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Comparison of Hydrologic Simulations using Regionalised and Catchment-Calibrated Parameter Sets for three Catchments in England

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Abstract: The objective of this study is to assess the performance of a regional hydrological model in catchments treated as ungauged. The Catchment Resources and Soil Hydrology (CRASH) model is a daily, catchment-scale, rainfall-runoff model that has been previously regionalised for England and Wales. In this paper, the regional CRASH is evaluated in three catchments located in East Anglia – eastern England - and it is compared to the catchment-specifically calibrated CRASH. The results demonstrate that the performance criteria are met in the three catchments for both the Nash-Sutcliffe (R^2) and the percent bias efficiency indexes. The R^2 results of the regional CRASH in the three catchments (0.70, 0.56 and 0.48) compare well with another study in one of the catchments using another hydrological model specifically calibrated and are within the range of results from other simulation studies in ungauged catchments in England, Australia, Canada and Norway. The degradation between the regional and the catchment specific models is only limited for all the efficiency indexes. Finally, the uncertainty analysis on the model parameters showed that there is a reasonable confidence in the regional model.

Keywords: Rainfall-runoff; assessment; ungauged; catchment-scale model.

1 introduction

The availability of reliable hydrological data is recognised to be a world-wide issue due to the costs and logistics involved in running extensive gauging networks, and because existing sets of data often include missing periods. For example, despite 1,100 river flow gauging stations in the UK, a large number of catchments are still without proper records of flow data. To address this global issue, the International Association of Hydrological Sciences (IAHS) launched the Predictions in Ungauged Basins (PUB) decadal initiative [Sivapalan *et al.*, 2003]. Ungauged basins are defined as catchments without adequate records of data in both data quantity and data quality or appropriate spatially and temporarily to the needs [Sivapalan *et al.*, 2003]. The work undertaken by Maréchal and Holman [2003, 2004] addresses one of the five PUB directions of work: objective 3 - to further develop methodologies for predictions in ungauged basins and for minimising uncertainty [Sivapalan *et al.*, 2003]. The aim was to develop a conceptual, continuous, daily, semi distributed catchment-scale rainfall-runoff model to be used in ungauged catchments. The modelling approach can be regarded as following the top-down methodology because the Catchment Resources And Soil Hydrology (CRASH) model was developed after the main factors affecting the hydrological response at the catchment scale were identified [Maréchal and Holman, 2003]. A regional parameter set for England and Wales has been derived from the calibration of CRASH for 32 mid-size catchments [Maréchal and Holman, 2003]. The aim of this paper is to assess the performance of the regional CRASH in three catchments, not used for the derivation of the regional parameter set, located in East Anglia (eastern England). The assessment of CRASH comprises a multi-criteria evaluation of the performance and an analysis of the effect of the uncertainty in the regional model parameters [Wagener, 2003].

2 Model

The CRASH model [Maréchal and Holman, 2003] was developed from the assumption that the transformation of rainfall into river flow at the catchment scale is driven by soil and land use properties. It was designed to be used solely with existing datasets of soil and land use. CRASH uses the Hydrology of Soil Type (HOST) system [Boorman et al., 1995], a conceptual representation of the hydrological processes in UK soils. It defines the hydrological behaviour of soils in terms of their influence on river flow at the catchment scale and gives a classification of all the soil types of the United Kingdom into 29 conceptual response models (or classes).

CRASH structures a catchment using four types of objects: the response units where the production of flow is predicted, and three routing objects: the sub-catchments, the rivers and the reservoirs. It also includes surface water discharge and surface and ground water abstraction.

The response units are defined within each sub-catchment as cells with homogeneous hydrological behaviour based upon a combination of soil type, land use and weather. Response units are composed of soil water and groundwater stores. They have a single hydrological input: precipitation and four hydrological outputs: actual evapotranspiration, runoff, intermediate flow and base flow. Actual evapotranspiration depends on climate, plant growth stage and soil moisture conditions. Both saturation and infiltration excess runoff processes are explicitly taken into account for the production of surface runoff. The surface depression store must be full before any excess surface runoff can be released from the response unit. The intermediate and base flows are proportional to the soil water store and ground water store contents, respectively.

CRASH has three parameters needing calibration for each HOST class, one for each flow path: surface runoff, intermediate flow and base flow. Results from response units of similar soil hydrological behaviour (or HOST class) are grouped together so that the model parameters are calibrated for each HOST class.

The sub-catchments, rivers and reservoirs are routing objects to transfer the flows to sub-catchment and catchment outlets using respectively the unit hydrograph method, the Muskingum-Cunge method [Cunge, 1969] and the reservoir routing routine from Chow [Chow et al., 1988].

The model requires several types of input data: the spatial distribution of soil and land use data for the definition and parameterisation of the response units; daily weather data; catchment physical properties or descriptors for the parameterisation of the unit hydrograph at the sub-catchment scale; river and reservoir characteristics for the flow routing, surface water discharge and surface and ground water abstraction data.

3 Catchments

The Bure, Wensum and Tud catchments are located in East Anglia (eastern England) (Figure 1) and drain areas of respectively 342, 501 and 88 km^2. They are flat and low-lying with altitude ranging from a few meters to 115 meters above sea level. The climate is relatively dry with annual average precipitation and potential evapotranspiration of 670 mm and 490 mm between 1979 and 1983, respectively. Despite an excess of precipitation over potential evapotranspiration of 180 mm, water resources are under significant stress during the summer months, when intensive farming practices require a significant amount of irrigation due to evaporation exceeding precipitation. Arable lands cover 80% of the three catchments where the main crops cultivated are cereals and irrigated potatoes and sugar beet. There are two major surface water intakes for public water supply in the Wensum catchment, and one sewage treatment work in each of the Wensum and Bure catchments.

The area is covered by the Chalky Boulder Clay in the Tud, Wensum and the upper part of the Bure catchments and by the North Sea Drift in the middle and lower parts of the Bure catchment [Soil Survey of England and Wales, 1984]. Soils in the Chalky Boulder Clay typically have a slowly permeable subsoil and are seasonally waterlogged. These soils belong to HOST classes 18 and 24 [Boorman *et al.*, 1995] and are characterised by likely surface runoff and seasonal saturated subsurface flows. On the other hand, soils developed in the North Sea Drift are sandy with permeable surface and subsurface layers [Soil Survey of England and Wales, 1984]. They are well drained and are not affected by ground water. These soils typically belong to HOST class 5. The spatial distribution of the HOST classes is presented on Figure 1.

The groundwater catchment for the Tud is smaller than the surface water one [Centre for Ecology and Hydrology, 2003]. The Tud catchment has therefore a tendency to lose water to its neighbour catchments among which is the Wensum. However, the effects of this transfer of water are smaller on the Wensum than on the Tud catchment due to the difference in surface area.

Abstraction licences were used to estimate the water abstraction from both surface and ground water for public water supply. It was assumed that the ratio between actual abstraction and licenced volumes was 80% [Anglian Water - *pers. comm.*]. The water demand for spray irrigation was estimated following the method of Knox *et al*. [1996] with a ratio between surface and ground water based on the spray irrigation licences. No specific data for industrial uses were available, it was therefore assumed that the percentage of licensed abstraction for industrial purposes over total licensed abstraction was constant for the three catchments. This percentage was taken as equal to the regional value for the Norfolk region. Finally, effluent return flows from the two sewage treatment works were used to account for the discharges into the rivers Bure and Wensum.

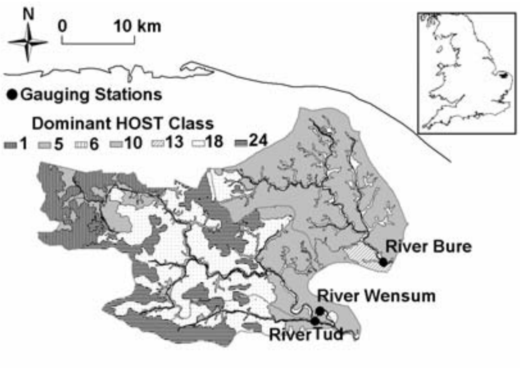

Figure 1. Location of the study catchments and their dominant HOST classes [Boorman *et al*., 1995].

4 REGIONAL MODEL

CRASH has been regionalised for England and Wales [Maréchal and Holman, 2004]. Firstly, it was calibrated individually for 32 catchments covering a wide range of climatic, topographic, soil and land use conditions in England and Wales. Secondly, a single, or regional, parameter set was defined from the results of the catchment-specific calibrations.

5 CATCHMENT SPECIFIC MODEL

CRASH has been calibrated specifically for the three catchments for the period 1979-1983 by optimising the multi-objective function (MOF):

$$MOF(\theta) = R^2(\theta) - FMOF(\theta) \tag{1}$$

where θ is a set of model parameters, R^2 the Nash-Sutcliffe efficiency index and FMOF the fuzzy multi-objective function defined by Yu and Yang [2000]. The most sensitive parameters of the four main HOST classes in the catchments are presented on Figure 2. The effect of the transfer of ground water from the Tud catchment has an influence on the base flow parameters and especially on the base flow parameter of HOST classes 5. Consequently, the parameter's value is significantly lower in the Tud catchment than in the regional parameter set (Figure 2).

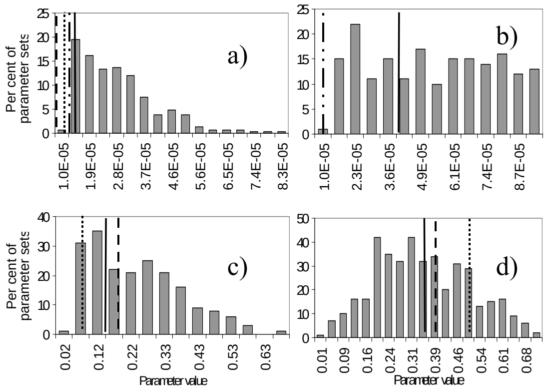

Figure 2. Model parameters for the catchments Bure (— · · ·), Tud (– – –) and Wensum (·······) and the regional model (——) with their uncertainty percentage distribution; a) base flow HOST class 5, b) base flow HOST class 6, c) intermediate flow HOST 18, d) intermediate flow HOST 24

6 RESULTS

6.1 Multi-criteria evaluation

Daily hydrographs are presented in Figures 3 to 5, and the results for the R^2, FMOF and PBIAS efficiency indexes are summarised in Table 1, where the percent bias PBIAS is defined as:

$$PBIAS = \frac{\sum_j \left(Obs_j - Sim_j\right)}{\sum_j Obs_j} * 100\% \tag{2}$$

with *Sim* and *Obs* the simulated and observed river flows and *j* the time step indice.

Table 1: Model performances for R^2, PBIAS and FMOF

Catchment		R^2	PBIAS (%)	FMOF
Bure	Specific	0.63	-2.5	0.30
	Regional	0.56	-2.3	0.32
Tud	Specific	0.58	18.4	0.55
	Regional	0.48	36.6	0.62
Wensum	Specific	0.71	0.1	0.21
	Regional	0.70	0.7	0.25

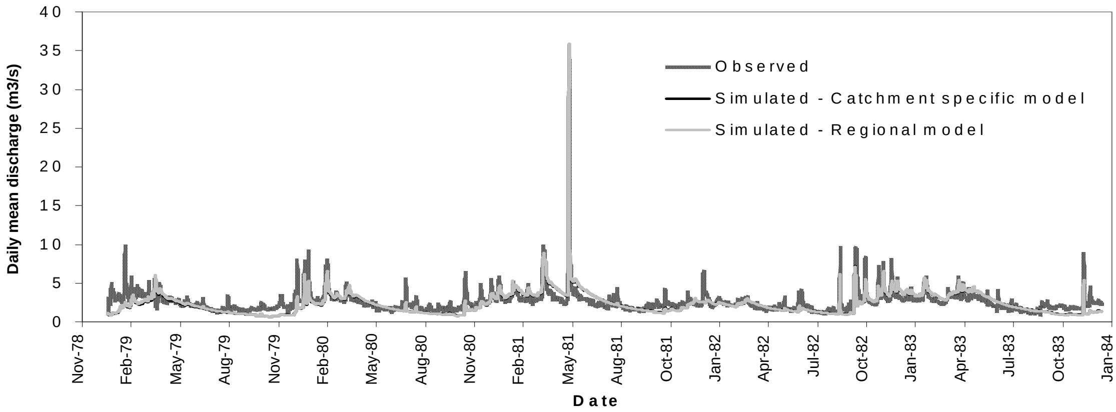

Figure 3. Daily results – Bure

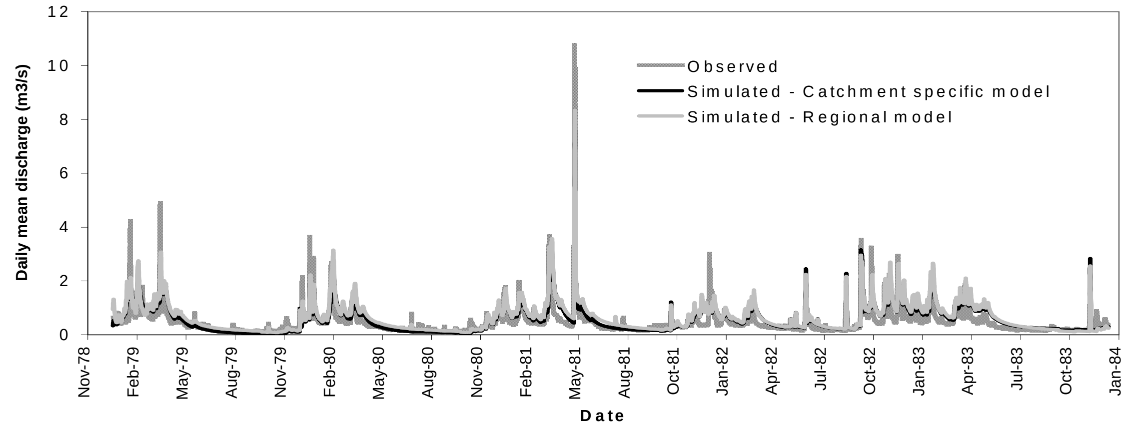

Figure 4. Daily results – Tud

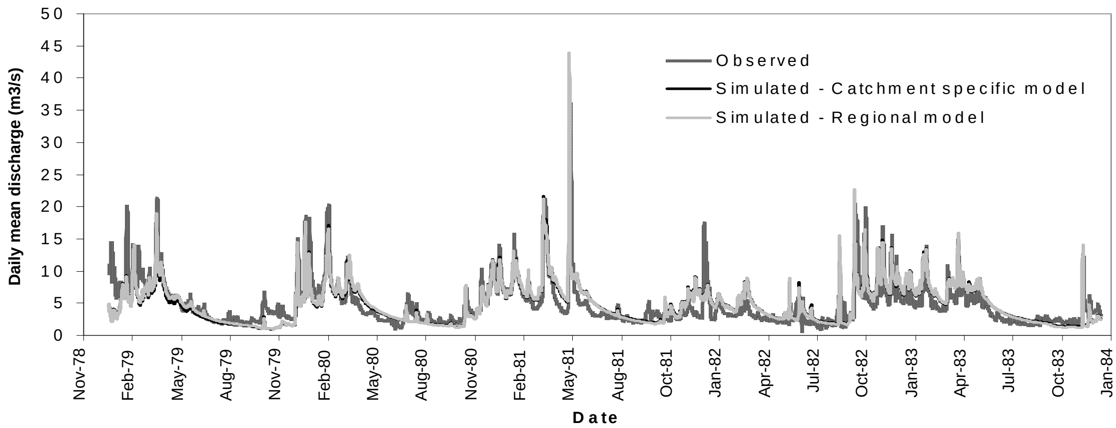

Figure 5. Daily results – Wensum

Table 2: Performance intervals

Efficiency index	Excellent	Very good	Good	Poor
R^2	>0.65	0.5-0.65	0.2-0.5	<0.2
│PBIAS│(%)	<10	10-20	20-40	>40

The results reveal that the general performance of the regional CRASH is slightly better in the Bure and Wensum catchments than in the Tud catchment

According to the scoring system proposed by Maréchal and Holman [2004] in ungauged catchments (Table 2), the regional CRASH performance is excellent in the Wensum catchment and very good and good in respectively the Bure and Tud catchments for the R^2 index. It is excellent in the Wensum and Bure catchments and good in the Tud catchment for the PBIAS index.

6.2 Multi-study comparison

The regional CRASH performs better than the Soil Water and Assessment Tool (SWAT) model [Arnold *et al.*, 1998] in the Wensum catchment, albeit for part of the 1990s. The R^2 index of the specifically calibrated SWAT model is 0.38 against 0.70 for CRASH [N. Kannan – *pers. comm.*].

The results for the three catchments are also within the range of values presented in other studies carried out in a wide variety of climates. Post and Jakeman [1999] tested their approach on 16 catchments in Australia by cross-evaluating the relations between physical catchment descriptors (PCDs) and dynamic response characteristics (DRCs) derived from the 15 other catchments. Their R^2 results ranged from 0.71 to -1.53 with an average of 0.37. Sefton and Howarth [1998] obtained R^2 of 0.61 and 0.53 for two catchments in England by applying PCDs-DRCs relations derived in other catchments. Van der Linden and Woo [2003] obtained R^2 results from 0.6 to 0.8 when they applied the parameters derived in a subarctic catchment in Canada to three catchments of similar size and characteristics. Beldring et al. [2003] derived model parameter values for 5 land use classes from the calibration of a distributed version of the HBV model in 141 catchments in Norway. R^2 was above 0.5 in 60% of the 43 independent catchments where these parameter values were used.

6.3 Regional vs catchment specific CRASH

There is only a limited deterioration in performance from the catchment specific and regional CRASH in the three catchments. The results stay in the excellent and very good categories for the Wensum and Bure catchments for R^2 and PBIAS, and change from very good to good for the Tud catchment.

The main deterioration experienced is for the Tud catchment (Table 1) where PBIAS increases from 18% to 37%. This overestimation of the flows is the consequence of the transfer of groundwater from the Tud to its neighbour catchments as illustrated by the difference between the catchment specific and regional base flow coefficient of HOST class 5.

6.4 Uncertainty on the model parameters

The posterior distributions of the model parameters from the calibration procedure of the regional model [Maréchal and Holman, 2004] were used to define the uncertainty bounds of the model parameters. The choice of the limit between a behavioural and a non-behavioural model is always a subjective choice [Beven and Freer, 2001] and it was decided to select the best 200 parameter sets for each HOST class. The distributions of the four most sensitive parameters are presented in Figure 2.

The model was run for 500 sets of parameters. The results for the three efficiency indexes are presented in Figure 6. There is a relatively good confidence in the regional model as it performs better, in terms of R^2, than 95% of the behavioural models in the Bure and Wensum catchments. The largest uncertainty for the R^2 efficiency index is in the Bure catchment where 90% of the R^2 results are between 0.55 and 0.05. There is only a limited influence of the parameters uncertainty on the PBIAS index. Finally, the variations of FMOF due to the parameters uncertainty are mainly the consequence of variations in the prediction of low flows.

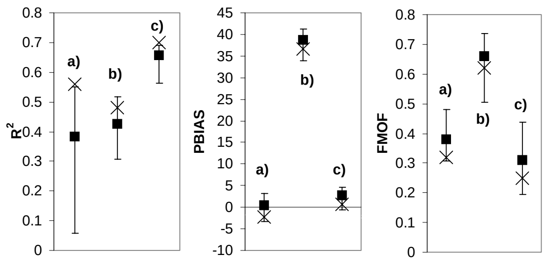

Figure 6: Uncertainty analysis. X regional model, ■ median result from the uncertainty simulations with its 90% probability limits for the a) Bure, b) Tud and c) Wensum catchments.

7 CONCLUSION

The aim of this paper was to independently evaluate the performance of a regional daily hydrological model for England and Wales in three catchments located in the East of England.

The overall performance of the regional CRASH is satisfactory as it meets the performance criteria in the three catchments for both the Nash and Sutcliffe (R^2) and the percent bias (PBIAS) indexes despite an over-prediction of the river flows in the Tud catchment. The R^2 results range between 0.70 and 0.48.

The results from the uncertainty analysis on the model parameters showed that there is a reasonable confidence in the regional model as it performed better than 95% of the 500 behavioural models in two catchments for R^2. The uncertainty in regional model parameters showed limited influence on the PBIAS index.

The deterioration between the regional and the catchment specific models is only slight in the two catchments where the model performs the best. It is more significant for the Tud where the catchment specific base flow parameters are influenced by the transfer of ground water to its neighbour catchments.

Finally, the R^2 results have been compared to results from similar studies in different climates and they are within the same range of values.

Therefore, it is found from the above-presented performances of the model that the modelling approach developed with CRASH gives promising results. It is especially noted that the incorporation of pre-existing knowledge, like the HOST soil classification, into new modelling tools has a valuable impact on simulating ungauged basins.

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