Preliminary Assessment of a Unit Hydrograph-based Continuous Flow Simulation Model for Bulgarian Rivers

Daniela Zlatunova[a], **George Gergov**[b] **and Ian Littlewood**[c]

[a]*Sofia University, Faculty of Geology and Geography, Tzar Osvoboditel 15, Sofia 1504, Bulgaria (zlatunova@gea.uni-sofia.bg)*
[b]*National Institute of Meteorology and Hydrology, Blvd Tzarigradski 66, Sofia 1784 (g_gergov@internet-bg.net)*
[c]*Centre for Ecology and Hydrology, Wallingford, Oxon, OX10 8BB, United Kingdom (igl@ceh.ac.uk)*

Abstract: Rainfall-runoff models with only a small number of parameters and modest data needs are useful for assisting with regional surveys and the management of water resources. This paper makes a preliminary assessment of the suitability of a unit hydrograph-based modelling methodology for application to small and medium-sized rivers in south-east Europe. Hydrometeorological data (rainfall, streamflow and air temperature) for four catchments in Bulgaria having contrasting flow regimes are analyzed. Using a previously published model for a catchment in Wales as a reference point, the potential of the unit hydrograph approach for assisting with regional surveys and water resources management in Bulgaria is discussed. In principle, dominant quick and slow flow components of streamflow can be quantified in terms of their characteristic response decay times and relative mean volumetric contributions to streamflow. The paper discusses some aspects of uncertainty in the quick and slow response unit hydrographs. It is suggested that further research is required to establish the structure of a loss module (which precedes the unit hydrograph module) that better represents the hydroclimatological conditions in Bulgaria where, for many catchments, snow is an important component of the annual water balance.

Keywords: Bulgarian rivers; Unit hydrograph; Streamflow modelling.

1. INTRODUCTION

Precipitation-streamflow models that can make efficient use of data from regional and national monitoring networks play an important role in modern sustainable water resources management.

The modelling methodology of this type that is applied here is known as IHACRES (identification of unit hydrographs and component flows from rainfall, evaporation and streamflow data) and has been described in the literature [e.g. Jakeman *et al.*, 1990], so only brief details are given.

The only data required by IHACRES are concurrent time series of rainfall, streamflow and representative air temperature data. The model structure comprises two modules in series: an evaporation loss module to calculate effective rainfall; and a unit hydrograph module. Effective rainfall output from the loss module forms the input to the unit hydrograph module.

The concept of the unit hydrograph was introduced by Sherman [1932]. It assumes linearity between effective rainfall and the resultant streamflow response. The version of IHACRES applied in this paper [PC-IHACRES v1.02; Littlewood *et al.*, 1997; Littlewood, 2002] imposes this linearity such that effective rainfall input to the unit hydrograph module comprises the part of rainfall that eventually contributes to streamflow over the model calibration period. Hydrological processes of lower-order importance at catchment scale, such as depression storage and interception by vegetation, are not accommodated explicitly in PC-IHACRES v1.02.

The mathematical representation of the IHACRES unit hydrograph leads easily to quick flow (q) and slow flow (s) sub-unit hydrographs, each being completely defined by its exponential decay time constant ($\tau^{(q)}$ or $\tau^{(s)}$) and its relative average contribution to streamflow ($v^{(q)}$ or $v^{(s)}$) (i.e. there are just two parameters for each unit hydrograph). The IHACRES methodology also allows assessment of the uncertainties associated with the unit hydrograph parameters.

2. THE CATCHMENTS AND THEIR DATA

In this paper a preliminary assessment of PC-IHACRES v1.02 for conditions in south-east Europe is undertaken by applying it to four Bulgarian catchments, using a catchment in Wales for comparison. The IHACRES approach can assist with integrated water resources management, e.g. where shortages of water occur due to some climate change effect or strong anthropogenic impact. Both of these issues are important in Bulgaria but systematic application of a parametrically parsimonious model like IHACRES to Bulgarian hydrometric data has yet to be undertaken.

The quantity and the regime of precipitation in Bulgaria are strongly affected by Atlantic anticyclones and Mediterranean cyclones. Winter cyclones are usually associated with increases in temperature and precipitation. In Spring, Atlantic cyclones/anticyclones increase together with precipitation. Typically air temperature crosses 0°C several times during Winter, but mainly in January and February. Anticyclones are associated with rainfall in the Summer accompanied by a decrease in air temperature.

Some characteristics of many Bulgarian rivers are as follows:

- Snowmelt can account for 40-60% of annual runoff volume.
- The relief of upper catchments is dominated by steep mountain slopes.
- Due to infiltration and snow accumulation, the Spring flood period might last several months. In the Summer, flows can become very low.
- The hydrograph comprises many high peaks.The steep slopes of the catchment and river bed lead to a short time of travel of surface water and the rivers can exhibit flash floods, which can cause much damage and even loss of life. From a water resources point of view the Spring flood volume is not available for use later in the year unless large reservoirs are constructed.

Bearing these points in mind rainfall-runoff modelling for Bulgarian rivers has the following three goals:

- modelling the total amount of surface water formed during the Spring flood period
- modelling the peak flows throughout the year
- modelling the low flow regime.

Details of the catchments investigated in this paper, and their periods of record, are given in Tables 1 and 2. There may be longer records for some of the catchments but they were not readily available for this paper.

Table 1. Basic catchment details

River	Area (km^2)	Mean annual precipitation (mm)	Mean annual runoff (mm)	Mean % runoff
Eleshnitza	315	700	214	31
Vit	2236	630	248	39
Gospodareveska	387	630	110	18
Rosica	101	908	724	79
Teifi	894	1300	960	74

The Gospodarevska River is located in south-east Bulgaria and flows in a north-west direction, across the low land around the town of Bourgas, and then to the Black Sea (Figure 1). Snow cover is observed for 10-15 days in January. The Vit and Rosica River catchments are situated in the central

Table 2. Data availability

River	Site	Period of data available for analysis*
Eleshnitza	Vaksevo	1st January 1964 – 31st December 1988*
Vit	Turnane	1st January 1970 – 31st December 1979**
Gospodareveska	Svetlina	1st January 1960 – 31st December 1965**
Rosica	Valevcy	1st January 1970 – 31st December 1980**
Teifi	Glan Teifi	1st January 1961 –***

* Time series of daily precipitation and streamflow, and monthly air temperature, compiled by the second author (missing rainfall 1966, 1967 and 1972) and analyzed previously by Littlewood (2000).

** Unbroken (no gaps) time series of daily precipitation and streamflow, and monthly air temperature, compiled by the first author.

*** Time series of daily precipitation and streamflow, and monthly air temperature, compiled by the third author.

northern Bulgaria and they both spring from the Stara Planina mountain range. The relief of that area is very complex. The climate is modest continental type with Summer maxima of precipitation and severe cold Winters. The Elisnitza is situated in west Bulgaria with its headwaters on the border between Bulgaria and Macedonia.

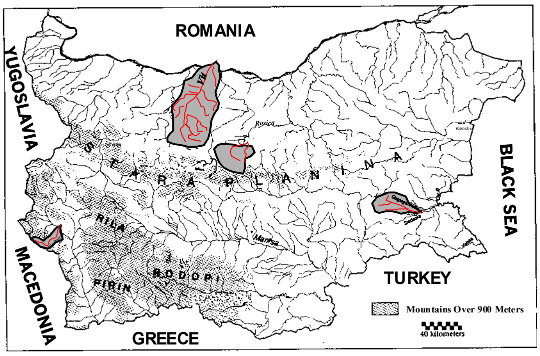

Figure 1. Locations of the catchments

3. MODELLING RESULTS

Finding a good model was not straightforward for any of the four Bulgarian catchments listed in Table 1. A provisional 'best' model is obtained in the IHACRES methodology by repeatedly calibrating the unit hydrograph module using different values of the loss module parameters (τ_w and f), searching for a good model-fit and good precision on the unit hydrograph parameters.

For each of the four Bulgarian catchments convergence of the unit hydrograph parameters was not well behaved. However, details of 'best' models for these four catchments are listed in Tables 3 and 4 (where results for the Teifi are included for comparison).

The first point that can be noted from Table 3 is that, in terms of a trade-off between the Nash-Sutcliffe efficiency, D, [Nash and Sutcliffe, 1970] and good precision on the unit hydrograph parameters (i.e. a low %ARPE), the model-fit for the Teifi is much better than that for any of the four Bulgarian catchments. The model-fit plots are shown in Figure 2.

The uncertainty in $\tau^{(q)}$ for the Teifi of -7.7%/+8.7% (Table 4) is smaller than for any of the Bulgarian catchments, whereas the uncertainties in $\tau^{(s)}$ for all five catchments are not too different from each other. The Eleshnitza at Vaksevo gives better results than the other three Bulgarian catchments.

Table 3 Model calibration details (1)

Catchment	f $^{o}C^{-1}$	τ_w days	D	Bias m^3s^{-1}	% ARPE
Eleshnitza[1]	3.2	4	0.745	-0.06	0.40
Vit[2]	2.4	10	0.699	-0.97	0.29
Gospod-areveska[3]	3.6	3	0.336	0.07	1.70
Rosica[4]	2.4	15	0.528	0.09	0.84
Teifi[5]	1.1	10	0.882	-0.07	0.03

Notes: Bias is the difference between mean observed and mean modelled flow
%ARPE: average relative parameter error (Jakeman *et al.*, 1990)
1. 30th September 1986 – 30th September 1988
2. 1st July 1972 – 4th October 1974
3. 12th August 1960 – 5th September 1962
4. 1st October 1973 – 4th October 1976
5. 26th July 1982 – 29th July 1985

Close inspection of the model-fit plots is not possible at the scale they are presented in Figure 2 but the effects of snow accumulation and snowmelt are common for the Bulgarian catchments. For example, Figure 3 is an expansion of the year 1973 for the River Vit in Fig. 2(b) and shows that, during February to April of that year, modelled streamflow exhibits peaks when precipitation (as snow) was measured but did not actually generate river flow peaks because the snow accumulated on the catchment.

Table 4 Model calibration details (2)

Catchment	$\tau^{(q)}$ days	$\tau^{(s)}$ days	$v^{(s)}$ x 100%	$P^{(s)}$ x 100%
Eleshnitza	4.32 (2.48, 9.80) *(-42, +127)*	28.9 (25.5, 42.3) *(-12, +46)*	85 [57, 92]	48 [24, 61]
Vit	2.76 (1.95, 4.05) *(-29, +47)*	20.6 (17.0, 31.8) *(-17, +54)*	69 [55, 78]	26 [14, 35]
Gospod-areveska	1.07 (0.65, 1.74) *(-39, +63)*	18.5 (14.7, 29.0) *(-21, +57)*	79 [70, 85]	25 [15, 34]
Rosica	0.935 (0.694, 1.23) *(-26, +31)*	10.9 (8.38, 17.3) *(-23, +59)*	63 [54, 69]	18 [11, 25]
Teifi	2.97 (2.74, 3.23) *(-7.7, +8.7)*	39.9 (30.8, 58.9) *(-23, +48)*	27 [23, 31]	3.1 [1.9, 4.4]

Notes: Uncertainty at the 95% confidence level: round brackets (.) indicate lower and upper confidence limits for $\tau^{(q)}$ and $\tau^{(s)}$; italicized round brackets *(.)* indicate confidence limits expressed as percentage difference from estimated $\tau^{(q)}$ and $\tau^{(s)}$; square brackets [.] indicate lower and upper confidence limits of $v^{(s)}$ and $P^{(s)}$ (as %)
$\tau^{(q)}$: decay time constant of the quick flow unit hydrograph
$\tau^{(s)}$: decay time constant of the quick flow unit hydrograph
$v^{(s)}$: mean percentage of modelled flow comprising slow flow
$P^{(s)}$: peak of the slow flow unit hydrograph (as % of total unit hydrograph peak)

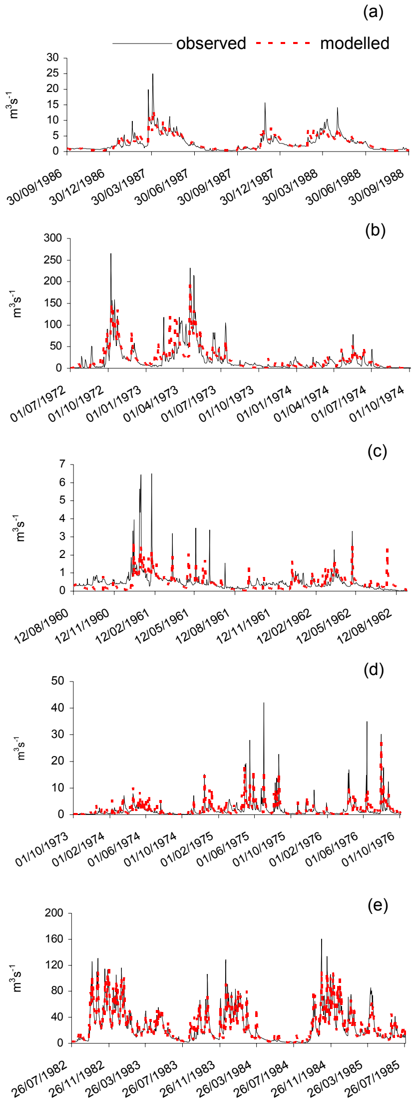

Figure 2. Calibration model-fits (a) Eleshnitza at Vaksevo, (b) Vit at Turnane, (c) Gospodareveska at Svetlina, (d) Rosica at Valevcy, (e) Teifi at Glan Teifi

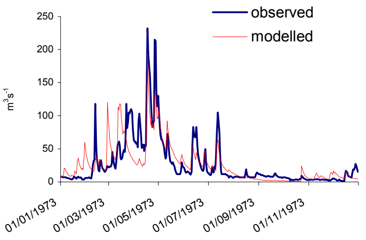

Figure 3. Vit at Turnane, 1973

Subsequently, when the snow melted, river flow peaks were recorded but the model did not respond because there was little (if any) precipitation. All four Bulgarian catchments are affected in this way to some extent, perhaps several times each winter.

Although snow affects the Teifi catchment in a similar way occasionally, most of the winter precipitation there usually falls as rain. Amongst the Bulgarian catchments the relatively good model-fit for the Eleshnitza at Vaksevo may be because the calibration period, 30th September 1986 to 30th September 1988, was not substantially affected by snow.

The model in PC-IHACRES v1.02 represents rainfall-streamflow dynamics and does not account for snow accumulation and snowmelt. It cannot be expected, therefore, to perform as well on Bulgarian catchments affected by snow as it does for the Teifi at Glan Teifi, which is largely unaffected by snow.

4. DISCUSSION

Regular hydrometric measurements in Bulgaria are made at 206 gauging stations. The average size of gauged catchments in Bulgaria is 539 km^2. Their distribution according to catchment area, mean altitude and period of record (some from 1920) has been documented by Gergov [1997].

The Eleshnitza catchment is dominated by its slow flow component whereas the much wetter Teifi catchment is dominated by its quick flow component [Littlewood, 2000]. It is interesting to compare the percentage uncertainties for $\tau^{(q)}$ and $\tau^{(s)}$ in Table 4. Much of the information in the Teifi flow record is in the form of quick flow responses to precipitation, making quantitative characterization of its slow flow relatively more difficult than for its quick flow. For the Eleshnitza River, much of the information in the flow record is in the form of slow flow responses to precipitation, and it is therefore the quick flow sub-unit hydrograph that is relatively more difficult to identify.

The model results are sensitive to the choice of the representative meteorological (rainfall) station. The search continues for alternative representative meteo-stations.

The Vit River catchment is famous for the widespread karst area and leakage of water from the basin. The peculiarities of this karst basin may explain some of the peaks in 1973. Water abstractions from the river amount to 1-3 m^3/s, which is negligible compared with the flow peak values of 120-210 m^3/s. The abstractions are important in Summer, during low flows, but not during the Spring flood period.

The results of the modelling for the Rosica are shown in Fig 2d. They reveal good co-ordination between the observed and modelled runoff for the period 1973-1976. The choice of the representative meteo-stations is successful and the model is effective and might have practical use.

5. CONCLUDING REMARKS

The paper has investigated the potential applicability of PC-IHACRES v.1.02 to four quite different Bulgarian catchments. Several factors that affect the quality of model-fit obtained using PC-IHACRES v1.02 have been either demonstrated or discussed.

Although PC-IHACRES v1.02 is applicable for Bulgarian catchments it is clear that the technique requires a good-quality time series of rainfall that is representative for the whole basin. A single raingauge is unlikely to provide such a record, especially if it is located outside the catchment. Further work is necessary to improve the Bulgarian hydrometric network for basic hydrological survey and modelling purposes, and to systematically collate the records from river flow measurement stations and raingauges to facilitate modelling using techniques like IHACRES.

Previous work [Schreider *et al.*, 1996, 1997; Steel *et al.*, 1999] has developed the IHACRES approach for application to snow-affected catchments in Australia and Scotland. Results presented and discussed in this paper show that similar work is required to develop IHACRES for application to Bulgarian catchments affected by snow accumulation and snowmelt.

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