A semi-distributed approach to rainfall-runoff modelling – aggregating responses from hydrologically similar areas

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Abstract: Hydrologists are often faced with the question, how human activities, e.g. a clear cut, may affect the hydrological behaviour of a catchment. This study presents a methodology that explicitly takes into account areas of variable characteristics within a catchment. The rainfall-runoff modelling technique is based on dividing a catchment into hydrologically similar units (HSUs), which aggregate areas of hydrologically similar behaviour. HSUs, which may have differences in e.g. land use, slope, soil, and vegetation, are characterised by typical cross-sections derived from the available data. The total runoff produced by the HSUs is routed through the channel network by using a linear reservoir. The parameters of the routing procedure, unlike the parameters connected to physical properties of the HSUs, are calibrated against flow data recorded at the basin outlet. A hydrological model which utilises the concept of HSUs is applied to a small forested catchment (0.18 km^2) in Siuntio, southern Finland. A conceptual rainfall-runoff model IHACRES is calibrated on the same set of data, which gives some basis to evaluate the performance of the proposed hydrological model.

1 INTRODUCTION

The construction and application of mathematical models relating meteorological forcing upon a catchment to the flow measured in the stream has been a major focus of surface water hydrology for decades. A plethora of models, which vary greatly in complexity, have been proposed in the literature to accomplish this task. According to Beck [1991], rainfall-runoff models may loosely be classified into three generic model types, which are 1) metric, 2) conceptual and 3) physics based.

Metric models are strongly observation oriented seeking to characterise system response by extracting information from the existing data, with little or no consideration of the structure of the hydrological system.

The idea behind conceptual models is to describe all the hydrological processes, which are perceived to be of importance, as simplified conceptualisations. This usually leads to a system of interconnected stores which are recharged and depleted by appropriate component processes of the hydrological cycle.

Physic-based models rely on concepts of classical continuum mechanics. The governing partial differential equations can be solved numerically by applying finite difference or finite element computation schemes.

Traditionally rainfall-runoff models have often been applied to problems related to water quantities only, such as real-time flood forecasting, and assessment of the reliability of natural water resources. But increasingly, outputs of such models are used to investigate wider environmental problems. These include water quality issues [e.g. Christophersen and Wright, 1981; Cosby et al., 1985a,b; Chapman et al., 1993], ecological and biological relations in water environment, and implementation of land-surface schemes for climate models [e.g. Kuhl and Miller, 1992; Wood et al., 1992].

Complex problems call for hydrological models, which can make a distinction between different water transport mechanisms within a catchment, and which account for spatial variability of terrain properties in the area of interest.

Incorporation of detailed process descriptions in the model structure, and allowance for small-scale spatial variability, easily result in overwhelming data requirements and poorly identifiable model parameters [Beven, 1989; Grayson et al., 1992].

The modelling scheme presented in this paper is one approach to characterising the distributed nature of catchment hydrological processes. The modelling is based on the subdivision of a catchment into hydrologically similar areas, which are identified using spatial data on terrain properties. The water balance in each area is calculated using a characteristic hillslope model, which relies on a physically consistent description of water movement. Runoffs from the characteristic hillslopes are combined with the aid of a streamflow routing procedure.

2 MODEL

2.1 General concept

The model consists of two parts. The first part describes the water balance at a hillslope scale, and the second part routes the water through the channel network to the basin outlet.

The idea is to use spatial data to objectively identify hydrologically similar areas, which have relatively homogeneous properties, such as slope, vegetation, soil type, and depth to the bedrock. Each of these areas, referred to as *hydrologically similar units* (HSU), is assigned with a water balance model called a *characteristic hillslope model*. The routing procedure combines the runoffs from the HSUs.

2.2 Characteristic hillslope model

A characteristic hillslope represents a typical water travel path from the water divide to the nearest stream channel (Fig 1).

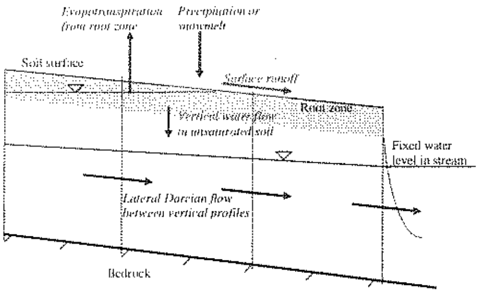

Figure 1. Characteristic hillslope, adopted from [Karvonen et al., 1999].

The unsaturated-saturated flow in soil-root system is described using the Richards' equation [Richards, 1931]

$$C(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left(K_z(h)\cdot\frac{\partial h}{\partial z}\right)-\frac{\partial K_z(h)}{\partial z}-S(h)-Q(h) \qquad (1)$$

where h is the soil water potential (m), $K_z(h)$ is the soil hydraulic conductivity (md^{-1}), z is distance from the surface (m), t is the time (d), and $C(h)$ is the differential water capacity. $S(h)$ represents the volume of water taken up by roots from a unit volume of soil in unit time (m^{3}m^{-3}d^{-1}), and $Q(h)$ accounts for the influence of additional sinks and sources.

Lateral flow is assumed to take place only in the saturated part of the soil profile. The hillslope is divided into vertical soil columns, and for each column the vertical soil water fluxes are computed from (1). Thereafter, the downslope water movement between the soil columns is derived by applying Darcy's law

$$q_{lat} = -K_S D\frac{dh}{dl} \qquad (2)$$

where q_{lat} is the horizontal flow between two columns (m^{2}d^{-1}), K_s is the saturated hydraulic conductivity (md^{-1}), D is the thickness of the saturated zone (m), and dh/dl is the water table gradient between two columns.

The characteristic hillslope model is quasi-two-dimensional, since the vertical and lateral water fluxes are computed separately. Vertical water fluxes in each column are solved first, followed by the computation of Darcian flow along the hillslope.

The model generates infiltration excess overland flow [Horton, 1933], if rainfall or snowmelt intensity exceeds the soil surface infiltration capacity. Saturation of the entire soil column results in overland flow generated by the Dunne mechanism [Dunne and Black, 1970]. Surface runoff is routed along the hillslope using the kinematic wave approximation of the St. Venant equations. The implementation is identical to the overland flow computation scheme of the SHE model [Abbott et al., 1986], except for that our model operates in one dimension only.

The snow accumulation and snowmelt module is based on the energy balance scheme. The reader is referred to Koivusalo et al. [1999] for further details.

More detailed description for the characteristic hillsope model can be found in Karvonen et al. [1999]. Their model implementation, however, differs slightly from the one presented here.

2.3 Channel network model

Karvonen et al. [1999] used the geomorphologic instantaneous unit hydrograph [Rodriquez-Iturbe and Valdes, 1979] to route the water through the channel network. In this paper a single linear store is used for this purpose.

3 CASE STUDY

3.1 Catchment and data

The Rudbäck study catchment (0.18 km^2) is situated in Siuntio, southern Finland (Fig 2).

Elevation ranges from 34 m to 65 m. Bedrock is exposed on the hill tops, and soils are composed of silty and sandy moraines. According to seismic refractions, the soil depth varies from 0 to 5 metres [Lepistö, 1994].

Climate is cold temperate and characterised by rainfalls of relatively low intensity. Mean annual precipitation (uncorrected) during 1991-96 was 700 mm, which includes 15-25 % of snowfall. Snowmelt dominates the annual maximum runoff.

Intensive monitoring programme has been running in Rudbäck since February 1998. Hourly micrometeorological and runoff data, and a digital elevation model (DEM) in 5 m x 5 m resolution are available from the study area. Koivusalo et al. [1999] present a more thorough discussion on data collection, data checks, and data processing.

3.2 Setting up the model

The determination of hydrological similarity within the catchment was based on topography. The whole area is forest covered, so there is no variability in the hydrological response arising from different land use types.

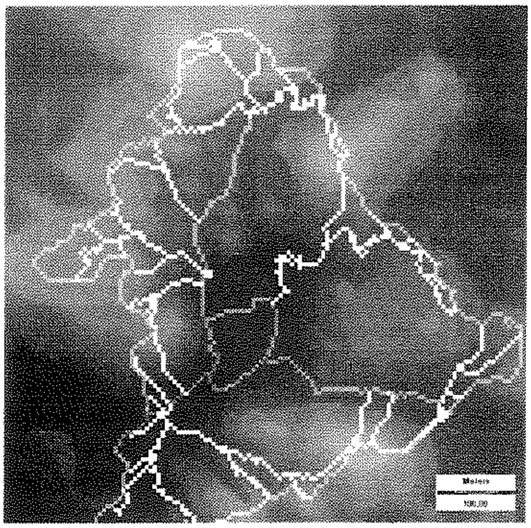

Figure 2. DEM, catchment border, channel network (gray), flowpaths from the water divide (white).

Channel network was constructed by combining mapped locations of drainage ditches and flow accumulation information derived from the DEM. Then all the flowpaths starting from the water divide and ending in a stream were computed. Only a small portion of the catchment was left out due to data problems in the DEM. Flow directions were computed using the Rho8 method of Fairfileld and Leymarie [1991]. Some of the flowpaths are presented in Figure 2.

Figure 3 shows the cross-sections of the flowpaths extracted from the elevation data. Three distinct groups were identified by looking at the geometry of the cross-sections.

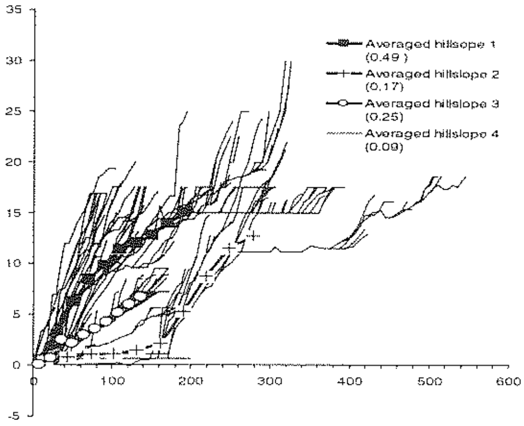

Figure 3. Hillslope shapes. The share of flowpaths belonging to each group is shown in parentheses.

A fourth group was formed from short flowpaths less than 60 metres in length. Within each group an average cross section was calculated to represent the entire group. The relative shares between the groups were obtained by comparing the number of flowpaths belonging to each group (Figure 3).

Other hillslope properties, such as the saturated hydraulic conductivity (0.62 m/h), the soil retention curves, Manning coefficient (0.2 sm$^{-1/3}$), and depth to the bedrock (0-1.5 m), were adopted from earlier studies [Koivusalo et al., 1998; and Jauhiainen and Nissinen, 1992], or fixed a priori using the best information available. They have not been calibrated against flow data.

3.3 Results

The model was applied to a period from June 1st 1998 to April 22nd 1999. The channel network submodel, i.e. the time constant of the linear store, was calibrated using data from June 1st 1998 to November 7th 1998. The remaining data were used to test model performance outside the calibration period.

Time series of observed and computed streamflows along with the modelling error are graphed in Figure 4 (calibration period) and Figure 5 (validation period).

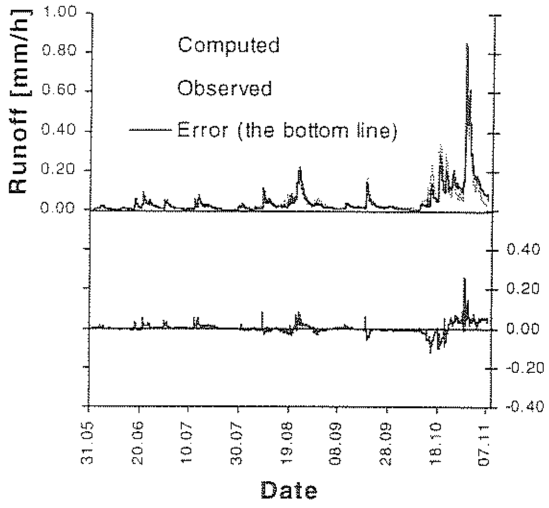

Figure 4. Modelled and observed runoffs in the calibration period.

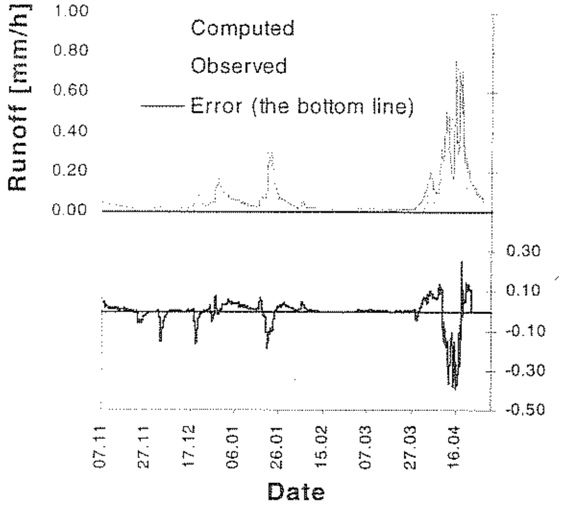

Figure 5. Modelled and observed runoffs in the validation period.

The modelling results were compared against the performance of a simple-structured conceptual rainfall-runoff model IHACRES, that was applied in the form it is presented in Ye et al. [1998]. This setup of IHACRES uses a four- parameter nonlinear filter to generate rainfall excess from precipitation and potential evapotranspiration data. Rainfall excess is defined to be the amount of rainfall which eventually appears in the stream. The output of the nonlinear filter is routed through a single linear reservoir, which adds one more parameter into the model structure. In winter periods IHACRES was driven with the same snowmelt time series that was used to drive the model presented here.

The two models had only little difference in their performances. The graphed streamflows for IHACRES are very similar to those shown in Figures 4 and 5, and therefore they are not presented here. Table 1 gives the coefficients of efficiency [Nash and Sutcliffe, 1970] for both models and both modelling periods.

Table 1. Coefficients of efficiency for the HSU-model and IHACRES.

	Calibration	Validation.
HSU	0.90	0.62
IHACRES	0.90	0.60

The modelling results indicate that when calibration is performed on snowless period, runoff peaks in wintertime are overpredicted. We believe that snow cover causes an additional delay to the hydrological system, which is not accounted for in either of the two models. This results in too sharp a model response during the winter.

In order to investigate the differences of hydrological behaviour between the four hillslopes, water balance components were computed separately for each hillslope (Table 2).

Table 2. Water balance components for each hillslope computed for the time period from February 16th, 1998, to April 25th, 1999.

	Hs1	Hs2	Hs3	Hs4
		[mm]		
Groundwater	23	45	8	231
Surface runoff	529	507	553	305
Actual evapotrans.	187	192	196	202
Change in storage	32	27	14	33
TOTAL	**771**	**771**	**771**	**771**

Except for the fourth hillslope, which represents all the short flowpaths, the hillsopes behave in a rather similar fashion. Water is predominantly transported to the nearest stream channel as an overland flow.

The hillslope model was also run with an alternative set of parameters. Their values were perturbed from the original fixed values, the most noticeable difference being the increase of the hydraulic conductivity from 0.62 m/d to 1.44 m/d. The water balance components of this model run are listed in Table 3.

Table 3. Water balance components for each hillslope computed with the alternative set of parameters.

	Hs1	Hs2	Hs3	Hs4
		[mm]		
Groundwater	186	267	61	427
Surface runoff	365	287	494	128
Actual evapotrans.	191	195	193	202

Change in storage	29	22	23	14
TOTAL	**771**	**771**	**771**	**771**

As expected, the portion of groundwater flow is much greater than in the water balances listed in Table 2. And unlike in the previous model run, there are considerable differences between the responses of all four hillslopes. The steep hillslopes one and two generate much more surface runoff than the flat hillslope number three.

4 DISCUSSION AND CONCLUSIONS

The results of the case study revealed no significant difference in performance between the two very different modelling approaches. If the only objective is to reproduce a streamflow time series from meteorological data, the simple conceptual model is preferable due to ease of its operation. The motivation behind the more laborious and data intensive semi-distributed modelling approach is to explicitly take into account areas of variable characteristics within a catchment. Such a model framework gives some tools to quantify the effects human activities may have on the hydrological response of a catchment. For example, how much does the peak discharge increase, if a part of a forested catchment is furnished with drainage ditches?

The characteristic hillslope parameters were not calibrated against runoff data, but they were fixed a priori according to the best available information. Yet, the semi-distributed model was capable of reproducing the measured streamflow with a fairly good accuracy. This is encouraging with respect to modelling streamflows on ungauged catchments where long historical time series of flow data are not available. However, further research is required to verify whether the model performs equally well in other catchments, in particular at larger scales.

The performance of both models dropped significantly in the validation period. This is believed to be largely due to the fact that models were calibrated on a snowless period, and then applied to a winter period. More work is needed to better understand the reasons for differences in runoff response between summer and winter conditions. The processes affecting the water transport on snowcovered hillslopes are complex, and therefore accounting for them in a physically consistent way may not yet be feasible.

In this study only topography was considered to cause differences in the hydrological behaviour within the catchment. When the hillslope water balance model was run with the pre-fixed parameters, only little difference was observed between the behaviours of the four characteristic hillsopes. The fore mentioned is true not only for the integrated water balance components, as shown in Table 2, but also for the response dynamics. With another set of parameters, considerable differences were detected between the responses of the hillslopes (Table 3). In the first model run surface runoff was the dominant water transport mechanism, whereas in the second run groundwater flow contributed greatly to the stream input. The results indicate that when the overland flow is predominant the hillslope water balance model is relatively insensitive to the terrain topography.

Future research will be directed towards gaining more appreciation in 1) how the characteristic hillslopes should be determined using remotely and locally measured data, and 2) how many of them are required to sufficiently represent the spatial varibility of terrain properties. At larger scales the influence of the channel network becomes more important. Therefore, when modelling bigger catchments the channel network submodel has to be further developed. For example, it may be necessary to consider the relative locations where different characteristic hillslopes connect to the stream system.

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6 REFERENCES

Abbott, M.B., J.C. Bathurst, J.A. Cunge, P.E. O'Connell, and J.L. Rasmussen, An introduction to the European Hydrology System "SHE", 2: Structure of a physically-based, distributed modelling system, *J. Hydrol.*, 87, 61-77, 1986.

Beck, M.B., Forecasting environmental change. *J. Forecasting*, 10, 3-19, 1991.

Beven, K.J., Changing ideas in hydrology: the case of physically-based models. *J. Hydrol.*, 105, 157-172, 1989.

Chapman, P.J., B. Reynolds, and H.S. Wheater, Hydrochemical changes along stormflow pathways in a small headwater moorland catchment in mid-Wales, U.K. *J. Hydrol.*, 151, 241-265, 1993.

Christophersen N., and R.F. Wright, Sulphate budget and a model for sulphate concentrations in stream water at Birkenes, a small forested catchment in southernmost Norway, *Water Resour. Res.*, 17, 377-389, 1981.

Cosby, B.J., G.M. Hornberger, J.N. Galloway, and R.F. Wright, Modelling the effects of acid deposition: assessment of a lumped parameter model of soil water and streamwater chemistry, *Water Resour. Res.*, 21, 51-63, 1985a.

Cosby, B.J., R.F. Wright, R.F., Hornberger G.M. and J.N. Galloway, Modelling the effects of acid deposition: estimation of long-term water quality responses in a small forested catchment, *Water Resour. Res.*, 21, 1591-1601, 1985b.

Dunne, T., and R.D. Black, Partial area contributions to storm runoff in a small New England watershed, *Water Resour. Res.*, 6, 1296-1311, 1992.

Fairfield, J., and P. Leymarie, Drainage networks from grid digital elevation models, *Water Resour. Res.*, 27, 709-717, 1991.

Grayson, R.B., I.D. Moore, and T.A. McMahon, Physically based hydrologic modeling, 2, is the concept realistic? *Water Resour. Res.*, 28, 2659-2666, 1992.

Horton, R.E., The role of infiltration in the hydrological cycle, *Transactions. Am. Geophys. Union,* 14, 446-460, 1933.

Jauhiainen, M and A. Nissinen, Calibration of the SOIL model with autumn and summer data of forest soil water tension, In: Kettunen, J., K. Granlund, M. Paasonen-Kivekäs and H. Sirviö (Eds), Spatial and temporal variability and interdependencies among hydrological processes, Proceedings of A Nordic Seminar in Kirkkonummi, Finland, *NHP Report No 36*, 17-30, 1994.

Karvonen, T., H. Koivusalo, M. Jauhiainen, J. Palko, and K. Weppling, A hydrological model for predicting runoff from different land use areas, *J. Hydrol.*, 217, 253-265, 1999.

Koivusalo, H., M. Jauhiainen and T. Karvonen, Use of characteristic hillslopes to model hydrological effects of land use change in forested areas, In: Kajander, J. (Ed), XX Nordic Hydrological Conf. Helsinki, *NHP Report no 44*, Vol. 1., 132-141, 1998.

Koivusalo, H., T. Kokkonen, T. Karvonen and A. Lepistö, Modeling snow processes and streamflow generation under forest canopy and on a forest clearing, MODSIM99, this publication, 1999.

Kuhl, S.C., and J.R. Miller, Seasonal river runoff calculated from a global atmospheric model, *Water Resour. Res.*, 28, 2029-2039, 1992.

Lepistö, A., Areas contributing to generation of runoff and nitrate leaching as estimated by empirical isotope methods and TOPMODEL, *Aqua Fennica*, 24,2, 103-120, 1994.

Nash, J.E. and J.V. Sutcliffe, River flow forecasting through conceptual models, Part I - A discussion of principles. *J. Hydrol.*, Vol. 10, p. 282-290, 1970.

Richards, L.A., Capillary conduction of liquids through porous mediums, *Physics 1*, 318-333, 1931.

Rodríguez-Iturbe, I., and Valdés, J., The geomorphologic structure of hydrologic response, *Water Resour. Res.*, 15, 1409-1420, 1979.

Wood, E.F., D.P. Lettenmaier, and V.G. Zartarian, A land-surface hydrology parameterisation with subgrid variability for general circulation models, *J. Geophys. Res.*, 97(D3), 2717-2728, 1992.

Ye, W., B.C. Bates, N.R Viney, N, M. Sivaplan, and A.J. Jakeman, Performance of conceptual rainfall-runoff models in low-yielding ephemeral catchments, *Water Resour. Res.*, 33, 153-166, 1997.