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David Maréchal

Ian P. Holman

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**David Maréchal and Ian P. Holman**

*Institute of Water and Environment, Cranfield University, UK.*
*(d.marechal.s00@cranfield.ac.uk)*

**Abstract:** A conceptual rainfall-runoff model, the Catchment Resources and Soil Hydrology (CRASH) model, designed for catchment management purposes, has been developed to compute continuous river flow at the catchment or river basin scale. Its input data requirements are limited to data normally existing in any catchment of potential interest. The mechanistic model is driven by soil, land use and weather data, and is parameterised according to the soil series types within the catchment. One model parameter related to runoff is derived from computed coefficients from the soil hydrological classification of the Hydrology Of Soil Types (HOST) system. HOST is a conceptual representation of the hydrological processes in the soil for which calibrated values of Base Flow Index and Standard Percentage Runoff have previously been computed. The three other parameters are calibrated for each HOST class. Due to the specification of the HOST system CRASH has been evaluated at first in the United Kingdom. It has initially been independently applied to medium size catchments with acceptable results. As a second step, the model has been tested with a common set of parameter values in two catchments of similar size and soil characteristics but with contrasting climate condition. The results are reasonable through the range of the flow duration curve and would tend to confirm that it is possible to derive unique model parameters for soils with similar hydrological behaviour. It is however necessary to test the model more widely to obtain a robust set of parameters that would allow the use of the model in ungauged catchments without catchment-specific calibration.

**Keywords:** model; rainfall-runoff; catchment scale; soil.

## 1. INTRODUCTION

Rainfall–runoff models can be used to investigate various hydrological issues relevant to environmental managers and decision–makers. Several modelling approaches are available for the continuous prediction of stream flow.

The approach chosen can be influenced by the availability of input and parameterisation data, particularly if it becomes necessary to extend existing data temporally and/or spatially, and by the representativeness of the processes [Beven, 2000]. Physically based models such as the SHE model [Abbott et al., 1986] describe hydrological processes in a detailed manner. However their use has been questioned because of the actual significance of the parameters and the great amount of physical characteristics they require [Beven, 1989]. Conceptual models represent only the main component processes of importance. They are simpler and the parameters are generally optimised using observed streamflow data. They can be utilised for ungauged catchments by relating the model parameters to physical descriptors of the catchments [e.g. Schmidt et al., 2000; Seibert, 1999]. However, conceptual models calibrated without restriction on parameters can be over-parameterised and several parameter sets can be equally satisfactory. In order to make up for this limitation, the calibration can be done using the rule-based approach or the clustering of areas with similar dominant hydrological processes [Peschke et al., 1999]. Dunn and Lilly [2001] showed that it was possible to determine model parameters according to a soil hydrological classification but failed to adequately calibrate the fast response.

A simple conceptual model using the Hydrology Of Soil Types (HOST) system [Boorman *et al*, 1995] is presented in this paper. The Catchment Resources and Soil Hydrology (CRASH) model is a catchment scale model for predicting daily

river flows that requires only the distribution of soil, land use and weather data.

## 2. MODEL DESCRIPTION

The CRASH model is a catchment-scale daily time step, rainfall-runoff model designed for use with minimum existing data sets, but primarily driven by soil properties, climate and land use data. The structure of the CRASH model is outlined in Figure 1.

CRASH runs for cells of each soil series/land use combination and the simulation results for all cells of similar soil hydrological behaviour (or HOST class) are grouped together so that the unknown parameters are calibrated for each HOST class.

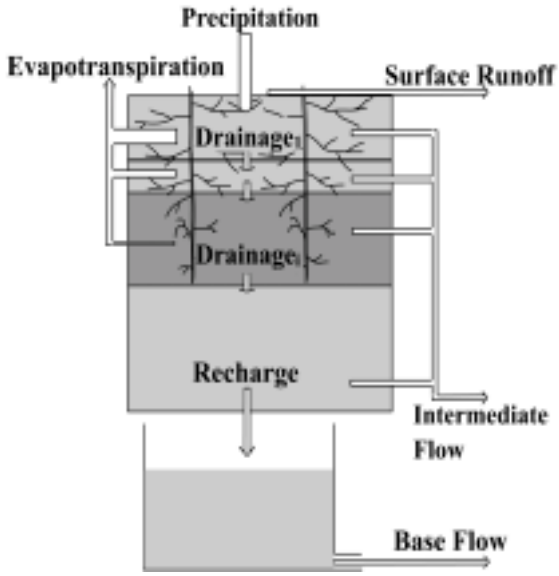


**Figure 1:** CRASH Model Structure

The symbols used in the equations in the following sections are described in section 7.

### 2.1 Soil water balance model

A soil water balance computes the movement of water through each soil layer using soil series data (horizon thickness, water content at several suction pressures, saturated hydraulic conductivity) to the groundwater store, and allows temporary perched water tables within the soil profile.

The mass balance of layer *i* is expressed as:

$$\Delta\theta_i = D_{i-1} - D_i - AET_i - IF_i \quad (1)$$

Or for, respectively, the top and bottom horizons:

$$\Delta\theta_1 = I - D_1 - AET_1 - IF_1 \quad (1')$$

$$\Delta\theta_n = D_{n-1} - Re - AET_n - IF_n \quad (1'')$$

#### 2.1.1 Drainage and recharge

Drainage occurs only from horizons where the water content is above field capacity. In that case, the water movement from the layer *i* the layer *i+1* is derived using Evans et al. [1999].

$$D_i = Min(K_i^{sat}, K_{i+1}^{sat}, \frac{\theta_i - \theta_i^{FC}}{\Delta T}, \frac{\theta_{i+1}^{Sat} - \theta_{i+1}}{\Delta T}) \quad (2)$$

In a similar way, the recharge to the groundwater store is computed (3) if the water content of the bottom horizon is above field capacity:

$$Re = Min(K_n^{Sat}, LBK, \frac{\theta_n - \theta_n^{FC}}{\Delta T}) \quad (3)$$

LBK parameterises the parent material and values were proposed for each HOST class by Evans et al. [1999].

### 2.2 River flow

The predicted river flow is composed of the contributions of intermediate flow from the soil water store, base flow from the groundwater store and surface runoff (infiltration excess and saturation excess) for each area of soil type/land use combination within the catchment.

#### 2.2.1 Intermediate and base flows

The intermediate and base flows are proportional to the water contents within each horizon and the groundwater store respectively:

$$IF = \sum_i IF_i \quad (4)$$

where:

$$IF_i = Max\{(\theta_i - \theta_i^{FC}) * IFK; 0.0\} \quad (5)$$

$$BF = GWSC * BFK \quad (6)$$

The groundwater store fluctuates according to the variations in recharge and base flow.

$$GWSC_t = GWSC_{t-1} + Re - BF \quad (7)$$

The parameters *IFK* and *BFK* are derived by calibration.

#### 2.2.2 Surface runoff

Surface runoff from each soil type can be either saturation excess flow or Hortonian flow, if the

rainfall intensity exceeds the top horizon saturated hydraulic conductivity. The different cases are summarised below:

Case1 $\theta_1 = \theta_1^{sat}$ :

$$I = D_1 \quad (8)$$

$$Ru = R - I \quad (9)$$

Case2 $\theta_1 < \theta_1^{sat}$ :

Case2.1: $R < Ks$

$$I = R \quad (10)$$

$$Ru = 0 \quad (11)$$

Case2.2: $R > Ks$

$$Ru = R - I \quad (12)$$

In the Case 2.2, infiltration is computed with the Philip's equation [Philip, 1957], in which the infiltration after ponding for the one directional Richard's equation for a homogeneous medium can be expressed as:

$$I_{ap} = \sum_j \phi_j T_{ap}^{\frac{j}{2}} \quad (13)$$

If equation (13) is limited to its first two terms [Chong, 1983], the total infiltration becomes:

$$I = R * T_p + A(T - T_p) + S\left[\sqrt{T - \frac{S^2}{4A\left(\frac{R^2}{A} - R\right)}} - \sqrt{T_p - \frac{S^2}{4A\left(\frac{R^2}{A} - R\right)}}\right] \quad (14)$$

with [Kutilek, 1980]:

$$T_p = S^2 \frac{1 - \frac{A}{2R}}{2R^2\left(1 - \frac{A}{R}\right)^2} \quad (15)$$

and the sorptivity $S = B\sqrt{\theta^{Sat} - \theta^{Ini}}$ (16).

The calibration of the parameter *B* in the equation (16) is achieved by applying the Hydrology Of Soil Types (HOST). HOST is a conceptual representation of the hydrological processes in the soil. All soil series from United Kingdom have been grouped into one of the 29 response models (or classes) for which calibrated values of Base Flow Index (BFI) and Standard Percentage Runoff (SPR) have been computed [Boorman *et al*, 1995]. BFI is the long-term average proportion of flow that comes from stored sources and SPR is the "percentage of rainfall that causes the short-term increase in flow seen at the catchment outlet" [Boorman *et al*, 1995]. BFI holds long-term averaged information while SPR is dynamic and depends upon antecedent soil moisture conditions.

In the HOST system, the response runoff *RRu* for a soil at field capacity is expressed as:

$$RRu = SPR * R \quad (17)$$

*RRu* is defined as the volume of fast flow during a period of 5*LAG.

In CRASH, *RRu* is the sum of the surface runoff and the intermediate flow. The parameter *B* is then determined by combining equations (4), (5), (12), (14) and (17).

The parameter *A* is the third parameter to be calibrated in the model.

### 2.3 Actual Evapotranspiration

The evapotranspiration is computed according to Allen [1998] as the potential evapotranspiration corrected by a crop coefficient and a water stress coefficient.

The water root uptake in the soil is calculated following the model from Jarvis [1989] and the development of the root zone is predicted following the empirical equation from Borg and Grimes [1986].

## 3. STUDY CATCHMENTS

Two study catchments with soils of similar HOST classes but contrasting climate conditions were selected. The Harraby Green catchment is located in the North-West of England and covers an area of 160 km$^2$. The annual average precipitation is 840 mm and the annual average flow at the catchment outlet is 430 mm. The Shotesham catchment is situated in the east of England. It has an area of 146 km$^2$, annual average precipitation of 630 mm and annual average river flow of 150 mm.

The main soil series in the two catchments and their HOST classes are listed in Table 1 in order of decreasing area.

**Table 1:** Soil Series in the study catchments

| **Shotesham** | | **Harraby Green** | |
|---|---|---|---|
| **Soil series name** | **HOST class** | **Soil series name** | **HOST class** |
| Beccles | 24 | Clifton | 24 |
| Ragdale | 24 | Wick | 5 |
| Burlingham | 18 | Newport | 5 |
| Wighill | 18 | Crannymoor | 5 |
| Wick | 5 | Claverley | 24 |
| Newport | 5 | Salwick | 18 |

The conceptual model of HOST class 24 is a slowly permeable soil which suffers prolonged seasonal saturation [Boorman *et al*, 1995]. Surface runoff is likely and there is little recharge to an underlying aquifer.

The HOST class 18 is similar to the class 24, but perched water tables occur for shorter periods. In HOST class 5, the soil is freely drained and the main flow component is recharge to an underlying aquifer. Surface runoff is occasional.

The Shotesham catchment is dominated by classes 24 and 18 with, respectively, 68% and 20% of the total area. Consequently, surface runoff has a major contribution to the hydrograph. Classes 24 and 5 both cover about 35% of the area of the Harraby Green catchment. Base flow is thus relatively more important in this catchment.

## 4. RESULTS

### 4.1 Independent simulations

The model has been independently calibrated and tested in the two catchments. The model requires calibration for three parameters per HOST class: *A*, *IFK* and *BFK*. CRASH is insensitive to changes in parameter *A* in the surface runoff equation (14). The values for the parameters *IFK* and *BFK* are summarised in Table 2 for the two catchments.

The *IFK* parameter is a measure of the drainage network density and of the distance the intermediate flow must travel laterally through the soils to the drainage network. It has not been found in the present simulation that this parameter was significantly different between HOST classes as all the classes, except 5 which is freely drained, may have a similar drainage density due to their seasonal waterlogging.

The *BFK* parameter defines the base flow recession of the hydrograph and is linked to hydrogeological characteristics. HOST class 5 has a macroporous, coarse aquifer. The storage is large and flow rates are rapid. Consequently, the *BFK* parameter for this class is significantly larger than for the other classes. The bottom of the soil profile is normally saturated for the classes 7 and 10. So that lateral subsoil flow is the main component and base flow is relatively low. The small value of the parameter for the classes 18 and 24 represents seepage from an underlying groundwater store into the surface water network through a low permeability layer. The difference in *BFK* for the class 24 between the two catchments is explained by the fact that Beccles and Ragdale soil series have an horizon with a very low hydraulic conductivity, leading to a lower *BFK* value for Shotesham than for Harraby Green.

**Table 2:** Model parameters for Shotesham (S) and Harraby Green (HG) - independent simulations

| HOST class | *IFK* | | *BFK* | |
|---|---|---|---|---|
| | S | HG | S | HG |
| 5 | 0.1 | 0.1 | 0.15 | 0.35 |
| 7 | | 0.1 | | 0.04 |
| 10 | | 0.1 | | 0.04 |
| 18 | 0.1 | 0.1 | 0.05 | 0.04 |
| 24 | 0.2 | 0.1 | 0.005 | 0.03 |

Daily hydrographs and the flow frequency duration curve of the observations and simulations are presented in the Figures 2 and 3 for 14 months of the Harraby Green catchment.

The model satisfactorily predicts low flows and winter runoff events, but appears to under-predict the contribution of base flow in winter and to over-predict summer runoff events. This suggests that in summer some of the surface runoff generated on certain soils re-infiltrates before reaching the surface water network.

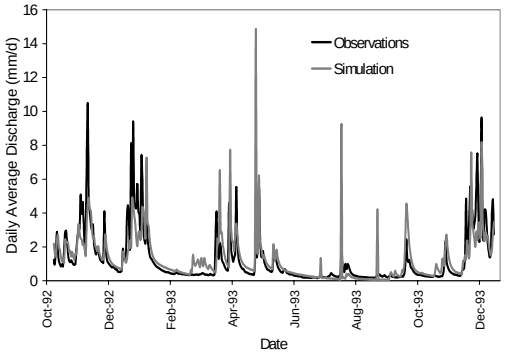


**Figure 2:** Daily hydrograph Harraby Green catchment – independent simulations

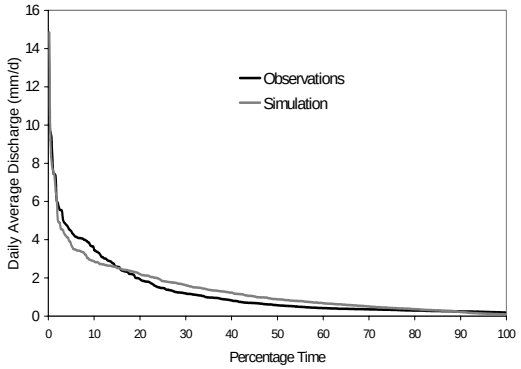


**Figure 3:** Flow duration curve Harraby Green catchment – independent simulations

### 4.2 Linked simulations

In the second set of simulations, CRASH has been applied to the two catchments using a single set of parameter values (Table 3).

**Table 3:** Model parameters – linked simulation

| HOST class | *IFK* | *BFK* |
|---|---|---|
| 5 | 0.1 | 0.35 |
| 7 | 0.1 | 0.04 |
| 10 | 0.1 | 0.04 |
| 18 | 0.1 | 0.04 |
| 24 | 0.15 | 0.012 |

The results for the simulations from Harraby Green (Figures 4 and 5) and from Shotesham (Figure 6) are shown.

Figures 5 and 6 show that CRASH captures the range of flow distributions from low flow through to high flows and that there is little deterioration in simulations (Figures 3 and 5) compared to using the catchment-specific calibration factors.

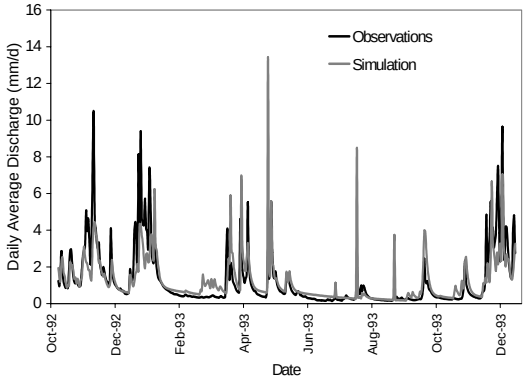


**Figure 4:** Daily hydrograph Harraby Green catchment – linked simulation

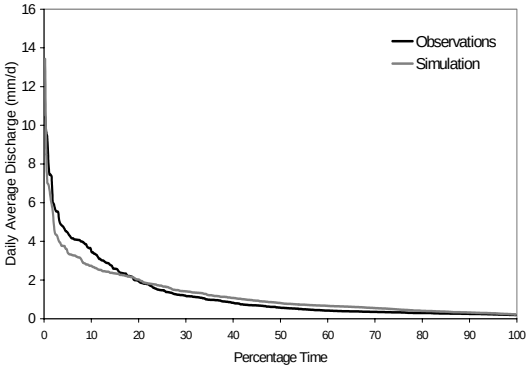


**Figure 5:** Flow duration curve Harraby Green catchment – linked simulation

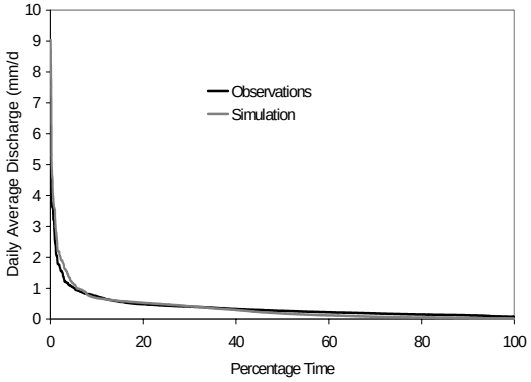


**Figure 6:** Flow duration curve Shotesham catchment – linked simulation

## 5. CONCLUSION

A simple conceptual catchment scale rainfall-runoff model with three unknown parameters has been presented and tested for two catchments in England. Although the CRASH model runs for cells of each soil series/land use combination, the simulation results for all cells of similar HOST class are grouped together so that the three unknown parameters are calibrated for each HOST class.

It has been shown that the model is fairly successful when applied and calibrated for a specific catchment. One of the three parameters was found to be insensitive and did not affect the model predictions. The parameter for the base flow could be related to the hydrogeological characteristics of each HOST class. Thus it has got a clear physical significance. The intermediate flow parameter represents the distance to the drainage network and was found to be similar for the soil classes examined.

It has also been demonstrated that a single set of parameters gives reasonable results across the flow ranges for two catchments with similar soil properties and contrasting climatic conditions.

The results show that a model with a simple structure and a limited number of parameters can be applicable for practical purposes. This also offers the promise that this modelling approach may provide a useful tool in ungauged catchments. However, further work is planned with additional catchments containing different soil properties to verify more widely whether the assumption that the model parameters can be defined according to the HOST classes is suitable.

## 6. ACKNOWLEDGEMENTS

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## 7. SYMBOLS

| | |
|---|---|
| $\theta_i$ | Volumetric water content of layer i ($cm^3/cm^3$) |
| $\theta^{Sat}$ | Volumetric water content at saturation ($cm^3/cm^3$) |
| $\theta^{FC}$ | Volumetric water content at field capacity ($cm^3/cm^3$) |
| $\theta^{Ini}$ | Initial volumetric water content ($cm^3/cm^3$) |
| $\Delta z$ | Layer thickness (mm) |
| $\Delta T$ | Time step = 1 day |
| *A* | Surface runoff Parameter |
| *AET* | Actual evapotranspiration (mm/d) |
| *B* | Surface runoff Parameter |
| *BF* | Base flow (mm/d) |
| *BFK* | Base flow coefficient ($d^{-1}$) |
| *D* | Drainage (mm/d) |
| $I_{ap}$ | Infiltration after ponding (mm) |
| *I* | Infiltration (mm/d) |
| *GWSC* | Groundwater store content (mm) |
| *i* | Layer indices, increasing downward. |
| *I* | Infiltration (mm/d) |
| *IF* | Intermediate flow (mm/d) |
| *IFK* | Intermediate flow coefficient ($d^{-1}$) |
| $K^{Sat}$ | Saturated hydraulic conductivity (mm/d) |
| *LAG* | Time delay between the centroid of rainfall and the centroid of flow peaks (d) |
| *LBK* | Lower boundary hydraulic conductivity (mm/d) |
| *n* | Indices of the bottom layer |
| *R* | Rainfall (mm/d) |
| *Re* | Recharge to groundwater store (mm/d) |
| *RRu* | Response runoff (mm) |
| *Ru* | Runoff (mm/d) |
| *S* | Sorptivity |
| *SPR* | Standard percentage runoff (%) |
| *t* | Time step (d) |
| *T* | Time (h) |
| $T_p$ | Time to ponding (h) |

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