Integrated Hydrologic Modeling on a Catchment Scale for Prediction of Floods

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(1) ABSTRACT
A spatially distributed hydrologic model is developed for simulation of runoff in a river basin. The generation of runoff is triggered by the rain intensity and soil moisture status. The runoff is routed through the basin along flow paths determined by the topography using a diffusive wave transfer model. Inputs to the model consist of detailed GIS raster data of topography, soil type and land use. The model is applied to a Barebeek basin in Belgium and results are found to be in harmony with observations. A one hundred years series of hourly precipitation data is processed with the model and the resulting hydrograph is analyzed statistically to determine the characteristics of extreme floods.

(2) INTRODUCTION
Sound prediction of flood runoff from a storm event is one of the challenges in hydrologic modeling. Prediction techniques such as the classical rational method have already been applied for this purpose at a scale of small river basins since long time. Another approach in estimation of flood runoff is on the basis of the soil moisture conditions and geophysical characteristics, as for instance Dickinson et al. (1993).

However, as the size of the river basin of interest for hydrology modeling increases, lumped parameter models are not applicable because hydrologic parameters can vary widely in space and time. In such cases spatially distributed hydrologic models are appropriate. For instance, Naden (1992) and Troch et al. (1994) present spatially distributed hydrologic rainfall-runoff

In this work a spatially distributed hydrological model is presented that uses detailed basin characteristics to predict hydrological processes. At this stage of the work emphasis is given to the simulation of runoff. The model is validated for a small basin 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.

**(3) THEORY**

The present model is an extension of WetSpa developed by Wang *et al.* (1996), in which the hydrological processes in a river basin are simulated at grid cell level. The processes considered in the model are precipitation, interception, evaporation, surface runoff, infiltration, transpiration, 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 behavior of a river basin. The generation of runoff is based on the following classical relationship

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

(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, for which values are collected and compiled from literature. 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^{-1}], $D$ the wave damping coefficient [L^2 T^{-1}], $c$ the wave celerity [L T^{-1}], $x$ the distance along the flow path [L] and $t$ the time [T]. The wave transport parameters $c$ and $D$ depend upon the flow velocity and terrain characteristics. If the flow velocity, $v$ [L T^{-1}], is computed with the Manning equation

$$v = \frac{1}{n} R \frac{3}{2} \sqrt{i}$$

(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

$$c = \frac{3v}{2}$$

(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 equations (3), (4) and (5) that $c$ and $D$ only depend upon position. The solution of equation (2) can be approximated as a response function relating the discharge at the end of a flow path to the available runoff at the start of the flow path

$$Q = V \left( \frac{1}{2} + \frac{t_0}{t} \right) \exp \left[ -\frac{(t - t_0)^2}{2\sigma^2} \right]$$

(6)

where $t_0$ is the average flow time [T] and $\sigma$ the standard deviation of the flow time [T], given by
\[ t_0 = \int \frac{dx}{c} \]  

(7)

and

\[ \sigma = \sqrt{\int \frac{2D}{c^2} dt} \approx \sqrt{\int \frac{2D}{c^3} dx} \]  

(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 basin, 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. Notice that the integrals in equation (7) and (8) can be calculated with standard GIS tools.

(4) APPLICATION

The model was tested on the 67 km² Barebeek basin, situated north of Brussels, Belgium. The study area was divided into grid cells of 50 m. The topography was digitized from 1/10,000 maps and the soil types were obtained from the physical system map of Flanders. 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. About thirty land use classes are shown on this map. However, because not all of these are relevant from hydrological point of view, or the knowledge is lacking about their hydrologic behavior, 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 with forest (16.8%) predominant in the river valleys, while the higher terrain consist 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 result 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 are 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, down to 5% for forests in the valleys with practically zero slopes. Next the overland flow velocity was calculated with equation (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$^{-1}$ or more. On the other hand, in the valleys the flow velocity is 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 urbanization has a large impact.

The model was verified and the different components of the hydrological cycle were calculated in each cell on an 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 over-parameterized, we did not intend to optimize 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, the results were accepted 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 basin was analyzed statistically to determine the characteristics of peak discharges. The largest flood is presented 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 saturates the soils such that the following 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 the estimated return periods. Such information will enable to determine the influence of changes in land use or soil cover on the hydrological behavior of the river basin.

(5) CONCLUSIONS
A physically based distributed hydrological model was presented for simulating the hydrologic behavior and especially runoff in a river basin. The generation of runoff depends upon rain intensity and soil moisture status and a runoff coefficient, which determined in function of 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 analyze the effects of topography, soil type, and land use or soil cover on the hydrologic behavior of a river basin.

The model was validated on a small basin 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 hydrograph compares favorably with measurements, without any need
to model optimization. The usefulness and utility of the model was subsequently demonstrated by forecasting peak discharges resulting from an observed 100 year precipitation series, which shows that the model has great potentiality to determine the influence of changes in land use or soil cover on the hydrological behavior of the river basin.

(6) REFERENCES

FIGURES

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

Figure 5: Observed and simulated discharges
Figure 6: Simulated peak flood in the 100 years series

![Graph showing simulated peak flood in the 100 years series]

Figure 7: Simulated peak discharge versus return period

![Graph showing simulated peak discharge versus return period]