

UNSATURATED ZONE AS THE KEY ELEMENT FOR BALANCING WATER AND SOLUTE FLUXES WITHIN THE URBAN WATER CYCLE

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ABSTRACT

Integrating groundwater into an urban water balance scheme requires the quantification of seepage in the unsaturated soil zone generated by different kinds of infiltration sources. These seepage processes are characterized by a large spatial and temporal variability of soils and infiltration sources and affect the urban groundwater in terms of quantity and quality. The development of approaches to obtain a simplified water and mass balances based on physical process description has been found essential to deal with the large complexity in urban areas. Assuming independent, individual infiltration sources in urban areas could reduce the effort of calculating infiltration processes in the unsaturated zone. The developed approach distinguishes between areal and point sources due to their one-dimensional and three-dimensional hydraulic behaviour respectively. The hydraulic conditions at the infiltration sources are a further distinction for areal sources. Respecting the transient conditions for the infiltration from the different sources was found to be very important for an improved and realistic water and mass balance at the groundwater table. GIS applications have been developed to manage the spatial parameter variability and the source distinction. Furthermore, the simplified approaches offer the possibility to prepare statistic analyses for risk assessment purposes. For instance, the balance of areal infiltration from precipitation based on yearly averages resulted in a unfavourable estimate of residence times and a misleading assessment of the impact on the groundwater.

Key words: unsaturated zone, residence times, flow and mass balancing, spatial parameter variability, GIS

1. INTRODUCTION

Integrating groundwater into an urban water balance scheme requires the quantification of seepage in the unsaturated soil zone generated by different kinds of infiltration sources. These seepage processes are connecting the usually considered urban water systems, i.e. supply and drainage systems, to the urban groundwater in terms of quantity and quality. In particular, the infiltration sources in urban areas are characterized by a large spatial and temporal variability of the major parameters determining water and mass fluxes to the groundwater. The spatial variations (horizontal and vertical as well) are the result of the variability of the soil properties and the source locations, whereas the temporal variability is generated by the hydrologic conditions and the related operational management of the urban water systems.

The major sources of infiltration in urban areas are infiltration of precipitation from permeable surface areas, groundwater recharge from flood plain areas during flood events, rain water infiltration from rain water infiltration ponds, septic tanks and leaks in the water supply pipe system as well as the sewer system (Fig. 1). The pollution load of the seepage water from the different sources is also very different and causes groundwater quality problems. Major pollution sources to be considered are contaminated flood water infiltrating in flood plain areas, contaminated rain water runoff collected in ditches or rain water infiltration ponds, e.g. from roads, and waste water infiltrating directly from the users, mainly in developing countries, or from leaking sewers, mainly in industrialized countries. The quantification of these infiltration processes in urban areas is a large challenge due to the large variability of the soils and the sources as well.

Within the EU-funded Joint Project AISUWRS (<http://www.urbanwater.de>) a methodology has been developed to couple the urban water systems to the urban groundwater by quantification of the infiltration processes in the urban soils. However, it is impossible to set-up a complex three-dimensional flow and transport model on the regional urban scale for such processes. Therefore, it is

strongly required to simplify the process descriptions in an appropriate way, by representing the important quantities and their dependencies in order to balance the infiltration at the entire urban area. Solute transport associated with that infiltration has to be quantified to assess the impact of urban areas on groundwater quality respecting transport and transformation processes in the unsaturated zone.

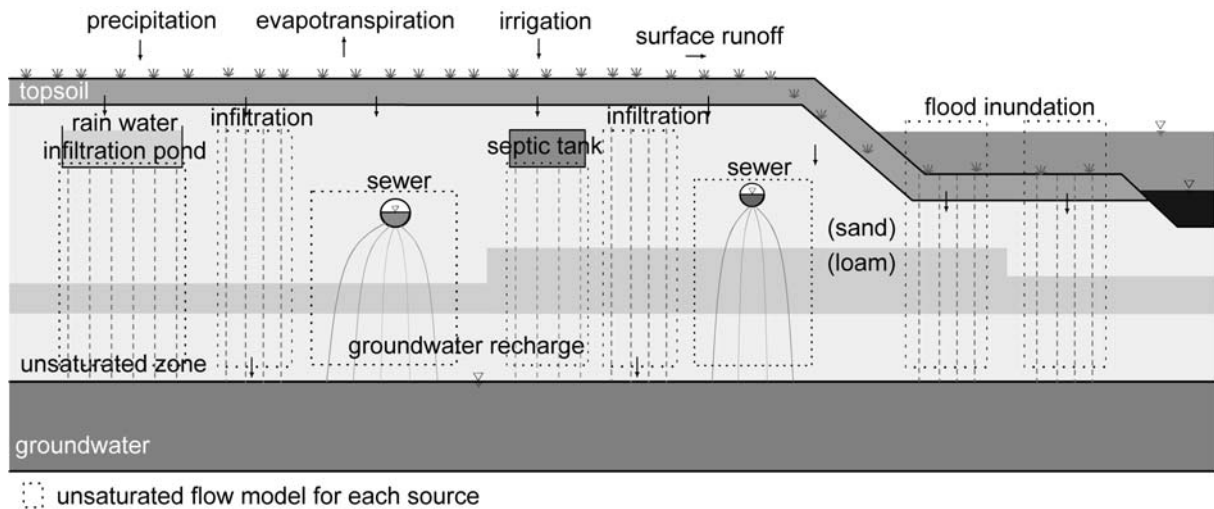


Figure 1: Different kinds of infiltration sources in urban areas.

2. BALANCING METHODS

Multiple single infiltration sources with independent unsaturated flow patterns were defined with separate and independent models for each source respecting the local conditions at each source location. The models were distinguished according to the hydraulic conditions and flow pattern. Flood water infiltration was described by areal sources with prescribed hydraulic heads. Infiltration from the topsoil generated by precipitation, from infiltration ponds or septic tanks were considered as areal sources with prescribed infiltration rates. Sewer and other pipe leaks were considered as point sources also with prescribed infiltration rates. Areal sources produce a one-dimensional flow pattern whereas point sources generate a three-dimensional flow pattern (Fig. 1). At each source location the selected model has to take into account different soil profiles, different distances between source and groundwater table and time-dependent hydraulic boundary conditions.

2.1. Areal sources with prescribed hydraulic head

Infiltration in flood plain areas is characterized by a large spatial variability of soil structure and related hydraulic parameters. This kind of infiltration is determined hydraulically by the flood water level. For the balance of water and solute fluxes from flood plains a one-dimensional approach has been developed respecting the topsoil and the unsaturated zone below (Fig. 2a). The spatially varying parameters and boundary conditions have been taken into account by defining several independent one-dimensional models. In the topsoil water flow is described by the analytical solution of Braud *et al.* (2005). Considering the existence of macropores in the topsoil defining preferential flow and transport paths infiltrating water is partly transferred directly to the unsaturated zone below. The unsaturated zone is assumed to consist of a homogenous sediment layer. A simple water volume balance has been developed to route the infiltration front through the unsaturated zone. Within the developed approach solute transport has been assigned with the water flow.

These concepts have been implemented in the model FWinf. The progress of the infiltration front in a two-layered soil calculated by FWinf was in good agreement with a comparable numerical simulation by HYDRUS1D (Simunek *et al.*, 2005). Also the saturation and the rise of the groundwater table could be represented well (Fig. 2b).

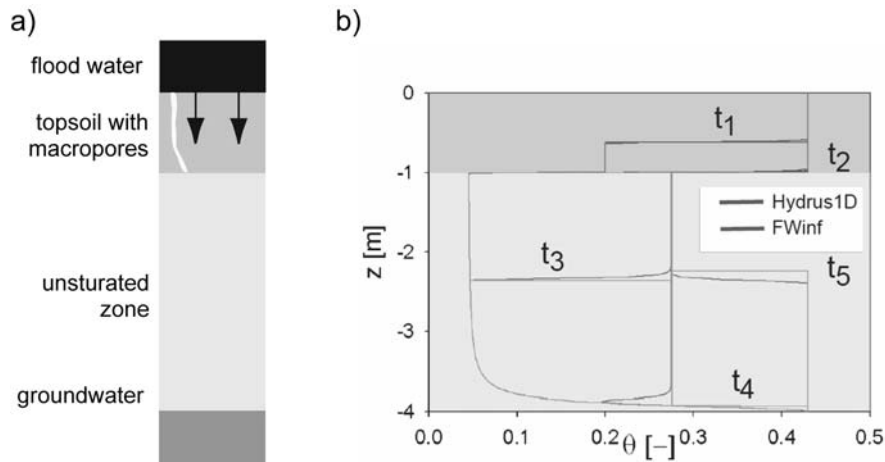


Figure 2: Modelling infiltration from flood plain areas, a) simplified unsaturated zone profile, b) computed progress of the infiltration front in such a profile without macropores.

2.2. Areal sources with prescribed infiltration rate

Other areal sources generate also an one-dimensional flow pattern and can be characterized hydraulically by prescribed infiltration rates. For steady state conditions an analytical solution considering several soil layers has been developed (Mohrlök, 2006) that describes the water content distribution within the soil profile above the groundwater table and can be used to calculate residence times additionally. Based on this analytical solution and a simple water balance scheme the model UL_FLOW has been developed (Mohrlök, 2005, Mohrlök, 2006) for the computation of infiltration and residence times under transient infiltration conditions. From the averaged change in water content an effective steady state infiltration rate for each time step is calculated (Fig. 3). This procedure enables the application of the steady state analytical solution for quasi transient computation while the time step length can be chosen without numerical constraints. By that, UL_FLOW is able to compute very efficiently residence times for a non-reactive tracer migrating through the unsaturated zone in dependence on the selected time step length. UL_FLOW has been validated by comparison with numerical simulations with HYDRUS1D.

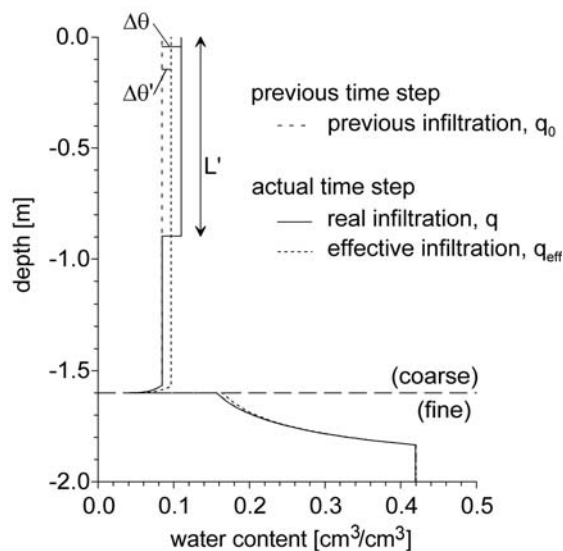


Figure 3: UL_FLOW concept of effective steady state infiltration rate to approximate transient infiltration (Mohrlök, 2006).

2.3. Point sources with prescribed infiltration rate

Infiltration processes from point sources like sewer leaks generate three-dimensional flow pattern with additional lateral spreading of the infiltrated water and contaminants. This pattern is dominated by a strongly non-uniform flow field and complex transport behaviour particularly under transient conditions. Furthermore, storage processes are expected to be more important in such a three-dimensional case. This kind of sources has been characterized hydraulically by infiltration rates.

However, for the estimation of groundwater recharge and solute fluxes from point sources no approach similar to UL_FLOW is available. Therefore, the transient flow and transport processes in the unsaturated zone caused by a point source infiltration were investigated by means of the recently developed numerical model WSTM (Bücker-Gittel *et al.*, 2003, Cata and Mohrlök, 2006). This model is based on the random walk method. The moving particles (mobile phase) represent a certain water volume and might be loaded additionally with contaminant masses. The water content and concentrations are derived by counting the particles and summing up the carried masses within cells (immobile phase). Mass transfer between the mobile and the immobile phase is calculated by a linear equilibrium relationship. WSTM has been validated by means of two-dimensional laboratory experiments.

3. RESULTS AND DISCUSSION

For each kind of infiltration source an example result is presented because the development of the several approaches is not yet finalized. However, these examples demonstrate the applicability of the models to represent the large spatial variability of the hydraulic parameters. The importance of respecting this spatial variability as well as the transient conditions of the infiltration processes is shown additionally. Because of the additional large parameter uncertainty the simple approaches particularly for the one-dimensional flow patterns have not been developed for deterministic modelling. Instead they enable Monte Carlo simulations and statistical analyses of the water and mass fluxes to the groundwater table from the different infiltration sources.

3.1. Flood plain infiltration

FWinf has been applied to assess non-reactive mass fluxes from flood plain areas to the groundwater for a certain flood event. The transient condition of the infiltration and the related mass transport show important differences according to the soil hydraulic properties (Fig. 4), the thickness of the unsaturated zone and the flood water depth at the specific location. Further, the influence of macropores that bypass mass fluxes at the topsoil and lead to a fast breakthrough at the groundwater table has been elaborated. The FWinf approach is a useful and efficient approximation of the infiltration processes from flood plains representing the variability of soils as well as flood water levels. It provides a tool for Monte Carlo simulations for risk assessment purposes.

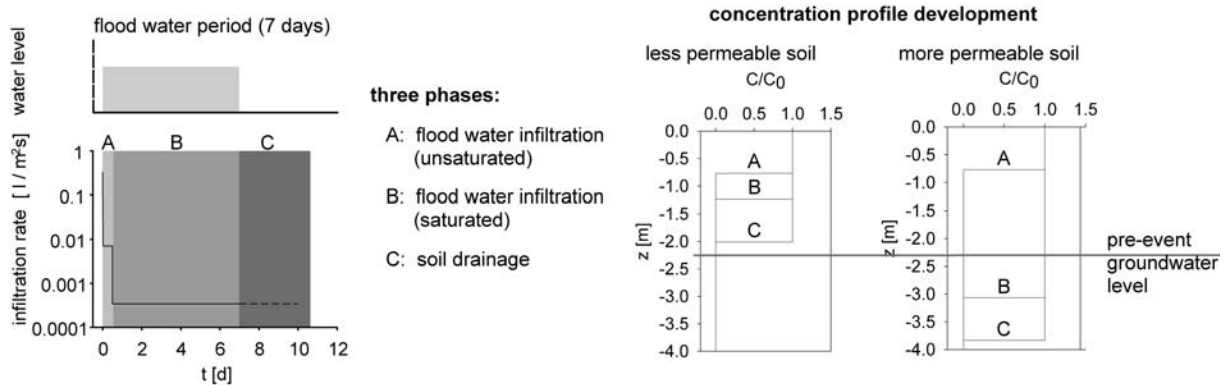


Figure 4: Concentration development in two different soils during the three phases of a flood event.

3.2. Areal infiltration from precipitation

The infiltration from precipitation results from the climatic water balance when precipitation is balanced with evapotranspiration and surface run-off. In the presented example a two-year infiltration time series has been applied to a soil profile with groundwater table at a certain depth. Times series of groundwater recharge and residence times for a non-reactive tracer were computed using UL_FLOW. The influence of different time step lengths on the tracer residence times was investigated. The obtained results were analyzed by means of statistical values of the computed time series (Fig. 5). The residence times considered as statistically representative were the minimum and the maximum values as well as the 10, 50 and 90 percentiles, threshold values that have not been exceeded in the respective portion of all time steps.

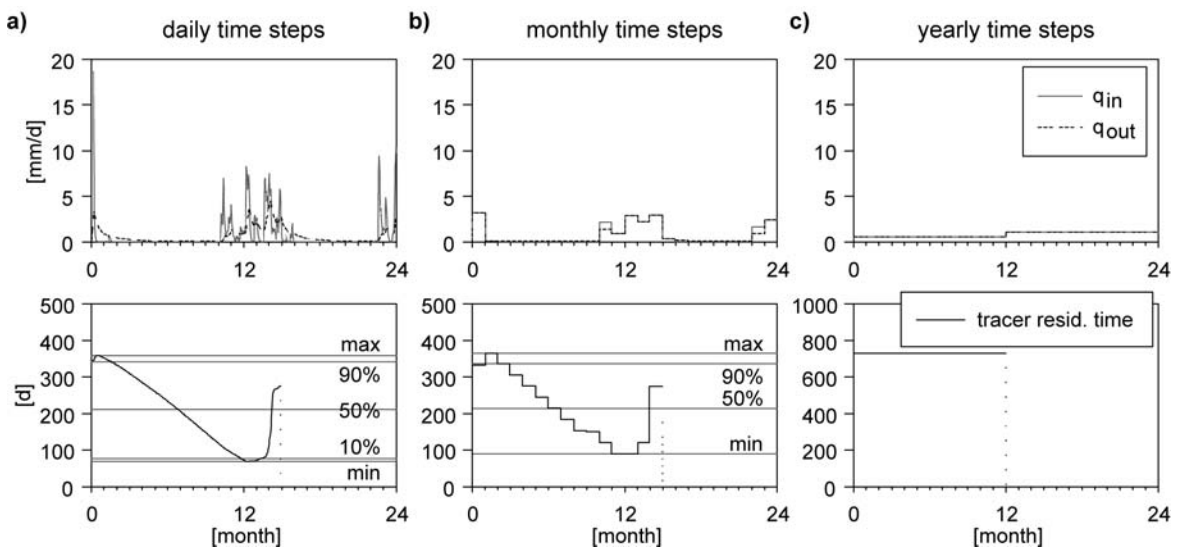


Figure 5: Computation of groundwater recharge q_{out} and tracer residence times using UL_FLOW for a two year infiltration time series q_{in} with a) daily time steps, b) monthly time steps, c) yearly time steps (Mohrlök *et al.*, 2007).

The temporal variations of groundwater recharge rates were similar for the daily and monthly time step results except the time resolution. However, the yearly time steps provide only an average over all that variation. Comparable results were found regarding residence times. No significant differences were found for the tracer residence times in the time series of daily and monthly time steps. This means that the statistics were similar regarding unsaturated soil processes which can reduce computational effort using UL_FLOW in integrated urban water balances. These time series break down after month 15 when the computed residence time exceeded the remaining time within the considered period. In conclusion, the yearly time steps, i.e. annual recharge rates, should not be used if temporal variations are of importance for the assessment of transport behaviour through the unsaturated zone. In particular, the calculated residence times based on yearly time steps could not be related even to any of the statistical values of the time series with daily and monthly time steps.

Mohrlök *et al.* (2007) demonstrated the applicability of UL_FLOW to an entire urban area respecting the spatial variability of soils and groundwater table depth. This simple approach could be adapted very simple to GIS database and therefore it is very flexible with respect to data availability.

3.3. Pipe leak infiltration

Flow and transport from point sources could only be investigated in terms of a very limited parameter study for a very short infiltration period since the computational effort for the application of WSTM was very large. The infiltration from a pipe leak source emplaced about 0.9 m above the

groundwater table into a homogeneous initially dry sediment was simulated numerically by varying soil types and infiltration rates. For reasons of symmetry only one quarter of the domain has been calculated to reduce computational effort (Fig. 6a). Adding solute concentrations of a non-reactive tracer to that infiltration enabled the estimation of residence times in the unsaturated zone beneath a pipe leak.

As point infiltration produces a three-dimensional flow field additional horizontal seepage flow occurs. Due to continuity requirement the water content is decreasing strongly with increasing distance from the point source. Even for large infiltration rates no completely saturated region exists beneath the source and above the groundwater table (Fig. 6a). Additionally, the volume affected by seepage depends on the infiltration rate as well as on the sediment properties. Furthermore, the capillary rise due to high saturation in the vicinity of the point source location was found to have a strong influence on the water content distribution.

In the case of three-dimensional flow patterns a certain amount of the infiltrated water is spread laterally with long residence times. This results in a transient behaviour and a long term storage of a certain portion of the infiltrated water. Therefore, no unique residence time exists even for homogeneous sediments. At the groundwater table a spatial distribution of residence times is obtained due to the different pathways and the different conditions along them (Fig. 6b). However, it was found that even for silty soils an early breakthrough was obtained after a few hours. Furthermore, for sandy sediments a steady state mass flux at the groundwater table was not obtained after one day due to large variances of the travel times along the different transport paths within the three-dimensional flow pattern (Fig. 6b). In general, very low concentration values were calculated due to strong dilution effects at the groundwater table.

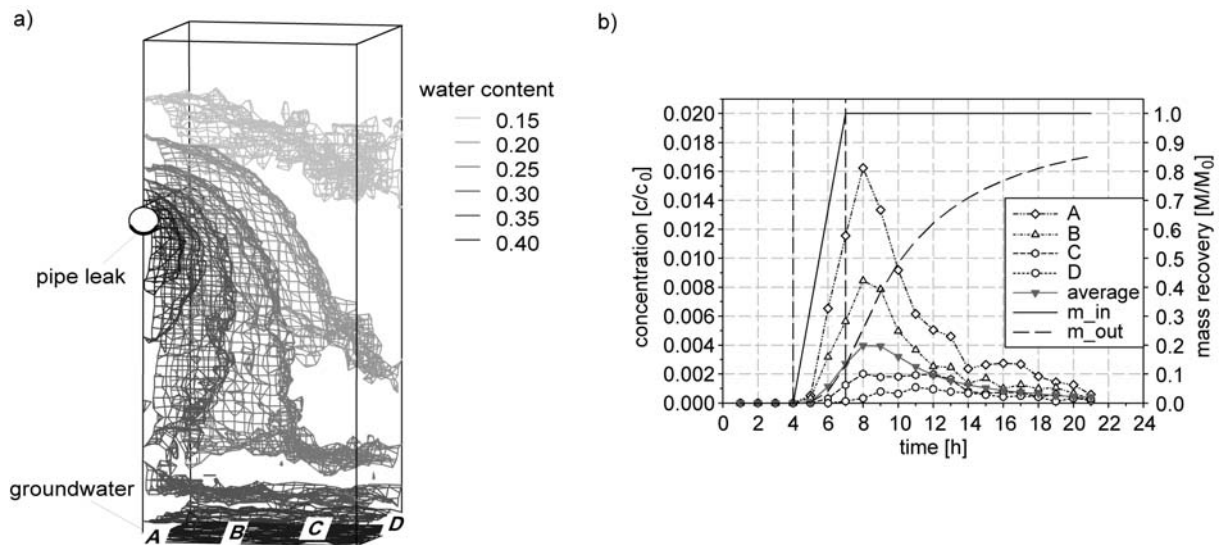


Figure 6: Computation of water content distribution (a) and tracer arrival at the groundwater table (b) for a sandy soil using WSTM.

4. CONCLUSION

A detailed quantification of the infiltration processes in urban areas is impossible due to the lack of data and the large variability and strong non-linearity of the important parameters, particularly the unsaturated hydraulic properties of the soils. The development of approaches to obtain a simplified description of the physical processes determining groundwater recharge and contaminant transport in urban areas has been found essential. Considering independent, individual infiltration sources in urban areas was the major simplifying assumption in order to reduce the effort of calculating infiltration processes in the unsaturated zone. The developed approach distinguishes between areal and point sources due to their one-dimensional and three-dimensional hydraulic behaviour respectively. The hydraulic conditions at the infiltration sources are a further distinction for areal sources.

In order to account for the spatial variability of the different parameters determining groundwater recharge and residence times GIS applications were developed and combined with data base manipulations at each source location for the data flow to the model and for the graphical presentation of the results. An additional classification approach based on the GIS is required to reduce significantly the number of models to be defined.

The application of UL_FLOW to a case study demonstrated the possibility to assess transport processes in the unsaturated zone of an entire urban area (Mohrlok *et al.*, 2007). Particularly, it was possible to avoid complex transport modelling by computing tracer residence times representing purely advective transport for the assessment of the impact on groundwater quality. For the representation of the strong daily variations in the infiltration rates monthly time steps associated with monthly averages have been found useful since several infiltration processes are running on that time scale. Steady state assumptions based on yearly averages should be avoided.

The results demonstrated the applicability and flexibility of simplified but physically based balance approaches in order to estimate groundwater recharge and tracer residence times in environments with large parameter heterogeneities. Such approaches are strongly required for the development of expert or decision support systems in the context of integrated urban water management. The development of a simplified balance approach for the complex behaviour of point source infiltration similar to the approach implemented in UL_FLOW is required. The mapping of statistical values derived from time series analyses provides additionally a tool to visualize the impact of different water management scenarios.

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