Using the UVQ Model for sustainability assessment of the urban water system

J. Klinger, L. Wolf
Department of Applied Geology, Karlsruhe University
E-mail: klinger@agk.uka.de, wolf@agk.uka.de

Abstract
Groundwater in urban areas is gaining importance as a drinking water resource but it is severely endangered through impact of dense human activities. Therefore it is necessary to apply a new cost effective approach for urban water management including groundwater. Within the scope of the AISUWRS project, Assessment of the Sustainability of Urban Water Resources and Systems will be done with the help of computer tools (Burn et al 2003). One special focus is the UVQ model, which has been developed to estimate water flows and contaminant loads within the urban water system. UVQ was applied on a smaller scaled study area situated at the urban area of Rastatt/Germany. Performed flow measurements inside the sewer system have delivered a calibration and validation dataset. The small scaled application serves the determination of requirements and evaluation of suitability of UVQ for whole urban areas. This model is one major pillar in a model chain that is trying to identify the sources of contaminants, their flow paths and the sinks in the urban water cycle. UVQ is an urban water balance and contaminant balance analysis tool covering the water system from source to discharge point. The modelling is the integration of the potable supply-wastewater disposal network and the rainfall run-off network into a single framework (Mitchell 2000).

Key words: urban water cycle, pollution impact, urban groundwater, water balance

INTRODUCTION

With over 40% of the water supply of Western and Eastern Europe and the Mediterranean region coming from urban aquifers, efficient and cost effective management tools for this resource are essential to maintain the quality of life. Traditional water planning regularly concludes that future water demands will inexorably rise and eventually exceed water supplies available in any given location (Eiswirth et al 2002).

Within the scope of the AISUWRS project, with the main objective of an Assessment and Improvement of Sustainability of Urban Water Resources and Systems, a model chain of different modelling codes is developed and applied on different case study cities. Figure 1 shows schematically the configuration of the models, which will be executed successively. The whole model cycle realises almost all available data e.g. the geological setting of the respective study area, climatic conditions in time series, building development of the urban areas, land use of the different areas, sewer system, consumption behaviour of the citizens, etc. The model cycle allows the prediction of effects of urban infrastructure on groundwater contamination. The model chain starts with a modelling code, which is called UVQ. It comprises climate, land use and existing infrastructure and simulates the water and contaminant balance of an urban area. The simulated results, e.g. water flow given in daily time steps and the contaminant loads are plugged into the connected Pipe Leakage Model (PLM). The PLM calculates spatially distributed water levels in the sewer and also exfiltration rates from the sewer to the soil due to sewer defects recorded with CCTV (Burn et al 2003). The modelled leaking rates from the sewer system are incorporated in the following Unsaturated Flow Model (UFM). Beneath the input through leakage from sewer defects the actual unsaturated flow below open space area is calculated. To estimate the fluxes of reactive solutes and pathogens that are expected to reach the aquifer from leaks in sewers and storm water an Unsaturated Flow Model (UFM) is linked (Burn et al 2003). The modelled data from the different codes will then be implemented into the Saturated Flow Model and the Saturated Transport Model (SFM, STM).

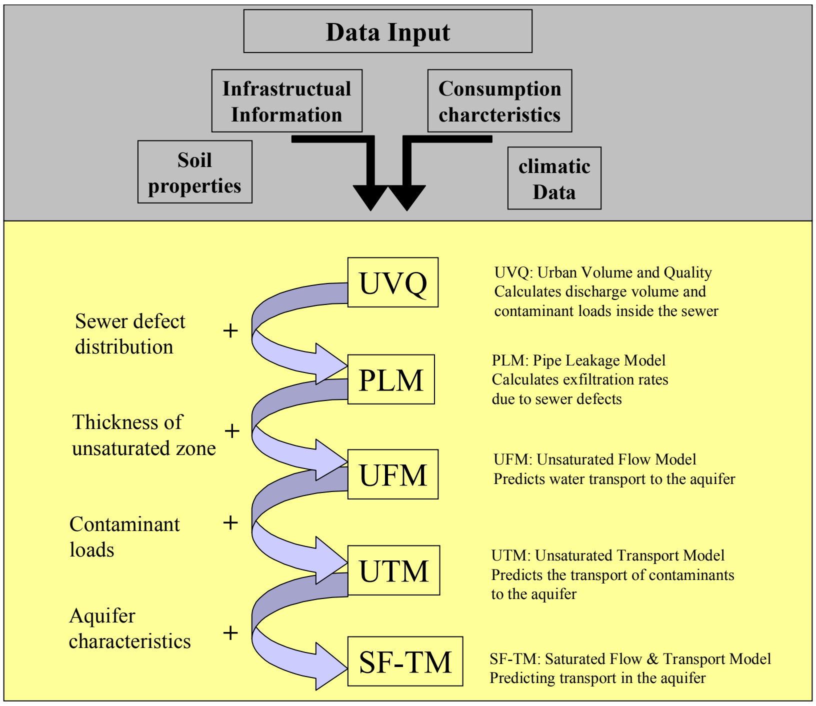

Figure 1: Model chain

The attention in this paper is turned in particular on the application of the UVQ code on the case study city Rastatt.

METHODS

UVQ - Conceptual representation -

The UVQ model used in the project represents water and contaminant flows through the existing water, wastewater and storm water systems from source to discharge point. The modelling approach taken in UVQ is the integration of the potable supply-wastewater disposal network and the rainfall-runoff network into a single framework. This affords a more holistic view of the urban water system and offers the opportunity to investigate alternative scenarios (e.g. water reuse, etc.) (Mitchell and Maheepala 1999, Mitchell 2000). UVQ operates on several spatial scales (land block, neighbourhood and study area) with the primary function to carry out what-if scenarios of traditional and alternative urban water supply and disposal schemes. The model receives input from both precipitation and imported water, which passes through the system, calculates the output in form of evapotranspiration, storm water, or wastewater. UVQ can store storm water and wastewater separately and utilize them as supply sources for water applications according the users specifications.
For the **conceptual representation** (see Figure 2) the model includes processes of interception, depression storage, soil infiltration and soil drainage. Pervious surface runoff occurs alongside the ‘introduced’ processes of pipe infiltration and exfiltration, unplanned storm water inflow and impervious surface runoff. Input quantities into the storm water drainage network are not only derived from rainfall, but also include contributions from the reticulation system through outdoor water use (Mitchell et al. 2000).

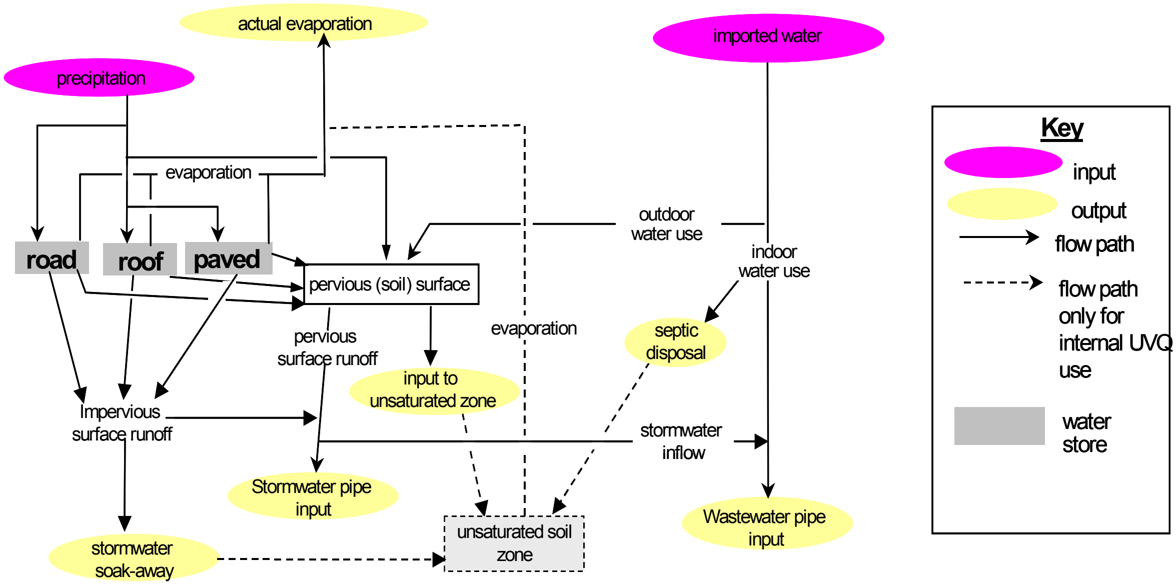

Figure 2: Conceptual representation of the urban water system. (Mitchell et al. 2000)

For the contaminant balance there are two types of sources implemented. The first are sources like rainfall or snowfall events with a mean concentration. The second types are the indoor water use contaminant sources (e.g. kitchen, bathroom, laundry and toilet). The indoor water use sources are assigned a contaminant load, expressed as mg/person/day. The use of contaminant load rather than event mean concentration allows the model to account for changes in water demand or quality of water used within the house on the contaminant loads and concentration in the wastewater (Mitchell et al 2003).

Input Data set

The UVQ offers the possibility to enter in highly sophisticated data sets but also accounts for poor databases of same investigation areas by providing characteristics of the study area. The data input is specified for each neighbourhood, which comprises land parcels, paved areas, roads, open space area, etc. The ascertainment of different neighbourhoods will be done due to homogenous criteria. A general separation will be done between areas like residential properties, commercial areas, industrial areas, etc. For each of these neighbourhoods information about the land use, applicable indoor and outdoor water demands, infiltration and exfiltration rates, if available, will be implemented. Further information about the occupancy per land block or allotment is needed as well as area size of the allotments and the areas that are covered by paved area, garden area, roof area and open space area (Mitchell et al 2003).
The input concentrations of the contaminants have to be entered on neighbourhood scale which assumes that contaminant input is the same for every household inside the neighbourhood. Four contaminant sources can be specified: bathroom, toilet, kitchen and laundry. For contaminant loads from impervious areas different loads are specified for road, paved or roof area runoff and further loads from e.g. fertilizer, rainfall, etc.
If local data are not available contaminant loads and concentration can be applied from international literature. Available information from case study sites describing output flows or concentration will then provide a basis for model calibration.

Output data set

Data output from UVQ provides details of water flows and quality from land blocks, neighbourhoods and the whole study area. However, as contaminant input data is usually in form of the mean concentration or Event Mean Concentration (EMC) the validity of reporting daily contaminant outputs is limited, therefore contaminant balance values are reported on a monthly or yearly basis at different scales. The contaminant loads output by UVQ are the first step in assessing the impact of water systems on the environment, as they should be interpreted in the context of specific location into which they are discharged (Mitchell et al 2003).

Study City Rastatt

The city of Rastatt has been selected as one of the case study cities for the AISUWRS – project. Rastatt (Figure 3) is situated in the southwest of Germany in the eastern part of the upper Rhine valley 20km south of Karlsruhe. It is bordered by the river Rhine in the west and the foothills of the Black Forest in the east. The city is built on quaternary gravel and sand sediments. The population reaches approximate 50.000 with about 35.000 residents living in the urban centre of the administrative area. The urban area of Rastatt covers about 15km². For modelling purposes it has been divided into 30 wastewater and catchment areas (Eiswirth 2002). The entire length of the sewer system in Rastatt reaches approximately 200 km and consists of separated (30%) and combined sewers (70%) (Eiswirth 2002). In close cooperation with the Civil Engineering Office of Rastatt it was possible to access a sufficient dataset for UVQ-modelling purposes.

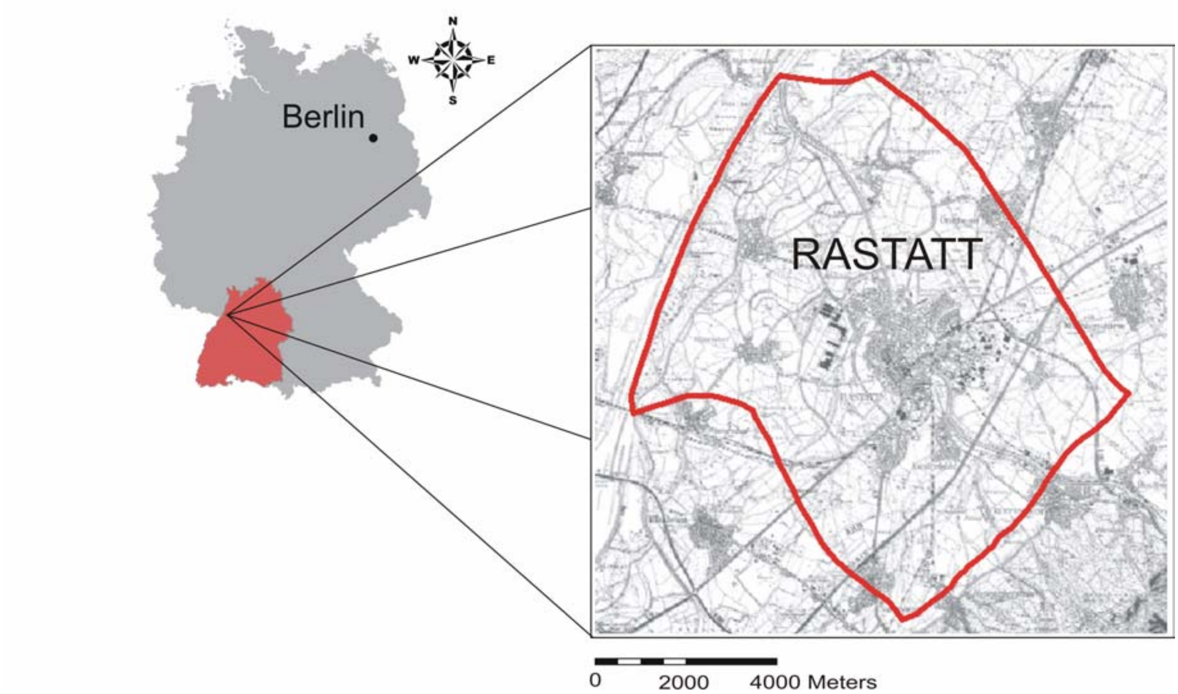

Figure 3: Case Study City Rastatt, Germany.

Application on the Study Area

The UVQ model is currently applied to several small urban catchment areas in the city of Rastatt. With the help of a Geographic-Information-System (GIS) the sewer-network of Rastatt, which consists mainly out of combined sewers, was analysed for describing different catchment areas. To apply the UVQ code in detail, three study areas (Danziger, Ottersdorfer and Zay) were defined. The outlet of each study area is a defect sewer. Close to the sewer special groundwater observation wells have been drilled and water deterioration of groundwater quality has been observed (Wolf et al 2004). Up to now only one catchment area of the sewer system Danziger-Strasse (Figure 4) has been modelled with UVQ and will be documented in this paper. The small scaled application renders an impression about the functionalities of UVQ and allows assessment of suitability and transferability to the whole area of Rastatt.

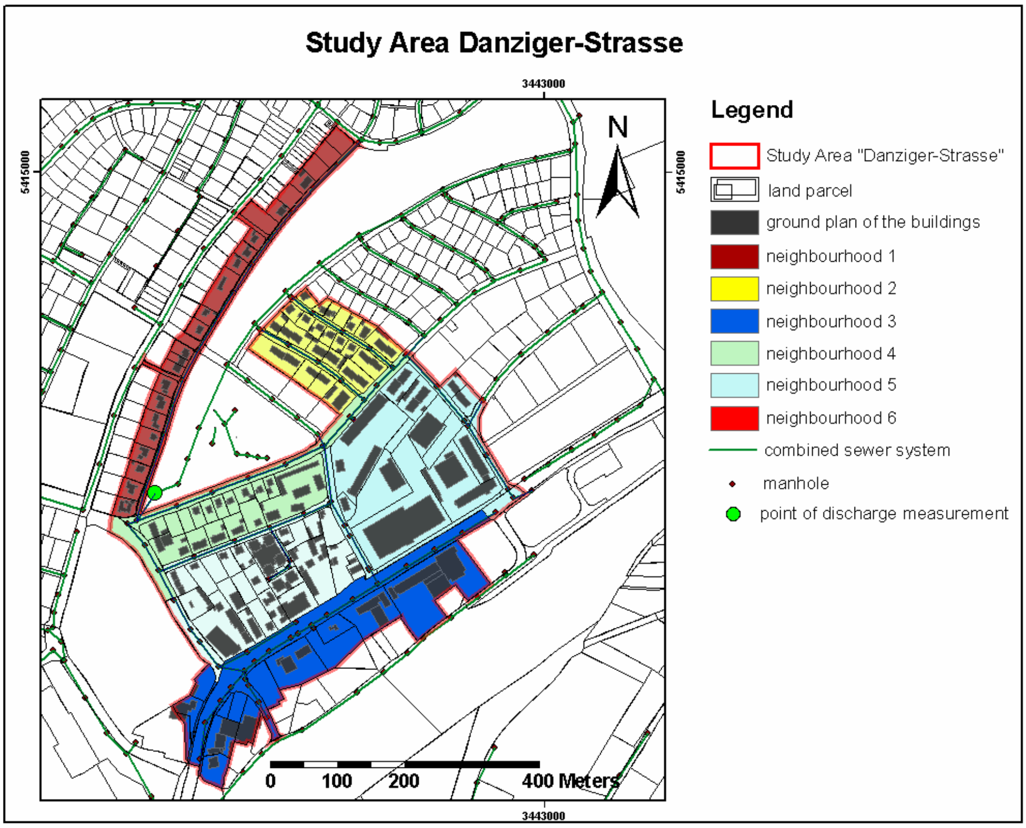

Figure 4: Study Area Danziger-Strasse with neighbourhoods

UVQ works on three scales: Study area - Neighbourhood – Land block. The study area is represented through the catchment area Danziger-Strasse. It contains several neighbourhoods, areas of different size but respectively similar use. Each neighbourhood contains land blocks like residential properties or commercial areas, which are characterising the different neighbourhoods. Land blocks are representing the smallest unit and that area is typically covered by the base area of the house and the garage and by paved and garden area.

After a GIS based analysis of digital maps of land parcels, ground plans and infrastructure the considered study area was divided in six neighbourhoods with almost homogeneous land use characteristics (Table 1). To confirm and to correct the assumptions, based on the GIS analysis, a field trip to the study area was undertaken.

Table 1: Division of the Study Area Danziger-Strasse.

Neighbourhood	Area [ha]	Land blocks [nb]	Av. occupancy [nb]	Land use
1	2.60	20	4	Residential area
2	2.26	22	15	Residential area
3	5.02	14	4	Industrial area
4	3.00	14	8.5	Residential area
5	5.53	13	30	Commercial area
6	4.08	20	20	Mixed Residential & Commercial area
Study area	21.51	103	13.5	

Physical information about impervious areas like roof area, paved area and roads and pervious areas like garden or even open space areas are entered on neighbourhood scale. Water characteristics, daily consumption per capita, contaminant loads per person in kitchen, laundry, toilet and bath are entered on land block scale. The domestic water demand per person and household is based on international values (Eiswirth 2002) as well as data taken from the Federal Agency for Statistics (2001). Water usage per person in Rastatt approximates 120-140 l/d according to a report from Arcadis Trischler & Partner (1999) and results of the Federal Agency for Statistics (2001). The consumption is divided in different sources and is consumed as shown (Table 2):

Table 2: Water consumption and contaminant loads per person (SS = Suspended Solids) (Arcadis Trischler & Partner 1999).

	Water [l/p/d]	SS [mg/p/d]	N [mg/p/d]	P [mg/p/d]
Bathroom	56.8	803	462	22
Toilet	21.0	36240	13709	1568
Kitchen	13.2	3390	238	42
Laundry	44.8	4858	327	52
Total	135.8	45291	14736	1684

Soil Properties and Climate file

UVQ implements the soil properties through values of field capacity and the linked soil store moisture. Soil store properties are entered on neighbourhood scale.

To take the climatic conditions into account, a climate file containing time series of precipitation and potential evapotranspiration in daily time steps has to be entered. For the study area recordings from a weather station that is situated at a wastewater treatment plant close to the city of Rastatt provided a detailed data set.

Default Assumptions due to the model chain

In regarding the approach and the objectives of the application of the model chain as shown in Figure 1 various constraints for the UVQ application have been set for the catchment area Danziger-Strasse:

- No sewer leakage due to sewer defects (Pipe leakage will be calculated in a different model).
- If the maximum capacity of the soil store is reached surface runoff occurs.
- No septic tanks.
- All impervious areas are 100% effective and directly connected to the sewer.

These assumptions will only be made at this step of the project, as it is the function of other model approaches to determine these effects in detail.

RESULTS AND DISCUSSION

Measurement Campaign

A detailed measurement campaign was carried out in Rastatt for the period from 13.10.2003 to 23.10.2003. In three sewer segments, which were located closely to known groundwater quality problems flow meters were installed. The flow meters recorded water level (Figure 5), water velocity and the corresponding water flux in intervals of one minute. During the same period online multiparameter probes have been placed inside the sewer for the description of water quality parameters (sp. Electrical conductivity, pH, temperature). Parallel multiparameter probes were installed in nearby groundwater wells. The measurements can be used as a calibration dataset for the UVQ model and gave the inputs for modelling the catchment area of these sewers.

Sensitivity Analysis
A sensitivity analysis of the model was performed for selected parameters. Especially the field capacities of the different soil stores were considered as there are short distance facies changes in the urban sedimentary cover layers leading to uncertainties in this parameter. However it turned out that there was almost no influence of changed soil store capacity on the generated storm water flow (Table 3).

Table 3: Change of stored volume in the soil store (grey: time of measure campaign, dark grey: rain period)

Date (Oct.2004)	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Change of stored volume in soil store [mm]	-0.58	-0.47	-0.38	-0.41	-0.30	-0.32	-0.29	-0.29	0.01	3.37	1.19	-0.65	-0.29	-0.18

The very low reaction of the soil store on the precipitation event (Table 3) can be explained by the rain intensity of 18.8 mm in three days (Table 4) following a long dry period, which is insufficient for a complete filling of the soil stores (capacities between 50 mm and 400 mm).

Table 4: Precipitation in Rastatt, Oct. 2003 (grey: period of measure campaign, dark grey: rain period)

Date (Oct. 2004)	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Precipitation [mm]	0	0	0	0	0	0	0	0	0	0.8	12.8	5.2	0	0	0	0

Concerning dry weather flow the model is sensitive to demographic data (e.g. number of persons per household), water usage patterns and the base flow index, which accounts for groundwater infiltration. These parameters can be easily assessed and averaged for rather recently planned and constructed cities, as they are present in Australia where the code has been developed. However, it has proved difficult to obtain reasonable data on the rather heterogeneous conditions in almost mediaeval European settings.

Discussion of the calibration process
Storm water and wastewater generation was calculated separately in the UVQ model (Figure 5). In the course of the interpretation storm water and wastewater flow in the sewer were added to represent the combined flow.
The water fluxes during dry weather periods can be represented quite well as the storm water component is zero. What cannot be modelled due to the non-time variant input parameters is the change of water demand during weekends or public holidays. These effects have proven to be of limited importance in the flow measurements during the observation period (see Figure 5). Mainly changing the number of inhabitants per household has performed the calibration of the wastewater flow. However, this is not the only significant influence on the wastewater volume. Also the water usage pattern (especially for industrial blocks) and the baseflow index which accounts for groundwater infiltrating into the sewer system can be used to achieve similar calibration results. Regarding the study area Danziger-Strasse the complete sewer system is above the groundwater table and also above the zone of groundwater fluctuation.

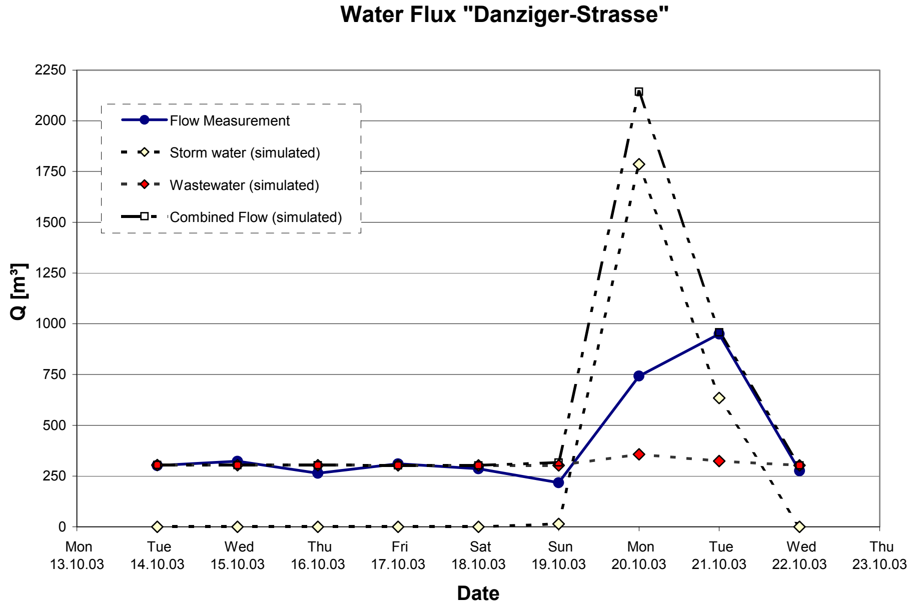

Figure 5: Measured and simulated water fluxes during calibration period.

CONCLUSION

The Urban Water and Quality model developed in Australia could be applied to a small catchment in a European urban area without major problems concerning data acquisition. Appropriate geographic information systems proved to be a major help for successful application. However the validation of the model results with a measured data set was not completely satisfactory yet and feedback has been provided to the model developers. It became clear that the UVQ model has been designed basically as a planning tool for alternative water scenarios and can not be compared with state of the art real time hydrodynamic sewer models. Further program developments are foreseen and the whole chain of models developed in the AISUWRS project will be applied to the catchment area Danziger Strasse as soon as possible.

Acknowledgements

Grace Mitchell, CSIRO Manufacturing and Infrastructure and Technology, is particularly acknowledged for an introduction of the UVQ code and for allowing its application within the project. Acknowledgement also goes to Inka Held and the Civil Engineering Department of Rastatt for providing this work with a large amount of data. The entire work was only possible due to the initiative of the recently deceased Matthias Eiswirth who started the AISUWRS project.

References

Arcadis Trischler & Partner (1999): Kanalisations-Einzugsgebiete „Links der Murg“, unpublished report, Civil Engineering Office Rastatt, Germany.

Burn S, Dhammika DS, Tjandraatmadja G, Mitchell G, Diaper C, Corell R, Dillon P, Eiswirth M (2003): Pipes Wagga Wagga, Pressure Sewer Seminar, 19-24 Oct. 2003, Wagga Wagga, Australia.

Eiswirth M, Hoetzl H, Cronin A, Morris B, Veselič M, Bufler R, Burn S, Dillon P (2002): Assessing and Improving Sustainability of Urban Water Resources and Systems. In Proc. of the 2nd IMAGE-TRAIN Cluster Meeting, 51-56, Oct. 2002, Krakow, Poland

Eiswirth M. (2002): Bilanzierung der Stoffflüsse im urbanen Wasserkreislauf - Wege zur Nachhaltigkeit urbaner Wasserressourcen. – Postdoctoral lecture qualification. University of Karlsruhe, Germany.

Mitchell VG (2000): Aquacycle Users Manual. CRC for catchment hydrology, Monash University.

Mitchell VG, Diaper C, Gray SR, Rahili M (2003): UVQ: Modelling the Movement of Water and Contaminants through the Total Urban Water Cycle. In: 28th International Hydrology and Water Resources Symposium, Wollongong, NSW.

Mitchell VG, Gray S, Farley T (2000): Accounting for Water and Contaminants in Urban Areas. In: Proceeding of the Xth World Water Congress, 12-17 March 2000, Melbourne, Australia.

Mitchell VG, Maheepala S (1999): Urban water balance modeling. CSIRO urban water program Document T 1-11, Dbce Doc. 99/195, Melbbourne.

Statistisches Bundesamt (2001): Fachserie 19, Reihe 2.1., Germany.

Wolf L, Held I, Eiswirth M, Hoetzl H (2004): Environmental impact of leaky sewers on the groundwater quality beneath a medium sized city. Paper accepted by Acta hydrochimica et hydrobiologica.