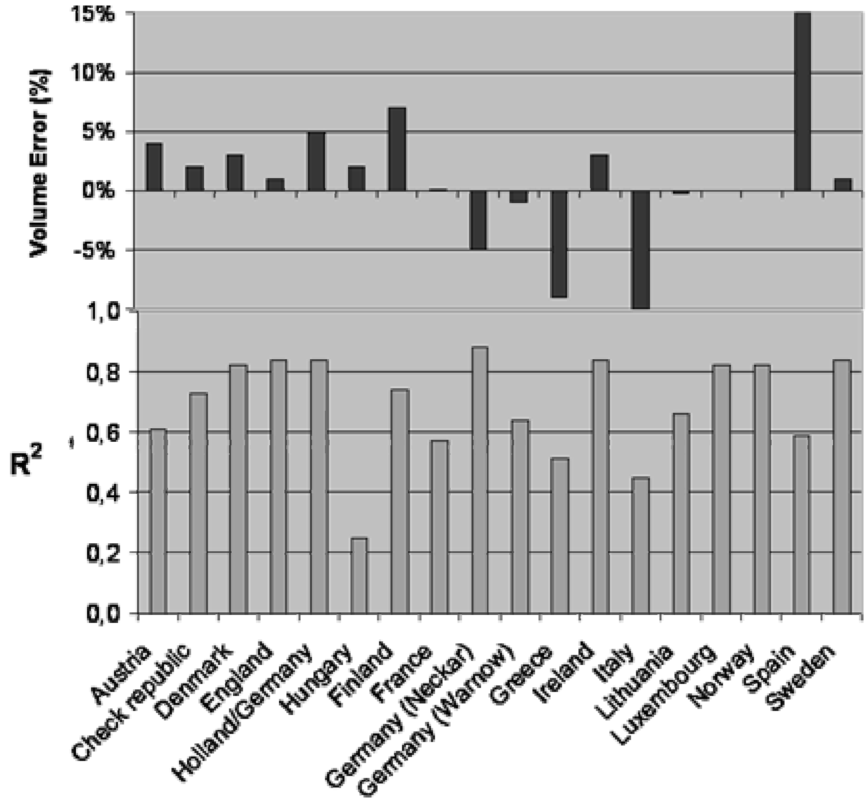

Fig. 2 HBV model performance according to the evaluation criteria.

the groundwater divides covered a larger area than the catchment boarders. Both the Greek and the Hungarian basin include karsts areas, and hence, the flow patterns are complex and difficult to capture by using a rainfall–runoff approach as the HBV model.

In Hungary, France, and for the German River Warnow it was also difficult to find representative precipitation data. For Hungary, only one station had continuous precipitation time-series, and in France only monthly information was available. For Warnov, the modelling was based on a 1°grid weather information, which resulted in the whole basin being part of one single grid. For the Lithuanian basin, on the other hand, the low accuracy with observations was related to limited information of observed water flow; only monthly measurements were available. This means that daily model results were compared to the more smooth dynamics of monthly values, and it is possible that the model reproduced the dynamics more correctly than what may have been described by monthly observations. It should be noted that, for Lithuania, the overall volume error is very low ($VE = 0.002$).

All results were based on automatic model calibration, using the routine by Lindström (1997), which gave different parameter values for each basin (Fig. 3). However, no significant relation between parameter values and physical conditions could easily be found by correlation (Fig. 4). This is probably an effect of the parameter interaction, which has already been well documented for the HBV model (Bergström, 1976; Harlin & Kung, 1992; Seibert, 1997; Ulenbrook *et al.*, 1999). Similar model performance according to the evaluation criteria used can result from

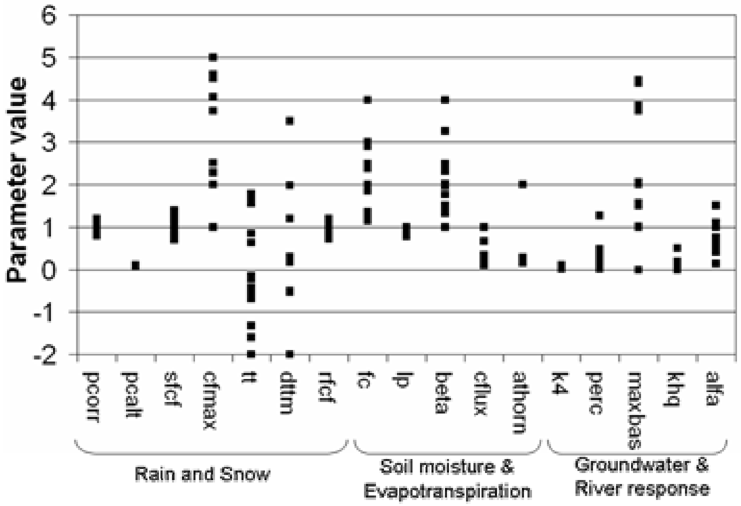

Fig. 3 Range of calibrated parameter values in the HBV modelling of European basins. Order of magnitude is adjusted for a few values. Parameter functions are described in Table 2.

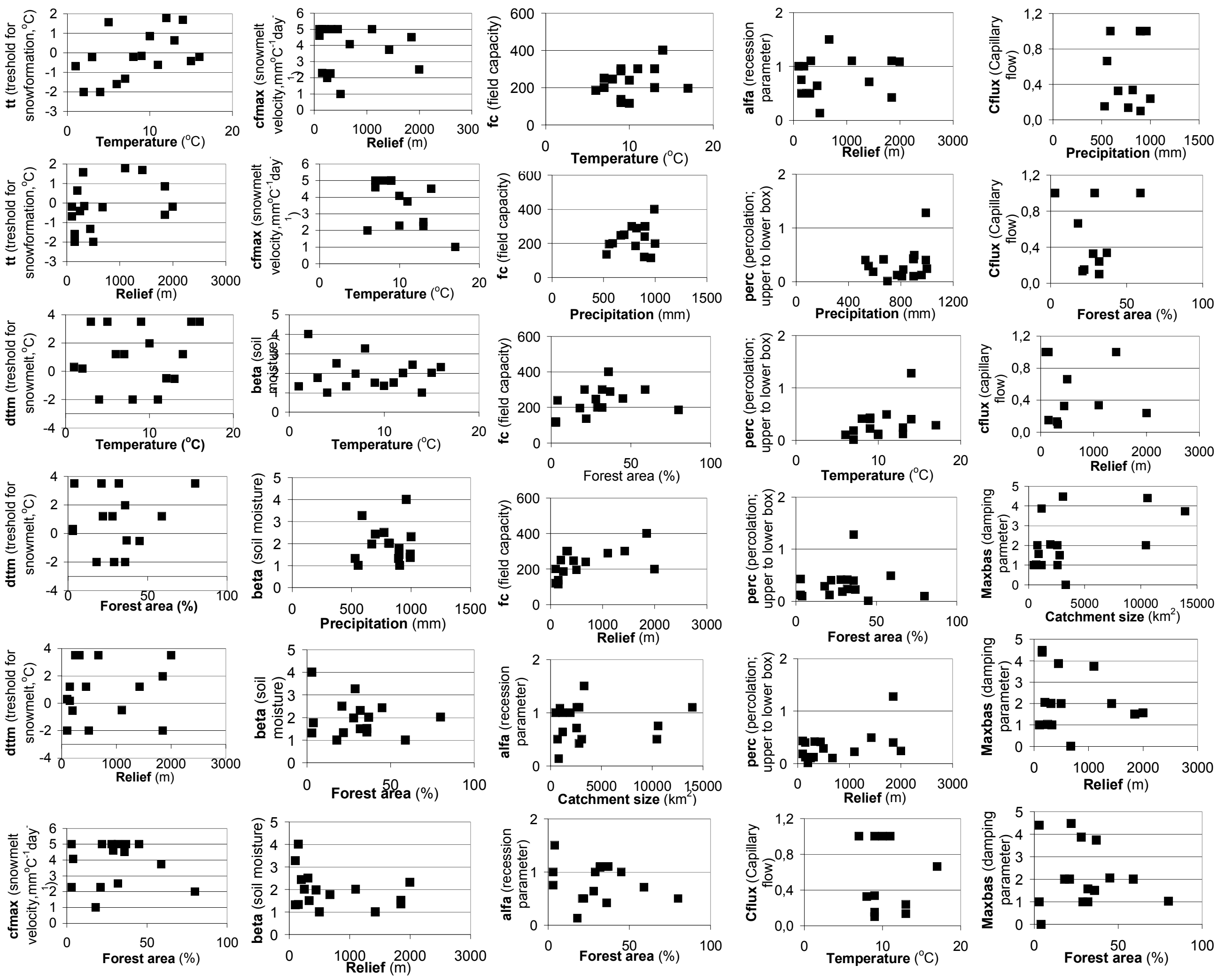

Fig. 4 Correlation between parameter values and different basin characteristics.

very different combinations of parameter values. Nevertheless, it would be interesting to study whether there is a relationship between groups of parameters and basin characteristics. Based on experience and common sense, some parameter combinations are less likely to appear and some parameter values are more probable than others during specific conditions. This should be tested more scientifically in the future and could be implemented in the automatic calibration routine by giving more weight to more likely parameter values or combinations. Yet, it must be admitted that uncertainty in model parameters exist and if possible it is better to give results as an interval and not fixed values.

Surprisingly good results where obtained when using *a priori* values for basins without access to monitoring data (e.g. the blind tests). The results of evaluation criteria were only slightly increased after model calibration (Table 3). For Norway, the first results in Table 3 show model performance without using any lake routing. The model was radically improved after implementing a general routing curve for the outlet lake of the basin. Hence, lake routing had much more influence on the results than calibration of parameter values. In the English basin, the explained variance was not much improved by calibration while the volume error could be improved a lot. The model gave very poor results in the Italian basin due to lack of rainfall in the database used. High discharge was observed in the basin although no rainfall was present. Local rainfall may be very intense in parts of the Mediterranean Alps, and was probably not captured by the two meteorological stations available. This could not be improved by any calibration of the hydrological model, but a weather simulator might have helped in this case.

Table 3 HBV model performance in three of the basins.

Basin, Country	PUB / Blind test (1990–1995)		Calibrated simulation (1990–1995)		Independent validation (1996–2000)	
	R^2	*VE*	R^2	*VE*	R^2	*VE*
Vansjø–Hobøl, Norway	0.33	–0.04				
with general lake rating curve	0.74	–0.03	0.81	0.01	0.82	–0.004
Yorkshire Ouse, UK	0.79	0.15	0.83	0.03	0.85	0.005
Enza, Italy	0.11	–0.25	0.14	–0.21	0.29	–0.29
time period 1995–1996	0.40	–0.18	0.45	–0.10		

Nitrogen concentrations and load were simulated in six European basins and blind tests were performed in three basins to judge the model’s performance when uncalibrated. However, no statistical evaluation criterion was used for the evaluation of concentration modelling as observations were rather sporadic. Visual inspections indicated that concentration levels were often in agreements with observations but the dynamics, on the other hand, were more difficult to capture. In England and Italy, the Swedish TRK concept generally overestimated the concentrations, although the modelled loads were in agreement with observations (Fig. 5).

CONCLUSIONS

Daily estimates of water discharge cover the country of Sweden for the period 1961–2002. These are based on rainfall–runoff modelling using HBV in 1000 sub-basins, of

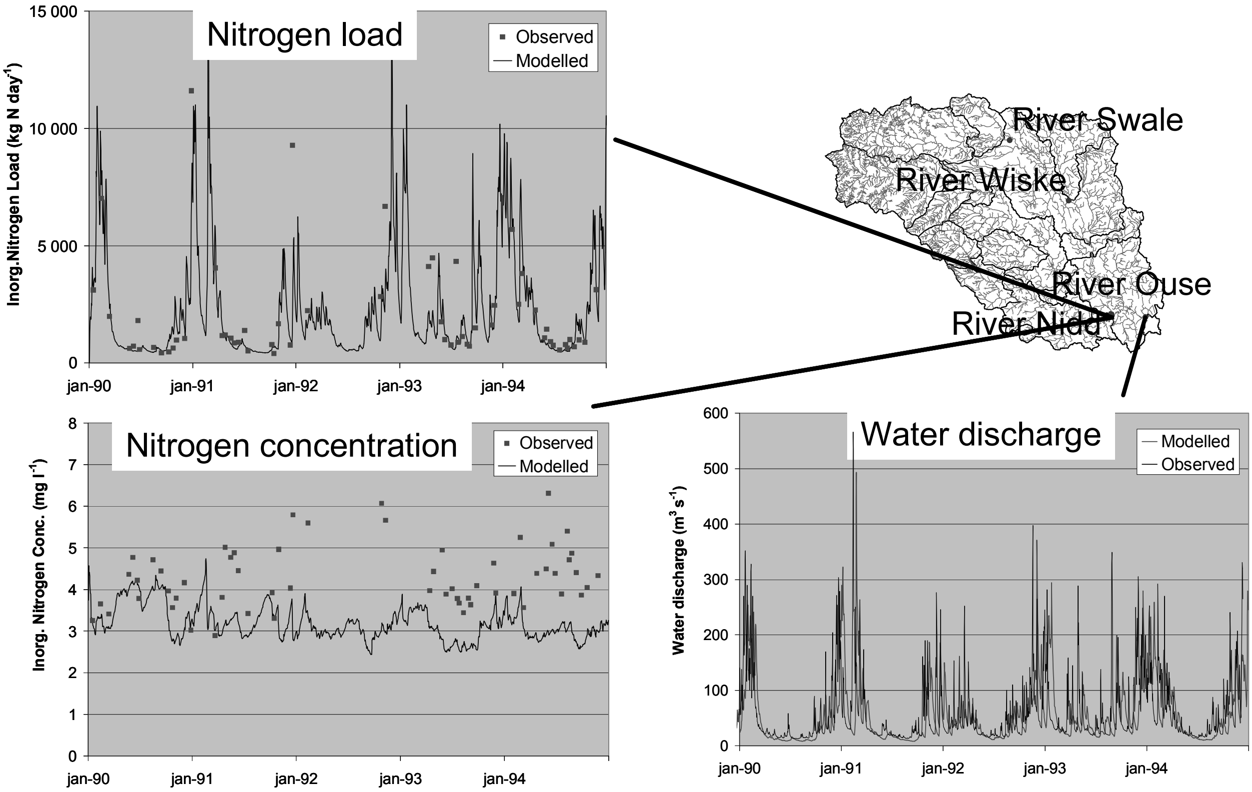

Fig. 5. Blind tests (uncalibrated results) of daily water and nitrogen flow in the English basin.

which 700 are ungauged. The model evaluation, which is based on 1/3 independent stations and 2/3 independent time periods, shows that normally the relative volume error is <5%.

The HBV model delivers trustworthy results for European basins (R^2 >0.7 and *VE* <5%) when rainfall data is representative.

It is difficult to relate the most efficient parameter values based on automatic calibration of the HBV model to simple and easily available basin characteristics. Further studies are requested to develop the function for parameter value estimation using automatic calibration.

A conceptual rainfall–runoff model (HBV) may be used for predictions in ungauged basins, using only *a priori* parameter values. The model results were only slightly improved by calibration. Thus, the modeller's experience and knowledge is very important for the model results when using conceptual models for ungauged conditions.

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