17th International Conference on the Applications of Computer
Science and Mathematics in Architecture and Civil Engineering
K. Gürlebeck and C. Könke (eds.)
Weimar, Germany, 12–14 July 2006

INTEGRATED RAINFALL RUNOFF MODELLING IN SMALL URBANIZED CATCHMENTS

A. Klawitter[*] **and M. Ostrowski**

[*] *Technische Universität Darmstadt, Fachgebiet ihwb*
Petersenstraße 13, 64287 Darmstadt, Germany
E-mail: klawitter@ihwb.tu-darmstadt.de

Keywords: integrated hydrologic modeling, Geographical Information System (GIS), catchment modeling, urbanization

Abstract. *A concept for integrated modelling of urban and rural hydrology is introduced. The concept allows for simulations on the catchment scale as well as on the local scale. It is based on a 2-layer-approach which facilitates the parallel coupling of a catchment hydrology model with an urban hydrology model, considering the interactions between the two systems.*

The concept has been implemented in a computer model combining a grid based distributed hydrological catchment model and a hydrological urban stormwater model based on elementary units. The combined model provides a flexible solution for time and spatial scale integration and offers to calculate separate water balances for urban and rural hydrology. Furthermore, it is GIS-based which allows for easy and accurate geo-referencing of urban overflow structures, which are considered as points of interactions between the two hydrologic systems. Due to the two-layer-approach, programs of measures can be incorporated in each system separately.

The capabilities of the combined model have been tested on a hypothetical test case and a real world application. It could be shown that the model is capable of accurately quantifying the effects of urbanization in a catchment. The affects of urbanization can be analyzed at the catchment outlet, but can also be traced back to its origins, due to the geo-referencing of urban overflow structures. This is a mayor advantage over conventional hydrological catchment models for the analysis of land use changes.

1 INTRODUCTION

Traditionally, rainfall runoff analyses are looked at from a totally different point of view in rural and urbanized catchments respectively. Also, they are usually modelled independently from each other, meaning that there exist numerous models to model either rural or urban catchments. Only a few models are known that are capable of modelling both urban and rural catchments simultaneously and in a detailed manner; however interactions between the systems are hardly taken into account.

This paper presents an approach to simultaneously model rural and urban catchments and their interactions, gives some general information about possible interactions and their effects, and finally presents two model structures which can be used to model the integrated system.

The natural flow patterns on the soil surface which evolve from natural conditions such as topography and land use, are altered dramatically in urbanized regions. Here the flow patterns are mainly predefined by the sewer system; flow paths on the soil surface are short and are not subject to any significant retention processes. The flow patterns on the surface do not follow the natural topography, but are influenced by buildings, sidewalks, ditches etc. Interflow processes are mainly disturbed in urban areas by either dense sewer systems or deep basements of buildings, or both. Effects of urbanisation are e.g. that actual evaporation rates are reduced tremendously due to the fast transport of precipitation water on the soil surface into the sewer system. Due to the increase of impermeable area, the infiltration rates into the soil are reduced which leads to a lower soil moisture and in the end to a reduced baseflow.

Also, after a heavy rainfall, natural areas can contribute considerably to the flow in the urban sewer system [1, 2]. On the other hand, the discharge from wastewater treatment plants and sewer overflows in urban areas contributes flow to the natural receiving water bodies, and hence causes alteration of the flow dynamics in the natural system.

Leaching of waste water from sewer pipes into the soil matrix can cause soil contamination; or a groundwater table lying near the soil surface can lead to an excessive amount of imported water in the sewer system. Discharges from sewer overflow structures not only put a strain on the receiving water body through pollution load, but also due to the resulting hydraulic stress. The fact that temperatures are higher in urban settlements can lead to reduced snow cover periods as well as higher snow melting rates within the winter months.

There could be more effects listed that an urban area has on the hydrological cycle, and more interactions between the systems could be named. However, at this point it should be clear, that for a detailed statement on the water cycle and the effects of urban settlements on the water cycle in rural catchments, some of the interactions named above should be considered in an integrated hydrological modelling system. Hence, to better account for these interactions an approach, that simultaneously couples two existing hydrological models, is introduced.

2 THE IMPORTANCE OF INTEGRATED MODELLING

Different system characteristics of urban and natural catchments resulted in the development of two distinct model categories: urban hydraulic/hydrologic models and rainfall-runoff models for natural catchments, often called catchment or basin models. However, the trend of modelling “integrated systems” shows that the systems cannot be looked at separately in all cases, since dependencies between the systems are obvious and interactions occur, as stated above.

Conventional modelling systems focus on either one of the systems (urban or natural), and treat the other system in a very simplified manner. Then again, it is well accepted, especially with regard to the European Water Framework Directive [3] that the integrated management approach becomes more and more important. Therefore, in the past years many different models have been coupled, and there is a great effort to facilitate the coupling process. The latter becomes clear when looking at the HarmonIT project [4] which aims at providing an open modelling interface (OpenMI) for model integration. Efforts have been put in modelling the integrated system of sewer system, wastewater treatment plant and receiving water body, see for example [5] or [6]. Often the receiving water body is either assumed to be at a steady state, or an extremely simplified model is used to represent it, since the main focus is not on discharge, but lays on the effects of spills of combined sewer overflows on the water quality.

Despite all efforts on model coupling, no detailed and comprehensive model exists, that considers both urban and natural catchment hydrology including the interactions between the two systems. However, different authors demand for a more integrated view of urban and natural hydrology. O'Loughlin et. al [7] criticise that hillslope processes have found only little application in urban hydrology. Ostrowski [8] remarks that the investigation of flood events must include both urban and natural system hydrology, hence a coupled model is needed. Drawback of coupling models however is that aggregation processes are often necessary, due to model applications in different spatial and time scales. Therefore Ostrowski [8] points out that different ways of coupling urban and natural systems must be found. Andrieu and Chocat [9] look at catchments as a patchwork of urbanised and natural lands. Therefore, they ask for a hydrology of "anthropogenic areas" that will bring together "the best ideas and methods of the urban and general hydrology".

3 OBJECTIVES

Aim of this study is the implementation of an integrated modelling concept in a detailed rainfall-runoff model that is able to calculate discharges from both urban and rural areas, and that is applicable both on the catchment and on the local scale. This requires the integration of a microscale urban stormwater model into a mesoscale natural catchment hydrology model. The model integration is carried out using a 2-layer-approach, which enables a flexible integration of different spatial scales. Furthermore, interactions between the natural and the urban hydrologic systems should be considered, such that the model representation is as close to reality as possible.

A detailed description of both urban and natural hydrology within one modelling system longs for a distributed model type approach, which bears a high data demand. In order to assure a proper data management, the modelling system is supported by means of a GIS where both urban and natural catchment hydrologic parameters are supplied. The modelling system aims at representing small catchments up to 100 km^2 only, since effects of urbanization become more and more negligible as catchment area increases [8].

The main goal of the work is to find a way of integrating two existing models, taking into account the above named interactions of the two modelling systems and to account for the correct modelling of flow peaks in streams during rainstorm events when sewer overflows intermittently discharge waste water.

4 METHODOLOGY

An important issue, when coupling models, is the consideration of different spatial and time scales of the models. Not only spatial and time scales are different in natural and urban hydrology models, but in many cases also their model structure. Whereas urban hydrology models mostly use a structure built from elementary units and channel segments, natural catchment hydrology models mainly use regular grid cells or stream tubes. This results from the different flow pattern in the two systems. While in natural hydrology the discharge is being transported according to the natural topography of the landscape, urban areas are altered such that flow is transported according to the channel network, so the flow pattern resembles a vector system.

There have been studies, trying to use grid models for the representation of urban areas, e.g. Bellal et al. [10] or Valeo [11]. Even though these studies could show that such a catchment representation would lead to good results, Bellal et al. had to make some rather unrealistic adjustments to the model in order to make it work. Valeo could show that the influences of hillslope hydrology are important for urban hydrology, but did not consider the discharge behaviour of urban areas in detail, but only through reduced infiltration. However a grid representation of urban areas demands for an extremely high resolution which results in huge data quantities [12].

Therefore, two points were crucial at the beginning of the study. 1.: Two existing models should be combined, rather than developing a new integrated model. 2.: Since urban and natural catchments are best represented by different model structures, these structures should be kept, in order to leave an optimal model representation in each system. Hence, two readily available models, a grid based natural catchment hydrology model and an urban hydrological pollution load model, based on elementary areas, are combined under one software shell to achieve the stated objectives.

The natural catchment model considers all important aspects of the hydrological cycle to simulate runoff from rural areas and in the receiving river. It considers a detailed soil moisture accounting algorithm to determine runoff from hillslopes and transports discharge on a grid to grid basis, based on the kinematic wave approach. Most of the model's process simulation algorithms are based on conceptual approaches with a physical basis. The model is described in full detail by Lempert [13] and Klawitter [14].

The urban pollution load model comprises a conceptual rainfall runoff model based on linear reservoir cascades. It handles both combined and separate sewer systems. Transport in the sewer network is carried out by a hydrological method, however a simplified method to account for backwater effects in pipes is implemented. The model can handle several different forms of sewer overflow buildings and branchings. A simple description of flow through a waste water treatment plant has been added during this study. The urban hydrology model is thoroughly described by Mehler and Leichtfuß [15] and Muschalla [16].

The approach of modelling the two combined systems simultaneously can be compared to a 2-layer approach, which is described in the following section. One layer represents the rural system and the second layer represents the urban system. Within each time step, both layers have to be simulated and data can be exchanged between the layers.

5 DESCRIPTION OF THE MODELING INTEGRATION CONCEPT

Basis for the integration concept is a two-layer-approach, which represents each hydrologic system within a separate layer while allowing for system interactions. Besides a short presentation of this approach the spatial and time scale integration will be explained.

5.1 The 2-Layer-Approach

The coupling of the models described above, is achieved by a 2-layer-approach, which assigns each sub-model a separate layer. This is shown in Figure 1, where the top layer denotes the urban, and the bottom layer the natural catchment. The two layers are connected using interactive grid cells which are defined prior to the model run. Through interactive grid cells, discharges can be interchanged between the two layers.

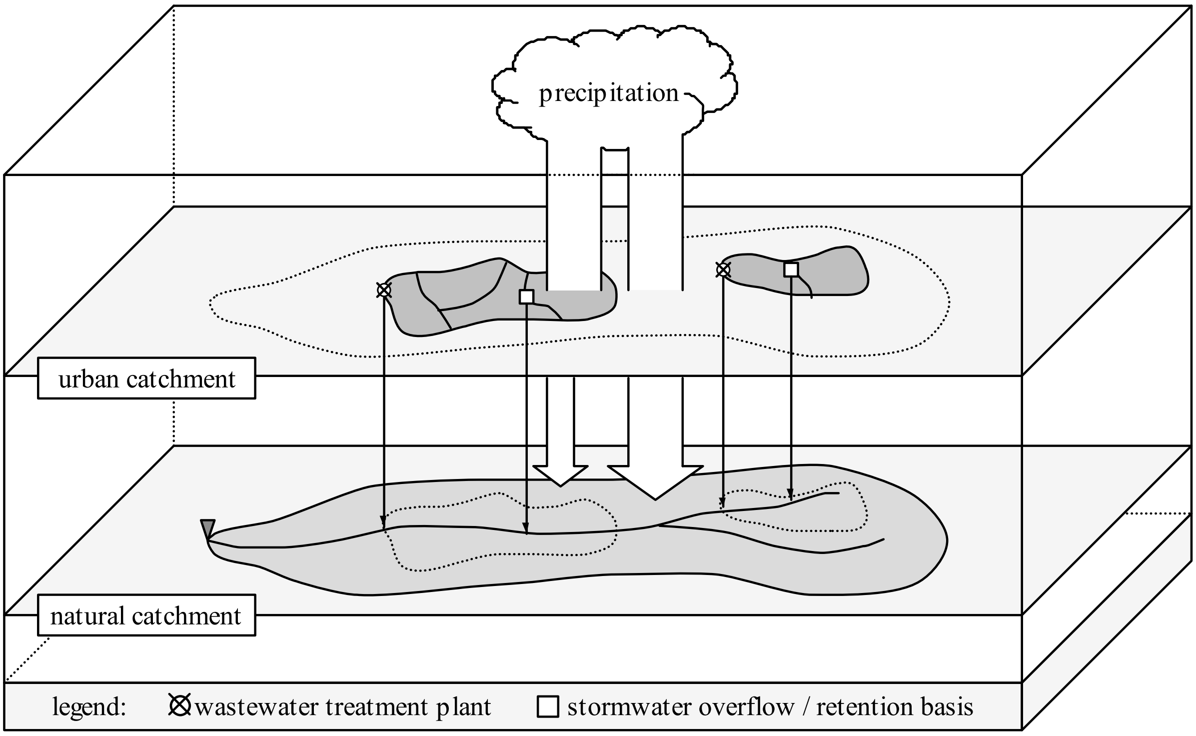
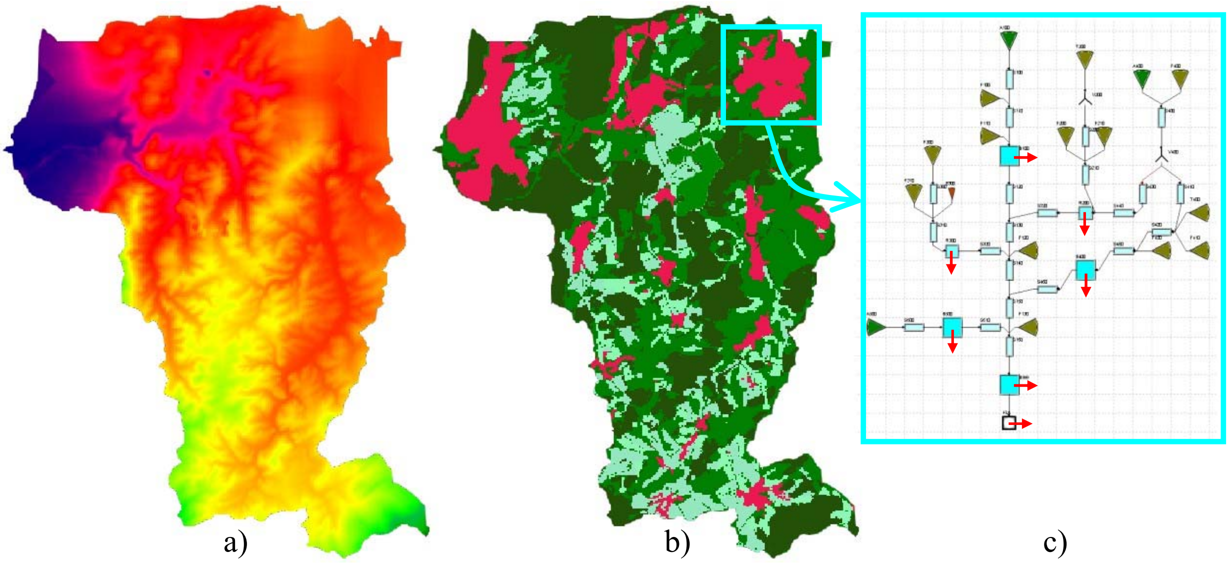


Figure 1: visualisation of the 2-layer approach

Both layers are described by several maps in the GIS. The bottom layer has information about topography, soil structure and land use. Hereby, the land use map indicates where urban areas are located on the top layer. On the top layer, further information about the urban sub-catchments is given. Furthermore it holds information about the location of sewer network buildings, such as wastewater treatment plants or stormwater overflows, as indicated in Figure 1. No GIS data are needed on the location of the sewer network, since these are given by means of a flow pattern plan within the urban hydrology model. However, this also means that no geo-referencing of the sewer network takes place. Hence, percolating water in, or leakages from the sewer system are not taken into account. Due to the fact that it is virtually not possible to exactly quantify these effects, neglecting percolating water and leakage seems reasonable at this modelling scale.

Figure 2 further illustrates the two layer approach by means of an example, as it is used in combination with the GIS. Figure 2a depicts a digital elevation model (DEM) which is used to extract the flow patterns within the rural regions. For the natural catchment hydrology model, land use and soil distribution is also needed. The land use distribution is shown in Figure 2b. The red areas in Figure 2b represent urban settlements. These areas have to be identified prior to a simulation and can then be modelled separately. Here, the percentage of impervious area within the urban settlement plays an important role. It basically controls the partitioning of precipitation on layer 1 and layer 2 as indicated in Figure 1.



a) b) c)

Figure 2: a) Digital Elevation Model, b) land use characteristics, red areas indicate urban settlements, c) system plan for an urban settlement

The red arrows in Figure 2c indicate possible points of interaction between the urban and the rural system. However, only sewer overflows are marked with an arrow here. The overflow discharges are added to the streamflow in a grid of the natural system, which means that every overflow building is assigned to a certain grid cell. Further interactions concern the modification of surface and subsurface flow patterns, where some assumptions have to be made. E.g. the interflow process underneath urban areas is "deactivated" in the according grids in the rural model; hence only vertical flow processes are considered. Overland flow from rural areas that runs into an urban settlement will then be processed according to the flow patterns given in the urban system (Figure 2c). Leaching of pipes or infiltration of water into the sewer system is neglected since it is hardly not to quantify on the catchment scale.

5.2 Spatial and time scale integration

When combining models, scaling is a major issue. As mentioned above, different models operate in different scales and hence aggregation procedures often are needed for model coupling.

In the described modelling system no aggregation has to be carried out for the spatial integration, which means that every model can keep its model structure. However, the basic overall model structure used, is the grid cell. Shown in Figure 3a is a natural catchment with a portion of urbanized area depicted in grey. It needs to be mentioned, that the outline of the urban area is given through the edges of the grid cells. Hence, the only restriction for a good representation of the outline of an urban area is the size of the grid cell that has to be chosen appropriately. Figure 3b shows the urban area only, extracted from the natural area, also indicating urban sub-catchments. The sub-catchments will then be put in order by means of a flow pattern plan within the urban model. This is shown in Figure 3c. Here, the grey circles denote points, where sewer network buildings, such as sewer overflows, retention basins, branchings etc. can be located.

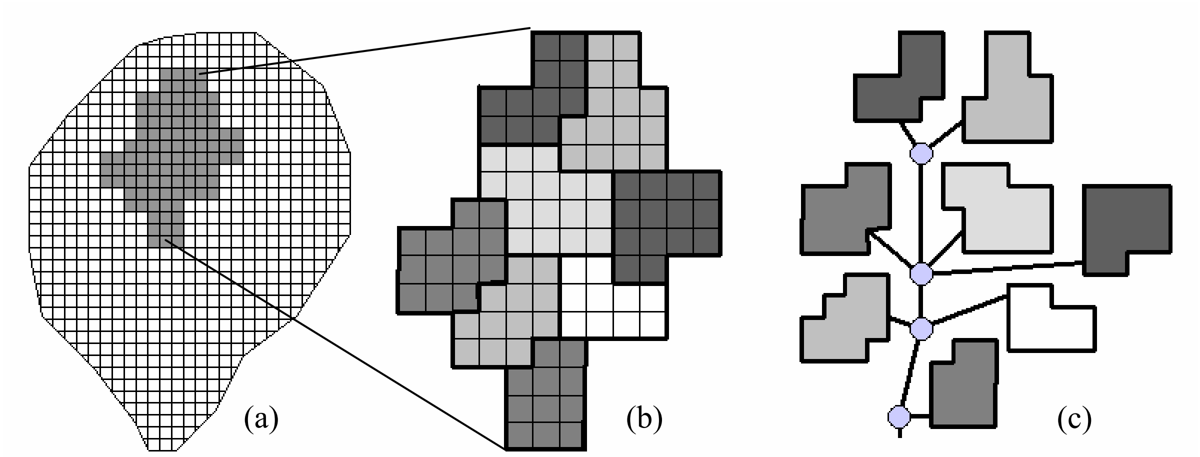


Figure 3: spatial integration of urban sub-catchments in the grid structure

A theoretically optimal solution for time scale integration would be to use a constant small time step for urban areas and a variable time step for natural catchments. However, this solution is not feasible due to scaling effects of the model parameters of the natural hydrology model (see for example [17). Hence, the model offers two practicable solutions for time scale integration. The first solution is using the same time step within both models. 5, 10 or 15 minutes can be chosen. A larger time step would not permit an appropriate representation of the dynamics of the urban system. However, using such a small time step for the natural hydrology model makes calibration more difficult and slows down computational speed. The second solution, using a constant 5-minute time step for urban systems and a multiple of this time step (e.g. 30 min or 1 hr) in natural systems, is more elegant. However, the major disadvantage of this method is that discharges from urban areas have to be averaged over the larger timestep of the natural catchment model and will therefore be dampened.

5.3 Description of submodel interactions

Points of interactions between the models are defined by GIS maps. The GIS map indicating the location of sewer network buildings defines where discharges from urban areas will be assigned to a single grid cell of the natural hydrology model (indicated in Figure 1). Here, discharges from wastewater treatment plants, sewer overflows and separate sewer systems are considered. Hence, total discharge within the natural channel is made up of natural base flow, dry weather flow from the wastewater treatment plant and discharges from sewer overflows during heavy rain events. The total discharge in the natural channel is then routed to the outlet within the natural hydrology model.

Other points of interactions are defined by the GIS map indicating the location of the urban sub-catchments. Whenever the natural catchment model (bottom layer) calculates overland flow on a grid cell, that is associated to urban land use, the flow is transferred to the top layer during each time step, and is being routed according to the flow pattern of the urban model. This mechanism underlies the assumption that natural areas within urban areas (such as parks, playgrounds …) will add to the flow in the sewer network. However this mechanism assures, that overland flow will be computed by a soil moisture accounting scheme considering detailed processes of hillslope hydrology. Also when overland flow from natural areas reaches an urban grid cell, the natural flow pattern is rejected, and the flow is transferred to the top layer and being transported by means of the urban hydrology model. Whereas interflow processes play a role in natural catchments, they are neglected underneath urban areas, since it is assumed that interflow is hampered by buildings.

5.4 Climatic boundary conditions

Climatic boundary conditions for both sub-models are precipitation, evapotranspiration and temperature. The distribution of rain can be carried out by means of Thiessen polygons, by several different inverse distance methods or simply by a topography dependent method, which relates the actual rainfall intensity to the elevation of the watershed. Evapotranspiration is divided into evaporation from interception storage, evaporation from the upper soil layer and transpiration from the root zone. In both sub-models, the temperature is used to trigger the snow routine, which is based on the snow-compaction method, as described by Knauf [18]. The temperature and hence the snow routine can be applied elevation dependent.

Depending on the location of the urban area within in the rural model, a mean precipitation value is determined for each urban sub-catchment. Depending on the degree of impermeability in the urban sub-catchment, the precipitation is apportioned between the urban and the rural area, as indicated in Figure 1. This results in a lower soil moisture and a diminished groundwater recharge rate underneath urban areas. The temperature of each urban sub-catchment is determined according to the mean sub-catchment height. To account for urban warming effects, a flat-rate value of 1°C is added to urban temperature values. Values for evapotranspiration are adjusted according to the land use by means of Haude factors [19]. The evapotranspiration value is then apportioned into evaporation and transpiration for calculations in the natural catchment model. In urban areas potential evaporation is used to empty depression storages.

6 MODEL APPLICATTION AND RESULTS

Model application will be shown by means of two examples, the Bieber and the Modau catchment. The Bieber catchment has a size of 39 km² and is located some kilometers east of Frankfurt (Germany). It contains two urban settlements, each connected to a separate wastewater treatment plant. The urban settlement area makes up 29% of the total catchment, having a portion of about 51% paved area. Characteristic for the catchment is the high portion of dry weather flow from the wastewater treatment plant within the natural channel.

The results of a 12 day simulation period of the Bieber catchment are shown in Figure 4. The solid line shows the total runoff from both rural and urban areas at the catchment outlet. The total discharge can be separated into several discharge components.

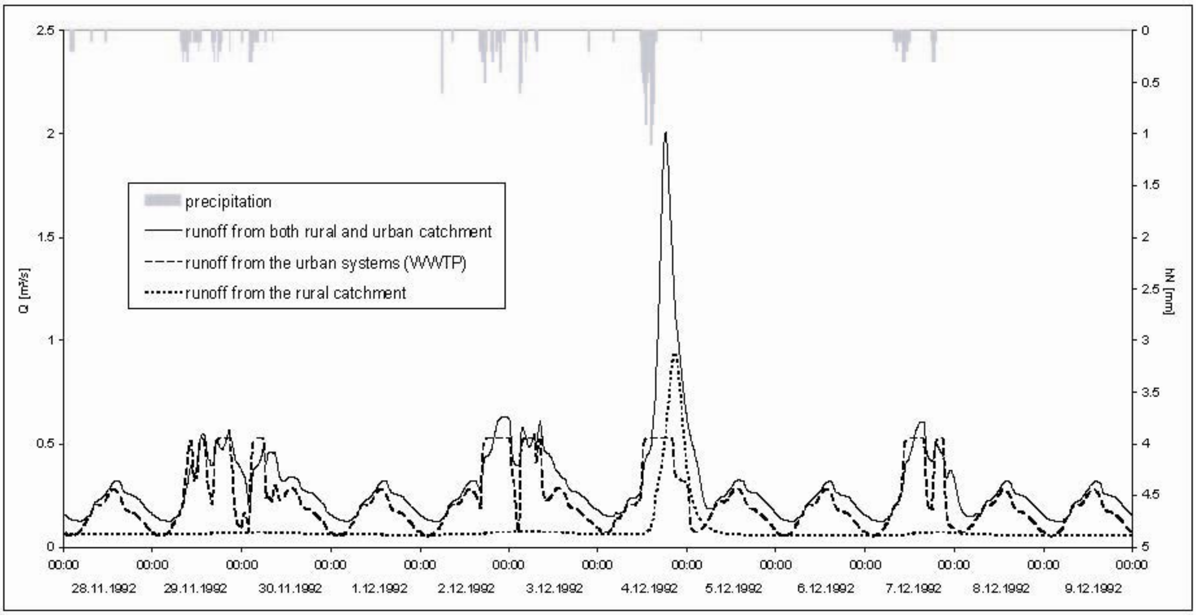


Figure 4: example modelling system result for a 12 day period

- The dotted line shows the runoff from the natural catchment. Here, no noticeable change can be seen for the smaller rainfall events before the 4th of December (Figure 4), as rainfall is absorbed by the soil.
- The dashed line shows the runoff from the two urban settlements, in this case the outflow from the wastewater treatment plants are shown. It can be seen, that the maximum influx to the wastewater treatment plants is limited to 0.5 m³/s. Also noticeable are the daily dynamics in the dry weather flow hydrograph.
- Not shown in Figure 4 is the discharge from the sewer overflows and retention basins, which however contributes to the total discharge (solid line) in the receiving stream.

As can be seen from the displacement of the hydrograph, especially under dry weather flow conditions, translation and retention effects in the receiving water are taken into account during transport of the total discharge between the location of the settlements and the natural catchment outlet. This means that the position of urban settlements within the rural catchment is of mayor importance and is represented correctly by the model.

The catchment of the Modau is 90.5 km² large and has a 15% portion of urbanized area. Most of the settlements are located relatively close to the catchment outlet. The catchment is located in South Hesse some kilometers south of Darmstadt (Germany).

The results of a 7-day calibration period are shown in Figure 4a. Simulation and measurement show very good agreement, which is affirmed by a Nash-Suttcliffe coefficient of 0.962. By discarding the urban settlements and replacing them with natural land uses, the effects of urbanization at the catchment outlet can be quantified (Figure 4b). It can be shown how the total discharge is made up of a flow from natural areas and a faster reacting hydrograph from urban areas. From the two hydrographs shown in Figure 4b, the emptying of the urban storage after a storm event becomes visible (see e.g.: 14.4.1994, 0:00 – 8:00 a.m.). By looking at different points within the river course, the effects of urbanization on river discharge can be traced back to its origins. This can not be accomplished by conventional catchment models, in such detail.

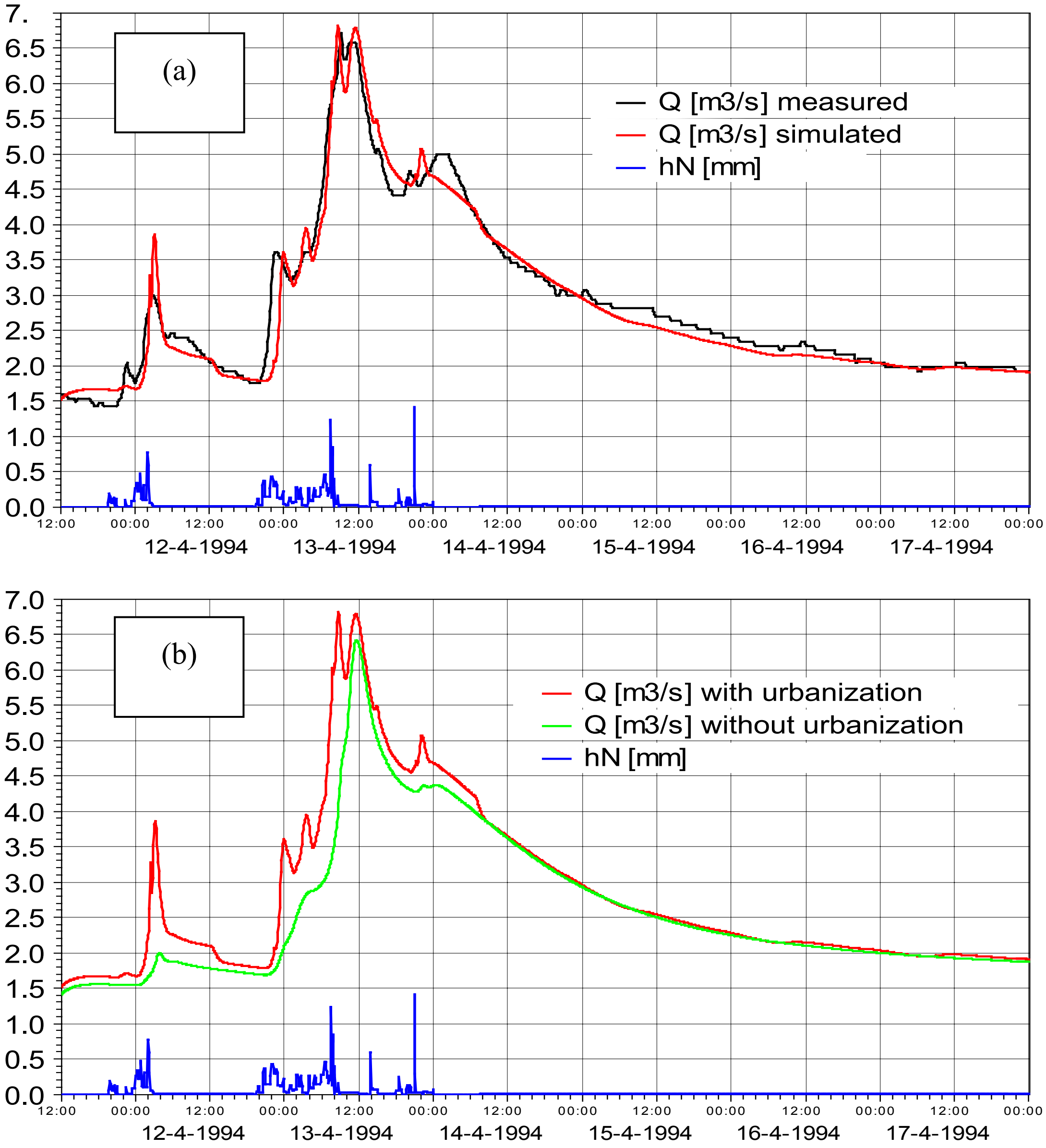


Figure 4: (a) Calibration period (b) Effects of urbanization

7 CONCLUSIONS

The integrated modelling system focuses on the simulation of highly anthropogenic deteriorated small catchments up to a size of 100 km² where discharge in the receiving water is partly or even mainly due to discharges from urban settlements. The modelling system is capable of computing runoff from both urban and rural systems in a detailed manner with consideration of interactions between the hydrologic systems. Hence, the mutual influences of the systems can be modelled. On the other hand, the water balance for each system can be calculated separately and influences on the water balance of each system can be quantified.

The modelling concept has proven to function well on a theoretical test case [20] and on two practical examples shown here. Model results are promising, but experience has shown that model calibration imposes a severe task, since both the urban and the natural hydrology model have to be calibrated in order to produce good model results. In this respect, another problem is the availability of detailed calibration data in high spatial and temporal resolution. However, once calibrated, the model is a helpful tool for integrated watershed modelling that allows simulation and evaluation of a bundle of different measures in both the urban and the natural system, or in a combination. Using a detailed representation of urban hydrology within the natural catchment hydrology model will clearly enlarge the significance of predictions on the effects of urbanization. This is a clear advantage over conventional natural catchment models.

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