USING URBAN WATER CYCLE MODELS FOR IMPROVED URBAN GROUNDWATER MANAGEMENT

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ABSTRACT

Urban groundwater is not managed in a sustainable fashion in many cities worldwide due to a lack of information on the quantitative and qualitative impact of anthropogenic changes on urban aquifers. Numerical groundwater models are suitable tools to predict these impacts under different water management scenarios. They models do, however, require an appropriate specification of groundwater recharge beneath urban areas incorporating surface sealing, leakage from water mains and sewer systems, irrigation activities in quantitative terms as well as contaminant fluxes introduced by atmospheric deposition, road salting, fertilizer applications, wastewater leakage and single spot contamination. The paper demonstrates how current urban water cycle models can be used to generate the necessary input data for groundwater risk assessment using numerical groundwater modelling. Two frameworks for model coupling are presented, AISUWRS DSS deriving from a joint European-Australian research initiative and UGROW, which is developed as a part of UNESCO IHP activities. The application of these frameworks allows the impact assessment of various management scenarios, including decentralised infiltration and water sensitive urban design. Considering the large number of input parameters additional research is required in future to enhance reliability of the results.

Key words: groundwater recharge, integrated urban water management, numerical modelling, scenario analysis

INTRODUCTION

Problems in urban GW-management

Quality and quantity of urban groundwater resources are directly linked to urban water supply and drainage management concepts. However these interconnections are frequently not incorporated into the town planning process. Consequently, cities worldwide experience problems either with rising or falling groundwater levels often accompanied by serious groundwater contamination (Kofod 2000), (Lerner, 2003, Howard, 2006, Howard and Gelo, 2002, Wolf et al., 2006). Table 1 lists consequences and examples of changed groundwater quality or quantity.

The drivers and relevant processes causing these changes are manifold. While surface sealing in urban areas leads to increased surface runoff, it also decreases evaporation significantly. In addition, leaky water mains and leaky sewer systems must be taken into account. Leaky sewer systems which are not operated under pressure can also act as drains if groundwater levels are above the sewer bottom. Also irrigation of gardens and public open spaces can contribute significantly. The water balance might be changed further by decentralised rainwater infiltration systems, managed aquifer recharge, or the application of water sensitive urban design concepts (Barton and Argue, 2004) in general. There is increasing acceptance that the analysis should be based upon the urban water cycle concept (Mitchell and Diaper, 2005, Marsalek et al., 2006), if possible including beyond the water fluxes also fluxes of sediments, chemicals, microorganisms and heat attached to the water flows. However, integrated tools to incorporate this wide range of processes do not exist today, and the problem must be addressed by model coupling.

Table 1: Urban groundwater changes and their consequences.

Groundwater Status	**Drivers and causes**	**Potential Consequences**	**Example Cities**
Rising groundwater levels	Reduced pumping rates from urban aquifers (often as result of contamination), Leaky water mains, excessive irrigation in high-income areas.	Cellar & basement flooding, increased infiltration of groundwater into the sewer systems, increased construction costs for new buildings, etc.	London, Hamburg, Berlin (Kofod 2001), Moscow (Dhzamalov 2001), Barcelona (Kofod 2001). Buenos Aires, San Luis potosi (upper aquifer),…
Declining groundwater levels (in topmost ore deeper aquifers)	Over-pumping, Urban drainage systems	Water scarcity, land subsidence, damage to buildings, drying of groundwater dependent aquatic habitats, increased flooding danger in coastal cities (e.g.Venice)	Mexico City, Bangkok, Venice, San Luis Potosi (lower aquifer), Jinan, Bejing,…
Water **quality deterioration**	Contaminant spillages, lack of sewer networks, leaking sewer networks, atmospheric deposition, traffic, fertilizer & pesticide application, waste deposits	Health risks, usage restrictions, water scarcity, abandoning of wells leading to changed water balances	Almost every urban area. Example for fatal consequences: Lusaka.

MODELLING FRAMEWORKS

AISUWRS

Urban water cycle concept

The AISUWRS modeling approach links a chain of different models to draw a holistic picture of the urban water system and the associated mass fluxes (Figure 1). The data exchange between the different models is facilitated by the AISUWRS DSS front end (Burn et al., 2006). The AISUWRS urban water cycle thinking (see Figure 3) starts with water input from rainfall, and from public and private water supplies (imported water). With regard to the volume, the principal water input in humid climates is precipitation, occurring either as rainfall or snow. The rain falls either on roofs, paved areas, gardens or public open spaces. While most urban drainage calculations employ integrated runoff coefficients, these are very approximate and do not permit differentiation of pathways that could have different water quality implications (e.g. runoff from de-iced roads versus roof runoff). The most upstream AISUWRS model -UVQ- provides the ability to schedule the actual area demand of each of these surfaces for a neighborhood of similar water usage, providing more flexibility in simulation of alternative settings. For each surface type, the amount of runoff can be calculated and specified contaminant loadings added. In this fashion, the quantity and quality of water that infiltrates on-site through green space or local soakaways and the stormwater component in the separate pluvial or combined sewer system can be calculated. In combined sewer systems, the stormwater mixes with wastewater and leaves the area where it is generated via leaks, combined sewer overflows (CSOs) or the wastewater treatment plant. Rainfall percolating through unsealed areas like gardens or public open space enters the soil moisture store. Losses due to actual evapotranspiration can be calculated from climate parameters and the available soil moisture at a given time step. The excess water passes as seepage downwards to the groundwater body. For water entering the system via unsealed surfaces, contaminant contributions from sources like fertilizer application or atmospheric deposition are added.

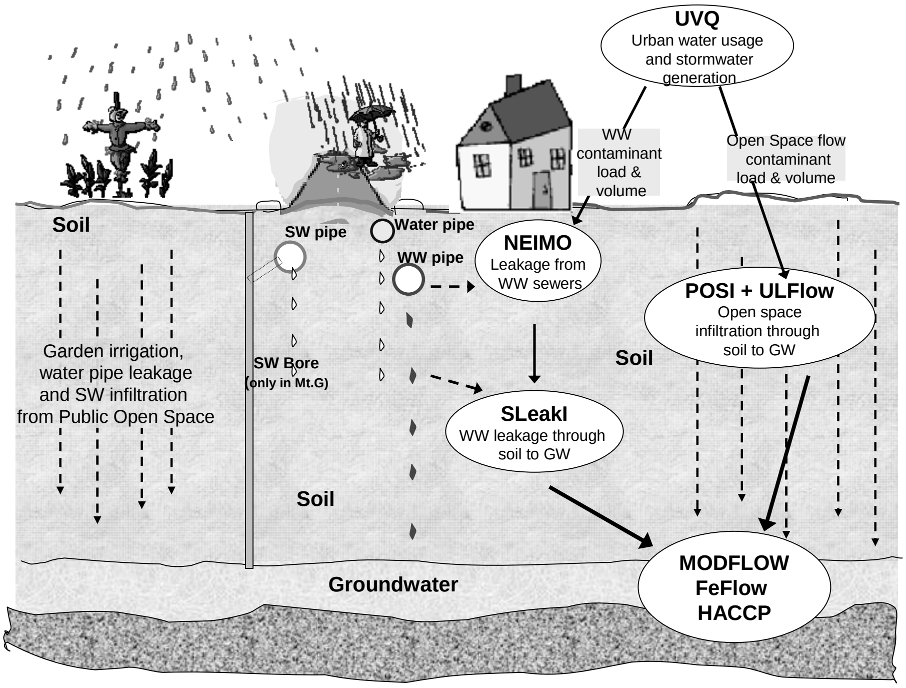

Figure 1: Models coupled within the AISUWRS framework (Burn et al., 2006).

UVQ

Urban Volume Quality (UVQ) is a conceptual, daily time step, urban water and contaminant balance model that simulates an integrated urban water system (Mitchell and Diaper, 2005). UVQ estimates the contaminant loads and the volume of water flowing through the water system, from sources (e.g. precipitation or mains inflow) to discharge points (e.g. drainage systems or groundwater). The model has been developed to provide a means for rapidly assessing the impacts of conventional and non-conventional urban water supply and stormwater and wastewater development options on the total water cycle (Diaper and Mitchell, 2006). The large number of processes included requires more than a hundred different input parameters. An overview is given in Table 2

Sewer leakage

The quantification of leakage from sewer systems is fraught with uncertainties, which stem not only from the lack of knowledge of sewer leak distribution but from the complex nonlinear and transient characteristics of the colmation or clogging layer at sewer leaks. In urgent need for an estimation tool which satisfy the information requirements of existing or future legislation, the NEIMO model was developed to quantify sewer leakage for each asset in a network based on pipe condition information (DeSilva et al., 2006). Considering the inherent uncertainty also a simplified Monte-Carlo approach might be sufficient, as demonstrated for the city of Rastatt, Germany (Wolf, 2006). NEIMO replicates the complexity of large sewer networks in a dynamic fashion, but with sufficient simplification concerning time stepping. Based on the results of the UVQ-model, NEIMO calculates the water level in the sewer pipe and applies it to a Darcy-based prediction of exfiltration and infiltration. The most sensitive input parameters for exfiltration are the defect size and position and the hydraulic conductivity and thickness of the colmation layer. For towns with an incomplete coverage of CCTV (Closed Circuit Television) visual sewer inspection records, generic curves are available which relate the defect size to pipe age, diameter and material. For the calculation of the infiltration rate, NEIMO requires the mean depth of the sewer pipe below the water table. The reliability of the combined predictions of UVQ and NEIMO is a key question to the method. Naturally, the few measured parameters are not sufficient to allow for a unique solution within the model calibration process.

Table 2 Summary of combined input data for UVQ and NEIMO and the reliability of the used information; modified (Wolf et al., 2007).

Module	Required input data	Unit	Data class				Reliability	Use for calibration
			A	B	C	D		
UVQ	Number of neighborhoods	[-]	x				High	
	Road area per neighborhood	[m²]	x				High	
	Public open space area per neighborhood	[m²]	x				High	
	Percentage of open space irrigated	[%]		x	x		Medium	
	Inhabitants per neighborhood	[m²]	x	x			High	
	Number of landblocks	[-]	x				High	
	Average roof area per landblock	[m²]	x				High	
	Average paved area per landblock	[m²]	x				High	
	Average garden area per landblock	[m²]	x				High	
	Percentage of irrigated garden area	[%]		x			Medium	
	Total water use per capita	[l/c/d]	x		x		High	
	Water uses for compartments (kitchen, bathroom, laundry, toilet)	[l/c/d]			x		Medium	exception
	Loads generated by indoor water use for each contaminant considered	[mg/c/d]			x	x	Low	yes
	Contaminant concentrations in groundwater	[mg/l]	x				High	
	Contaminant concentrations in imported water	[mg/l]	x				High	
	Contaminant concentrations in rainwater	[mg/l]		x			High	
	Contaminant concentrations in runoff (pavement/roof/road/first flush)	[mg/l]			x	x	Low	
	Fertilizer application to public open spaces	[mg/ha]			x		Low	
	Fertilizer application to gardens	[mg/m²]			x	x	Low	
	Maximum soil store capacity	[mm]		x	x		Medium	yes
	Soil store field capacity	[mm]			x		Medium	yes
	Maximum daily drainage depth	[mm]				x	Low	yes
	Roof area maximum initial loss	[mm]				x	Medium	yes
	Effective roof area	[%]			x	x	Medium	yes
	Drainage Factor Ratio	[ratio]				x	Low	
	Base flow recession constant	[ratio]				x	Medium	
	Contaminant soil store removal	[%]	set to zero				Low	
	Wastewater infiltration index (disabled, calculated with NEIMO)			x	x		Medium	
	Percentage surface runoff as inflow to sewers	[%]			x	x	Low	yes
	Garden trigger to irrigate	[ratio]			x		Low	yes
	Open Space trigger to irrigate	[ratio]			x		Low	yes
	Rainfall	[mm]	x				High	
	Potential evapotranspiration	[mm]		x			Medium	
NEIMO	Tree structure schematization of sewer network	[list]	x				High	
	Pipe diameters	[mm]	x				High	
	Pipe material	[-]	x				High	
	Defect area per asset	[m²]	x				Low	
	Defect distribution in radial sectors	[ratios]				x	Low	exception
	Elevation of the sewerage	[m a.s.l.]	x				High	
	Hydraulic conductivity of bedding material	[m/s]		x		x	Medium	yes
	Hydraulic conductivity of colmation layer at cracks	[m/s]		x		x	Low	yes
	Hydraulic conductivity of colmation layer at joints	[m/s]		x		x	Low	yes
	Thickness of colmation layer in different sectors	[m]		x		x	Low	yes

Unsaturated zone flow and transport

The unsaturated zone and especially the soil layer is a major protective shield for groundwater, providing vital scope for attenuation processes (adsorption, biologically mediated transformations, complexation, dispersion, filtration, hydrolysis, precipitation) to either eliminate or reduce the contaminant load reaching the saturated aquifer. Within AISUWRS, three models were developed, two to model contaminant transport and one model to estimate travel times in more detail. Detailing on travel times, the analytical model UL_FLOW based on one-dimensional steady state analytical solutions allows the estimation of conservative tracer residence times in layered sediments under varying infiltration rates (Mohrlok, 2006, Mohrlok et al., submitted). The two developed transport models distinguish between point and spatial sources (Correll et al., 2006). Infiltration beneath unsealed urban surfaces is described using the POSI model (Public Open Space Index). It assumes that infiltration occurs over a sufficiently large area and absence of lateral subsurface flow (such as in perched aquifers above the regional water table) such that the boundary effects can be neglected and the flow pattern is one-dimensional. On the other hand, the leakage from point sources is described using SLeakI (Sewer Leak Index). The necessary consideration of three dimensions around a point source was achieved with a fast Gaussian quadrature that gave an accurate evaluation of the integral of moisture content over the depth of the unsaturated zone and hence provides an estimate of the minimum residence time. Each model allows up to two soil type layers.

Numerical groundwater models

In urban areas, groundwater models may already exist since they provide answers to a range of typical questions:

- Predicting the impact of groundwater abstraction resulting from construction-stage dewatering, public or private water supply or geothermal groundwater circulation schemes
- Delineation of catchment zones
- Prediction of groundwater quality deterioration as a result of accidental spillages or ongoing urban activities
- Planning of remediation measures for contaminated sites
- Prediction of groundwater quality deterioration from defective sewer systems

Within the AISUWRS framework, different models were applied in the case study cities, corresponding to the preferences and experiences of the individual users and also according to pre-existing model applications. Considering the user-friendliness, codes with advanced pre- and post processing capabilities like the finite element package Feflow^{TM} (Diersch, 2005) or finite difference packages like Visual Modflow^{TM} were preferred.

UGROW

Within the framework of the UNESCO IHP programme, the development of UGROW is currently brought forward, also aiming at a more integrated modelling approach. UGROW unites infiltration processes, soil water balancing and groundwater modelling within a single user interface. It is also capable to represent sewer systems and water mains (Figure 2). Within UGROW, the Richards equation is solved for the unsaturated flow field by the UNSAT module. This information is handed to the UGROW application itself, being a numerical groundwater model involving finite element techniques. At this time however, modelling of multilayered aquifer or transport processes is only possible for simple cases. While UGROW has the advantage of a closer model coupling, it does not calculate the urban water balance itself but relies on the user specification of generated wastewater volumes or leakage rates.

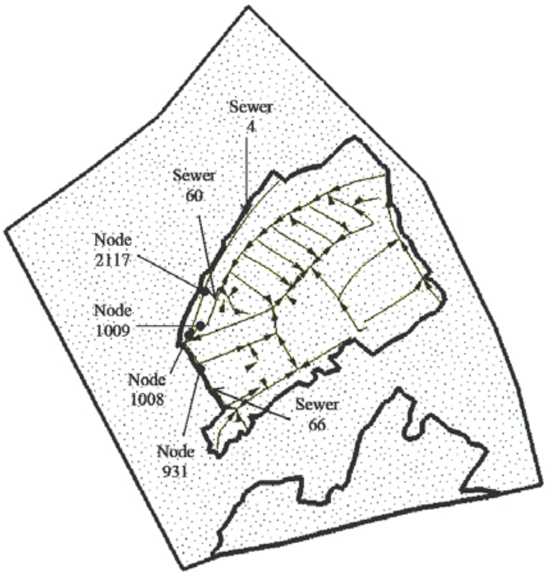

Figure 2: Joint representation of sewer network and finite element groundwater model mesh within UGROW for the Rastatt case study (Jaiprasart, 2005, Wolf and Schrage, in print).

CASE STUDIES

The entire AISUWRS modelling suite was applied to the cities of MtGambier, Australia (Cook et al., 2006), Doncaster, UK (Morris et al., 2006, Rueedi et al., 2005), Ljubljana, Slovenia (Souvent et al., 2006) and Rastatt, Germany (Klinger et al., 2006, Wolf et al., in print). A precursory application of only the UVQ model was recently performed for Hyderabad, India (Chapligin, 2007). Besides still unpublished case studies in Serbia, UGROW was applied to a subcatchment of Rastatt, Germany for validation purposes (Schrage et al., 2005, Schrage and Wolf, 2005, Jaiprasart, 2005, Wolf and Schrage, in print).

Only a few examples of the results obtained from the case studies are presented here. For each city, detailed urban water balance diagrams (Figure 3) were elaborated. Within the water balance diagrams, all water fluxes are expressed as $l/m^2/a$, equivalent to mm/a. As an example, it enables to understand the potential of using runoff from roofs for additional groundwater recharge, in this case 127 mm/a roof runoff compared to 347 mm/a existing groundwater recharge. Figure 1 also shows the minor quantitative impact which leaky sewer systems have on the groundwater system in the City of Rastatt.

For each of the case studies, a minimum of four different scenarios was specified and estimated using the AISUWRS tools. Table 3 shows the impact of water sensitive urban design scenarios on different hydrogeological system components.

Table 3: Selected results from the scenario calculation in the four case studies

City	Doncaster	Rastatt	Ljubljana	MtGambier
Scenario	Increased rainwater usage	Increased rainwater infiltration	Increased rainwater infiltration	Greywater reuse
	Change compared to baseline scenario			
Imported water	-24.09%	0.00%	0.00%	-21.78%
Evapotranspiration	0.00%	3.11%	-5.83%	0.00%
Groundwater recharge	-4.72%	8.93%	40.64%	0.00%
Total surface discharge	-15.93%	-7.11%	-10.86%	-20.43%

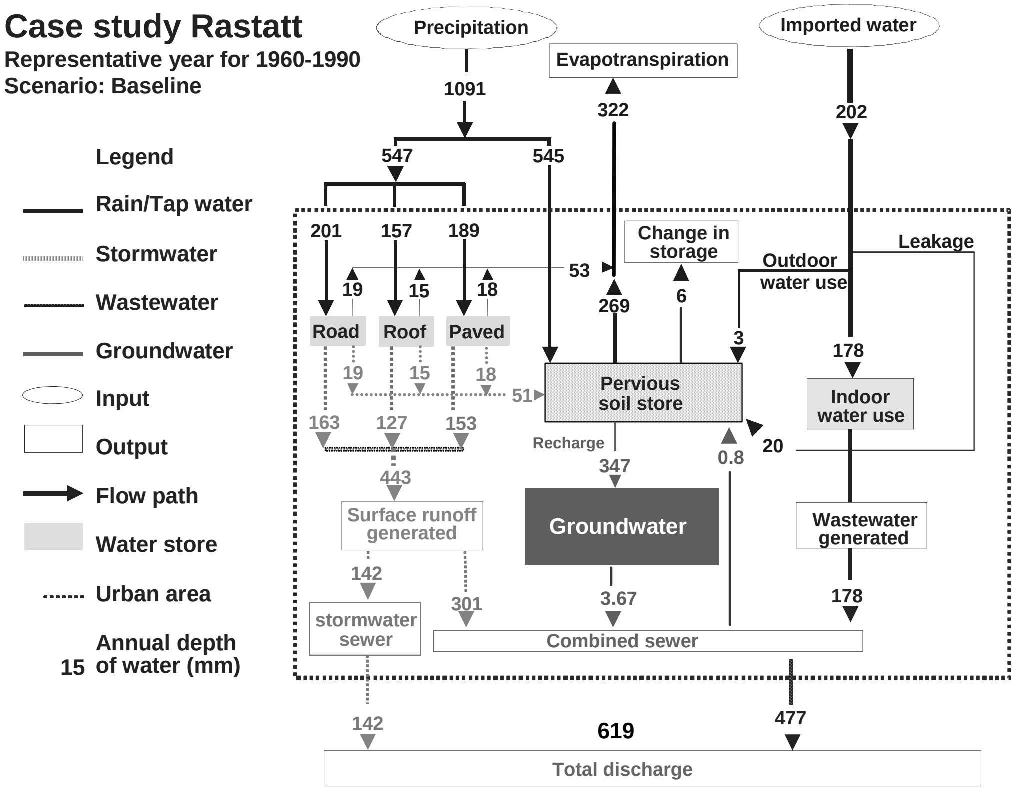

Figure 3: Water balance calculated for the baseline scenario for Rastatt (Wolf et al., 2007, Klinger et al., 2006).

The groundwater recharge information is passed to the groundwater models via a polygon shapefile. This necessitates the use of a geographical information system.

The application of UGROW to the case study Rastatt showed reasonably good agreements with the AISUWRS modeling suite. In addition, the validation with the commercially distributed FEFLOW® simulation software (Diersch, 2005) was successful. With regard to the calculation of groundwater recharge, sensitivity analysis showed that the correct assumptions must be ensured concerning the unsaturated zone parameters. As these vary significantly and over short distances in urban areas, they are not sufficiently known. As a result, the parameters are often hand-fitted for a case which does not allow a unique solution. However, the described parametisation problem is found for most of the unsaturated zone models in urban areas and may be minimized with model sensitivity studies. Furthermore, the application of UGROW to an urban subcatchment demonstrated that the groundwater model must encompass a much larger area than the sewer-watershed in order to predict the impact on the natural groundwater flow field reliable.

CONCLUSIONS

This paper provides a brief overview of recent model developments useful for a more integrated view of natural groundwater and anthropogenic influenced flows in the urban water cycle. However, in none of the individual urban water compartments, a complete list of existing models and approaches was given. Two model frameworks were presented which are able to couple anthropogenic urban surface water systems and groundwater.

The application of numerical groundwater models to urban areas is recommended for urban areas in order to detect current and future problems in terms of water quantity and quality. The necessary quantification of the groundwater recharge rates may be derived from holistic urban water balance models like UVQ, combined with models to predict the amount of sewer leakage. In cases where models which solve the soil water balance to calculate urban stormwater runoff are already in place, e.g. in Nantes (Rodriguez et al., 2003), they can also provide a good figure for urban groundwater recharge.

Holistic urban water balances should be established for urban centres as early as possible to allow for more sustainable investments into urban infrastructure and adapted water management schemes. It is recommended to employ integrated model frameworks for the analysis. Even considering the uncertainties included in these complex integrated models, the requirement for the formal description of the main water flows in the urban area already leads to a significant gain in system understanding and identifies gaps in the monitoring strategies. Furthermore, it requires the knowledge of different experts to be brought together into a single framework, thereby ensuring urgently needed inter-sectoral communication.

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LITERATURE

Barton, A. & Argue, J. (2004) Maximising water reuse in medium density urban development - An Adelaide case study. *WSUD2004*. Melbourne, Australia.

Burn, S., Cook, S., Meddings, S. & Wolf, L. (2006) Integrating it all: The Decision Support System. *Urban Water Resources Toolbox - Integrating Groundwater Into Urban Water Management* (eds L. Wolf, B. Morris & S. Burn), pp. 296. IWA, London.

Chapligin, B. (2007) *Assessment of the hydrochemical groundwater status and its relation to an integrated urban water system model based on an urban slum and a rural area in Hyderabad, India*. Diploma, University of Karlsruhe, Karlsruhe.

Cook, S., Vanderzalm, J., Burn, S., Dillon, P. & Page, D. (2006) A karstic aquifer system: Mount Gambier, Australia. *Urban Water Resources Toolbox - Integrating groundwater into urban water management* (eds L. Wolf, B. Morris & L. S. Burn), pp. 296. IWA, London.

Correll, R., Dillon, P., Miller, R., Miller, T. & Vanderzalm, J. (2006) Contaminant transport through the unsaturated zone: the SLeakI ans POSI models. *Urban Water Resources Toolbox - Integrating groundwater into urban water management* (eds L. Wolf, B. Morris & S. Burn), pp. 296. IWA, London.

DeSilva, D., Burn, S., Moglia, M., Tjandraatmadja, G., Gould, S. & Sadler, P. (2006) Network Exfiltrationand Infiltration Model. *Urban Water Resources Toolbox - Integrating groundwater into urban water management* (eds L. Wolf, B. Morris & L. S. Burn), pp. 294. IWA, London.

Diaper, C. & Mitchell, V. G. (2006) Urban Volume and Quanlity - UVQ. *Urban Water Resources Toolbox - Integrating groundwater into urban water management* (eds L. Wolf, B. Morris & S. Burn), pp. 296. IWA, London.

Diersch, H.-G. (2005) *Feflow 5.2 user manual* WASY Institute for Water Resources Planning and Systems Research Ltd., Berlin.

Howard, K. (2006) Urban groundwater policy concerns *4th World Water Forum*. http://www.iah.org/News/2006/WWF2.26%20Howard.pdf, Mexico D.F., Mexico.

Howard, K. W. F. & Gelo, K. (2002) Intensive Groundwater Use in Urban Areas: the Case of Megacities. *Intensive use of groundwater: Challenges and Opportunities* (eds R. Llamas & E. Custodio), pp. 35-58. Balkema.

Jaiprasart, P. (2005) *Analysis of interaction of urban water systems with groundwater aquifer: A case study of the Rastatt City in Germany*. Master Thesis, Imperial College, London.

Klinger, J., Wolf, L., Schrage, C., Schäfer, M. & Hötzl, H. (2006) A porous aquifer system : Rastatt. *Urban Water Resources Toolbox - Integrating groundwater into urban water management* (eds L. Wolf, B. Morris & S. Burn), pp. 296. IWA, London.

Lerner, D. N. (2003) *Urban Groundwater Pollution.* IAH / Taylor & Francis.

Marsalek, J., Jiménez-Cisneros, B. E., Malmquist, P.-A., Karamouz, M., Goldenfum, J. & Chocat, B. (2006) *Urban water cycle processes and interactions.* UNESCO, Paris.

Mitchell, V. G. & Diaper, C. (2005) UVQ: a tool for assessing the water and contaminant balance impacts of urban development scenarios. *Water Science and Technology*, **52,** 91-98.

Mohrlok, U. (2006) UL_FLOW: Simple Approach for Balancing transient unsaturated soil processes in urban areas by the analytical model *Urban Water Resources Toolbox - Integrating Groundwater into Urban Water Management,* (eds L. Wolf, B. Morris & S. Burn), pp. 296. International Water Association, London.

Mohrlok, U., Wolf, L. & Klinger, J. (submitted) Quantification of infiltration processes in urban areas by accounting for spatial parameter variability. *Journal of Soil Sciences*.

Morris, B., Rueedi, J. & Mansour, M. (2006) A sandstone aquifer: Doncaster, UK. *Urban Water Resources Toolbox - Models for Sustainability Assessment* (eds L. Wolf & B. Morris). IWA, London.

Rodriguez, F., Andrieu, H. & Creutin, J.-D. (2003) Surface runoff in urban catchments: morphological identification of unit hydrographs from urban databanks. *Journal of Hydrology,* **283,** 146-168.

Rueedi, J., Cronin A, Moon, B., Wolf, L. & Hoetzl, H. (2005) Effect of different water supply strategies on water and contaminant fluxes in Doncaster, United Kingdom. *Wat. Sci. Tech.,* **52,** 115-123.

Schrage, C. & Wolf, L. (2005) Testing and validation of the urban groundwater management model UGROW. *Unpublished Report for Unesco IHP-VI Urban Groundwater Model Group*, pp. 25. University of Karlsruhe.

Schrage, C., Wolf, L., Klinger, J. & Hötzl, H. (2005) Coupling urban drainage models with numerical groundwater simulations for integrated water management. *From data gathering and groundwater modelling to integrated management* Alicante, Spain.

Souvent, P., Vizintin, G. & Cencur Curk, B. (2006) A layered aquifer system: Ljubljana, Slovenia. *Urban Water Resources Toolbox - Models for Sustainability Assessment*. IWA, London.

Wolf, L. (2006) *Influence of leaky sewer systems on groundwater resources beneath the City of Rastatt, Germany - Abschätzung der Grundwasserbeeinflussung durch defekte Abwasserkanäle im Gebiet der Stadt Rastatt.* Schriftenreihe Angewandte Geologie, Universität Karlsruhe, Karlsruhe.

Wolf, L., Held, I., Klinger, J. & Hötzl, H. (2006) Integrating Groundwater into Urban Water Management. *Water Science and Technology,* **54,** 395-403.

Wolf, L., Klinger, J., Hötzl, H. & Mohrlok, U. (2007) Quantifying Mass Fluxes from Urban Drainage Systems to the Urban Soil-Aquifer System. *J Soils Sediments,* **7,** 85-95.

Wolf, L., Klinger, J., Hötzl, H. & Mohrlok, U. (in print) Quantifying Mass Fluxes from Urban Drainage Systems to the Urban Soil-Aquifer System. *European Journal of Soil Science*.

Wolf, L. & Schrage, C. (in print) Testing and validation of UGROW in Rastatt, Germany. *Urban Groundwater Management* (eds D. Pokrajac & K. Howard). Unesco, Paris.