

Combined deterministic – stochastic forecasting of monthly river flows for water management

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Abstract. Monthly discharges can be modelled and predicted by the decomposition of the runoff process model into two components – deterministic and stochastic. For such approach the term hybrid was often adopted. In this study a hybrid (deterministic-stochastic) modelling approach for one step ahead forecasting of mean monthly discharges at the gauging stations Banská Bystrica and Brehy on the Hron River in Slovakia was developed. The aim was to join the conceptual monthly rainfall runoff model KVHK and several time series models of the forecasting error time series of the conceptual model into a hybrid framework. Since these rainfall-runoff model error series may exhibit nonstationarity and heteroscedasticity, beside traditional ARMA models, GARCH type nonlinear time series models were also considered.

1. Introduction

Reliable forecasts of monthly inflows to reservoirs are of particular interest for scheduling of releases for many water resources management tasks, e.g. for hydropower production or low flow augmentation. Approaches used for monthly river flow forecasting include a wide range of methods from deterministic (usually conceptual water balance models) through stochastic approaches (mainly in the time series domain) to methods of artificial intelligence (e.g. neural networks). Especially when quantitative information on the uncertainty of predictions is required, reliable predictions remain a difficult task for physically based monthly watershed models owing to the complexity of the involved meteorological and hydrological processes. In the recent past therefore the so-called hybrid (combined deterministic-stochastic) modelling approaches gained increased interest, which try to combine the advantages offered by both deterministic and stochastic methods [1,2].

In this study a hybrid (deterministic-stochastic) modelling approach for one step ahead forecasting of mean monthly discharges at the stations Banská Bystrica and Brehy on the Hron River in Slovakia is presented. First the two modelling approaches, the conceptual monthly rainfall runoff model KVHK and several time series models of the KVHK model forecasting error time series are described. Since these error processes are in general nonlinear and in addition to that such forecast error series may exhibit nonstationarity and heteroscedasticity [3, 4, 5], beside traditional ARMA models, GARCH type nonlinear time series models are also considered here in the hybrid framework. We produce one - step - ahead forecasts from the fitted models and compare the forecasting performance of nonlinear



time series models with that of linear error series models, since there is limited knowledge of their predictive capabilities concerning the particular problem of forecasting modelling error series.

2. Data

The forecasting performance of the hybrid methodology was tested for one month ahead flow forecasting (without considering the uncertainty of the forecast) on the Hron River in Slovakia. From the practical point of view the flow forecasting problem in the upper part of the Hron basin is complex [6]. In the alpine mountain regions rainfall runoff processes are dominant in flow generation. Rainfall of cyclonic origin represent main danger to major cities and industrial areas along the river. The hydrological modelling therefore concentrates on rainfall runoff processes. While daily time step is sufficient for hydrological forecasting for flood protection, the monthly time step is needed for water resources management tasks.

The Hron River springs in the Low Tatry Mountains at an elevation of 980 m asl. With its length of 298 km it is the second largest river in the country, its basin has size of 5465 km². The map of the Hron River basin is shown in figure 1.



Figure 1. The Hron River (red dot – gauging station, dashed line- watershed boundary, blue lines-river network).

3. The KVHK rainfall-runoff model

For modelling mean monthly runoff time series the KVHK conceptual water balance model developed at the Slovak University of Technology was used [6]. This model (see figure 2) simplifies a river basin into 2 nonlinear reservoirs, and it simulates water accumulation in the basin, snowmelt, evapotranspiration, runoff from impermeable areas in the basin, surface and subsurface runoff and baseflow.

The inputs required for the modelling of the water balance in a monthly time step are: the mean monthly precipitation for the basin, the mean monthly discharges in the outlet of the basin and the mean monthly potential evapotranspiration. For calculating the potential evapotranspiration, various methods can be used and accordingly additional climate data may be required (e.g. the long-term mean monthly hours of the duration of sunshine, the long-term mean monthly values of the relative air humidity, and the mean monthly air temperature values). The model contains a snowmelt reservoir, which enables the distinction between solid and liquid precipitation on the basis of the principle of threshold temperatures. The total runoff is calculated as the sum of the direct, surface, subsurface runoff components and of the baseflow. In this study a genetic algorithm was used to calibrate the 11 model parameters, and the traditional Nash-Sutcliffe criterion was employed as an objective function. We fitted the model on 32 years of monthly data from the period January 1961 - December 1992 (altogether 384 observations).

4. The KVHK model forecasting error time series analysis

Rainfall runoff model forecasting error time series data exhibit three major differences when compared to natural runoff data. First the time series takes all possible values, not only positive numbers. Second, the general property of the hydrological model error processes seems to be heteroscedascity. This behaviour present in the hydrological model error series can be explained by the fact, that the modelling and forecasting of flood flows (pulse like rising discharge) is a more demanding task than that of droughts (slowly decreasing flows). Therefore, unlike in natural data, the variance of the time series may not be considered as constant. The heteroscedasticity concept has not received much attention in hydrological literature so far, but it is gaining popularity as well, see e.g. [3,4].

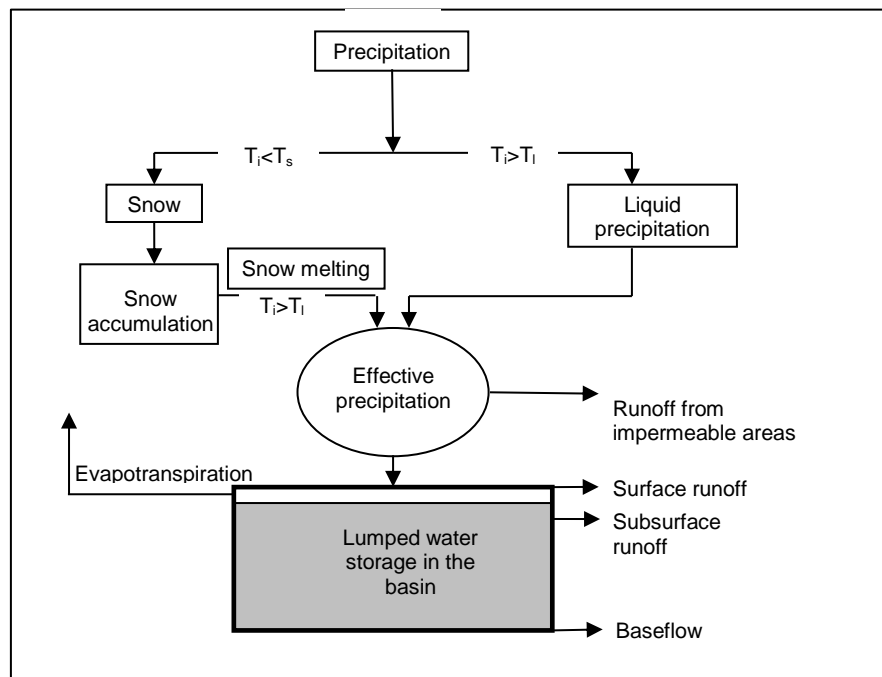


Figure 2. The flowchart of the KVHK monthly hydrological balance model
 T_i is the mean monthly air temperature, T_s and T_l are threshold temperatures for solid and liquid precipitation, $T_s < T_l$.

Third, unlike in natural discharge series, there is no physical justification for assuming seasonal and cyclical dependencies within the error time series. Model errors depend much more on the inadequate description of the modelled process within the conceptual model and the inputs. Large errors can occur anytime. Despite of this, for the sake of completeness, we analysed two cases - including and excluding the removal of the cyclical components from the time series (seasonality was not considered). We will denote the version of a model, where we removed the cyclical component with "-C".

Since in hybrid modelling schemes one of the oldest model classes the family of the autoregressive moving average models was usually applied [5], here these models were used as a basis for comparison to GARCH type models of the model error time series, too. The actual data analysis was arranged as follows (for details of the methodology see [2], where it was used on daily discharge data):

- We removed the deterministic components i.e. trend and cyclical components.
- We tested the stationarity using the Augmented Dickey -Fuller test (ADF) test, and fitted an appropriate ARMA model on the residuals. The choice of order of the ARMA model was based on the shape of the autocorrelation and partial autocorrelation functions (ACF and PACF). It may happen, that several alternative parameters of an ARMA model seem

acceptable. For this reason, the Akaike and Schwarz Bayes Information criteria (AIC, BIC) based on comparing the residuals from the different models were used and the model with the minimum information criterion value was preferred.

- Then we examined the residuals for possible heteroscedasticity. To test for existence of heteroscedasticity the Ljung-Box-Pierce Q-test was used on these to obtain the first estimate, and to verify it, we used the Engle's Lagrange multiplier ARCH test (ARCH LM test). Subsequently we fitted a GARCH or EGARCH model and examined the fit and the residuals.
- We gave a comparison of predictions produced by the GARCH or EGARCH models against ARMA type models using the modified Diebold-Mariano (DM) statistics.

The Diebold-Mariano test comparisons between the distinct models were given in a form of a result table, the entries have 3 possible values: 0, when the models have statistically same performance, 1, when model A delivers statistically significantly better performance than B, and -1, when model A delivers statistically significantly worse performance than B (for more details on the test see e.g. [7]). The Nash-Sutcliffe coefficient, which is the most popular model performance criterion in hydrology was also used [6].

5. Results and discussion

The ARCH LM test rejected no heteroscedasticity in 3 out of 4 possible cases, the exception was the Banská Bystrica KVHK error series after the removal the cyclical components. The spectral analysis showed only one significant value in Brehy, corresponding to 1 year period and 2 values in Banská Bystrica - 1 year and 6 months. Surprisingly both data sets showed very little correlation, especially after the removal of the cyclical components.

We fitted an AR(1) in all four cases. However the GARCH model in its original form was not applicable for the same reasons as in [2]. We used EGARCH(1,1) on all three heteroscedastic model error series. Surprisingly the forecasting performance of the models was by far not as good as it was in [2] when applying these to daily data. The DM values are in table 1 and table 2, the Nash Sutcliffe coefficients in table 3.

Table 1. Performance comparison based on the DM test – Brehy.

| | AR(1) | AR(1)-CEGARCH(1,1) | | EGARCH(1,1)-C |
|---------------|-------|--------------------|----|---------------|
| AR(1) | X | 1 | -1 | -1 |
| AR(1)-C | -1 | X | -1 | -1 |
| EGARCH(1,1) | 1 | 1 | X | 0 |
| EGARCH(1,1)-C | 1 | 1 | 0 | X |

Table 2. Performance comparison based on DM test – Banská Bystrica.

| | AR(1) | AR(1)-C EGARCH(1,1) | |
|-------------|-------|---------------------|----|
| AR(1) | X | 1 | -1 |
| AR(1)-C | -1 | X | -1 |
| EGARCH(1,1) | 1 | 1 | X |

Table 3. Nash Sutcliffe S coefficients for Brehy and Banská Bystrica.

| | NS Brehy | NS Banská Bystrica |
|---------------|----------|--------------------|
| AR(1) | -0.3452 | 0.1238 |
| AR(1)-C | -0.6352 | -0.1399 |
| EGARCH(1,1) | -0.0442 | 0.2974 |
| EGARCH(1,1)-C | 0.0447 | N/A |

Comparing the Brehy models, the AR(1) and AR(1)-C models actually performed worse, than if we approximated the values by the time series mean, the AR(1)-C model being the poorest in performance

altogether. The EGARCH(1,1) (-C) models did comparably against each other and outperformed the AR(1) (-C) models. Considering the Banská Bystrica models, again, the AR(1) -C delivered the worst performance. The EGARCH(1,1) model was slightly better than the simple AR(1) model. However, overall the EGARCH(1,1) models didn't offer much improvement compared to the already poorly performing AR models.

6. Discussion

The ARMA models may not properly reflect the structural properties of the heteroscedastic error series, but may outperform the GARCH models in practical performance. Indeed, as reported in the econometric literature, the EGARCH model showed better performance only on Banská Bystrica data, otherwise the forecasting performances were statistically equivalent with the respective ARMA models. Moreover, the forecasting performance of the hybrid framework did not match its performance gained with daily data in [2] and was not good enough for practical purposes. Unlike in econometric time series, here the γ parameter was positive, which means that the data tend to react more strongly on positive changes, rather than the negative ones. It underpins the need of a non-mechanistic approach in the case based analysis of such data and the physical interpretation of statistical modelling results. In this particular case the general property of hydrological processes was manifested in the error series, that the rise of discharge is rainfall driven (a highly nonlinear chaotic intermittent process) and the decrease of discharge is ruled by the damping effects of the water storage in the driven system (catchment or river reach), which filters and smoothes the pulse like behaviour of the inputs. The fact, that this behaviour is present in the hydrological model error series, can be explained by the fact, that the modelling and forecasting of floods (pulse like rising discharge) is a more demanding task than that of droughts (slowly decreasing flows).

7. Conclusions

The hybrid modelling framework was used by analysing the structure of the one step ahead forecasting error series of deterministic hydrological model and forecasting these by time series models. So far only a few attempts to apply various nonlinear time series models were reported in the hydrological time series literature e.g. [1, 3, 4]. The fitting, forecasting and simulation performance of such models have to be explored case based [2].

The investigation of model properties and performances was thoroughly tested. In general, besides the one case, heteroscedasticity was present in the model error data. Considering the monthly error series, since all models delivered very poor performances, it is questionable, if the improvement offered by the EGARCH model is to be considered as significant at all. In these applications the manifestation of heteroscedasticity in the data was not so persuasive as with daily data and other type of models, mainly from the regime switching class (such as STAR, SETAR, LSTAR, [1, 5]) may be more appropriate for the modelling.

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