AN INTEGRATED LOWLAND CATCHMENT MODEL: UPPER NAREW CASE STUDY

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The aim of this work is the development of an integrated model of the Upper River Narew catchment and the river reach between Bondary and Suraż suitable for scenario analysis. The modeling tool developed is formulated in MATLAB-SIMULINK language. It has a flexible, modular structure that can be easily extended by adding new features, such as a snow-melt module, or a distributed routing module. We describe the basic system structure and rainfall-flow and flow routing modules based on a Stochastic Transfer Function (STF) approach combined with nonlinear transformation of variables using a State Dependent Parameter (SDP) method. One possible application is the derivation of a management strategy for the Siemianówka reservoir, situated upstream of the Bondary gauging station, taking into account both economic and ecological goals. Another future application is on-line data assimilation and forecasting.

We chose the River Narew catchment (Figure 1) as a case study. The river reach studied starts at Siemianówka reservoir and goes down to Żółtki over a lowland, agricultural area. The lower part of the area encloses valuable wetland ecosystems of the anastomosing Upper Narew River and forms the area of the Narew National Park (NPN). Both NPN flora and fauna include many protected species and due to its unique habitats the NPN site became part of the European Ecological Natura 2000 Network (Dembek and Danielewska 1996, IWOR 2002).

In recent years both a reduction of mean flows and shorter flooding periods in the Upper Narew River have resulted in a serious threat to the rich wetland ecosystems situated along the river in NPN. These undesirable changes were caused by changes in the local climate, manifesting in mild winters and a reduction in annual rainfall that have resulted in a reduction of valley's water resources. Additionally, river regulation works performed in the river reach downstream of NPN have lowered water levels in the NPN upstream. Flood peaks are also reduced by the water storage reservoir constructed upstream of NPN in Siemianówka (near Bondary).

In our approach we follow the Data Based Mechanistic philosophy introduced by Young (2001 and references therein). This approach advocates the identification of a model structure and estimation of its parameters conditioned on available data using information-efficient statistical tools. Among the statistically feasible models only those that can be explained in a physically meaningful way are chosen. At the catchment (reach) scale, the discrete-time STF can be presented as (Young, 1984):

$$x_k = \frac{(Bz^{-1})}{(Az^{-1})} u_{k-\delta} \qquad (1)$$
$$y_k = x_k + \xi_k$$

where $u_{k-\delta}$ denotes STF model input (effective rainfall, flow or water level), x_k is the underlying 'true' flow or water level, y_{k1} is the noisy observation of this variable, δ is a pure, advective time delay of $\delta\Delta t$ time units, $A(z^{-1})$ and $B(z^{-1})$ are polynomials of the transfer function. These polynomials are in the following form

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_n z^{-n}; \quad B(z^{-1}) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_m z^{-m} \tag{2}$$

in which z^{-r} is the backward shift operator, i.e. $z^{-r}y_k = y_{k-r}$, and $A(z^{-1})$ is assumed to have real roots (eigenvalues) that lie within the unit circle of the complex *z* plane. The additive noise term ξ_k in (1) is usually both heteroscedastic (i.e. its variance changes over time) and autocorrelated in time. It is assumed to account for all the uncertainty at the output of the system that is associated with the inputs affecting the model, including measurement noise, unmeasured inputs, and uncertainties associated with the model structure. The orders of the polynomials *n* and *m* are identified from the data during the data-based identification process. The model structure identification and estimation of parameters is performed using the Simplified Refined Instrumental Variable (SRIV) method from Captain toolbox (Taylor *et al.*, 2007).The nonlinear transformation of variables is carried out with the help of the State Dependent Parameter approach (Young *et al.*, 2001). Following the DBM philosophy, all the model parameters are accepted only when a realistic physical explanation of the model structure can be found.

The available data include daily rainfall observations at Białystok and water level measurements at 7 gauging stations situated along the river reach and its tributaries (Bondary, Narewka, Narew, Ploski, Chraboły, Suraż and Żołtki). This is a very coarse time discretisation for a relatively small catchment (4303 km^2 up to Żółtki) and it limits the models's identifiability. The model of the entire catchment consists of independent modules, as shown in figure 2. Both rainfall-flow/water level catchment modules and flow/water level routing modules are derived using the STF approach with nonlinearly transformed input variables to account for the nonlinearity of the catchment hydrology, if necessary. The choice of the routing (output) variable depends on the available data and purpose of the modeling. We present here the first stage of our research, consisting of the development of STF modules to be implemented within the SIMULINK based integrated catchment model.

We derived a number of linear Single- and Multi- Input Single Output (SISO and MISO) STF models describing the River Narew reach from Bondary down to the Żółtki gauging station and its sub-reaches (Figure 1), using flows and water levels as input variables. Most of the routing models have first-order dynamics.

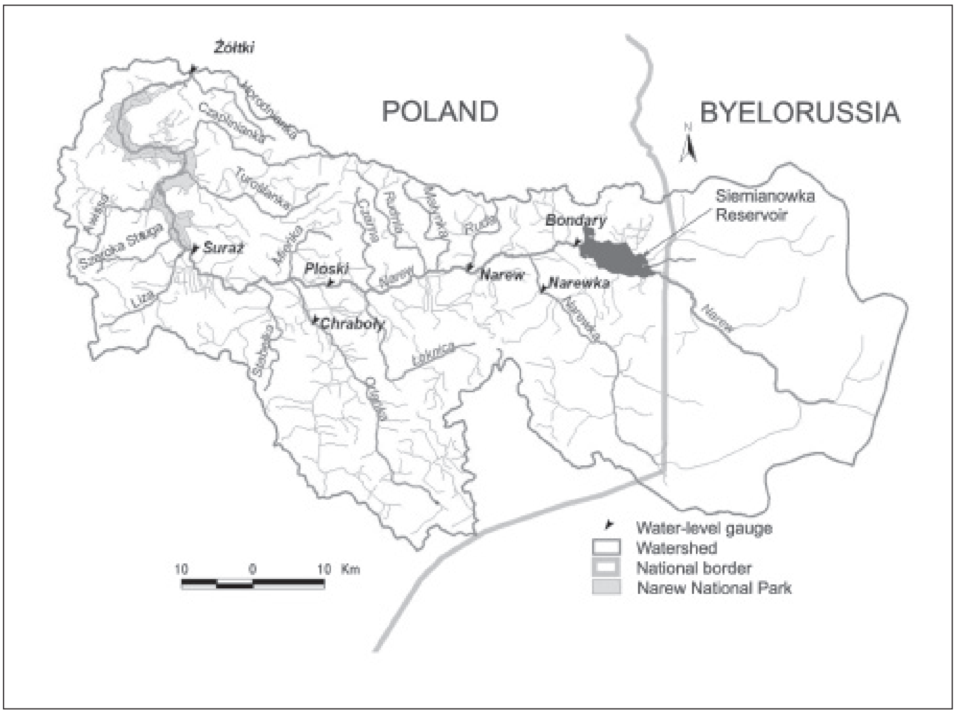

Figure 1. Upper Narew Valley showing the study area; stage gauging stations are shown as triangles.

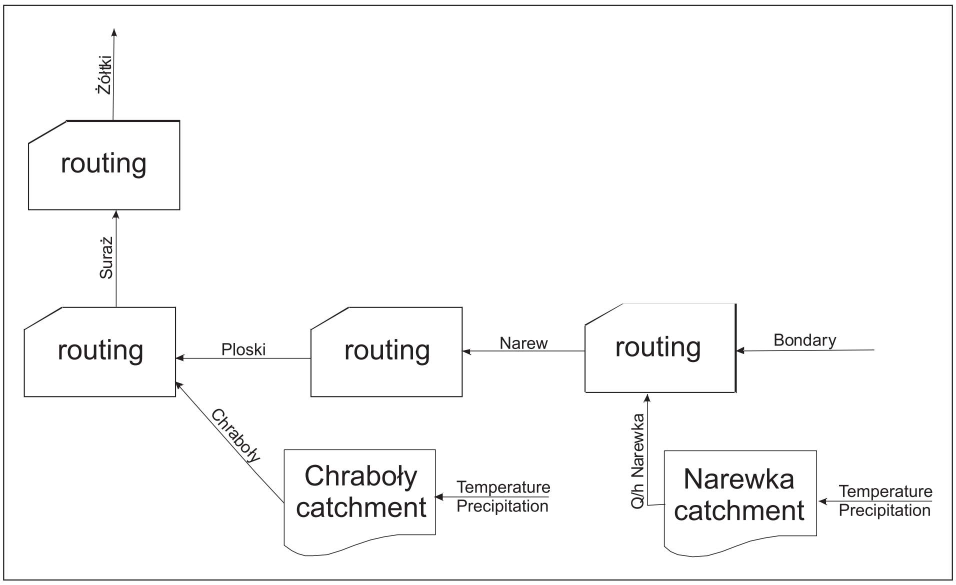

Figure 2. Block diagram of the transfer functions model of Upper Narew catchment

The best results were obtained for the neighbouring sub-reaches and there was no significant improvement of model performance if separate parallel inputs were used instead of an average sum. This result indicates that inflows from tributaries are highly correlated. Moreover, there are many unaccounted for tributaries along the river, which change the flow dynamics at the downstream reach. Therefore, even though the flood peak travels in about 4-5 days from Bondary to Suraż, the maximum advective delay obtained for the Suraż model with averaged flows from Bondary, Narewka and Orlanka on the input equals only 1 day. This model and the similar, MISO model using parallel inputs, are the only models suitable for flood forecasting. Models obtained without advective delay may be useful during scenario analysis. The residence time obtained for the sub-reach Narew-Ploski model, equal to 0.5 day, indicates that one day may be too large a discretisation period for that part of the river. Modelling results for the water levels are very similar to those obtained for the flows with the exception of the Suraż-Żółtki model. That model showed a much worse performance when water levels were used as the state variable. As the water levels are the observed variable and flows are obtained after applying the rating curve, we investigate the transformation between levels and flows for that station. An example of the validation of an STF Multiple Input Single Output (MISO) model for level routing in the river reach between the Ploski and Suraż gauging stations is shown in Figure 3. The estimated water levels are shown in black continuous lines, dots denote the observations and shaded areas show 0.95 confidence bounds of the predictions. This model explained 96.3% of output variation.

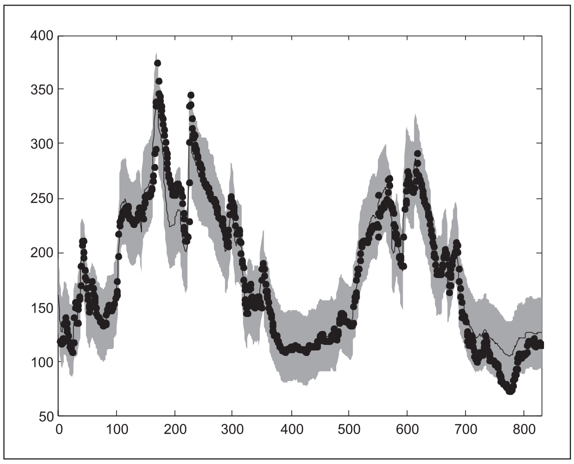

Figure 3. Validation of Multiple Input Single Output model for Ploski+Orlanka - Suraż, 96.3% of output variation explained (years 1982-83)

The derived STF modules describing rainfall-flow and flow routing in the Narew catchment were combined into the integrated rainfall-flow/level routing system (Romanowicz *et al.*, 2006). The system is subsequently used to build a SIMULINK model of the entire Upper Narew catchment, for the purpose of scenario analysis. That model will be also used for the testing and derivation of optimal reservoir releases for the purpose of draught and flood mitigation.

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