IMPROVED RESOLUTION IN URBAN WATER MODELLING FOR LARGE RIVER BASINS

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ABSTRACT

The model ArcEgmo-Urban is being developed which aims at deterministic and spatiotemporal modelling of water, nitrogen and phosphorus fluxes from all urbanised areas of a river basin. Pollution loads are calculated for discrete urban patches and balanced on the level of hydrological sub-basins.
To process space-related data a Geographic Information System (GIS) is linked to the model. Information about urban land use and general characteristics of the river basin are based on digital maps, partly generated from remote sensing data. Aside from these, statistical data e.g. of population, sewer systems, waste water treatment plants etc. are used.
Storm water runoff from sealed surfaces is calculated as one input to the sewer network. Waste water is considered with its main sewer system, pumping stations and treatment plants. Finally, the discharge is balanced for discrete river sections. The modelling results can be provided user-defined for any level of spatial and/or temporal aggregation, e.g. matter balances for river basins, river sections or months.
By the deterministic model matter fluxes and major pollution sources can be identified within river basins and also their seasonal variations can be considered. Furthermore, the model allows the analysis of scenarios with variable social, climatic and technological conditions.

KEYWORDS

urban runoff modelling, integrated waste water modelling, river basin management, water framework directive, GIS, phosphor, nitrogen, point and diffuse source

INTRODUCTION

Following Art. 4 of the European Water Framework Directive (EU 2000) a 'good ecologic status' (respectively ‘good ecologic potential’) has to be achieved within a set time frame for all surface waters. Therefore, all significant impacts to river water bodies have to be identified on the basin scale as basis for programmes of measures (Art. 11) and river basin management plans (Art. 13). In terms of physicochemical water quality nutrients input from both, diffuse sources and point sources must be analysed (Art. 10). Whereas sophisticated models already exist for diffuse sources (Krysanova et al. 1997) only statistical analysis or annual values are so far considered with regard to point sources on the scale of river basins. For the model point sources are defined as discharge into a surface water body at discrete points from urban or industrial facilities and activities.

Therefore the model ArcEgmo-Urban being developed aims at a deterministic and spatiotemporal modelling of water, phosphorus and nitrogen fluxes from urbanised areas of the river basin. For discrete urban patches pollution loads are calculated and balanced on the level of hydrological sub-basins. This requires to combine approaches of urban waste water modelling with catchment-wide hydrological modelling. As basis serve earlier findings by e.g. Beichert et al (1996), Behrendt et al (1999), Hahn et al (2000) and Hahn et al (2002). With the deterministic model matter fluxes can be balanced and major pollution sources in the river basin can be identified in a higher resolution than that of annual balances.

DESCRIPTION OF THE MODEL

The model is based on the rain-runoff-model ArcEgmo© (Pfützner 2002). It is coupled with a Geographic Information System (GIS), generally ArcInfo/ArcView©, which allows to process the disaggregating of a study area into patches with homogeneous features of its parameters. From the topology and related attributes most of the parameters of applied component models can directly be derived or estimated.

One main criterion for the selected input data is their availability at the river basin scale. Starting from this the essential input data for modelling urban matter fluxes on a river basin scale are identified (Rödder and Geiger 1996). At least six coverages (thematic layers of a GIS containing spatial information and attributes) are used to organise all required data for the model:

- Urban catchments
- Sewer network
- Land use
- Soil
- River network and basin
- Elevation

The coverages link the specific spatial data with statistical data as follows:

Urban catchments: The coverage contains the spatial information about assuming homogenous urban sub-catchments defined by the user. Depending on the available information these are at least the municipalities itself. If more detailed data are available this also can be single districts or neighbourhoods. For each area, at least information related to population number, the type of sewer system, the percentage of inhabitants connected to the sewer system, and about the next important installation (storage tanks or treatment facilities) which may influence the area. Normally these data are available from public statistics.

Sewer network: The coverage contains important interceptors, all relevant storage tanks in the sewer network and all waste water treatment plants (WWTP). For every object the coordinates and the relation to other objects must be known. The coverage displays a simplified sewer network considering its main constructions only. For every object in these networks the volume, maximal flow rate and dimension of nitrogen and phosphorous reduction must be known. In case that several storage tanks with unknown position are linked to one urban catchment they can be virtually considered and simulated as a single tank (Rödder and Geiger 1996).

Land use: The coverage contains data about sealed surfaces considering different degrees of impermeability, the surface structure and the vegetation. The spatial resolution should be as detailed as possible.

Soil: The coverage contains data about the soil type and soil thickness. It is necessary for calculating rainwater infiltration and ground water recharge.

River network and basin: The coverage contains the river network and the river sub-basin boundaries.

Elevation: The coverage contains data from a digital elevation model. It allows to calculate the gradient of rivers or urban catchments, river sections or sewer networks.

As pre-processing homogeneous modelling patches are defined by using GIS algorithms. These so-called "elemental units" (ELU) are the smallest spatial units. For each ELU and each time step all relevant processes are modelled. Figure 1 shows the interaction between data and model.

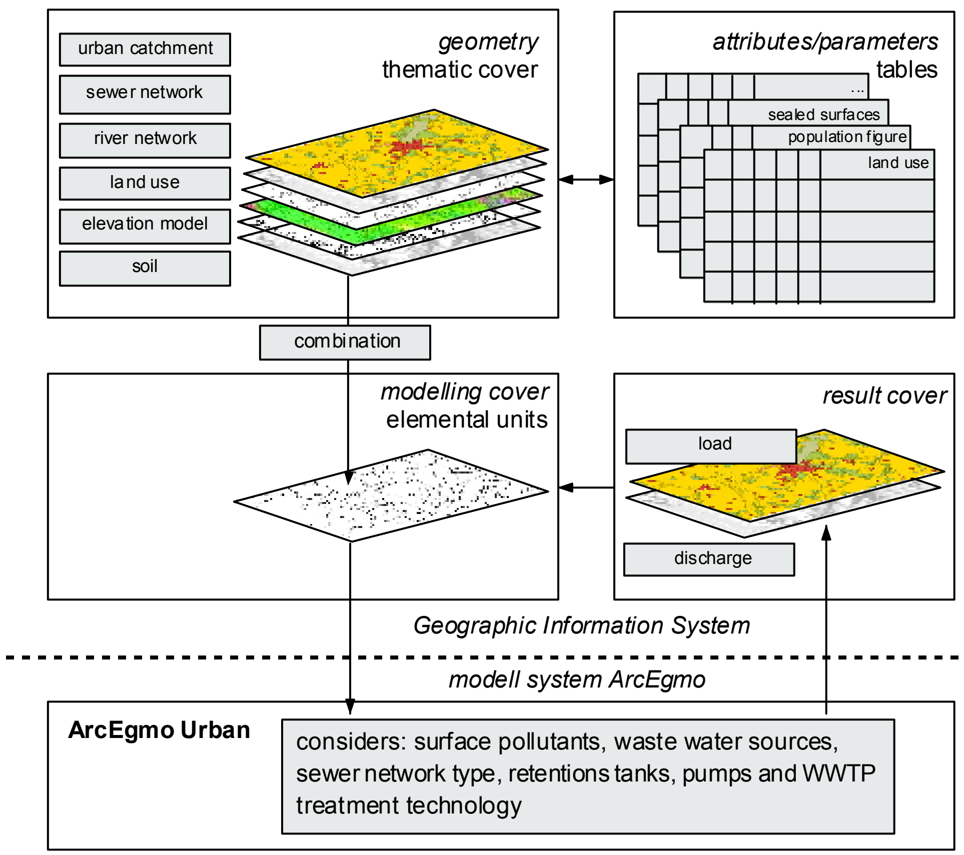

Fig. 1: Interaction between GIS-data and the model ArcEgmo-Urban

In the model the following phenomena are considered for each time step:

- Accumulation and wash-off of nitrogen and phosphorus deposits from the surfaces
- Storm water runoff
- Combination and propagation with urban waste water into different sewage network systems
- Treatment in WWTP

Finally, the discharge is added to the next body of surface water. The modelling results can be provided user-defined for any level of spatial and/or temporal aggregation, e.g. matter balances for river basins, river sections or months.

The mentioned phenomena are considered as follows:

Accumulation and wash-off of deposits
Land use is one of the most important factors for determining pollutants in urban storm water runoff. Therefore, different types of land use within an urban area can be considered, e.g. housing area, industrial areas, commercial area or roads. The intensity, the remobilisation, and the dilution effects of these accumulated matter deposition, and their transportation to the receiving water body, depends on the rainfall intensity and runoff volume during the rainfall period. There are two methods for calculating the nitrogen and phosphorus loads of the surface, which can be chosen by the user.

The first and basic method assumes that for a specific land use the average load per year is constant and thus the average nitrogen and phosphorus concentration of storm water depends only on the annual amount of storm water runoff (Sieker 1987).

$$c = \frac{P}{Ro_a}$$

c… average nitrogen or phosphorous concentration of storm water runoff
P… average annual potential load (nitrogen or phosphor)
Ro_a… average annual storm water runoff

The second method considers that depending on the surface type deposits accumulate in linear proportion to the time elapsed (Alley and Smith 1981).

$$\frac{dM}{dt} = PS - K_1 \cdot M$$

M… mass
PS… quantity of matter being deposited on the ground in time and space
K_1... pollutant "decay" factor

For the surface wash-off the model considers that the rate of erosion is proportional to the mass present on the surfaces.

$$\frac{dM}{dt} = K_2 \cdot M \cdot R$$

K_2... factor depending on the rainfall intensity
R... runoff intensity

Storm water runoff
For each ELU meteorological data from at maximum 4 meteorological gauging stations are used. The data are weighted in terms of distance and elevation. The specific precipitation, evaporation and storm water runoff for each ELU is calculated taking into account temperature, interception, depression storage, gradient and land use focused on sealing. Depending on the sewer network type and the fraction of impervious area connected to the sewer this runoff is subdivided into surface runoff, combined sewer system runoff and storm water system runoff.

Sewer network

Because of the large modelling scale, only the main system elements and WWTPs are considered. For each urban catchment at least information about the WWTP or the total retention volume is required. Each catchment is considered as homogeneous without taking into account single sewer reaches but the network type.

Separate sewer system

No detailed information about storm water discharge location is used for the model. Therefore, all storm water runoff and pollution loads are added within the "natural" river sub-basin. It is balanced at a virtual point by the sub-basin outlet. The runoff concentration is modelled with the isochrone method. That means that for each ELU a specific travel-time depending on gradient, distance and catchment size is calculated. The calculation is based on the strong correlation between the travel time on the one hand and the slope and catchment size on the other hand as Rödder and Geiger (1996) described. According to this approach, the maximum travel-time t_f can be estimated as:

$$t_f = a \cdot A^b$$

a, b.... gradient depending factor
A.... catchment size

The travel time for a specific ELU is directly proportional to the distance to the sub-basin outlet and the maximum distance in the sub-basin.

The sewage flow Q_s and sewage load is calculated from the population equivalents and data about industrial waste water Q_i and parasite water Q_p. Every inhabitant is assumed as constant source of nitrogen and phosphorus. The total amount of waste water is calculated from the specific drinking water consumption in the catchment. Industrial sewage is included taken into account measured values. Parasite water is considered as being a constant additional flow relative to the sewage flow Q_P/Qs. All water and load is transmitted to the WWTP without modification.

Combined sewer system

For the storm water runoff and pollution loads from each ELU a retention tank or WWTP is assigned. Thus the storm water and pollution load is "added" to a tank, pumping stations or WWTP after a specific travel-time, similar to the separate sewer system. Each tank is modelled as one fully mixed reactor and so waste water and storm water are homogenously mixed. If the flow rate towards WWTP exceeds certain critical value, the overflow is added to the closest surface water body.

Treatment in WWTP

Depending on the treatment technology the nitrogen and phosphorus loads are reduced by the WWTP. Up to now, the following assumption is applied:

The phosphorous reduction is considered in the model as follows:

- mechanical treatment: 12 %
- biological treatment: 30 %
- phosphorus elimination: 90%

The nitrogen elimination is included depending on the treatment technology as follows:

- mechanical treatment: 17 %
- biological treatment: 33 %
- biological treatment with nitrification: between 33% and 75%, depending on temperature
- biological treatment with denitrification: 75%

The elimination is related only to the nitrogen load from the households. The nitrogen load from all other sources – surface pollution, parasite water and industrial waste water – are only reduced in the model if they are combined with significant sources of organic load from these sources.
As an overview about the main structure Figure 3 shows the parameters and the modules of ArgEgmo-Urban.

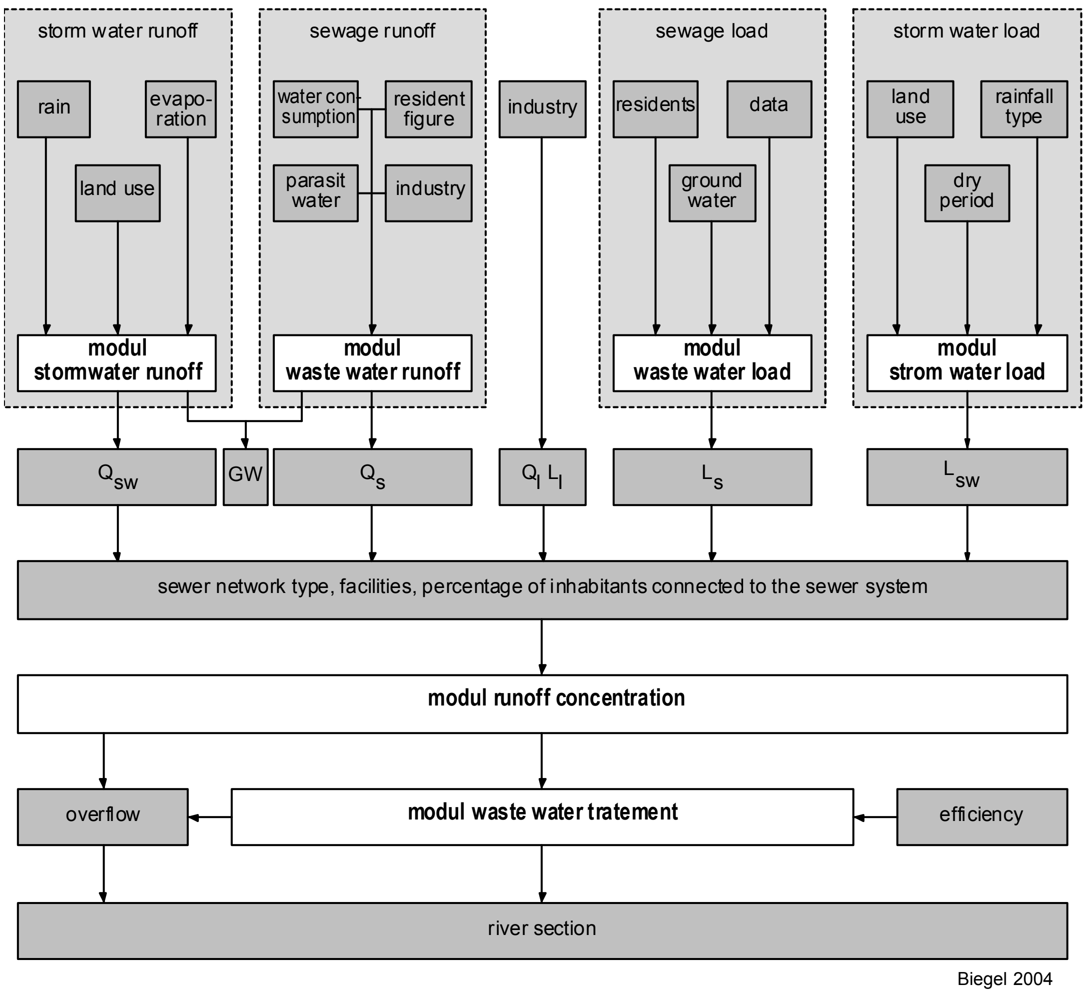

Fig 2: Input parameter and main structure of ArcEgmo-URBAN

DISCUSSION

The concept development of the model is done and the programming will be completed in February 2004. At the same time the input data for the pilot basin – the Havel river basin in Germany - are collected and pre-processed. The study area covers 13.932 km² and four countries (Bundesländer) with

2.528 river sub-basins according to the German "Länderarbeitsgemeinschaft Wasser" (LAWA). There are 828 urban catchments differentiated containing information about sewer network systems, percentage of inhabitants connected to the sewer system and about population density and figures. Data from all relevant 143 retention tanks and WWTPs are collected.

The degree of surface impermeability is differentiated with a new method using two Germany wide available digital maps (Weise 2003). It combines digital land use data characterised by high spatial resolution (Amtliches Topographisches Informationssytem) with airborne-land use data characterised by high thematic precision (Biotopnutzungskartierung). The result is a differentiated land use map as shown in Figure 3 for one catchment. In total 5,75 % of the study area is considered as impervious urban area.

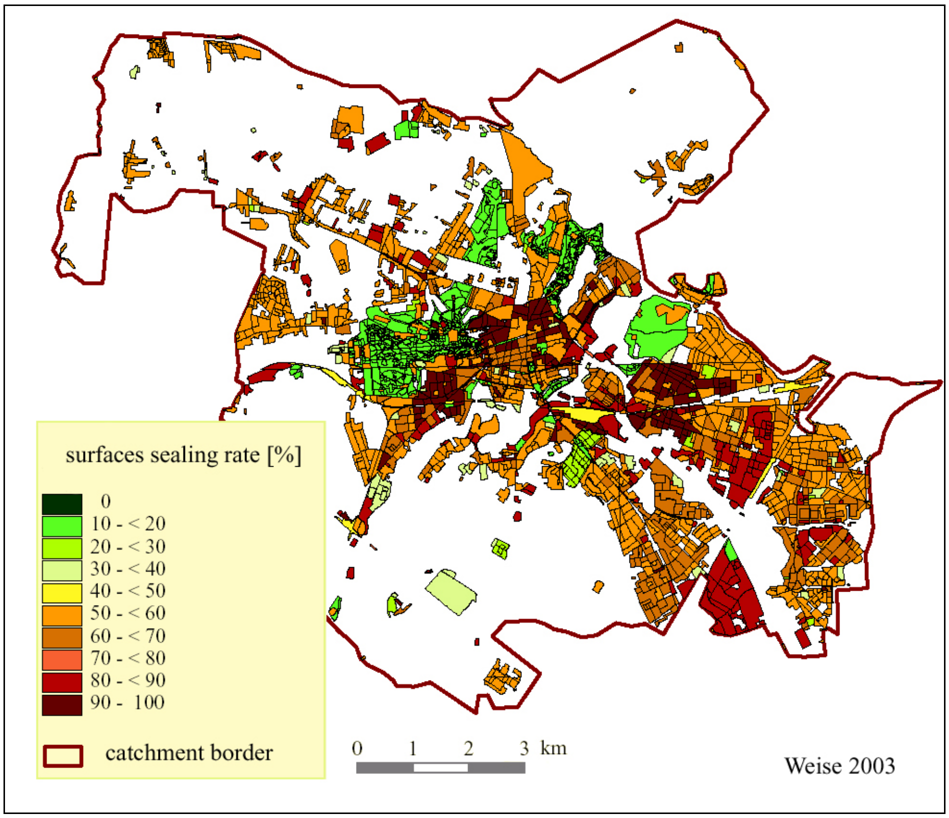

Fig. 3: Spatial resolution in one urban catchment after combining two different digital land use maps

For validation, weekly data from 35 river quality measuring points and daily data from three WWTPs are available. Without doubt the validation for a river basin is difficult because of incomplete data sets. There are more or less no data about storm water discharge from sewage systems and time. Data for WWTP with a high time resolution are mostly only available by the WWTP operator itself. Furthermore, the amount of retention, transportation, transformation and elimination of nitrogen and phosphorus within the river and input from diffuse sources is difficult to calculate. Therefore, validation is planned only for selected river sections and sub-basins. The chosen sections are located between two quality gauging stations in the river and include a WWTP providing daily data.

CONCLUSION

The aim of the model is to calculate urban pollution mass fluxes and loads of total nitrogen and phosphorus to be found as input into river basins. Given characteristics of the catchment, distribution of human activity and the structure of the sewer system need to be considered as mayor factors.

It is designed in a pragmatic way for the use in a river basin model with generally available data. Together with models for diffuse sources it will allow the identification of all significant impacts in water bodies as basis for programmes of measures and river basin management plans according to the WFD. By using the new model also variations between winter and summer conditions can be investigated. This is important for the identification of significant pollution sources, e.g. in the pilot basin Havel.

It is however possible, and even desirable, that the consideration of new experimental data and improved availability of data will lead to certain changes or added algorithms, and consequently to modifications of the current model.

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