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Investigating transitions of centralized water infrastructure to decentralized solutions – an integrated approach

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Abstract

The lifespan and therefore planning horizon of central organized water infrastructure can be up to 100years. The impact of climate change, water scarcity, land use change, population growth but also population shrinking can only be predicted for such a time horizon with uncertainties. One solution is to make centralized organized water infrastructure more flexible (i.e. implement decentralized measures). But these 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 (i.e. transitions from centralized to decentralized solutions).

Keywords: intergrated; coupled model; low flow coditions; water reduction; hydraulic modelling;

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1. Introduction

In developed countries, water infrastructure is historically organized centrally i.e. with water and sewer pipe networks. The expected lifespan of such systems can be up to 100years and even more. Therefore, to avoid inefficient use of capital investigations, the planning horizon for such systems is rather long and complex (e.g.

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Kleidorfer *et al.*, 2009). Upcoming challenges like climate change, water scarcity, land use change, population growth but also population shrinking can only be predicted for such a time horizon with uncertainties. 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 (e.g. Larsen, 2011, Urich *et al.*, in press). Also, waste water and storm water are more and more regarded as valuable resource (e.g. Barton and Argue, 2009), therefore these water streams are increasingly reused (e.g. Domènech and Saurí, 2010; Makropoulos and 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 an 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 introduced low flow conditions due to a reduction in dry weather flow production in urban drainage systems. These can cause problems with sediment deposition (Ota and Perrusquia, 2013). For water supply systems, an oversized design, respectively 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 (Sitzenfrei *et al.*, submitted) is applied and further developed. A GIS-based approach of sensitivity analysis (Moderl *et al.*, 2011; Mair *et al.*, 2012) is enhanced and implemented in the model. Whereby, integrated analysis of water reduction scenarios due to e.g. transition from centralized to decentralized water solutions are investigated. For visualization and communication of the results, a GIS-based approach of sensitivity analysis (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 but 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 it is evaluated to which extent the currently installed centralized solution can still perform sufficiently without changing any management and operation strategies. Therefore, different levels of decentralization are investigated. Usually GIS based SA are applied only with one scenario applied (e.g. water reduction scenario to 40%). These evaluations can miss critical points in the performance assessment (e.g. system performs sufficient for a reduction scenario of 60% but there is a significant performance drop when further reducing).

2. Material and Methods

In section 2.1 it is described 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 approach of GIS based sensitivity analysis (see section 2.2) is enhanced and implemented in the integrated scenario analysis approach in this work. In section 2.3, the test case is characterized and the investigated transition scenarios of centralized to decentralized solutions are described.

2.1. Integrated Scenario analysis of water infrastructure

For the investigated test case, the model for hydraulic simulation of water infrastructure (i.e. water distribution system – WDS and the urban drainage system - UDS) is coupled via the spatial referenced population densities (i.e. population equivalents –PE). With spatial referenced PE (see Fig. 1 PE), the dry weather flow 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 is the daily average water demand (Sitzenfrei *et al.*, submitted; ÖNORM B 2538, 2002; ÖWAV-RB 11, 2009).

Fig. 1. UDS and WDS coupled via population (PE) for real world case study

The WDS and UDS models have a different level of detail. Therefore, a group of WDS junctions are assigned to a dry weather inflow node of the UDS. For hydraulic modeling SWMM5 (Rossman, 2004) and EPANET2 (Rossman, 2000) are used.

2.2. GIS based application of sensitivity analysis for integrated assessment of water infrastructure

Sensitivity analysis (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 dry weather flow 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) (i.e. in this context change in dry weather flow production and water demand at one node respectively region) 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 of the model (component) change. For WDS models, Moderl *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 i.a. for capacity and CSO failure maps of UDS. In this work, this concept is enhanced for coupled WDS and UDS models. Specifically, the developed approach is used for low flow conditions in order to investigate transitions of centralized water infrastructure to decentralized solutions (i.e. reduction in dry weather flow production and water consumption).

For performance assessment of water infrastructure, there exists an extensive number of performance indicators (e.g. Sitzenfrei *et al.*, submitted). In this work, for each water infrastructure (WDS and UDS), one normalized performance indicator (PI) is used to describe system performance under low flow conditions. For WDS, a PI describing water age in the system (i.e. addressing stagnation problematic) denoted PI_{age} and for UDS a PI for shear stress performance denoted PI_{tau} is used. Both normalized PIs indicate sufficient performance with 1 and poor performance with 0. For threshold values, a time span below 24 hours is used as sufficient for PI_{age} and shear stress values above 1 N/m² is sufficient for PI_{tau}. A detailed description about the PIs can be found in Sitzenfrei *et al.*, (submitted). Although the relative changes in PIs due to a component modification can be low when modifying the dry weather flow production in only one node, this investigation still gives information on how to prioritize the different nodes.

Generally in GIS based SA, for each component one constant parameter variation is applied (e.g. reduction of dry weather flow production of 50%). But the system PI might be stable until a certain range (e.g. until a reduction to 40%) and then rapidly drop. Therefore, ranges for component modifications are applied (e.g. demand reduction between 0 and 90 % with intermediate steps). Such changes as water demand and dry weather flow production can be very local problems, but usually also happen on a larger scale. Therefore, different spatial levels of such reduction scenarios are investigated (see also Fig 1, Fig. 2 (a) and 2 (b)).

2.3. Case studies 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 Fig. 1 - PE. For drainage a combined sewer system is installed (see Fig. 1, UDS). The hydraulic model of the UDS consists of 247, 182 catchments, and 275 links. The WDS is under regular conditions gravity driven and consist of more than 7000 junctions and pipes.

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, 5 reduction scenarios (reduction to 80%, 60%, 40%, 20%, 10% of the initial value) are investigated (i.e. reduction in daily water consumption and dry weather flow production). The performance of the reduction scenarios are compared to the performance of the initial system.

The changes in dry weather flow 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 it is investigated how the different spatial levels have an impact on the sensitivity maps i.e. on the prioritization of the different components.

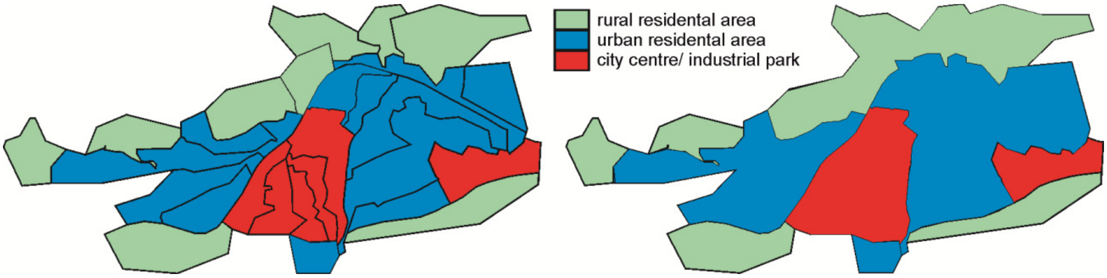

Fig. 2. (a) Left: medium zoning; (b) Right: coarse zoning.

For the highest spatial resolution, the fine zonings of PE of Fig. 1 (PE) are used. For medium zoning, the areas shown in Fig.2 (a) are used. For a coarse zoning the areas shown in Fig. 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.

3. Results and Discussions

Fig. 3 shows the evaluation of reduction scenarios for evaluation based on fine zonings. In Fig. 3 (a), the impact of dry weather flow reduction on shear stress performance (PI_{Tau}) is shown. Each line shows the results of reduction scenarios on the dry weather flow performance (PI_{Tau}) at one fine zone. The light grey lines in the background indicate zones which have only a marginal impact compared to the other zones (thick black lines). Of 88 fine zones, the most sensitive ones are evaluated in more detail. While most of the thick black lines show a continuous decrease in change in PI_{Tau}, the red lines 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.

One might argue that for shear stress performance, the zones with high dry weather flow production are the most important. Therefore, in Fig. 3 (b), the initial dry weather flows (no reduction factor applied) are shown in a cumulative distribution function (CDF). The circular markers show the dry weather flow production (Q) of the sensitive zones (thick black lines in Fig. 3 (a)). It can be observed, that these are distributed throughout the parameter range of Q and F(x) between 10 to 100 %.

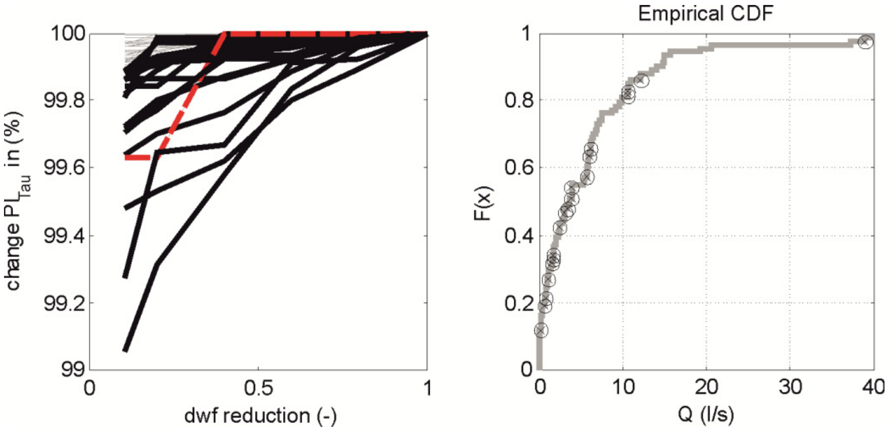

Fig. 3. UDS (a) sensitivity for fine zones; (b) evaluation of corresponding dry weather flows.

In Fig. 4, a similar evaluation to Fig. 3 applied for WDS is shown. The investigated PI in Fig. 4 (a) shows water age performance (PI_{Age}). It can be seen, that 3 zones are most sensitive (lowest values for PI_{Age} for high reductions). The corresponding investigation on water consumption in Fig. 4 (b), show slightly different results to Fig. 3 (b): the water consumption (Q) of the most sensitive zones is between 5 and 40 L/s, respectively the F(x) is between 60 and 100%. A few lines in Fig. 4 (a) are increasing and decreasing. This is due to changes hydraulics and therefore changes in flow paths in the WDS.

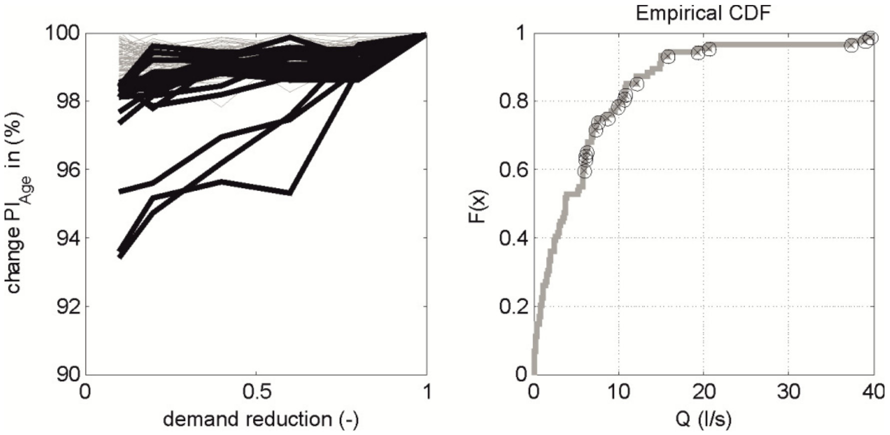

Fig. 4 WDS (a) sensitivity for fine zones; (b) evaluation of corresponding water consumption.

In Fig. 5. the results of Fig. (3) and Fig. 4 (a) are visualized at the location of the component modification i.e. at the zones (spatial join of PIs, GIS based SA). The results of the UDS evaluation are shown in shades of red and the results of WDS evaluation are shown in shades of blue. The yellow circular marker shows the position of the WWTP (waste water treatment plant) and the lilac circular marker shows the position of the main intake for water supply. The most sensitive zones for the UDS (red and dark red) are mainly located on the outer margin of the drainage area, while for the WDS the sensitive zones are distributed over the entire supply area. Two zones are sensitive for both WDS and UDS. These are colored in red and blue dashed.

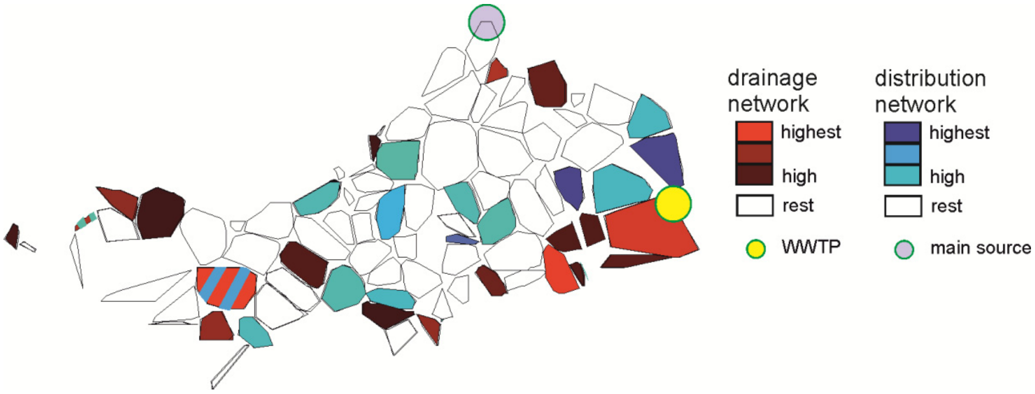

Fig. 5. spatial join of sensitivity at the location of component modification

In Fig. 6 (a) and (b), the results for the evaluation on medium sized zones are shown and in Fig. 6 (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 UDS evaluations in Fig. 6 (a), it can be observed that the medium 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 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 center of the city (W1, W3 and W4).

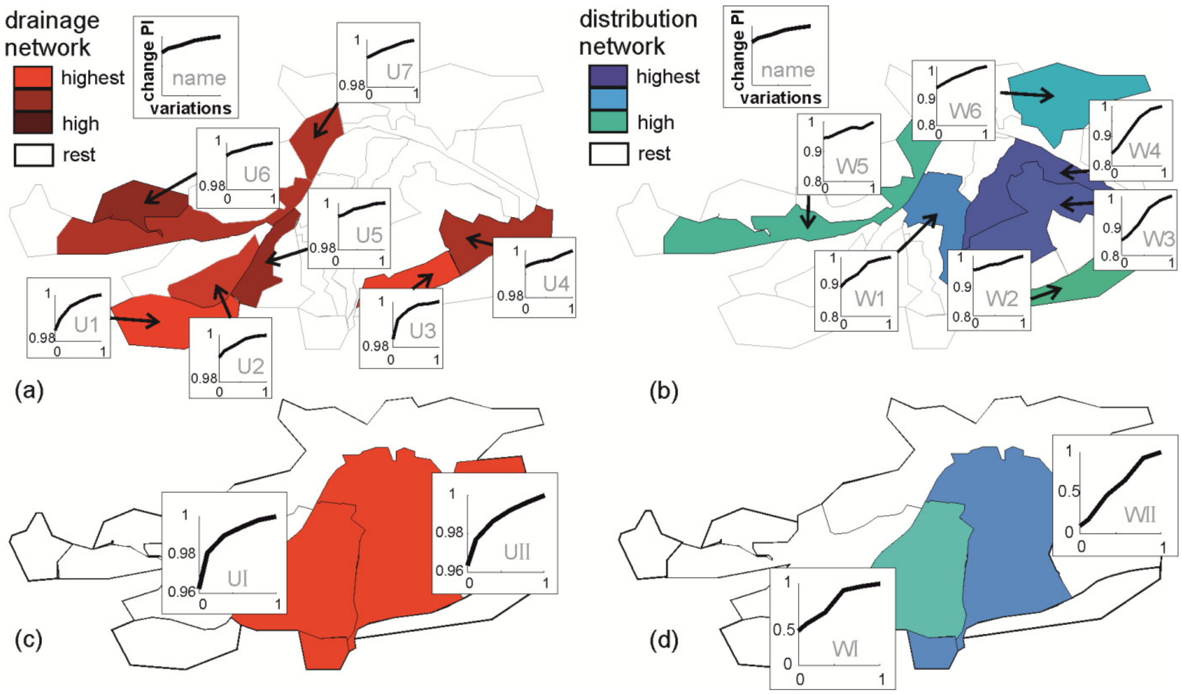

Fig. 6. results for medium zones for (a) UDS (b) WDS; results for coarse zones (c) UDS and (d) WDS.

In Fig. 6 (c), it can be seen, that contrary to Fig. 6 (a) and Fig. 5, the most sensitive areas are the central ones (UI and UII). For WDS (Fig. 6 (d)), the same coarse zones as for UDS are most sensitive (WI and WII).

In Table 1, the results of reduction scenarios applied to the entire drainage and supply area (i.e. 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} (respectively 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 (i.e. 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 (20days). 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 40hours).

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

Reduction factors (reduction to %)	0.1 (10%)	0.2 (20%)	0.4 (40%)	0.6 (60%)	0.8 (80%)	1 (100%)
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 measure such as e.g. 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.

4. Summary and Conclusions

In this work, a coupled model for integrated city scale analysis is successfully applied and further developed. Whereby, integrated analysis of water reduction scenario due to e.g. transition from centralized to decentralized water solutions are investigated. For visualization and communication of the results, a GIS-based approach of sensitivity analysis 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 but also to assess the impact of population decrease or water demand reductions. With the GIS based sensitivity analysis, 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 all) have a severe impact on the sensitivities. Furthermore, it was evaluated to which 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 evaluated, 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 (e.g. system performs sufficient 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 e.g. rapid growth scenarios, increase of water consumption, etc.), the presented approach can likewise be applied.

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