Sequential Development of a Conceptual Hydrological Model Considering Alpine Basin Processes

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Abstract: In the frame of an applied research project the authors had to develop a runoff forecast tool to enable a prediction of the hydropower potential with a lead time of four days. Therefore procedures for runoff, snow accumulation and snowmelt were sequentially generated, leading to model types ranging from a statistical approach via one storage/single outflow type, one storage/two outflow model to a two storage/triple outflow concept. This contribution presents a procedure to adapt model complexity as far as necessary to improve runoff simulation while still keeping the type of a parsimonious, conceptual model. The improvements of the results are interpreted in terms of hydrological process consideration and are evaluated by means of temporal efficiency criteria like the Nash-Sutcliffe and the correlation coefficients. The seasonality of alpine runoff processes could only be achieved with consideration of snowmelt and evaporation concepts. The model reliability increased with increasing model complexity but the increment of goodness was reduced and thus makes the choice of an appropriate model type dependant from the final application demands.

***Keywords**:* Conceptual hydrological modeling; rainfall runoff modeling; parsimonious models.

1. INTRODUCTION

1.1 General aspects and background

Rainfall runoff models play an important role in flood protection design or flood forecasting systems. References for different applications can be found in e.g. Donelly-Makowecki and Moore [1999], in Singh [1995] or in Cameron et. al. [1999]. In this paper the use of runoff models is presented with the background of forecasting the hydropower potential. The experiences are based on the development of a forecast system for the entire Austrian river systems. The areas of the subbasin ranged from 1,100 to 15,000 km^2.

As the operation of these basins requires excessive data management, there was a special demand for parsimonious model types, where the effort for the online data operations could be kept low. Several concepts of application were used regarding to different temporal resolutions and to different local or national demands.

This paper refers to the daily temporal resolution model. Runoff forecasts four days ahead are predicted for 13 power plants along the main Austrian water courses using multiple regression analysis. The independent predictors are the hydro meteorological data of the subbasins like areal precipitation, snowmelt, soil moisture accountings and upstream runoff.

The reliability of the statistical regression model depends on the performance of the above predictors. Therefore it can be considered as a hybrid model concept, where the emphasis is on the modeling of hydrological processes on subbasin scale.

1.2 Overview of the tested Model Types

The basic strategy of model development was to keep the model as simple as possible. Therefore the described methods start from simple concepts and increase complexity with the feedback of the model evaluation. The first assumption was to represent local runoff by the rainfall input. In this context, rainfall is defined as the areal precipitation of the basin. As rainfall represents a discontinuous process and runoff shows continuous behavior, direct comparisons of these values, e.g. by regression or correlation analysis, give poor results.

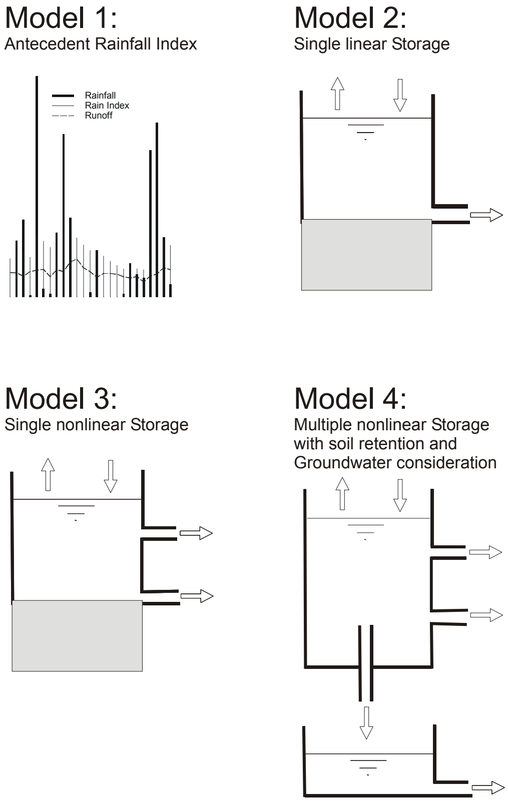

Figure 1: Scheme of the applied model types.

Therefore a filter procedure was used to transform rainfall into continuous input, which is referenced in the literature as antecedent rain index (ARI) method [see Chiew et. al., 1993]. A linear regression is applied to estimate runoff. A scheme is shown in Figure 1. More details are given in section 2.1.

To consider the storage behavior of the catchment, some further model assumptions were developed, based on linear (model 2) and nonlinear storage concepts (model 3). In addition soil moisture and groundwater accountings were stepwise included (model 4).

1.3 Snowmelt and Snow Accumulation

In this paper the continuous model development is reported for the subbasin of the Austrian river Enns. It is located in an alpine area, where snow accumulation and melting processes play an important role. Snowmelt is described by a simple day degree method with consideration of altitudinal discretisation.

1.4 Model evaluation criteria

As the model complexity is continuously increasing, also the number of the model parameters becomes larger. Independently from the preferred model type and its parameter dimension the model developer has to calibrate the parameter set to gain optimal model results. The description of model performance is manifold [see Gupta et. al. 1997, Perrin and Littlewood, 2000]. In this paper the Nash-Sutcliffe [Nash and Sutcliffe, 1970] and the correlation criteria were used. The first gives a good estimate of the weighted absolute errors, the second criteria characterizes the agreement of shape and variability. But it has to be mentioned, that the selection of a proper performance criterion (objective function) depends strongly on the operational demands of the runoff model.

1.5 Basin data and time series

The Enns river basin is located in the center of Austria. In its lowlands it consists of moderate hills but in the headwater part it forms high mountains up to 3000 m a.s.l. The median elevation is 1132 m a.s.l. Due to spatial heterogeneity the local annual rainfall depths vary from 840 mm in the lowlands up to 1588 mm in the mountains. The mean monthly and annual rainfall and air temperature data are listed in Table 1. The contributing basin area of the river Enns is 6861 km^2 at its reference gauge. For the model development daily hydrological and meteorological data were available for the years 1990 to 1996. The mean discharge is 202 m^3/s, the thirty years frequency flood is 2560 m^3/s. The runoff behavior shows significant seasonal variation due to the snow accumulation and snowmelt processes in the catchment and due to rainfall seasonalities with the maximum in June and July (see Table 1).

2. APPLIED MODEL TYPES

2.1 Rainfall regression Model

The first model type represents a simple statistical model based on the andecedent rain index (ARI) concept. The discontinuous rainfall is transformed using equation (1). The coefficients a and n were estimated by calibration. This transformation leads to a time series of continuous rain indices, which amount is equivalent to the rain input.

Table 1: Meteorological and runoff data 1990-96.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rain depth (mm)	55.8	61.9	94.9	94.5	110.4	158.7	151.6	131.1	124.5	89.0	107.7	91.1	1402
Air Temperature (^oC)	-0.61	0.81	4.93	8.36	13.33	16.34	18.71	18.71	13.91	9.7	4.07	-1.01	8.98
Mean Discharge (m^3/s)	116	109	191	275	345	287	247	184	192	161	169	144	202

ARI reasonably corresponds to the observed runoff Q. The interrelation can be described by a linear regression model described in equation (2), where Q_{comp} is the estimated runoff.

$$ARI_i = \frac{1}{\sum_{i=t}^{t-n} a^i} \cdot \sum_{i=t}^{t-n} (a^i \cdot P_i) \qquad (1)$$

were i … Time index (in days)
a … coefficient (=0.88)
P … Precipitation (plus snowmelt optional) in mm/d
n … memory length in days (=28)

$$Q_{comp,i} = 53.96 + 42.33 \cdot ARI_{i,RAIN} \qquad (2)$$

The results of equation (2) exhibit significant underestimation of the snowmelt period as this process is not considered by the applied concept (see Figure 2a). If the effective rain - which in this context is the wet rainfall plus the snowmelt depth - is used in equation (1), a new linear model can be defined (equation 3), which gives better results. The adapted model equation is as follows

$$Q_{comp,i} = 36.44 + 47.80 \cdot ARI_{i,RAIN+SNOWMELT} \qquad (3)$$

2.2 Single storage, single outflow model

This type of model is addressed as model 2 in Figure 1. It is based on the concept, that runoff response is the result of the total basin release, where the particular retention components like surface storage, soil storage and groundwater storage are summarized in one single storage. Model 2a does not consider immobile soil storage where version 2b takes it into account. Immobile soil storage serves as a pool for evapotranspiration to achieve the water balance components and considers soil retention.

The model parameters are the storage coefficient (or time constant) *k1* and the depth of the soil storage *h1*. The model program source is a Fortran code, the applied optimization routine is based on a combined Newton-Rhapson algorithm [Kuester and Mize, 1973]. The model input consists of the effective rainfall, which is the moist rainfall (excluding snowfall in higher areas) plus the snowmelt depth.

2.3 Single storage, double outflow

The single outflow version of the single storage model tends to underestimate the peaks of floods. Therefore a second outlet, which only contributes at high storage levels, was established (see model 3 in Figure 1). Consequently two further model parameters were added. *K2* is defined as the storage coefficient of the second outlet and *h2* as the depth of the upper outlet from the bottom of the soil storage.

2.4 Double storage, triple outflow

One storage models tend to run empty in dry phases. But in the humid environment of the Enns river basin we have in fact perennial conditions with significant discharge also in dry periods. Therefore a second storage was adopted, which is charged by a vertical outflow from the upper storage. The second storage can be interpreted as the groundwater storage, the vertical recharge as the percolation process starting at field capacity of the soil. The plant available water content is represented by the bottom storage of the first pool which corresponds to *h1*. Two further model parameters were added. The storage coefficient of the vertical recharge *k3* and the storage coefficient of the groundwater release *k4*. In total this model version M4 includes 6 model parameters.

2.5 Snowmelt and accumulation

In alpine environments runoff simulation has to consider snow accumulation and snowmelt. In all model variations a snowmelt procedure based on the day degree method was applied. Snow accumulation was assumed below a threshold temperature. To consider the contribution of the particular elevation zones, a hypsometric distribution with 500 m discretisation was used. The air temperatures of the layers were linearly interpolated between observed values to account for temperature gradients. The snow model parameters consist of the melting factor and the threshold temperature for melting. A more complex version considering seasonal variation of these parameters exists, but is not discussed in this paper [see Holzmann and Nachtnebel, 2000].

3. Simulation results and model evaluation

The model parameters of the particular model types were calibrated for the period from 1990 till the end of 1993. The first 150 days of 1990 were not considered for calibration to avoid inconsistencies due to the starting conditions of the model state. The period from 1st January 1994 to 31th December 1996 was used for model validation The efficiency criteria values were computed both for the entire validation period and for the single months to show seasonal effects of model validity.

The graphical results are displayed for the validation year 1996 (see Figure 2).

3.1 Rainfall regression Model using ARI

Using the single rainfall event data, the correlation with the runoff observations is poor (r = 0.22) and thus not applicable as a predictor in a linear regression model. The transformation of the rainfall data into the antecedent rainfall index (ARI) by means of equation 1 gives correlation coefficients of 0.67, the Nash-Sutcliffe (NS) value is 0.44 (see Table 2, Model 1a). But the monthly data show unsatisfying results for January, April, May and partially in August (see Figure 2a). This is caused by the poor representation of the snowmelt process in the ARI data, as this method uses only the precipitation data. Therefore a consideration of the snow accumulation and snowmelt processes lead to improved model results (Figure 2b and Table 2). This can be achieved by substituting the precipitation P in equation (1) by the effective rain plus snowmelt values.

Herewith the adopted ARI data lead to improved model performance with a correlation coefficient of 0.79 and a NS value of 0.63. As can be seen in Figure 2b, there is a moderate overestimation of the July and August values. This is caused firstly by the averaging effect of the applied linear regression model, which tend to underestimate the extremes and overestimate during the low flows. Secondly the missing concept of evapotranspiration, which in fact reduces the runoff during the vegetation period, leads to overestimations of summer discharge. This effect will also be demonstrated for the model version M2a in the next section.

Due to the linear regression approach the rainfall regression model using the ARI concept achieves the water balance requirements. This means that the totals of the simulation runoff agree with the observed.

3.2 Single storage, single outflow

For this model type two versions were developed:

- No soil storage, no evapotranspiration (2a)
- Soil storage and evapotranspiration. (2b).

The potential evapotranspiration was estimated by the Thornthwaite formula [see Bretschneider et al., 1990], which provides monthly data of mean evapotranspiration.

Version 2a gives a good representation of the annual dynamic, which is documented by the good correlation coefficient of 0.83. But due to the neglect of the evapotranspiration process, it is obvious, that runoff is overestimated for the summer period also indicated by the weak NS coefficient of 0.46.

The implementation of soil storage and evapotranspiration (version 2b) gives significant model improvements. The NS-coefficient is 0.68 and the correlation coefficient 0.87. But the runoff depletion after some flood events in July and December is to steep and the runoff extremes were underestimated by the model. Therefore the next development step includes a second outlet for a quick runoff component.

3.3 Single storage, double outflow

This model version (see Figure 1, model 3) adds to model 2b a second, upper outlet, which accounts for the quick runoff response. The improvement is shown in Table 2. Both validation coefficient are improving. The NS-coefficient is 0.71, the correlation coefficient 0.88. The temporal performance is satisfying, but in periods of low flow the simulated values are declining stronger (see Figure 5a). This indicates, that there is a need for a slow runoff component, which reflects the base flow of a river basin.

3.4 Double storage, triple outflow

The above conclusions lead to a model concept, which is shown in Figure 1 (model 4). It consists of two storages. The upper represents the surface and the soil storage. The lower storage represents the groundwater and slow runoff components.

For that model type all quality indicators are improving. The SN coefficient for the total validation period is 0.78, the correlation coefficient is 0.90.

4. Conclusions

The paper deals with hydrological modeling in alpine environments. Consequently it could be demonstrated, that hydro-meteorological processes like snow accumulation and snowmelt play a key role in reliable runoff modeling. The statistical model satisfactory describes the mean runoff behavior. But runoff extremes and low flow periods were not properly estimated. Therefore this model type will not work for flood applications.

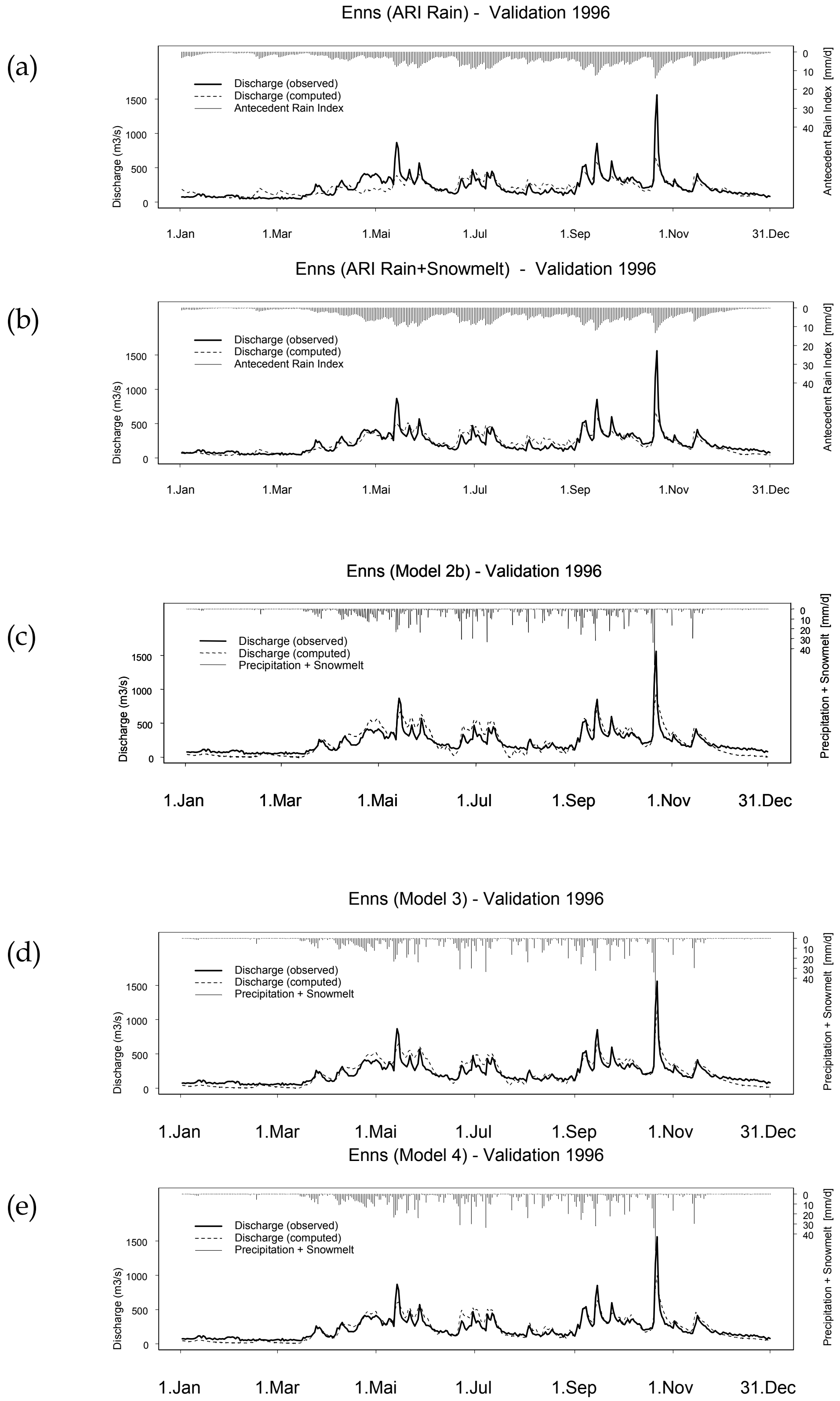

Figure 2: Validation performance of (a) Model 1a (ARI Rain), (b) Model 1b (ARI Rain+Snowmelt), (c) Model 2b (Single Storage + Soil Reservoir), (d) Model 3 (Single storage - double outflow), (e) Model 4 (Double storage - double outflow).

Table 2: Model performance (validation) using the Nash-Sutcliffe (NS) and the correlation (COR) criteria.

Model		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1a	**NS**	-1.66	0.04	0.36.	-0.82	-2.27	0.47	0.49	-1.82	0.73	0.65	0.21	-0.05	0.44
	COR	0.40	0.53	0.62	0.16	0.34	0.71	0.86	0.78	0.89	0.87	0.66	0.52	0.67
1b	**NS**	0.36	0.49	0.75	0.06	-0.37	0.45	0.20	-2.16	0.71	0.68	0.55	-0.09	0.63
	COR	0.68	0.76	0.88	0.67	0.40	0.75	0.88	0.77	0.89	0.87	0.75	0.55	0.79
2a	**NS**	-0.38	0.28	0.71	0.43	-0.12	-0.40	-1.48	-5.31	0.32	0.75	0.51	-1.44	0.46
	COR	0.77	0.90	0.92	0.66	0.60	0.82	0.92	0.80	0.89	0.87	0.86	0.54	0.83
2b	**NS**	-0.38	0.30	0.73	0.31	-0.10	0.59	-0.21	-0.17	0.74	0.72	0.71	-1.41	0.68
	COR	0.75	0.90	0.92	0.64	0.59	0.82	0.93	0.82	0.88	0.87	0.89	0.53	0.87
3	**NS**	-0.09	0.34	0.63	0.41	0.04	0.52	0.09	-0.11	0.66	0.86	0.57	-0.94	0.71
	COR	0.70	0.89	0.90	0.65	0.57	0.82	0.94	0.85	0.87	0.93	0.89	0.49	0.88
4	**NS**	0.20	0.53	0.77	0.46	0.22	0.52	0.52	0.31	0.80	0.85	0.62	0.09	0.78
	COR	0.77	0.92	0.93	0.72	0.65	0.83	0.93	0.89	0.91	0.93	0.91	0.68	0.90

All storage concepts require accurate estimates of the actual evapotranspiration. A neglect will lead to overestimated runoff for the summer period. The single storage concept leads to accelerated runoff decrease caused by the rapid depletion of the storage content. The two outlet version improves the estimation of extreme floods. The final version of the two storage concept also improves the results during the low flow periods. The slow release from the groundwater storage reliably reflects the natural behavior of the system. But in spite of the satisfying results some shortcomings are evident, which are based on several reasons. First the lumped rainfall input will not reflect reality even when the interpolation scheme is applied with caution. In the basin area natural rainfall will be spatial and temporal distributed, which affects the runoff response. Secondly the introduced models represent only a conceptualisation of the basin, describing the entire domain as a single column. Lateral processes like runoff propagation are simplified by linear storage concepts. This will obviously lead to model errors. Despite of these shortcomings, conceptual models are easily applicable tools to provide quick and reasonable results of the runoff behavior. Due to existing data limitations and data management demands, conceptual models - and also the parsimonious types - will furthermore hold their importance in future hydrologic modeling.

5. Acknowledgements

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