ArcEGMO-URBAN – Hydrological model for point sources in river basins

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Abstract The new model ArcEGMO-URBAN aims at deterministic and spatiotemporal modelling of water, nitrogen and phosphorus fluxes from all urbanised areas of a river basin considering all potential sources. Pollution loads are calculated for discrete urban patches and balanced on the level of hydrological sub-basins. Modelling results can be defined by the user of any level of spatial and/or temporal aggregation, e.g. matter balances for river basins or river sections and years or months, respectively. To process spatial data, a Geographic Information System is linked to the model. Information on urban land use and general characteristics of river basins is based on digital coverages, partly generated from remote-sensing data. Moreover, statistical data, e.g. on population, sewer systems, wastewater treatment plants etc. are included. Stormwater runoff from impervious surfaces is calculated as one input to the sewer network. Wastewater is considered with its main sewer system, pumping stations and treatment plants. Finally, the discharge is balanced for discrete river sections. Modelling results attest ArcEGMO-URBAN its ability to realistically quantify matter fluxes and major pollution sources as well as their seasonal variation. This makes the model an applicable tool for the analysis of scenarios with e.g. varying population distribution or climatic and technological conditions.

Keywords integrated wastewater modelling; nitrogen; phosphorus; point source; river basin management; water framework directive

Introduction Article 4 of the European Water Framework Directive (EU, 2000) requires the achievement of a ‘good ecological status’ (respectively ‘good ecological potential’) for all surface waters within a set time frame. Therefore, all significant impacts to bodies of surface water have to be identified on the basin scale as a basis for programmes of measures (Art. 11) and river basin management plans (Art. 13). In terms of physicochemical water quality, nutrient input from both diffuse sources and point sources must be analysed (Art. 10). Whereas sophisticated models already exist for diffuse sources (Krysanova et al., 1998; Klöcking and Suckow, 2003), only statistical analyses or annual values have been considered so far with regard to point sources on the scale of river basins. For the model presented here, point sources are defined as discharge into a surface water body at discrete points from urban or industrial facilities and activities.

Against this background, a deterministic and spatiotemporal model should be developed which calculates phosphorus and nitrogen impacts from urbanised areas on the catchment scale. Due to its overall architecture and focus on urban water and matter fluxes it has been named ArcEGMO-URBAN. This model combines approaches from urban wastewater modelling with catchment-wide hydrological modelling. Earlier findings and developments provide a basis, i.e. Beichert et al. (1996), Behrendt et al. (1999), Wiese and Schmitt (1999), Franz and Krebs (2002) and Fuchs et al. (2003). The deterministic model approach should be able to balance matter fluxes and identify major
pollution sources in the river basin at a higher temporal resolution than that of annual balances.

**Description of the model**

The model is based on the hydrological model system ArcEGMO\textsuperscript{©} (Becker *et al.*, 2002) and uses its algorithms to pre-process the meteorological input data and to describe the rainfall–runoff process. It is coupled with a Geographic Information System (GIS), usually ArcGIS\textsuperscript{©}, which allows us to process the disaggregation of a study area into patches with roughly homogeneous features of its parameters. Most of the parameters of applied component models can be directly derived or estimated from the topology and related attributes.

One main criterion for the selected input data is their availability at the river basin scale. The essential input data for modelling urban matter fluxes on a river basin scale are identified in 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:** The coverage contains the spatial information about urban sub-catchments defined by the user and assumed to be homogeneous. Depending on the available information such a sub-catchment is not larger than a municipality. If there are more detailed data available it also can be a single district or neighbourhood. For each area the following information is required: population number, type of sewer system, percentage of inhabitants connected to the sewer system and next important installation (storage tanks or treatment facilities). Normally all data are available from public statistics. Beside these data, additional information about water consumption, industrial sewage, parasite water, air pollution (NO\textsubscript{x}) and groundwater condition (NO\textsubscript{3}-N) can be used in the model.

- **Sewer network:** The coverage contains important interceptors, relevant storage tanks in the sewer network and all wastewater 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 efficiency of nitrogen and phosphorus reduction must be known. In the 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).

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

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

- **Elevation:** The coverage contains data from a digital elevation model which allows a GIS-based calculation of the slope of rivers or urban catchments, river sections or sewer networks.

- **Soil:** The coverage contains data about the soil type and soil thickness. This is necessary for estimating rainwater infiltration and groundwater recharge.

During pre-processing, homogeneous modelling patches are defined by using GIS algorithms. These so-called “elemental units” (ELU) are the smallest spatial units of ArcEGMO-URBAN. All relevant processes are calculated for each ELU and each time step. The processes can be divided into stormwater runoff, accumulation and wash-off of nitrogen and phosphorus deposits from the surfaces, urban wastewater propagation in
the sewer network systems and treatment in WWTP. Figure 1 shows the interaction between data and model.

Stormwater runoff
For each ELU, meteorological data from up to four meteorological gauging stations are used. The data are weighted in terms of distance and elevation. The specific precipitation, evaporation and stormwater runoff for each ELU is calculated taking into account temperature, interception, depression storage, gradient and land use focused on sealing. The hydrological algorithms used are based on the ArcEGMO® concept (Becker et al., 2002). Runoff is subdivided into surface runoff, combined sewer system runoff and stormwater system runoff depending on the sewer network type and the fraction of impervious area connected to the sewer.

Accumulation and wash-off of deposits
Land use is one of the most important factors for determining pollutants in urban stormwater runoff. Therefore, different types of land use within an urban area can be considered by different matter deposition, e.g. housing area, industrial areas, commercial areas or roads. Remobilisation and dilution effects of accumulated matter depositions and their transport to the receiving water body depend on the rainfall intensity and runoff volume during the rainfall period. Up to now there are two different methods implemented for estimating the nitrogen and phosphorus loads from the surface.

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 stormwater runoff (Sieker, 1987).

\[ c_1 = \frac{P_1}{R_{oa}} \]  

(1)

c_1 \quad \text{average nitrogen or phosphorus concentration of stormwater runoff}
P_1 \quad \text{average annual potential load (nitrogen or phosphorus) for a certain land use}
R_{oa} \quad \text{average annual stormwater runoff}

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

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

(2)

M \quad \text{mass}
PS \quad \text{quantity of matter flux being deposited on the ground in time and space}
K_1 \quad \text{pollutant “decay” factor}

For the surface wash-off the model supposes the rate of erosion being proportional to the mass present on the surfaces (Alley and Smith, 1981).

\[ \frac{dM}{dt} = K_2 \cdot M \cdot R \]  

(3)

K_2 \quad \text{factor describing matter erosion}
R \quad \text{runoff intensity}

Urban wastewater propagation in the sewer network systems

Because of the large spatial modelling scale, only the main system elements such as interceptors, storage tanks and WWTPs are considered. For each urban catchment at least information about the existing total retention volume and existing WWTPs is required. Each catchment is considered homogeneous without taking single sewer reaches into account, but including general network properties such as slope and length.

Separate sewer system. No detailed information about stormwater discharge location is necessary for the model. All stormwater runoff and pollution loads are balanced within the “natural” river sub-basin. The discharge is assumed at a point near the outlet of the sub-basin. The runoff concentration is modelled with the isochrone method. This means that for each ELU a specific travel-time depending on gradient, distance and catchment size is calculated. The calculation is based on a strong correlation between travel time on the one hand and slope and catchment size on the other hand, as Rödder and Geiger (1996) described for urban catchments. According to this approach, the maximum travel-time \( t_f \) can be estimated as:

\[ t_f = aA^b \]  

(4)

\( a, b \) \quad \text{factor depending on elevation}
A \quad \text{catchment size}

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

The sewage flow \( Q_s \) and sewage load are estimated from the population equivalents, water consumption, data about industrial wastewater \( Q_i \) and parasite water \( Q_p \). Every inhabitant is assumed as a constant source of nitrogen and phosphorus. The total sewage flow is calculated from the specific drinking water consumption in the catchment. Industrial sewage is included taking measured values into account. Parasite water is considered
as being a constant additional flow relative to the sewage flow $Q_P/Q_s$. All water and load is transmitted to the WWTP without conversion processes, i.e. neglecting biological degradation.

**Combined sewer system.** For stormwater runoff and pollution loads for each ELU a retention tank or WWTP is assigned. Thus, stormwater and pollution load are introduced to a tank, pumping station or WWTP after a certain travel-time similar to the separate sewer system. Each tank is modelled as a fully mixed reactor, so that wastewater and stormwater are homogenously mixed. If the flow rate to the WWTP exceeds a certain critical value, the overflow is discharged to the closest surface water body. Due to the complex processes in the sewer network, the sediments accumulating in the sewer system are not modelled yet.

**Treatment in WWTP**
A specific efficiency factor has been defined for each wastewater treatment technology. This factor depends on both temperature and wastewater composition. Alternatively, specific factors for single WWTPs are applied where efficiency is known from operation. Reduced nitrogen and phosphorus fluxes are included as input into the receiving water.

**Balance**
Finally, the discharge and matter fluxes from sub-basins with their ELUs are balanced after mixing in the receiving water. The modelling results can be provided for any user-defined level of spatial and/or temporal aggregation, in space down to the ELU and in time down to the time step of the meteorological data.

**Pilot study – Havel River Basin**
ArcEGMO-Urban is presently being applied in scope of the research project “Management options for the River Havel Basin” (Schanze et al., 2005). The project deals with river basin management in the light of the European Water Framework Directive (WFD) and is funded by the Federal Ministry of Education and Research (BMBF). The project will provide a methodology for a complex modelling of water quality issues on various levels of the catchment. Within this model system ArcEGMO-URBAN deals with the water and nutrient fluxes from urban areas.

The Havel river basin is one of the largest tributaries of the River Elbe. The study area covers about 14,500 km$^2$ in four Bundesländer with 2,528 river sub-basins according to the Federal Association for Water (LAWA). There are 828 urban catchments differentiated containing information about population figures, sewer network systems and percentage of inhabitants connected to the sewer systems. Data on treatment technology and capacity from all relevant 143 retention tanks and WWTPs are included.

Because of special interest in stormwater runoff and its influence on the mass balance, the fraction of impervious surfaces has to be estimated as exactly as possible (Butz and Fuchs, 2003). In this pilot study two Germany wide available digital databases are used to differentiate impervious surfaces as a portion of all surfaces. A new method (Weise, 2003) combines digital land use data characterised by high spatial resolution (ATKIS) with remote-sensing land use data characterised by high thematic precision (CIR-BNK). The result is a differentiated land use cover as shown in Figure 2 for the City of Potsdam. In total 5.75% of the study area is considered as impervious urban area.

First modelling results of the application of ArcEGMO-URBAN are shown in Figure 3 for the City of Rathenow. The area of the catchment is about 120 km$^2$, including the city itself and some small villages around. Most of the inhabitants (26,400 = 90%) are
connected to a separate sewer system. There is one WWTP with a capacity of 36,000 population equivalents. The figure shows the loads of nitrogen and phosphorus for the year 2000. The graph “catchment Rathenow” includes loads from the WWTP Rathenow, stormwater and small private WWTPs. The graph “public statistic WWTP” refers to the annual load for the WWTP Rathenow published by the government statistic. This database has been used for balancing point sources on river basins up to now.

For this study case, the model estimation of the monthly nitrogen and phosphorus loads represents the urban impacts more realistically than the information contained in the annual mean values of the public statistics. The dynamics over the year and the stormwater influence on the loads are clearly visible but – due to the hydrological processes

Figure 2 Catchment surface characterisation by using two digital land use databases

Figure 3 First results of ArcEGMO-URBAN for the city of Rathenow in the year 2000
and changes in the treatment efficiency considered in the model – not directly proportional. Still, the assumed correlation between treatment efficiency and temperature seems to be too dominant and needs further investigation. Initial results indicate that phosphorus is the critical nutrient in this area. The next step will be a model test by simulation of urban catchments with separate sewer systems and verification of the simulated river impact on the basis of river quality measurements. For this step, weekly data from 35 river gauges and daily data from four WWTPs are available. Verification is planned for selected river sections and sub-basins located between river quality gauging stations and including a WWTP providing daily data.

Conclusion
ArcEGMO-URBAN combines simplified approaches of urban wastewater modelling with catchment-wide hydrological modelling. The new approach is aiming at a higher spatial and temporal resolution of estimated water and matter fluxes and loads of total nitrogen and phosphorus on the river basin scale. The design provides a river basin model that makes use of generally available data. Characteristics of the catchment, distribution of human activities and the structure of the sewer system and WWTPs are considered as major factors. Seasonal variations can be investigated and major nutrient sources can be identified.

First results illustrate the ability of the model to provide more realistic nutrient load estimations than those based on annual values. The next steps of research will be to compare modelling results for sub-basins with measurement results from river gauges. Validation studies will be used for further development. The final version of ArcEGMO-URBAN will constitute a new tool for identification of input from point sources on water bodies as a basis for programmes of measures and river basin management plans according to the requirements of the European Water Framework Directive.

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References


