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APPLICATION OF A DISTRIBUTED PHYSICALLY-BASED HYDROLOGICAL MODEL ON THE UPPER RIVER BASIN OF SOMEŞUL MARE (NORTHERN ROMANIA)

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Abstract. The spatially distributed rainfall-runoff model TOPKAPI (TOPographic Kinematic APproximation and Integration) has been widely used for continuous modelling of floods. The model utilises three non-linear reservoir differential equations for the drainage in the soil, the overland flow on saturated or impervious soil, and the channel flow along the drainage network, respectively. The reservoirs derive from the integration in space of the non-linear kinematic wave model. The geometry of the catchment is described by a lattice of cells – the pixels of the digital elevation model (DEM) and their slope – over which the equations are integrated to lead to a cascade of non-linear reservoirs. The parameterisation relies on the digital thematic maps of soil, geology and land use. The model was applied on the upper river basin of Someşul Mare, upstream Beclean (4328 km²) for the 2000-2006 interval: the years 2000-2002 were used for calibration, the model being validated for the 2003-2006 period. The soil and the landuse maps were reclassified with respect to hydrological properties (*e.g.*, soil depth, soil texture, surface roughness, canopy interception). For the time-dependent input, precipitation and temperature from eight meteorological stations have been used. The trial-and-error calibration – based on visually matching the modelled streamflow with the observed one – managed to reproduce the behaviour of the catchment while keeping the parameters within their physically meaningful values. The model reproduced well the behaviour of the streamflow, the peak time, the increase and the recession of the floods. In general, the small floods were overestimated in terms of peak flow. However, considering that only one station (out of eight) is located inside the basin, the first modelling results are very satisfactory.

Key words: rainfall-runoff model, deterministic model, spatially-distributed model, kinematic wave, TOPKAPI, Someşul Mare.

1. INTRODUCTION

The paper presents a first attempt to simulate the rainfall-runoff processes on the upper basin of Someşul Mare, using the deterministic and spatially distributed hydrological model TOPKAPI. The model has been widely used for flood modelling and forecasting (*e.g.*, [1–4]), and it represents a valuable tool for assessing the impact of landuse or climatic changes on the streamflow regime. Formulated by Todini [5] and developed within the Hydrology Research Group at the University of Bologna, the model combines the watershed topography with the kinematic wave approximation and its integration in space. An important characteristic of the model is the ability to maintain the physical meaning of its parameters across scales.

2. THE TOPKAPI MODEL

TOPKAPI [5–8] is a spatially-distributed physically-based hydrological model with a simple parameterization, which simulates the rainfall-runoff transformation using precipitation and temperature time series. The acronym stands for TOPographic Kinematic APproximation and Integration.

Three non-linear reservoir differential equations are used to describe the subsurface flow, overland flow and channel flow, respectively. The primary processes of the hydrologic cycle are simulated at grid cell level with separate modules for infiltration, evapotranspiration, and snow accumulation and melting (Fig. 1).

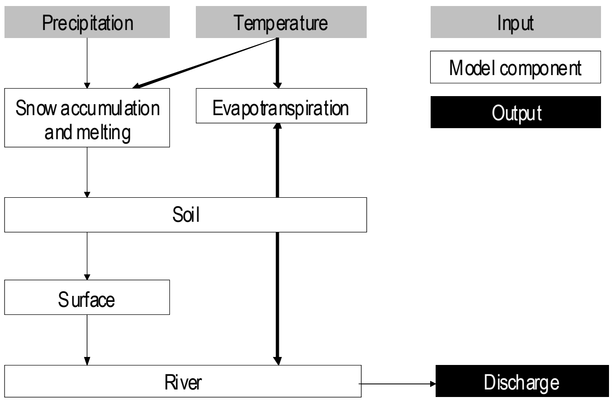


Fig. 1 – Flow chart of the TOPKAPI model.

The basic assumptions of the TOPKAPI model at the level of the grid cell are the following [9]:

(1) The saturation from below [10] is the only mechanism generating overland flow: all precipitation falling on the soil infiltrates into it, unless the soil is already saturated in the respective cell. The Hortonian mechanism (surface flow due to infiltration excess) is ignored, which is a reasonable assumption at catchment scale [11].

(2) The slope of the water table coincides with the slope of the ground; any slope smaller than 0.01% is set to 0.01%. This leads to the adoption of a kinematic wave propagation model for the horizontal flow / drainage [12].

(3) The local transmissivity depends on the total soil water content, *i.e.*, on the integral of the water content profile on the vertical direction.

(4) The saturated hydraulic conductivity is constant with depth in a surface soil layer but much larger than that of deeper layers.

The evapotranspiration (ET) component is taken from the ARNO model [13]. ET plays a major role in terms of cumulated temporal effect, and not in terms of instantaneous impact. This aspect, combined with the general lack of historical data needed for applying the Penman-Monteith formula, led to purposely neglecting the vapour pressure and wind speed. Therefore, the potential ET is estimated using the Thornthwaite and Mather formula [14]. The actual ET is computed with the radiation method [15]. The canopy interception is indirectly taken into account, by means of monthly values of crop factors [16].

The snowmelt module is driven by a radiation estimate (the same used for computing the evapotranspiration) based upon the air temperature measurements. A model parameter representing a temperature threshold is used to classify the precipitation into rain and snow.

For a given cell, the equations for the three non-linear reservoirs (soil, overland and channel) are obtained by combining the continuity and mass equations under the approximation of the kinematic wave model (Table 1).

A detailed description of the TOPKAPI equations can be found in Liu and Todini [9]. An overview of the relationship between the equations is well explained by Vischel *et al.* [17]. The equation of mass continuity of each of the three reservoirs corresponding to cell i at time t can be written as a classical differential equation of continuity:

$$\frac{\mathrm{d}V_i}{\mathrm{d}t} = Q_i^{in} - Q_i^{out}, \tag{1}$$

where: V_i is the total volume stored in the reservoir; $\frac{\mathrm{d}V_i}{\mathrm{d}t}$ is the rate of change of water storage; Q_i^{in} is the total inflow rate to the reservoir; Q_i^{out} is the total outflow rate from the reservoir.

The kinematic wave approach used in TOPKAPI (by neglecting the acceleration terms in the St. Venant equation) leads to a nonlinear relationship between Q_i^{out} and V_i, transforming Eq. (1) into an ordinary differential equation:

$$\frac{\mathrm{d}V_i}{\mathrm{d}t} = Q_i^{in} - b_i V_i^{\alpha}, \tag{2}$$

where α and b_i are constants that depend on the characteristics and type of the reservoir.

The parameter values for a given watershed are extracted from the digital elevation model (topology, slope) soil map (permeability, soil depth) and landuse map (interception, roughness). A trial-and-error calibration based on observed streamflow data is needed for tuning the model to reproduce the behaviour of the catchment.

Since its parameters have physical meaning, TOPKAPI is equally suitable for modelling ungauged river basins, using the literature and existing thematic maps for deriving the parameter values.

Table 1

Kinematic wave formulation for the subsurface, overland, and channel flow

$$\frac{\partial\eta}{\partial t} = p - \frac{\partial q}{\partial x} = p - \frac{\partial\left(C\eta^{\alpha}\right)}{\partial x}$$	**Sub-surface flow** η – soil water content along the vertical profile [m]; x – width of the grid cell [m]; t – time [s]; q – flow in the soil due to drainage, corresponding to a discharge per unit of width [m^2/s]; p – precipitation intensity [m/s]. C – local conductivity coefficient, depending on soil parameters, hydraulic conductivity, slope, and storage capacity; α – soil-related parameter [5].
$$\begin{cases} \frac{\partial h_O}{\partial t} = r_O - \frac{\partial q_O}{\partial x} \\ q_O = \frac{\sqrt{\tan(\beta)}}{n_O} h_O^{5/3} = C_O h_O{}^{5/3} \end{cases}$$	**Overland flow** h_O – water depth above ground surface; t – time; r_O – saturation excess [m/s], q_O – overland flow [m^2/s]; n_O – Manning friction coefficient for the surface roughness [m$^{-1/3}$/s], $C_O = \frac{\sqrt{\tan\beta}}{n_O}$ is the coefficient relevant to the Manning formula for overland flow.
$$\begin{cases} \frac{\partial h_C}{\partial t} = r_C - \frac{\partial q_C}{\partial x} \\ q_C = \frac{\sqrt{s_0}}{n_C} h_C^{5/3} = C_C h_C{}^{5/3} \end{cases}$$	**Channel flow** h_C – water depth in the channel [m]; t – time; r_C – lateral drainage input reaching the channel, i.e., the overland runoff and the soil drainage [m/s]; q_C – channel flow [m^2/s]; s_0 – channel bed slope, assumed to be equal to the ground surface slope $\tan\beta$; n_C – Manning friction coefficients for the channel roughness [m$^{-1/3}$/s]; $C_C = \sqrt{s_0}/n_c$ – coefficient related to Manning's formula for channel flow.

3. LOCATION AND DATA

The upper river basin of Someşul Mare (Fig. 2) is located in the intra-Carpathic area, a region generally affected by low pressure systems coming from the North of the country [18]. It has a drainage area of 4328 km² and a mean altitude of 711 m, spanning a vertical range of almost 2000 m. The river network density derived from 1:100 000 map is 0.6 km/km² [19]. Long-term trend analyses found no significant changes in streamflow regime [20, 21] or in snowpack [22] within the catchment.

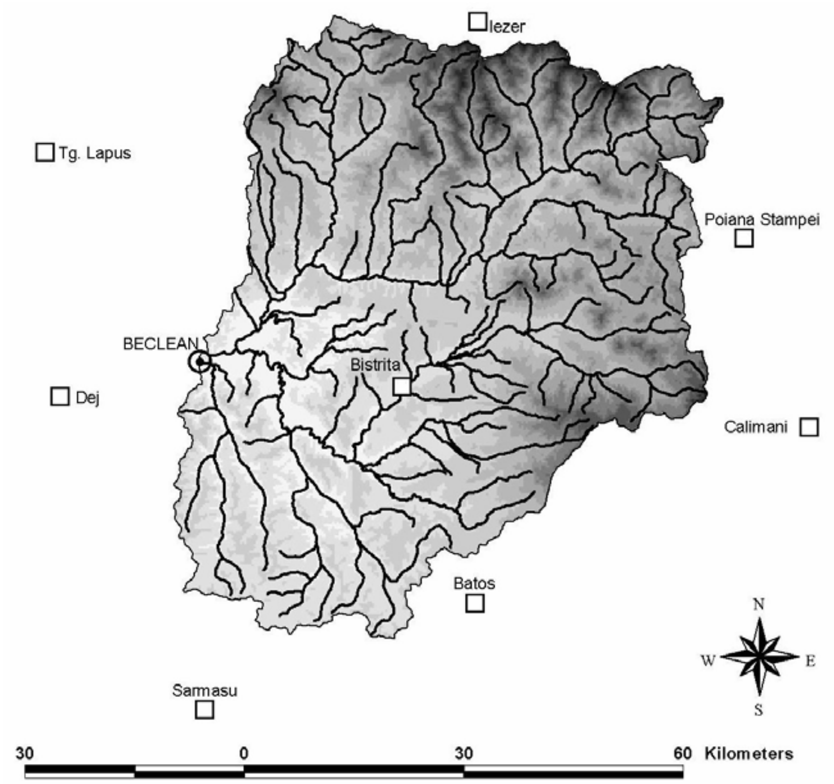
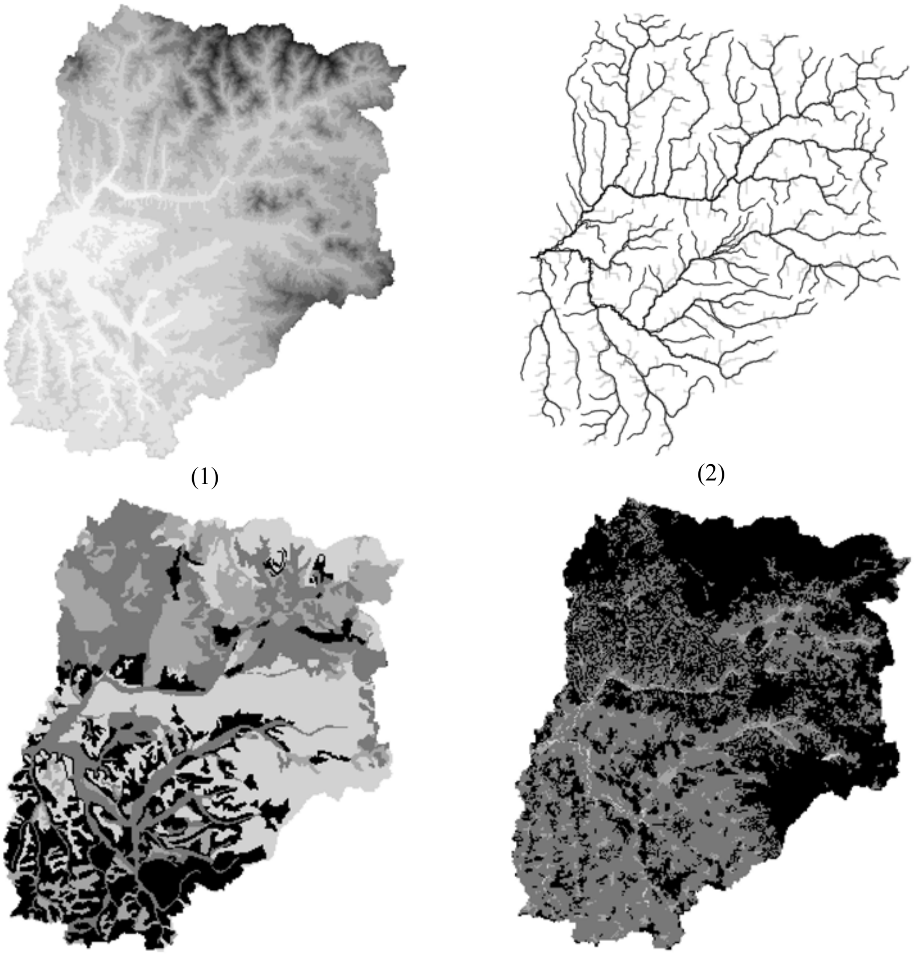


Fig. 2 – The upper basin of Someşul Mare. Location of the meteorological stations with precipitation and temperature time series, the river network and the outlet station Beclean.

The observed streamflow data for Beclean station (the basin exutory) has been provided by the National Institute of Hydrology and Water Management (INHGA) for the period 2000–2006.

For the same period, eight meteorological stations belonging to the National Meteorological Administration (Meteo Romania) with continuous record of precipitation and temperature data were used as input data.



(1) (2) (3) (4)

Fig. 3 – Input spatial data of the Someşul Mare river basin. (1) The digital elevation model (DEM); (2) Real and derived river networks; darker color indicates higher Strahler order; (3) Soil map: darker color indicates higher drainage potential; (4) Landuse map: darker color indicates higher surface roughness.

The river basin DEM (Fig. 3.1) was extracted from an improved SRTM [23]. The modelling size of the grid cell was fixed to 300 m. The extracted river network (determined by means of a threshold-based criteria) is shown in Fig. 3.2.

A reclassification of soil and landuse has been done in order to reflect the hydrological properties [24, 25] based on the US hydrologycal soil types [26].

From the digital soil map of Romania [27] the soil types were extracted and reclassified with respect to soil depth and texture / porosity (Fig. 3.3).

A similar procedure was made for the landuse layer, extracted from the Corine Land Cover 2000 product (CLC2000), published by the European

Environment Agency [28]. Landuse classes were regrouped taking into consideration their surface roughness and crop factors (Fig. 3.4).

4. RESULTS

The trial-and-error calibration – based on visually matching the modelled streamflow with the observed data series – managed to reproduce the behaviour of the catchment while keeping the parameters values physically meaningful. The class-related parameters involved in the calibration process were the soil depth, the saturated hydraulic conductivity, the residual and the saturated water content, and the surface roughness. Channel roughness coefficients were assigned for each stream order [29], using values from the literature [30, 31].

The model simulated well the behaviour of the streamflow, the peak time, the increase and the recession of the floods (Fig. 4). However, the small floods were generally overestimated.

The model was validated on the period 2003–2006 (Fig. 5). The rapid basin response, the recession and the timing of peak flows were also well reproduced. However, the low station density represents an issue especially for small events.

5. CONCLUSIONS AND FUTURE WORK

The spatially distributed rainfall-runoff model TOPKAPI has been applied on the upper river basin of Someşul Mare upstream Beclean (4328 km²). The model consists of five main modules representing the soil, the surface, the drainage network, the evaporation and the snow component. The first three are in the form of non-linear reservoir equations – which are structurally similar.

The model has been run for the 2000–2006 period: the first three years were used for calibration, the model being validated using the 2003–2006 data. The calibration was done visually, by matching the modelled streamflow with the observed one, in order to reproduce the behaviour of the catchment, while keeping the parameters within their natural values.

The model reproduced well the flood events, the peak time, the increase and the recession of the floods. Small floods were usually overestimated in terms of peak flow. But – considering the high spatial variability of the precipitation, and that only one station was located inside the catchment – the model performance was very good.

Future work shall explore multiple precipitation inputs and combinations (*i.e.*, pluviometers with various interpolation methods, radar and satelite data), a detailed calibration at sub-catchment scale, and a finer classification of the soil and landuse information.

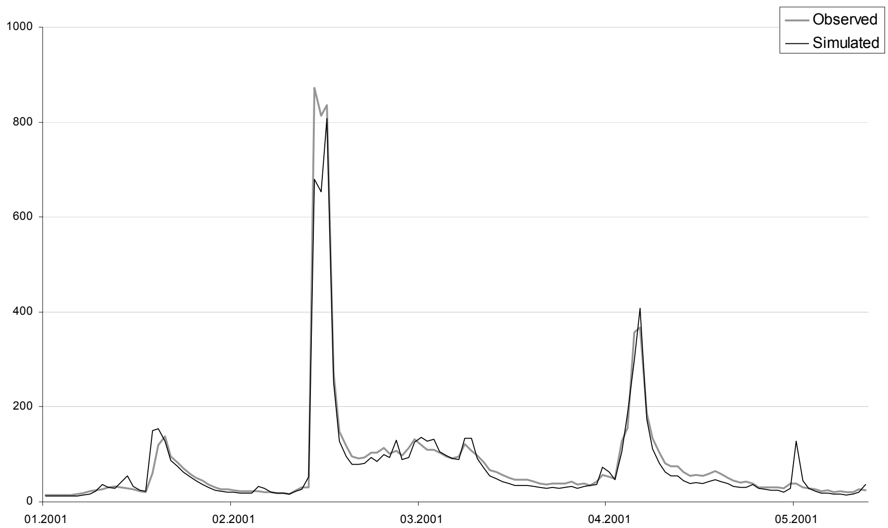


Fig. 4 – Calibration of the TOPKAPI model: simulated and observed streamflow at Beclean (m³/s) for the period Jan. May, 2001.

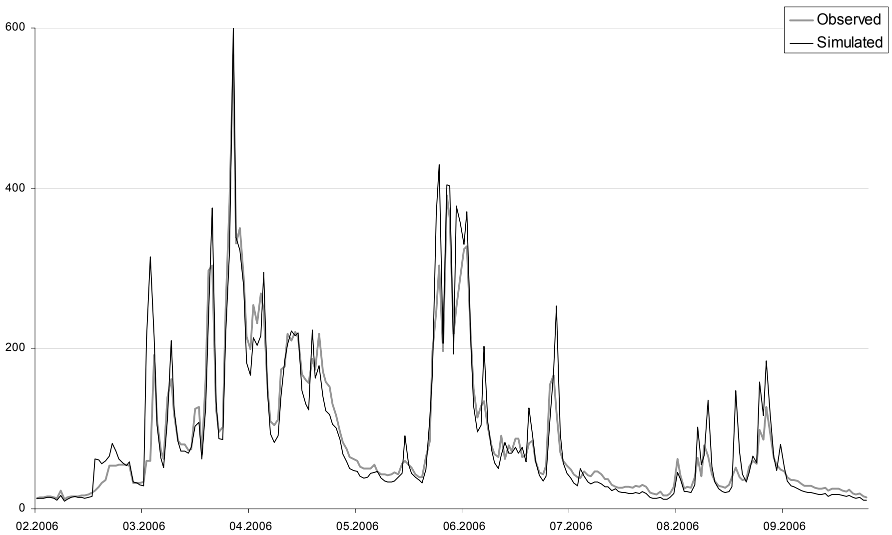


Fig. 5 – Validation of the TOPKAPI model: simulated and observed streamflow at Beclean(m³/s) for the period Feb. Sep, 2006.

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