

Modelling of Sewer Systems as a Component of a Global Hydrological Model

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Abstract

Hydrology often takes an important place in the domain of hydraulic structures management, and is a key component of many hydraulic studies. Modelling the main hydrological processes requires a particular attention in order to deal with problems in an optimal way. Instrumented basins studies has pointed out the considerable impact of the sewer system on the hydrological outputs dynamics on small basins, even poorly urbanized. The current models often take into account the distributed impervious areas by adapting the corresponding surfaces runoff or infiltration coefficients. This approach, which is suited to produce correct runoff volumes, is however unable to represent the real flow outputs dynamics in which important variations can occur with a hourly time step. Modelling this flow component is essential to catch the rapidly-varying flow inputs generated by the runoff on drained impervious areas. An efficient modelling method has therefore been developed to include the sewer system in a global hydrological model (WOLF), using accurate landuse data in vector format and available data on the sewage system. These developments have been successfully tested on the Berwinne basin, Belgium.

1 Introduction

The hydraulic and hydrologic studies, which are currently subject to increasing demands and expectations, often require to follow a complete modelling chain which can include multiple components, *e.g.* hydrological simulations (overflow, hypodermic flow, etc.), flows propagations in a river network, detailed studies of floods using quasi-3D simulations, sediment transport modelling or pressurized flows in water pipes. In the framework of these complex studies, hydrology takes an important place and requires a particular attention.

This paper focuses on the runoff induced by impervious surfaces. Currently, many different methodologies are used to model the impervious areas, depending on the hydrological model type, the size of the studied catchment, etc. The statistical hydrological models [1] naturally include the effects of impervious surfaces, as they are based on actual discharge measures. Nevertheless, such approaches are unable to take into account the evolution of the urban part of the basin. Other methods, such as the rational method [2], allow a simple representation of urban areas, using specific runoff coefficients representative of the landuse. These coefficients are in fact mean values which require an estimation of the urban density of the area [2, 3]. The SCS Curve Number method, which is amongst the most used methods worldwide, uses runoff coefficients depending on the soil type, the landuse and the rainfall volumes [4, 5]. Specific coefficients are used for the urban areas, by averaging the curve numbers values for impervious surfaces and surrounding landuses (often considered as gardens), according to the urban density of the area [4]. However, this approach does not take into account the presence of a sewage system which modifies the flow path and shorten the propagation time of water. Modelling this flow component is essential to catch the rapidly-varying flow inputs generated by the runoff on drained impervious areas

Urban hydrology is a particular application field where impervious areas cover the main part of a small basin. The objective of these studies is often designing the sewage system or linked structures. In this kind of studies, a complex modelling of the flows can be implemented, with an explicit modelling of the whole sewer system network [6, 7, 8]. Nevertheless, the complexity of this modelling limits its use to

small basins. At the other extreme, when dealing with huge catchments, the impact of the sewage system on the hydrological outputs is generally negligible, as most of the water travel time is spent in the river network. However, in mid-size catchment, the effects of the sewage network on the discharges is no more negligible, but can hardly be fully accounted for with the level of complexity used in urban hydrology [9].

An original methodology, developed in the framework of a physically-based and spatially distributed hydrological model, is proposed in order to compute impervious surfaces accurately and to take drainage effects into account without modelling the entire drainage network. The impervious surfaces are estimated on the basis of landuse maps in vector format and then divided into two categories: drained and undrained. The rain falling on undrained areas is discharged as overland flow, and can therefore be considered the same way as runoff generated from pervious surfaces. The drained areas are routed separately using a simplified modelling of the drainage network.

2 The Global Hydrological Model WOLF

The herein described model constitutes a part of the hydrological component of the modelling system “WOLF”, developed at the University of Liege. WOLF includes a set of complementary and interconnected modules for simulating free surface flows: process-oriented hydrology, 1D & 2D hydrodynamic [10, 11], sediment [12] or pollutant transport, air entrainment, as well as an optimisation tool based on Genetic Algorithms [13]. Other functionalities of WOLF 2D include the use of moment of momentum equations [12], the application of the cut-cell method [14], as well as computations considering vertical curvature effects by means of curvilinear coordinates in the vertical plane [15].

The hydrological component of the modelling system WOLF is physically-based and spatially distributed. It computes the main hydrological processes using a multi-layers model with depth-integrated equations (Figure 1).

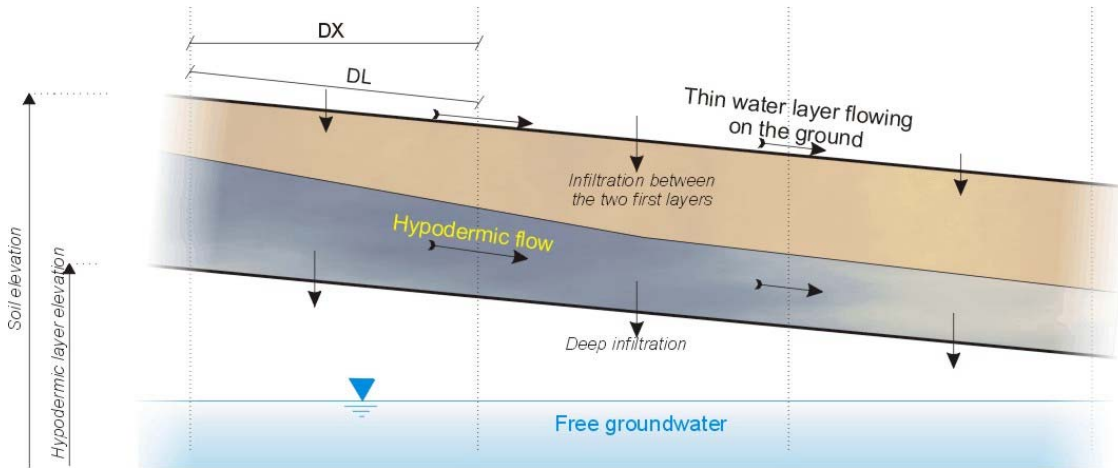


Figure 1: Flow layers computed in the hydrological model

Originating from the well-known shallow water equations (SWE) describing the flows, the diffusion wave approach is obtained by ignoring the inertia terms compared with the gravitational ones, friction and pressure heads. The SWE model can then be replaced by the following system of parabolic differential equations:

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = S \quad (1)$$

$$S_{fi} = \sin \theta_i - \cos \theta_i \frac{\partial h}{\partial i} \quad i = x, y \quad (2)$$

where h is the water height, u and v are the velocities along the x and y axis, S represents the source terms (rainfall and infiltration), S_{f_i} ($i = x, y$) are the friction slopes, and θ_x and θ_y are the projected ground slopes. Using the Manning-Strickler friction law, the velocities can be related to the friction slope following Eq.(3) :

$$\begin{aligned} u &= \frac{1}{n} h^{2/3} \frac{S_{f_x}}{(S_{f_x}^2 + S_{f_y}^2)^{1/4}} \\ v &= \frac{1}{n} h^{2/3} \frac{S_{f_y}}{(S_{f_x}^2 + S_{f_y}^2)^{1/4}} \end{aligned} \quad (3)$$

The infiltration is calculated using a Green-Ampt infiltration law [2], and the subsurface flow is computed with the depth-integrated Darcy equations. The subsurface flow is therefore modelled with a diffusive wave equation similar to the surface flow equation:

$$p \frac{\partial h_{sub}}{\partial t} + \frac{\partial(u_{sub} h_{sub})}{\partial x} + \frac{\partial(v_{sub} h_{sub})}{\partial y} = S_{sub} \quad (4)$$

$$S_{f_{sub,i}} = \sin \theta_{sub,i} - \cos \theta_{sub,i} \frac{\partial h_s}{\partial i} \quad i = x, y \quad (5)$$

$$u_{sub} = K_s \frac{S_{f_{sub,x}}}{(S_{f_{sub,x}}^2 + S_{f_{sub,y}}^2)^{1/4}} \quad (6)$$

$$v_{sub} = K_s \frac{S_{f_{sub,y}}}{(S_{f_{sub,x}}^2 + S_{f_{sub,y}}^2)^{1/4}}$$

where p is the soil effective porosity, h_{sub} is the subsurface water height, u_{sub} and v_{sub} are the subsurface flow velocities, S_{sub} represents the source terms (infiltration, deep percolation, evapotranspiration), K_s is the lateral hydraulic conductivity, $S_{f_{sub,i}}$ ($i = x, y$) are the subsurface friction slopes, and $\theta_{sub,i}$ ($i = x, y$) are the projected slopes of the soil layer along the axis.

The necessary data are prepared using the GIS interface of WOLF [16], using pre-processing tools to convert raw data. The Digital Elevation Model (DEM) is processed in order to remove depressions, using an algorithm proposed by Martz and Garbrecht [17], and a ‘‘Stream burning’’ method [18, 19] is applied in order to make the DEM-based flowpaths suit the real ones obtained from on-site surveys. The soils properties are extracted from pedologic maps using pedotransfer functions [20]. The impact of the landuse on the infiltration are taken into account by using effective values for the infiltration coefficients, as proposed by Nearing [21].

The river flow inputs generated from the hydrology module are routed in the river network by way of the 1D module. The coexistence of several flow rates with shocks and bores in ramified nets of variable cross section arms requires to deal with suitable shock capturing methods to solve the conservative form of the 1D Saint-Venant equations. The complete set of equations solved in WOLF1D for each flow bed (multiple flow beds in compound channels can be explicitly taken into account) is expressed as follows:

$$\frac{\partial}{\partial t} \begin{bmatrix} \omega \\ q \end{bmatrix} + \frac{\partial}{\partial x} \begin{bmatrix} q \\ \rho_\omega \frac{q^2}{\omega} + g \cos \theta p_\omega \end{bmatrix} + \begin{bmatrix} -q_L \\ -g \omega \sin \theta + g \omega J + g \cos \theta h l_b \frac{\partial(-h_b)}{\partial x} - g \cos \theta p_x \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (7)$$

where ω is the cross section, q the discharge, h the water height, q_L the lateral exchanges (external or with the other flow beds), J a global term for bottom roughness and shear fluid effect, θ the channel bottom slope and l_b the channel bottom width. The pressure terms are defined by:

$$\begin{aligned}
p_w(h) &= \int_0^h (h - \xi) l(x, \xi) d\xi \\
p_x(h) &= \int_0^h (h - \xi) \frac{\partial l(x, \xi)}{\partial x} d\xi
\end{aligned}
\tag{8}$$

The spatial discretisation of the equations is performed by a widely used finite volume method. Flux treatment is based on an original flux-vector splitting technique developed for WOLF. Fluxes are split according to the sign of the flow path, requiring a suitable downstream or upstream reconstruction for both parts of the convective term according to a stability analysis. Efficiency, simplicity and low computational cost are the main advantages of this scheme [22]. Variable reconstruction can be selected to gain first or second order accuracy on regular grids. However, it is well known that such second order finite volume schemes, although very accurate in smooth regions, cause unphysical oscillations near the discontinuities. The flux reconstructions are therefore limited to prevent such spurious effects. Besides, an explicit Runge-Kutta scheme or an implicit algorithm (based on the GMRES) is applied to solve the ordinary differential equation operator, and an original treatment of the confluences based on Lagrange multipliers [23] allows the modelling in a single way of large rivers networks. The hydrologic inflows are treated as lateral inputs (source terms). The hydrologic and the river flow equations are therefore uncoupled.

3 Methods

3.1 Impervious surfaces

In the distributed model WOLF, the impervious part of the surface is a property that can be defined on each cell. It is computed on the basis of a landuse mapping in vector format (Figure 2a). The impervious landuse (roads, houses, car parks, concrete structures, etc.) are selected and the corresponding surfaces are summed for each cell. After dividing the impervious surfaces by the cells surfaces, a resulting raster containing the impervious part of each cell is obtained (Figure 2b). This process results in a highly accurate computing of impervious surfaces, because it replaces the subjective estimation of urban density by a more accurate estimation based on high-resolution vector data.

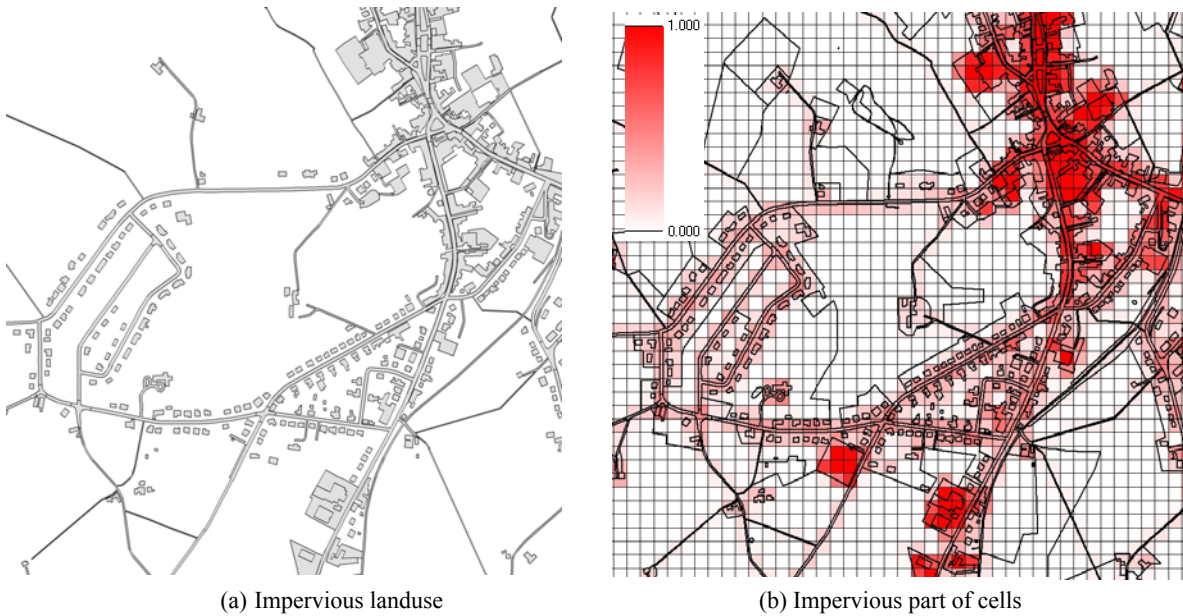


Figure 2: Computation of impervious areas

3.2 Drainage network

After computing the impervious part of each cell surface (using the method described above or any other method if sufficient data are not available), the following step consists in separating the drained cells from the undrained ones. If the needed information (*e.g.* drained areas delimited by vectors or a binary raster) is not directly available, this separation can be computed according to other sources of data. The first method proposed, if the pipe network data is available, assumes that all cells located within a fixed radius from the pipe network are drained. Therefore, a cell is considered as drained if the distance from its centre to the nearest pipe is below a fixed value, typically in a range from a few tenths of meters to a few hundred meters.

If the drainage network data is unavailable, the part of drained areas can be estimated by an analysis of rainfall events, following the approach suggested by Boyd [24] for urban catchments. Rainfall events of low intensity are selected, so that only the drained areas produce runoff. Calculating the runoff coefficients lower bound gives the part of drained areas. Nevertheless, this methodology should be applied to a sufficient number of rainfall events to reduce the risks of errors, coming either from bad data, or from the selection of inappropriate events where runoff is not induced by impervious drained areas alone. This method can also be used in combination with the previous method, either to check the adequacy of the results or to calibrate the maximal distance from the drained areas to the pipe network.

The real sewage system is a tree-shaped network, with numerous small pipes. The complete modelling of this system for the whole catchment requires huge quantities of data which are often unavailable. Moreover, the density of the network implies using very small cells (down to a few meters) to represent the numerous individual pipes, reducing consequently the time step and increasing drastically the total number of cells. Merging these tree networks into unique pipes is proposed in order to reduce the model complexity while still catching the essential phenomenon leading to the fast flow propagation to the river. The runoff from each cell drained to a tree network is discharged to the corresponding equivalent pipe at a distance from the outlet corresponding to the distance following the tree network.

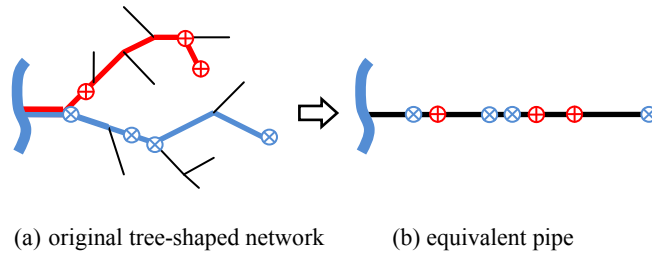


Figure 3: Transformation of the sewage network. The small circles represent examples of drained cells outlets

An alternative methodology is proposed if the sewage system structure is not available. In this case, the pipe network is supposed to follow the steepest slopes of the natural ground. This assumption enables the creation of a unique drainage network based on the DEM. An equivalent pipe can then be computed following the same method as the case where the drainage network is known.

The slope of the equivalent pipe is computed by a weighted mean of the real pipes slopes. The dimensions of the cross sections are computed along the pipe as a function of the corresponding drained impervious surface. A relation has been established in order to provide default values for the pipes diameter, as the optimal dimensions are dependant of the network structure and the original pipes dimensions (which are generally unavailable). The flow is assumed to follow the Manning-Strickler friction law for 1D flows:

$$i = J = \frac{n^2 u^2}{R_h^{4/3}}, \quad (9)$$

where J [-] is the friction slope, chosen equal to the pipe slope i [-] (uniform flow conditions), n [$\text{m}^{-1/3}\text{s}$] is the Manning coefficient, u [m/s] is the flow velocity and R_h [m] the hydraulic radius of the flow. The

circular pipes are designed in order to accept a constant rainfall of 50 mm/h over the drained areas with an occupancy rate of 80%. The Manning coefficient n of the pipes is chosen equal to $0.015 \text{ m}^{-1/3}\text{s}$. This results in the following relation:

$$D = 0.005 \left(\frac{S_{imp}}{i^{1/2}} \right)^{3/8}, \quad (10)$$

where D [m] is the pipe diameter, and S_{imp} [m²] is the impervious surface drained by the pipe.

4 Applications and results

4.1 Description of the catchment

The methodology is applied to the Berwinne catchment located in Belgium. The Berwinne River is an affluent of the Meuse River, and has a basin area of 132 km². The catchment is mainly covered with meadows, and includes a few low or medium-density towns. Figure 4 shows the DEM of the catchment, which has a mean slope of 7.2%. Two gauging sites are located on the river, and provide hourly discharge measurements. The rainfall data of the catchment is measured daily at 8 stations and hourly at one station. These stations are located either inside or nearby the catchment. A disaggregation process [25] is applied on the daily series to provide hourly rainfall intensities.

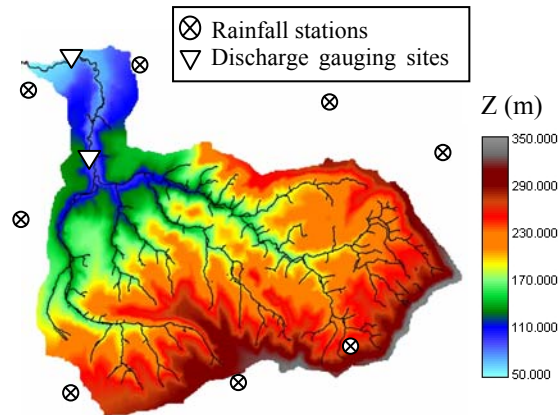


Figure 4: DEM of the catchment (meters)

4.2 Application of the methodology

The impervious surfaces are computed on the basis of a landuse map, according to the procedure described above (the landuse map in vector format [26] is available on 92% of the basin). Applying this method to the Berwinne basin results in a mean value of 6.3% impervious areas over the catchment.

The modelling of the drained impervious areas is based on the actual sewer system, provided in the PASH (“Plan d’Assainissement par Sous-bassin Hydrographique”, [27]). These maps include the X and Y coordinates of the existing pipes in vector format (Figure 5a). Using the method described in chapter 3, the sewage networks trees are merged into an equivalent channel and the channels with nearby outlets are combined in order to have a minimal distance of 1000 m between two adjacent outlets.

Applying this methodology results in a set of 30 equivalent channels representing the entire drainage network. The outlets of these channels are located on the rivers (Figure 5b). As these equivalent channels are virtual, they are not represented on the map.

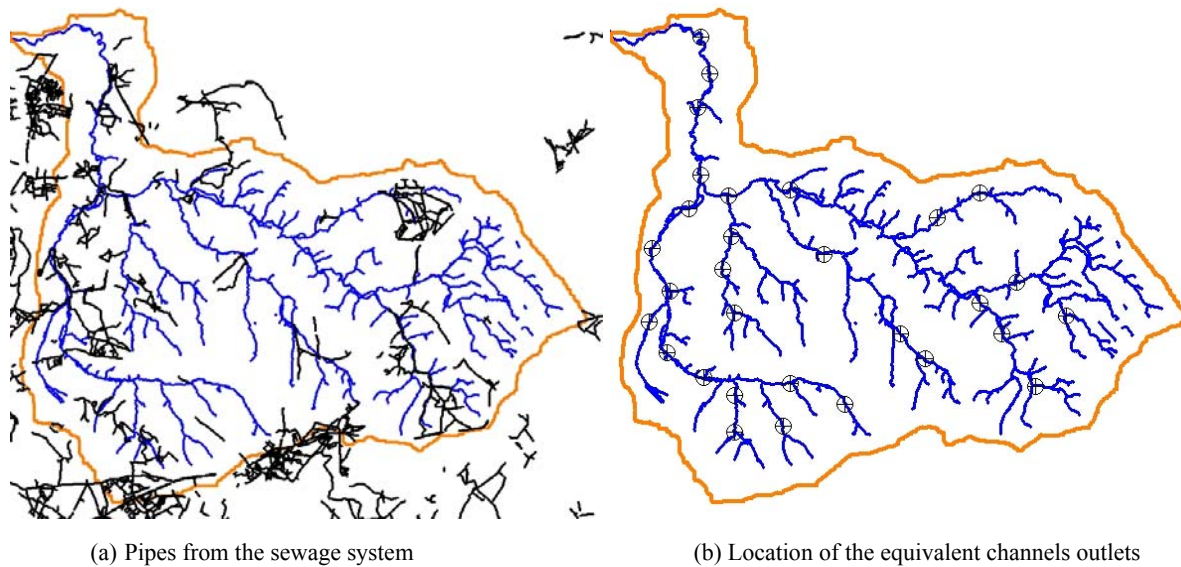


Figure 6: Modelling of the sewage system

The cells are considered drained by the sewage system if their centre is within a distance of 200 m from the pipes. This distance allows the main urban areas located near the sewage network to be drained. The computed drained impervious area covers 2.5% of the basin surface. Following the method explained in chapter 3, an additional analysis of the discharges measurements is realized to estimate the drained impervious areas from low intensity rainfall events. Figure 6 shows a rainfall-runoff plotting, after removing the baseflow component from the actual discharge measurements. The red line shows a runoff coefficient of 2.5%. It can be seen that most of the measured coefficients are bounded by this minimum value. This suggests that the drained impervious surface of the catchment is about 2.5% of its total surface. This value is fully consistent with the value estimated previously on the basis of the landuse map and the drainage network.

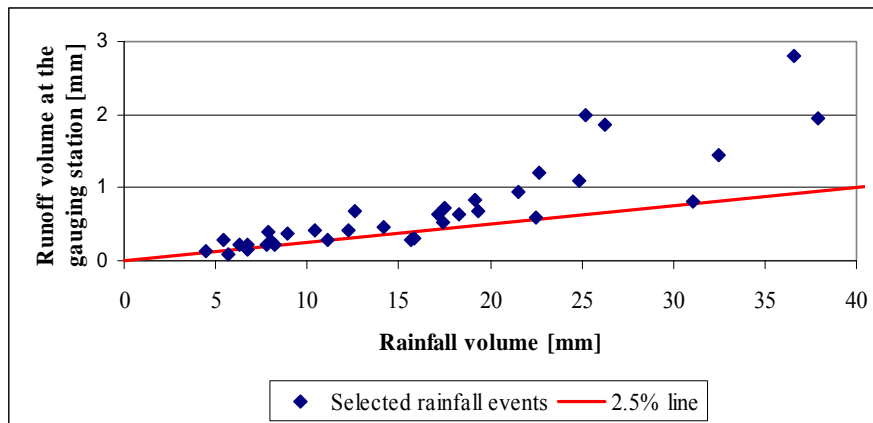


Figure 5: Analysis of Rainfall-Runoff values for low intensity events

4.3 Rainfall events

The parameters of the model have been calibrated according to the flooding event of august 1996. Two rainfalls events are proposed in order to assess the effects of the drainage network on the discharges. The first one is an arbitrary event involving two rainfall periods of 2h, separated by a 22h dry period (Figure 7a). The catchment is initially dry. Figure 7b shows the comparison of the hydrograph at the basin outlet, in the case where the sewage network (i) is not taken into account and (ii) is modelled using the above methodology. In the first moments of the simulation, the rain falling on the drained areas causes a

much faster increase of the discharge at the outlet. Nevertheless, as the rapid flow coming from the drained areas arrives before the runoff from the non-drained areas, it is not cumulated with any other discharge and its effect on the overall discharge is therefore attenuated. After the second period of rainfall, the inputs from the impervious areas are rather widespread in the first configuration, while the presence of the drainage network creates a sharper discharge peak. As this peak cumulates with the runoff from the antecedent rainfall period, the overall discharge difference is proportionally more significant.

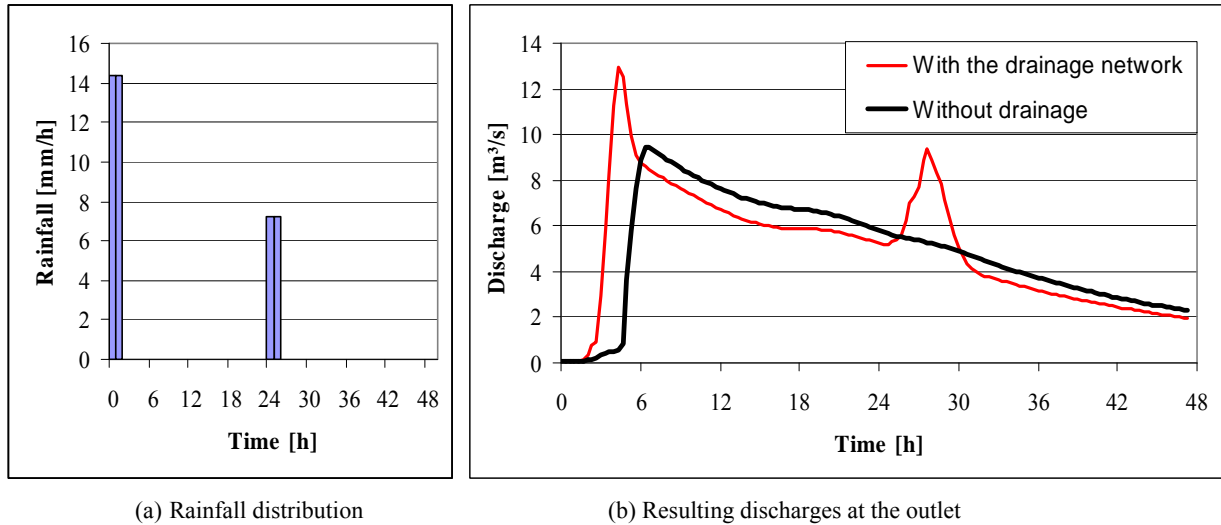


Figure 7: Simulation of the first rainfall event

The relative influence of the drainage network will depend on many factors: catchment size, shape and slope, urbanization rate, etc. This influence is more significant if (i) the drained surface is maximal, (ii) the sewage network reduces significantly the propagation time and (iii) this reduction is important compared to the propagation time in the river. The condition (iii) is necessary in order to have a superposition of the discharges generated in the impervious areas spread over the catchment. It can also be noted that in the case of rainfalls with lower intensities, the relative effect of the drainage network will be more considerable, as the runoff produced by the impervious areas becomes a more important component of total runoff.

In order to test the model on real conditions, the rainfall event from august 1996 is simulated and the results are compared to the measured discharges at the most downstream gauging site (Figure 8). As this event occurred in a low-water level period, the baseflow is negligible. Hourly rainfall values, disaggregated from daily values at the weather stations, are distributed over the catchment using the Thiessen polygons method. The rainfall intensities plotted in Figure 8 are the spatially weighted means. The dotted line represents the measured discharge at the gauging site.

The results show that the drainage network induces the addition of a fast flow component which modifies the discharge time distribution. This modification enables a better modelling of the actual discharges, as the fast flow component is indeed similar to the observed ones. Nevertheless, some differences remain between the two curves. Although runoff on drained areas creates a quickly varying flow component, other processes can simultaneously influence the computed discharge at hourly time steps. For example, saturated areas located near the river [28] can also provide such quickly varying flows, as they have a very low propagation time to the river. Moreover, the inaccuracy of the rainfall data at this time step can lead to significant differences between the simulated and measured discharge. In particular, the disaggregation process of daily rainfall to hourly series is a source of uncertainty.

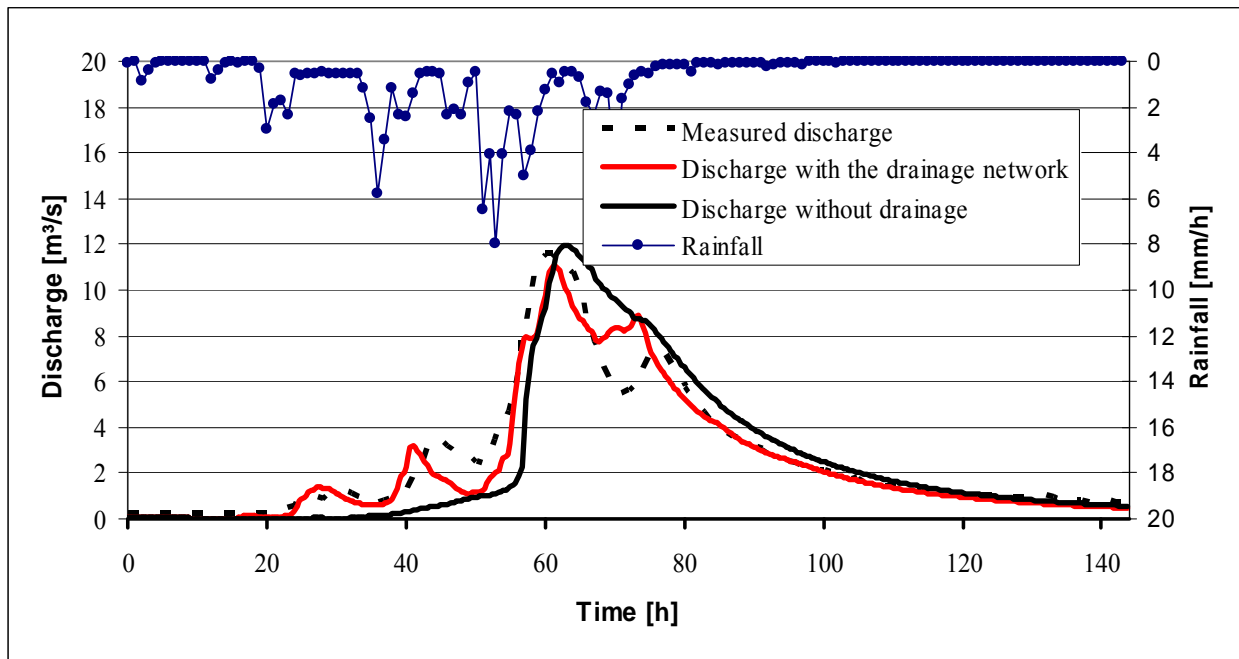


Figure 8: Real rainfall event (August 1996)

Therefore, adding the drainage network in the global hydrological model is not always sufficient to ensure the accurate modelling of hydrological inputs at an hourly time step, but it can have a considerable impact on these discharges and must therefore be accounted for.

6 Conclusion

Impervious surfaces can produce a significant part of surface runoff. In small and mid-size basins, the flow dynamics of the water falling on impervious areas is different whereas these areas are connected to a drainage network, such as a sewage system. A methodology has been developed in order to compute the contributions of impervious surfaces with high accuracy and to take into account the effect of the drainage network without its complete modelling. The impervious part of each cell surface is computed by summation of the impervious areas delimited in a landuse map in vector format. The sewage network is modelled by a simplified channel network which routes the rain falling on drained cells to the river.

The application to the basin of the Berwinne River showed the improved capacity of the model to represent the river dynamics at a hourly time step. Nevertheless, it has been noted that other hydrological processes (*e.g.* rainfall falling on saturated areas near the rivers) or the data resolution (*e.g.* daily rainfall time series which have to be disaggregated into hourly series) may also have a significant impact on the computed river discharge dynamics at these small time scales. Therefore, modelling the drained impervious areas is necessary to improve the modelling of the flow processes, but should not be seen as the only phenomenon able to influence the rapidly varying flow components of river hydrographs.

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