Integrated hydraulic modelling of water supply and urban drainage networks for assessment of decentralized options

R. Sitzenfrei and W. Rauch

ABSTRACT

The impact of climate change, water scarcity, land use change, population growth and also population shrinking can only be predicted with uncertainties. Especially for assets with a long planning horizon this is a critical part for planning and design. One solution is to make centralized organized water infrastructure with a long-planning horizon resilient and adaptive. For existing centralized infrastructure such a transition would be to increasingly implement decentralized measures. But such a transition can cause severe impacts on existing centralized infrastructure. Low flow conditions in urban drainage systems can cause sediment deposition, and for water supply systems water age problems may occur. This work focuses on city-scale analysis for assessing the impact of such measures. For that a coupled model for integrated city-scale analysis is applied and further developed. In addition, a geographic information system (GIS)-based approach for sensitivity analysis is enhanced and also implemented in that model. The developed approach is applied to assess the water infrastructure of an alpine case study. With the obtained results it is demonstrated how the planning process is enhanced by indicating where and where not to implement decentralized measures in an existing water infrastructure.

Key words | coupled model, hydraulic modelling, integrated modelling, low flow conditions, water reduction

R. Sitzenfrei (corresponding author)
W. Rauch
Unit of Environmental Engineering,
University of Innsbruck,
Technikerstr. 13,
6020 Innsbruck,
Austria
E-mail: *robert.sitzenfrei@uibk.ac.at*

INTRODUCTION

In developed countries, water infrastructure is historically organized centrally with water and sewer pipe networks. The expected lifespan of such systems can be up to 100 years and even more. Therefore, to avoid inefficient use of capital investments, the planning horizon for such systems is rather long and complex. Huge upcoming challenges like climate change, water scarcity, land use change, population growth and also population shrinking can only be predicted for such a time horizon with uncertainties (e.g. Kleidorfer *et al.* 2009). Furthermore, a possible change in resources requires a long-term water supply plan (Chung *et al.* 2008). One solution to bypass such difficulties in prediction is to make centralized organized water infrastructure more flexible and adaptable (Larsen 2011; Bach *et al.* 2013; Urich *et al.* 2013). Also, waste water and storm water are more and more regarded as a valuable resource (e.g. Barton & Argue 2009); therefore these water streams are increasingly reused (e.g. Domènech & Saurí 2010; Makropoulos & Butler 2010). Regarding sustainability, another goal is to preserve the natural water cycle in urbanized areas. To achieve this, an integrated water cycle management is required (e.g. Hardy *et al.* 2005). Integrated urban water management also aims to include water-sensitive urban design (e.g. Brown *et al.* 2009) to enhance a holistic approach (Hunt *et al.* 2005). Such measure (i.e. decentralized measures) can have severe impacts on the existing centralized water infrastructure.

There is still a knowledge gap in assessing the technical performance during the transition to decentralized solutions, especially in relation to the impact on operational measures. Such operational issues can be caused by a reduction in dry weather flow (DWF) production in urban drainage systems. These can cause problems with sediment deposition (Ota & Perrusquia 2013). For water supply

doi: 10.2166/wst.2014.326

systems, an oversized design, or a reduction in water consumption can cause an impact on water age and therefore water quality problems due to stagnation (US-EPA 2002). Also, the results of such analysis are difficult to communicate to other knowledge areas and decision makers. This work aims to close this knowledge gap.

In this work, the coupled model for integrated city-scale analysis based on Sitzenfrei *et al.* (2013a) is applied and further developed. A geographic information system (GIS)-based approach of sensitivity analysis (SA) (Möderl *et al.* 2011; Mair *et al.* 2012) is enhanced and also implemented in that model, whereby integrated analysis of water reduction scenarios due to transition from centralized to decentralized water solutions is undertaken. For visualization and communication of the results, a GIS-based approach of SA is enhanced and implemented in the integrated city-scale analysis approach. These kinds of sensitivity maps can be used for estimating the impact of transitions of centralized water infrastructure to decentralized solutions and also to assess the impact of population decrease or water demand reductions. With the GIS-based SA, the results can easily be communicated to stakeholders and decision makers. In this work the extent to which the currently installed centralized solution can still perform sufficiently without changing any management and operation strategies is evaluated on different spatial scales. From the evaluations on different scales it was found that for the investigations the spatial resolution of the zoning (fine, medium, coarse and all) have a severe impact on the sensitivities. Furthermore, it was evaluated to what extent the currently installed centralized solution can still perform sufficiently without changing any management and operation strategies. Therefore, different levels of decentralization were systematically investigated. Usually GIS-based SA is applied only with one scenario (e.g. water reduction scenario to 40%). But such evaluations can miss critical points in the performance assessment if the system performs sufficiently, for example, a reduction scenario of 60% but there is a significant performance drop when further reducing.

METHODS

This section first describes how the city-scale test case is coupled for an integrated scenario analysis of water infrastructure. For investigation of transitions of centralized water infrastructure to decentralized solutions, the existing approach of GIS-based SA is enhanced and implemented in the integrated scenario analysis approach in this work.

Integrated scenario analysis of water infrastructure

For the investigated test case, the model for hydraulic simulation of water infrastructure (water distribution system – WDS – and the urban drainage system – UDS) is coupled via the spatial referenced population densities (represented by population equivalent – PE). With spatial referenced population densities, respectively PE (see Figure 1(b)), the DWF production and the water consumption are determined on the same basis. For the two types of water infrastructure, different design loads are required. But the basis for calculating both design loads are the PE (Sitzenfrei *et al.* 2013a). With that, commonly applied design loads for WDS modelling, like the peak flow on the maximum day (ÖNORM B 2538 2002), can be determined. For calculation of water age in the WDS, the pattern of an average day (with water losses) is used (see Figure 1(a)). To determine low flow conditions in the sewer system, the minimal DWF according to ÖWAV-RB 11 (2009) is calculated and applied. In Figure 1(a), different loads are shown for the used test case as hourly multipliers of the daily averaged demand (Figure 1(a) – dashed line).

The WDS and UDS models have different levels of detail (Figure 1(b)). Therefore, a group of WDS junctions are assigned to a DWF node of the UDS with the shortest distance to it. As a result of that geometrical analysis, catchments for DWF production (dwfC see Figure 1(b)) are determined. For hydraulic modelling, a parallel version of SWMM5 (Burger *et al.* 2014) and the EPANET2 programmers' toolkit (Rossman 2000) are used. For coupling of the two different models and systematic scenario analysis, Matlab® scripts are developed and applied.

GIS-based application of SA

SA is used to investigate the change in model output due to changes in model input. To achieve this, the hydraulic models of the water infrastructures are used. The model input in this context is the change in DWF production and water consumption, respectively. The change in model output is the impact on the hydraulic system performance of the different water infrastructure models. GIS-based SA has sensitivity maps as results. To create such maps, the impact of component modifications (one at a time) (in this context change in DWF production and water demand at one node or region respectively) on the entire system performances are spatially linked to the location of the component modification. Basically there is a spatial join of the information about the model response, at the location

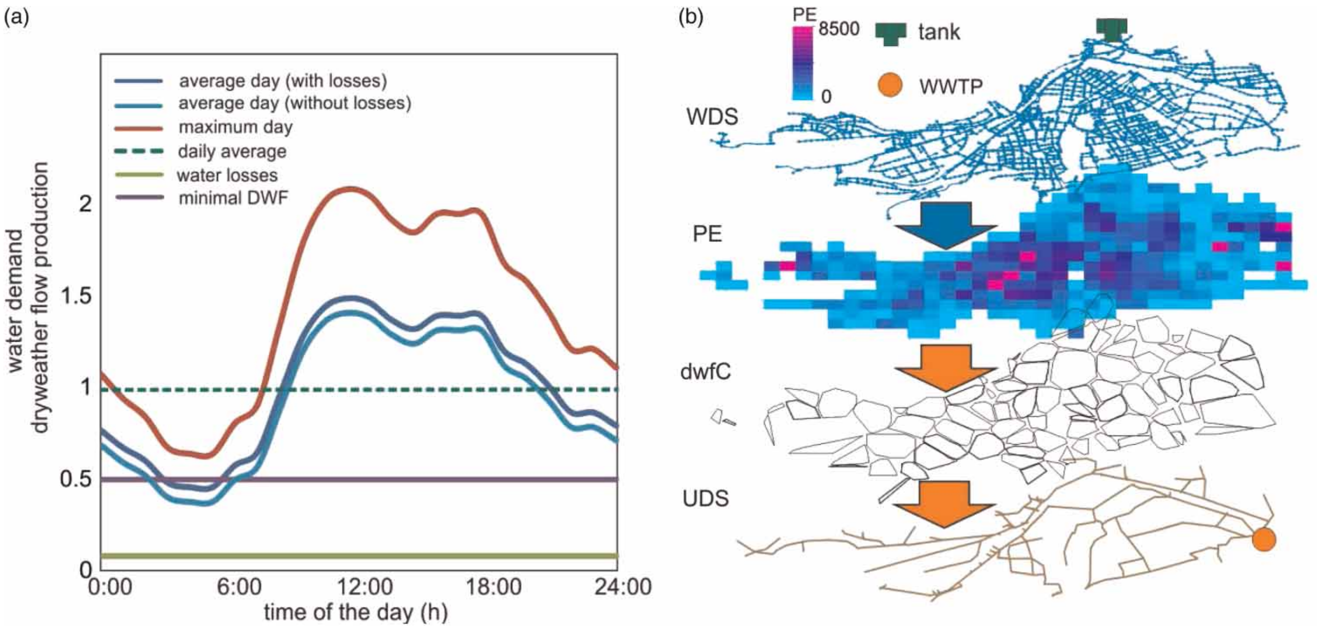

Figure 1 | (a) Different patterns and demand loads for WDS and UDS. (b) UDS and WDS coupled via population (PE) for real-world case study.

of the model (component) change. For WDS models, Möderl *et al.* (2011) showed an application of GIS-based SA to create, among others, sensor placement and vulnerability maps. For UDS models, Mair *et al.* (2012) showed an application for creation of uncertainty and calibration maps. Sitzenfrei *et al.* (2012) used GIS-based SA for capacity and combined sewer overflow failure maps of UDS. In this work, this concept is enhanced for coupled WDS and UDS models. Specifically, the developed approach is applied to investigate low flow conditions in order to investigate transitions from centralized water infrastructure to decentralized solutions (in this work a reduction in DWF production and water consumption).

Hydraulic modelling and performance assessment

For performance assessment of water infrastructure, there exists an extensive number of performance indicators (PIs). In this work, for each water infrastructure (WDS and UDS), one normalized PI is used to describe system performance under low flow conditions. Both normalized PIs indicate sufficient performance with 1 and poor performance with 0.

For WDS, a PI describing water age in the system (addressing stagnation problematic), denoted PI_{age}, is applied (Sitzenfrei *et al.* 2013b). For that in each node j of the WDS, the water age is determined with EPANET2 based on a 240 hours simulation (to model water age correctly also in the tank) with a hydraulic time step of 1 hour and quality time step of 5 minutes. If for the investigated scenario the water age in a node is below a threshold value, it is assessed with $\alpha_j = 1$; if it is above, it is assessed with $\alpha_j = 0$. The obtained values for each node are summed up demand-weighted (demand at node j: d_j). The obtained value is subsequently normalized with the total demand (td) and the number of junctions (J) (see Equation (1)). For threshold values, a water age below 24 hours is defined as sufficient performance.

$$PI_{age} = \frac{1}{J \cdot td} \sum_{j=1}^{J} (\alpha_j * \cdot d_j) \quad [0\ \ 1] \tag{1}$$

For UDS a PI for shear stress performance denoted PI_{tau} is used. The shear stress τ_i (N/m^2) of a pipe i is calculated with $\tau_i = \rho \cdot g \cdot S_i \cdot D_{H,p,i}$ with density of water ρ (1,000 kg/m^3), gravitational acceleration g (9.81 m/s^2), slope of pipe i (S_i) and hydraulic radius for partial filling $D_{H,p,i}$ (m). The hydraulic radius for partial filling is calculated based on the water levels for DWF simulated with SWMM5 with a 24 hour simulation and 1 hour time step. A shear stress values τ_i above 1 N/m^2 is regarded as sufficient performance and is therefore assessed with $\tau_i{*} = 1$. For $\tau_i < 1$, the shear stress in that pipe i is assessed with the actual shear stress $\tau_i{*} = \tau_i$. The obtained values for each pipe are summed up DWF-weighted (DWF at pipe i: dwf_i). The obtained value is subsequently normalized with the total DWF ($tdwf$) and the number of pipes P.

$$\mathrm{PI}_{\mathrm{tau}} = \frac{1}{P \cdot tdwf} \sum_{i=1}^{P} (\tau_i * \cdot dwf_i) \quad [0 \;\; 1] \tag{2}$$

Although the relative changes in PIs due to a component modification can be low when modifying the DWF production in only one node, this investigation still gives information on how to prioritize the different nodes.

Usually in GIS-based SA, for each component one single parameter variation is applied (e.g. reduction of DWF production of 50%). But the system PI might be stable until a certain reduction (for example until a reduction to 40%) and then rapidly drop. Therefore, ranges for component modifications are applied (demand reduction between 0 and 90% with intermediate steps).

Case study and scenarios

For a test case, an alpine city with a population of 121,000 is used. With an assumed average water demand of 120 L/(PE d) and the metered water consumption, about 400,000 PE (including industry, business, agriculture) are provided with the water infrastructure. A spatial distribution of the PE is shown in Figure 1(b). For drainage a combined sewer system is installed (see Figure 1, UDS). The hydraulic model of the UDS consists of 247 nodes, 182 catchments, and 275 links. The location of the waste water treatment plant (WWTP) is shown in Figure 1(b) – UDS. The WDS is under regular conditions gravity driven and consists of more than 7,000 junctions and pipes. The WDS major intake is one tank with a total volume of about 26,000 m^3 (see Figure 1(b) – WDS).

For investigation of transitions of centralized water infrastructure to decentralized solutions, water reduction scenarios are investigated. These scenarios can also be interpreted as population decrease scenarios. In total, five reduction scenarios (reduction to 80, 60, 40, 20, 10% of the initial value) are investigated (reduction in daily water consumption and DWF production). The performance of the reduction scenarios are compared to the performance of the initial system.

The changes in DWF production and water demand reduction can be a very local process, but such changes can also take place on a regional level (entire parts of a city or even the entire city. Therefore the described approach is applied at different spatial levels, and the impact of these spatial levels on the sensitivity maps and therefore on the prioritization of the different components is investigated.

In total, three different spatial resolutions are investigated (fine, medium and coarse resolution). For the highest spatial resolution, the fine resolution zonings of PE of Figure 1 (dwfC) are used. For medium zoning, the areas shown in Figure 2(a) are used. For a coarse zoning the areas shown in Figure 2(b) are used. For all investigations, the spatial layout of the networks (UDS and WDS) are kept constant; therefore it is neglected that the spatial layout of the infrastructure systems might change over time.

The different transition scenarios also have an impact on the technical performance regarding storm water. But the main focus of this work is to show the application of the interlinked hydraulic model for water supply and drainage system. Therefore, the impact on storm water management is not addressed in this manuscript.

RESULTS AND DISCUSSION

Figure 3 shows the evaluation of reduction scenarios for evaluation based on fine resolution zonings. The results of the UDS (Figures 3(a)–(c)) and the WDS (Figures 3(d) and (e))

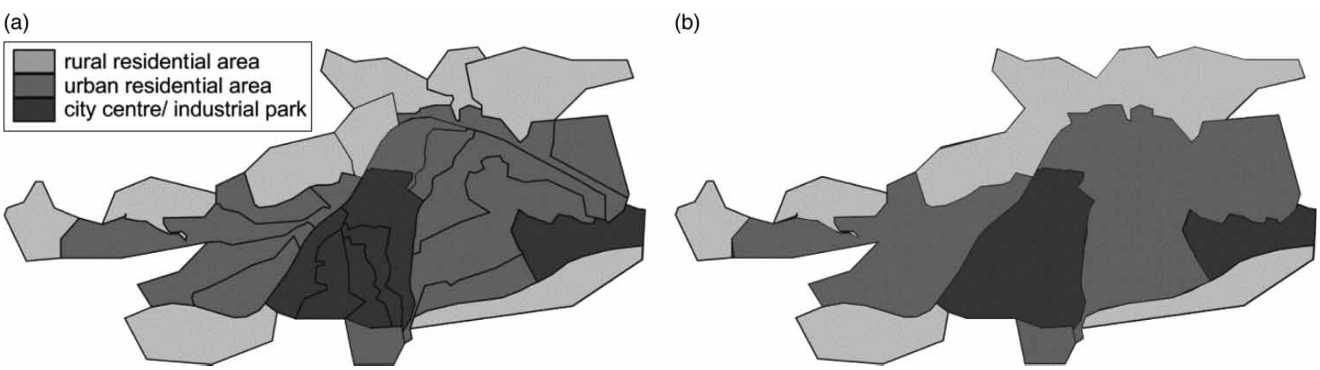

Figure 2 | (a) Medium resolution zoning; (b) coarse resolution zoning.

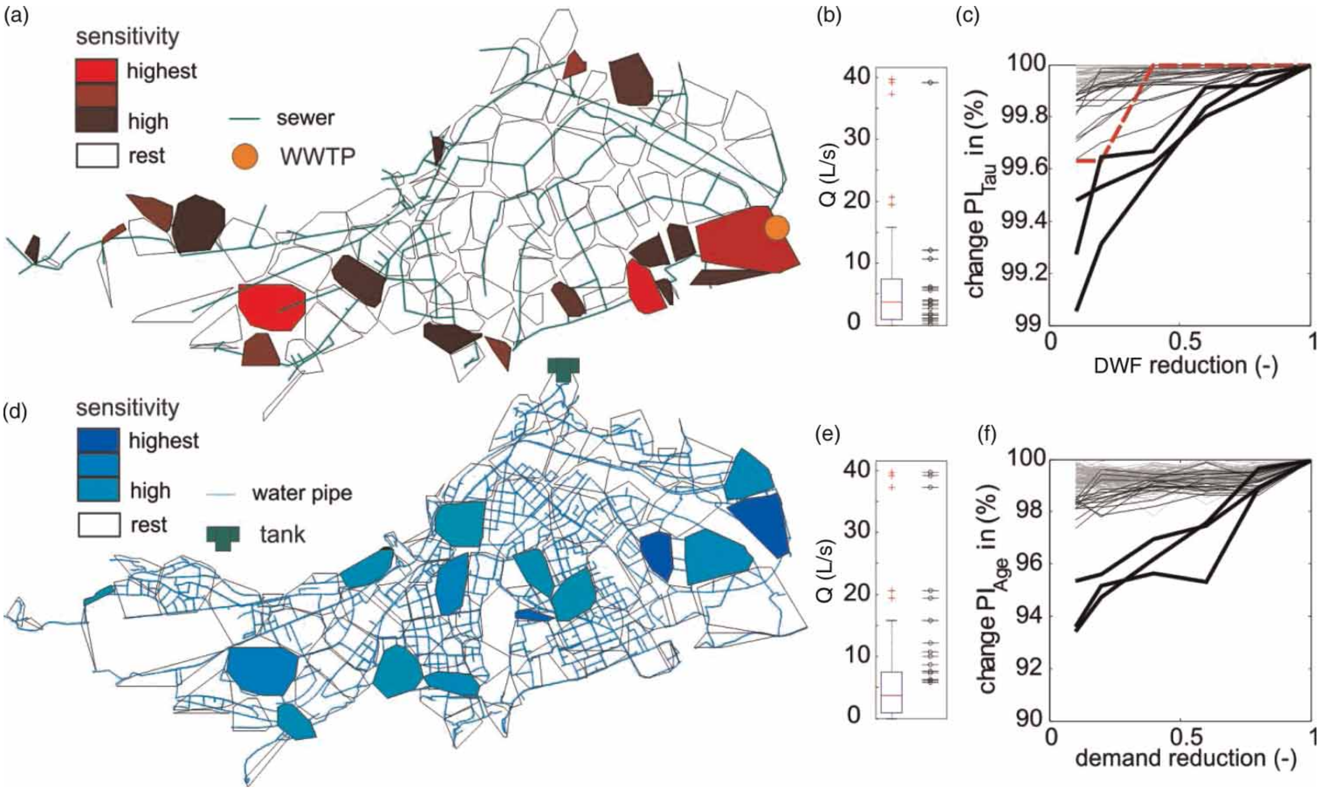

Figure 3 | (a) UDS sensitivity for fine resolution zones; (b) evaluation of sensitive DWFs; (c) sensitivities for different DWF reduction scenarios; (d) WDS sensitivity for fine resolution zones; (e) evaluation of sensitive demands; (f) sensitivities for demand reduction scenarios.

evaluation are shown. High-prioritized fine resolution zones are given with different shades of grey according to their prioritization. In Figure 3(a), the impact of DWF reduction on shear stress performance (PI_{Tau}) is visualized at the location of the component modification. The sensitive areas are mostly on the margin of the drained area. A reduction of DWF production in these areas has the highest impact on shear stress of the entire system.

One might argue that, for shear stress performance, the zones with high DWF production are the most important ones. Therefore, in Figure 3(b), the initial DWFs (L/s) (no reduction factor applied) are shown in a box plot. The markers show the initial DWF production (Q) of each sensitive zone. It can be observed, that these are distributed throughout the parameter range of Q. Also zones with a low DWF (Q below the median value of 4 L/s) have a high prioritization. In Figure 3(a), investigations are only visualized for a reduction scenario of 80%. In Figure 3(c), the results for all reduction scenarios are shown. Each line shows the results of reduction scenarios on the DWF performance (PI_{Tau}) at one fine resolution zone. The light grey lines in the background indicate zones which have only a marginal impact compared to the other zones (black lines). The thick black lines indicate the zones with the highest sensitivity. While most of the black lines exhibit a continuous decrease in change in PI_{Tau}, the dashed line shows one case for which the system performance is sufficient until a reduction to 40%. Compared to the other zones, there is a higher drop when decreasing further.

In Figures 3(d)–(f), the same evaluations are now made with the WDS and the water quality analyses (PI_{Age}). It can be seen, that three zones are most sensitive (lowest values for PI_{Age} for high reductions). The corresponding investigation on water consumption in Figure 3(e) shows slightly different results to Figure 3(b): the water consumption (Q) of the most sensitive zones are between 5 and 40 L/s. For the detailed analysis, a few lines in Figure 3(f) are increasing and decreasing. This is due to by the scenarios' induced changes in flow paths in the WDS.

In Figures 4(a) and (b), the results for the evaluation on medium resolution zones are shown, and in Figures 4(c) and (d) the results for coarse zoning are shown. In addition, for the evaluation of each zone, the trends of the change in PIs depending on the reduction factors are shown. For the

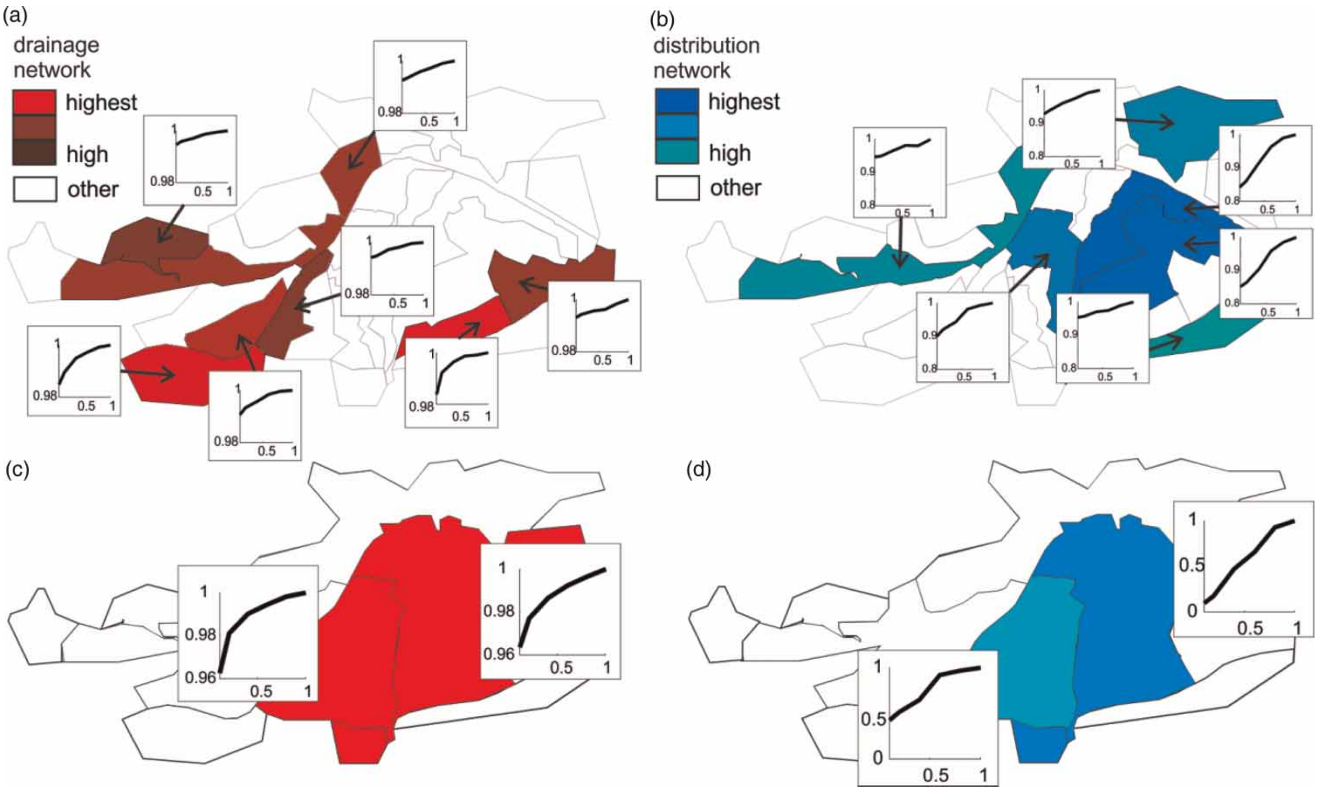

Figure 4 | Results for medium resolution zones for (a) UDS and (b) WDS; results for coarse zones for (c) UDS and (d) WDS (Sitzenfrei & Rauch 2014).

UDS evaluations in Figure 4(a), it can be observed that the medium resolution zones at the margin of the UDS are most sensitive. The zones U1, U2, U5, U6 and U7 are at the upstream part of the UDS. For U1 and U3 (the medium resolution zones with the highest sensitivities), a reduction to 50% does not result in a higher impact when compared to other zones, but further reduction results in a major drop in the impact on PI_{Tau}. For the WDS, the sensitive zones are mainly in the centre of the city (W1, W3 and W4).

In Table 1, the results of reduction scenarios applied to the entire drainage and supply area (reduction scenarios are applied to all zones simultaneously) are summarized. The results for UDS show that, until a reduction to 40%, the drop in PI_{Tau} (the relative change) is lower when compared to a further reduction. For the WDS, with the applied thresholds, any reductions have a severe impact on PI_{Age}. The results are strongly impacted by the operation of the main tank (residence time in the main tank). The tank is designed accordingly without any reduction factor and the results for the entire system are based on an extended-period simulation (20 days). Therefore, when no operational strategies are applied for tank management, the water age in the tank increases when applying reduction scenarios to the water demand (e.g. for a reduction to 40%, the water age in the tanks is up to 40 hours).

Table 1 | Results of reduction scenarios applied to the entire UDS and WDS area

Reduction factors (reduction to %)	10%	20%	40%	60%	80%	100% (initial)
PI_{Tau}	0.6248	0.6671	0.7210	0.7433	0.7565	0.7646
Relative PI_{Tau} (PI_{Tau}/PI_{Tau}(factor = 1)	0.8171	0.8724	0.9430	0.9722	0.9894	1
PI_{Age}	0.0000	0.0000	0.0000	0.0386	0.3116	0.7824
Relative PI_{Age} (PI_{Age}/PI_{Age}(factor = 1)	0.0000	0.0000	0.0000	0.0493	0.3982	1

Both centralized water networks could also operate sufficiently for reduction scenarios when applying operational measures such as cleansing measures for the sewer sediments or a change in tank operation for water supply. But such measures are connected to additional expenses. However, such measures are not included in the presented evaluations.

From the evaluations on different scales it was found that for the investigations the spatial resolution of the zoning (fine, medium, coarse and all) have a severe impact on the sensitivities. Furthermore, it was evaluated to what extent the currently installed centralized solution can still perform sufficiently without changing any management and operation strategies.

With the developed approach, GIS maps can be provided that allow results to be easily communicated to decision makers. On one hand it can be identified in which areas of the city an implementation of decentralized measures should not be considered (areas with high sensitivities). On the other hand, in areas which were not identified as sensitive, such decentralized measures should preferably be installed. With the obtained results it is demonstrated how the planning process is enhanced by indicating where and where not to implement decentralized measures in an existing water infrastructure. With this information decisions such as in which areas decentralized measures should be enforced by regulation are provided for the urban planning process.

SUMMARY AND CONCLUSIONS

In this work, a coupled model for integrated city-scale analysis is successfully applied and further developed. An integrated analysis of water reduction scenario due to transition from centralized to decentralized water solutions for instance is investigated. For visualization and communication of the results, a GIS-based approach of SA is enhanced and implemented in the integrated city-scale analysis approach. These kinds of sensitivity maps can be used for estimating the impact of transitions of centralized water infrastructure to decentralized solutions, and also to assess the impact of population decrease or water demand reductions. With the GIS-based SA, the results can easily be communicated to stakeholders and decision makers.

It was found that for the investigations the spatial resolution of the zoning (fine, medium, coarse and total area) has a severe impact on the sensitivities. Furthermore, it was evaluated to what extent the currently installed centralized solution can still perform sufficiently without changing any management and operation strategies. Therefore, different levels of decentralization are investigated. In this context it was found that the traditional GIS-based SA with one single scenario applied (e.g. water reduction scenario to 50%) can miss critical points in the performance assessment (for example system performs sufficiently for a reduction scenario of 60% but there is a significant performance drop with further reductions). Also when boundary conditions for investigations change (case studies with rapid growth scenarios, increase of water consumption, etc.), the presented approach can likewise be applied. The impact on the WWTP was in this study not evaluated as the focus was on hydraulic modelling of the pipe networks. Also on that infrastructure, significant impact can occur during the described transitions.

ACKNOWLEDGEMENTS

This work was funded by the Austrian Science Fund (FWF) in the project DynaVIBe P23250. The authors gratefully acknowledge the financial support. With kind permission from Elsevier, parts of this article are based on the Sitzenfrei and Rauch paper presented at the 12th International Conference on Computing and Control for Water Industry 2013 (creative commons licence, http://creativecommons.org/licenses/by-nc-nd/3.0/).

REFERENCES

Bach, P. M., McCarthy, D. T., Urich, C., Sitzenfrei, R., Kleidorfer, M., Rauch, W. & Deletic, A. 2013 A planning algorithm for quantifying decentralised water management opportunities in urban environments. *Water Science and Technology* **68** (8), 1857–1865.

Barton, A. B. & Argue, J. R. 2009 Integrated urban water management for residential areas: a reuse model. *Water Science and Technology* **60** (3), 813–823.

Brown, R. R., Keath, N. & Wong, T. H. F. 2009 Urban water management in cities: historical, current and future regimes. *Water Science and Technology* **59** (5), 847–855.

Burger, G., Sitzenfrei, R., Kleidorfer, M. & Rauch, W. 2014 Parallel flow routing in SWMM 5. *Environmental Modelling & Software* **53**, 27–34.

Chung, G., Lansey, K., Blowers, P., Brooks, P., Ela, W., Stewart, S. & Wilson, P. 2008 A general water supply planning model: evaluation of decentralized treatment. *Environmental Modelling & Software* **23** (7), 893–905.

Domènech, L. & Saurí, D. 2010 Socio-technical transitions in water scarcity contexts: public acceptance of greywater reuse technologies in the Metropolitan Area of Barcelona. *Resources, Conservation and Recycling* **55** (1), 53–62.

Hardy, M. J., Kuczera, G. & Coombes, P. J. 2005 Integrated urban water cycle management: the UrbanCycle model. *Water Science and Technology* **52** (9), 1–9.

Hunt, J., Anda, M., Mathew, K., Ho, G. & Priest, G. 2005 Emerging approaches to integrated urban water management: cluster scale application. *Water Science and Technology* **51** (10), 21–27.

Kleidorfer, M., Moderl, M., Sitzenfrei, R., Urich, C. & Rauch, W. 2009 A case independent approach on the impact of climate change effects on combined sewer system performance. *Water Science and Technology* **60** (6), 1555–1564.

Larsen, T. A. 2011 Redesigning wastewater infrastructure to improve resource efficiency. *Water Science and Technology* **63** (11), 2535–2541.

Mair, M., Sitzenfrei, R., Kleidorfer, M., Moderl, M. & Rauch, W. 2012 GIS-based applications of sensitivity analysis for sewer models. *Water Science and Technology* **65** (7), 1215–1222.

Makropoulos, C. K. & Butler, D. 2010 Distributed water infrastructure for sustainable communities. *Water Resources Management* **24** (11), 2795–2816.

Möderl, M., Hellbach, C., Sitzenfrei, R., Mair, M., Lukas, A., Mayr, E., Perfler, R. & Rauch, W. 2011 GIS-based applications of sensitivity analysis for water distribution models. *World Environmental and Water Resources Congress 2011*, pp. 129–136.

ÖNORM B 2538 2002 *Long-Distance, District and Supply Pipelines of Water Supply Systems – Additional Specifications Concerning ÖNORM EN 805* (in German). Österreichisches Normungsinstitut, Vienna, Austria.

Ota, J. J. & Perrusquia, G. S. 2013 Particle velocity and sediment transport at the limit of deposition in sewers. *Water Science and Technology* **67** (5), 959–967.

ÖWAV-RB 11 2009 *Standard for Assessment and Design of Drainage Systems* (in German). Normungsinstitut, Vienna, Austria.

Rossman, L. A. 2000 *EPANET 2 User Manual*. National Risk Management Research Laboratory – US Environmental Protection Agency, Cincinnati, Ohio, USA.

Sitzenfrei, R. & Rauch, W. 2014 Investigating transitions of centralized water infrastructure to decentralized solutions – an integrated approach. *Procedia Engineering* **70**, 1549–1557.

Sitzenfrei, R., Möderl, M., Fritsch, E. & Rauch, W. 2012 Schwachstellenanalyse bei Mischwasseranlagen für eine sichere Bewirtschaftung (Vulnerability analysis for combined sewer systems to ensure reliable operation). *Österreichische Wasser- und Abfallwirtschaft* **64** (3–4), 293–299.

Sitzenfrei, R., Möderl, M. & Rauch, W. 2013a Assessing the impact of transitions from centralised to decentralised water solutions on existing infrastructures – integrated city-scale analysis with VIBe. *Water Research* **47** (20), 7251–7263.

Sitzenfrei, R., Möderl, M. & Rauch, W. 2013b Automatic generation of water distribution systems based on GIS data. *Environmental Modelling & Software* **47**, 138–147.

Urich, C., Bach, P. M., Sitzenfrei, R., Kleidorfer, M., McCarthy, D. T., Deletic, A. & Rauch, W. 2013 Modelling cities and water infrastructure dynamics. *Engineering Sustainability* **166** (5), 301–308.

US-EPA 2002 *Effects of Water Age on Distribution System Water Quality*. United States Environmental Protection Agency, Washington, DC, USA.

First received 26 February 2014; accepted in revised form 9 July 2014. Available online 24 July 2014