Hydrologic modelling on a catchment scale using GIS and remote sensed land use information

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Abstract

A spatially distributed hydrologic model is presented for simulation of runoff in a river basin. The generation of runoff is triggered by the rain intensity and soil moisture status, and is calculated as the net precipitation times a runoff coefficient, which depends upon slope, land use and soil type. The runoff is routed through the basin along flow paths determined by the topography using a diffusive wave transfer model, that enables to calculate response functions between any start and end point, depending upon slope, flow velocity and dissipation characteristics along the flow lines. All these calculations can be performed with standard GIS tools.

1 Introduction

The problem of estimating runoff from a storm event is one of the key points in hydrologic modelling. Classical techniques as the rational method or the Soil Conservation Service curve number approach are still widely used in practice. More accurate is to estimate runoff on the basis of the soil moisture conditions
and geophysical characteristics, as for instance presented by Willmott et al. [1] and Dickinson et al. [2].


In this paper we present a physically based distributed hydrological model that uses detailed basin characteristics to predict hydrological processes. We will focus especially on the simulation of runoff. The model is validated for a small watershed in Belgium by comparing calculated and observed hourly discharges for a 6 months period. Next, the utility of the model is demonstrated by forecasting peak discharges resulting from an observed 100 year precipitation series.

2 Theory

The present model is an extension of WetSpa developed by Wang et al. [13], in which the hydrological processes are simulated in a grid based schematisation of a river basin. The processes considered in the model are precipitation, interception, evaporation, surface runoff, infiltration, evapotranspiration, soil moisture storage, interflow, percolation, groundwater storage and discharge. The main outputs of the model are river flow hydrographs and spatially distributed hydrological characteristics as soil moisture, infiltration rates, groundwater recharge, surface water retention or runoff, etc. The model is especially useful to simulate the effects of topography, soil type, and land-use or soil cover on the hydrologic behaviour of a river basin.

In this study we will only focus on the runoff and flood routing components of the model. The calculation of the runoff is rather classical:

\[ V = CP(\theta/\theta_s) \]

(1)

where \( V \) is the amount of surface runoff [L], \( P \) the net precipitation [L] (rainfall minus interception), \( \theta \) the soil moisture content, \( \theta_s \) the saturated soil moisture content, and \( C \) the runoff coefficient, which is assumed to depend upon slope, soil type and soil cover. Runoff coefficients were collected from the literature (Kirkby [14], Chow et al. [15], Browne [16], Mallants & Feyen [17], and Pilgrim
& Cordery [18]) and a table was generated, linking values of the runoff coefficient to slope, soil type and land-use classes.

Next, the generated runoff needs to be routed through the basin such that river discharge can be computed. In this study, the diffusive wave approximation is used to simulate both overland flow and channel flow:

\[
\frac{\partial Q}{\partial t} = D \frac{\partial^2 Q}{\partial x^2} - c \frac{\partial Q}{\partial x},
\]

(2)

where \( Q \) is the discharge \([L/T]\), \( D \) the wave damping coefficient \([L^2/T]\), \( c \) the wave celerity \([L/T]\), \( x \) the distance along the flow path \([L]\) and \( t \) the time \([T]\). The wave transport parameters \( c \) and \( D \) depend upon the flow velocity, flow depth and terrain characteristics. In case the flow velocity, \( v \) \([L/T]\), is determined by the Manning equation

\[
v = \frac{1}{n} \frac{R^{2/3}}{\sqrt{i}},
\]

(3)

where \( R \) is the hydraulic radius \([L]\), \( n \) the roughness coefficient \([L^{-1/3}T]\), and \( i \) the slope \([-]\). \( c \) and \( D \) are given as

\[
c = \frac{3}{2} \frac{v}{c},
\]

(4)

and

\[
D = \frac{vR}{2i}.
\]

(5)

If it is assumed that the hydraulic radius is a static terrain characteristic that does not change during a flood event, it follows from eqns (3) and (4) that \( c \) and \( D \) only depend upon position. In such case, we propose an approximate solution of eqn (2) in the form of a response function, relating the discharge at the end of a flow path to the available runoff at the start of the flow path:

\[
Q = V \left( \frac{t + t_0}{2} \right) \exp \left[ -\frac{(t - t_0)^2}{2\sigma^2} \right],
\]

(6)

where \( t_0 \) is the average flow time \([T]\) and \( \sigma \) the deviation of the flow time \([T]\), i.e.

\[
t_0 = \frac{\int dx}{c},
\]

(7)

and

\[
\sigma = \sqrt{\int \frac{2D}{c^2} \, dt} \approx \sqrt{\int \frac{2D}{c^2} \, dx}.
\]

(8)
Hence, the flow routing consists of tracking the runoff along its topographic
determined flow path, such that a response function is obtained for every grid
cell to the outlet of the catchment, or any other downstream convergence point.
This routing response serves as an instantaneous unit hydrograph and the total
discharge is obtained by convolution of the flow response from all grid cells.

Very convenient is the fact that the response functions can be obtained using
standard GIS techniques. First maps are produced of c and D with eqns (4) and
(5). Next, the contributing area is determined from topographic data for a
particular downstream convergence point, and for each contributing grid cell the
value of $t_0$ and $\sigma$ are calculated by integration along each flow path, using eqns
(7) and (8). Finally, the total river discharge at the downstream convergence
point is obtained by superimposing all contributions from every grid cell.

3 Application

The model was tested on the 67 km$^2$ Barebeek catchment, situated north of
Brussels, Belgium. The study area was divided into grid cells of 50m by 50m.
The topography was digitised from 1/10.000 maps and the soil types were
obtained from the physical system map of Flanders (Vlaamse Landmaatschappij).
Figure 1 presents the topography of the area, with the basin boundary,
main river courses, and measuring stations. The soil cover was obtained from the
digital land use map of Flanders, which is based on remote sensed data of 1995
(Ondersteunend Centrum GIS-Vlaanderen). About thirty land use classes are
shown on this map. But because not all of these are relevant from hydrological
point of view, or the knowledge is lacking about their hydrologic behaviour, the
map was resampled to 5 hydrologic land use classes, i.e.: urban areas,
agricultural crops, pasture, forest, and open water. Figure 2 shows the resulting
land use map. One can notice a mosaic of land uses. Forrest (16.8%) is
predominant in the river valleys, while the higher terrain consists of agricultural
areas, with pasture (24.7%) or crops (36.9%), strongly intermixed with urban
areas (16.2%), as villages, roads and Brussels airport in the south.

Figure 3 shows the runoff coefficients that results from the different slope,
soil type and land use class combinations. The influence of the urban areas is
self-evident. Notice, that due to the grid size, urban areas were assumed to be
impervious for 30% and behaving as pasture for the remaining percentage. This
results in runoff coefficients around 40% in the urban areas, while other areas
have much smaller values, up to 5% for forests in the valleys with practically
zero slopes. Next the overland flow velocity was calculated with eqn (3). Also,
here the urban areas have a marked influence, due to the artificial drainage
facilities as sewer systems, that results in flow velocities of order 1 m/s or more.
On the other hand, in the valleys the flow velocity is very small, due to the high
resistance of the soil cover, being mostly forest, and the very faint slopes. With
this information the response functions were calculated using the diffusive wave
approximation. Figure 4 shows the resulting average flow time from each grid
cell to the outlet of the basin. Again, marked differences result from the land
uses; especially urbanisation has a large impact.
Figure 1: Topography of the study area.

Figure 2: Land use map.
Figure 3: Distribution of the runoff coefficients.

Figure 4: Average flow time of surface runoff.
The model was verified and the different components of the hydrological cycle were calculated in each cell on a hourly basis for a period of about 6 months. A comparison of calculated and observed discharges in the most downstream measuring station is presented in Figure 5. Results for the other measuring stations are similar. One can notice a reasonable agreement between the model results and the observed data. Peaks in the hydrograph are rather well simulated, as well for size as for time of occurrence. Because the model is clearly overparameterised, we do not intend to optimise its performance by calibration, also in view of the fact that hydrological observations are never completely free from errors. Moreover, due to the natural variability of hydrologic processes and the complexity of basin characteristics, it is evident that mathematical models will never reach perfection. Hence, we accept the results as they are.

To demonstrate the usefulness and performance of the model, a historical 100 year series of hourly precipitation data was processed and the resulting hydrograph for the total catchment was analysed statistically to determine the characteristics of peak discharges. The largest flood is given in figure 6. It shows a typical pattern that is present in all of the precipitation events that lead to flood discharges. In all cases the actual storm is preceded by another storm, which generally does not lead to flooding, but which suffices to saturate the soils to such an extent that the second storm as a maximal impact leading to large runoff volumes and flooding in the river system. Figure 7 shows the resulting peak discharges of the fifty highest floods versus return period. Such information will
enable to determine the influence of changes in land use or soil cover on the hydrological behaviour of the river basin.

Figure 6: Simulated peak flood in the 100 years series.

Figure 7: Simulated peak discharge versus return period.
4 Conclusions

A physically based distributed hydrological model was presented for simulating the hydrologic behaviour and especially runoff in a river basin. The generation of runoff depends upon rain intensity and soil moisture status and is calculated as the net precipitation times a runoff coefficient, which depends upon slope, land use and soil type. The runoff is subsequently routed through the basin along flow paths determined by the topography using a diffusive wave transfer model, that leads to response functions between any start and end point, depending upon slope, flow velocity and dissipation characteristics along the flow lines. The model uses detailed basin characteristics and calculations are for the most part performed by standard GIS tools, such that the model is especially useful to analyse the effects of topography, soil type, and land-use or soil cover on the hydrologic behaviour of a river basin.

The model was validated on a small watershed in Belgium for which topography and soil data are available in GIS form, while the land-use and soil cover was obtained from remote sensed images. The resulting calculated hydrograph compared favourably with measurements, without any need to model optimisation. The usefulness and utility of the model was subsequently demonstrated by forecasting peak discharges resulting from an observed 100 year precipitation series. The resulting discharges were analysed statistically to determine the characteristics of extreme flood events. We believe that the model has great potentiality to determine the influence of changes in land use or soil cover on the hydrological behaviour of the river basin.

References


