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Transformation strategies for wastewater systems under uncertain conditions

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Summary

In most rural and especially in peripheral regions, demographic and economic changes are threatening the functionality and economic operation of existing urban water infrastructures. A software-based optimization and decision support system can enable the systematic analysis and multi-criteria evaluation of future developments and options for adaptation and transformation processes of water infrastructures. "Optimal decisions" are significantly influenced by the level of importance given to the evaluation criteria selected in the multi-criteria procedure. A problem-oriented visualization with intuitive scenario development is particularly important for achieving a high transparency of possible solutions and a good understanding among the model application's target groups.

Keywords

multi-criteria optimization, transformation processes, visualization, decentralized water technologies, demographic change

Introduction

Future developments like demographic and climate change as well as changes in the energy sector have high impacts on existing municipal water infrastructures (water supply, urban drainage and wastewater disposal). Innovative sanitation systems in combination with source-based stormwater management measures enable the adaptation and transformation of existing systems towards new decentralized and flexible concepts of water supply and wastewater disposal. The assessment of future small scale developments and their local impacts on the existing infrastructures is a challenging issue; in conceptualising new solutions of decentralised infrastructural adaptation measures (cf. Meinzinger, 2010). Therefore the development of a model with a chronological and spatial sequencing of adaptation measures is necessary (cf. Kaufmann Alves, 2013; Schiller, 2010).

Methods

In the BMBF (German Federal Ministry of Education and Research) funded research project SinOptiKom an innovative software-based optimization and decision support system for long-term transformation of wastewater infrastructure has been developed. The optimization and decision support system is structured along three components. These components are an input data pre-processing tool with a database and a scenario manager, a mathematical optimization model and an interpretation tool (Kaufmann et al., 2014; Schmitt et al., 2014). Input data and generated results (e.g. geodata, demographic data or adaptation measures) are stored in a knowledge and evaluation database. As a database management system the open-source software PostgreSQL (Version 9.3) has been applied (Worreschk et al., 2014; Baron et al., 2015).

The **database** includes a list of measures for defining the options for action. Combined sewers, sanitary sewers and stormwater sewers ensure the urban drainage. The model provides the possibility to access various maintenance measures (flushing, reparation, renovation) and can identify the need of decommission of sewers. Furthermore the identification of a possible implementation of stormwater discharge in trenches or blackwater diversion in pressure and vacuum mains is possible. Roof greening, unsealing of paved areas, bio-swale infiltration measures and rainwater harvesting for domestic use and gardening are included as stormwater management measures. The wastewater treatment can be ensured with centralized wastewater treatment plants or decentralized small waste water treatment plants like sequence batch reactors, membrane bio reactors or constructed wetlands. At last innovative and resource-oriented technical elements like the separation of blackwater (flush toilets) and greywater, the greywater reuse on household level or a public greywater recycling, a technical nutrient recycling, the co-fermentation of blackwater in digesters or biogas plants can be chosen (Wölle et al., 2015).

The developed scenario-manager enables the generation of comprehensive scenarios by combining different drivers. These scenarios can be created both for individual local communities as well as for groups from several localities, which are connected by sewage systems. In the development scenarios, the main drivers for a change can be combined with different weighting factors. As drivers for rural areas, the engineering and planning factors were identified as water demand, energy demand, water and energy prices, costs of technical equipment, legal framework, climate change, as well as population and settlement development (Baron et al., 2016).

The impact of demographic change is a key factor in the development of rural settlements, as a significant decline in population due to negative natural population and migration balances is predicted in the municipalities of the study area. An analysis of the settlement and milieu structure scaled on the level of individual roads and buildings (micro level) allows the settlements to be subdivided into small-scale *transformation areas.* Three different possible scenarios considering future developments of population, housing and vacancies are assumed for each *transformation area* (Hoek et al., 2016). The three scenarios (Figure 1), namely *trend scenario*, *de-densification and dispersion scenario* and *scenario of restructuring the settlements center*, all deal with the current resident population according to data, which include the address-based dates of age and gender of the inhabitants. The approach stands out against conventional population projections, since it uses primary data of the *de facto-population* in opposite to aggregated census data (Schmitt et al., 2016).

The trend scenario is based on standard assumptions of the population projection, considering the regional net migration rate and the national fertility and mortality rate. No constructional measures in terms of the settlements housing are assumed. Population decline and vacancies occur in the settlement centers in a shorter term and on the fringe in the long term perspective. The *de-densification and dispersion scenario* synthesizes a stronger population decline in the settlement centers due to their structural abandonment, increasing vacancies and a lack of in-migration in these *transformation areas,* whereas little housing construction on the settlements fringe is assumed. The scenario that synthesizes the *restructuration of the settlements centers* deals with their structural and demographic revitalization and a decline in vacancies in central *transformation areas.* Small numbers of vacancies are assumed on the fringe due to the increased attractiveness in the settlements centers.

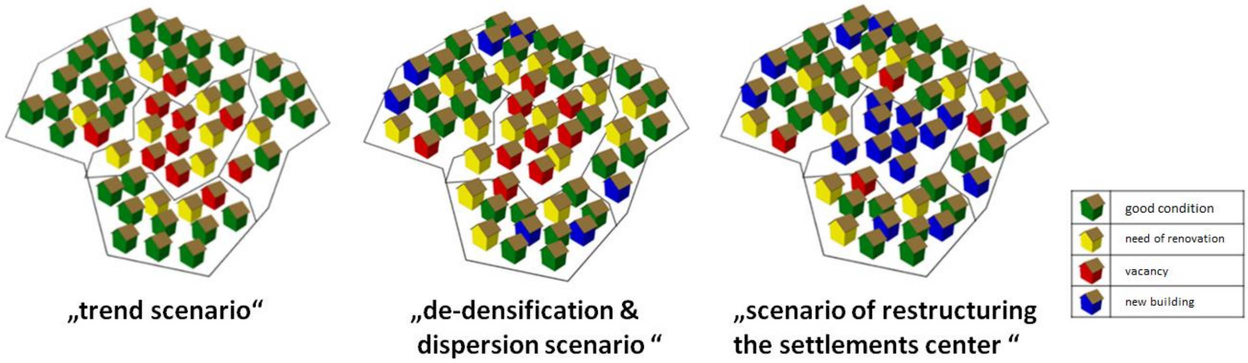

Fig. 1: *Visualisation of the demographic and structural scenarios (Wölle et al., 2016)*

The three scenarios offer the opportunity to analyze the impact of different realistic structural and demographic developments on water infrastructures according to the population densities on the micro level of defined *transformation areas*.

Taking future developments into account, a consistent, weak or strongly decreasing as well as a user-defined water demand can be selected. The possible range of water demand per capita and the three projections for the model villages were calculated and stored in the database, as well as design rainfall intensity and general conditions. The approach is described in Baron et al. (2016). Reference values are defined for the costs of the individual measures and future investments. Reinvestment and operating costs are recorded in the model with a real price change rate. The price change and the interest rate can be chosen by the user. Thereby, it is also possible to reduce future investment costs for new, innovative technologies. Assuming that new technologies are subject to a considerable price reduction through further dissemination and use, price adjustment curves for the corresponding technology components are provided in the database. The energy needs of individual measures is reflected in operating costs and changes in energy prices are taken into account in the generation of biogas (Wölle et al., 2016; Baron et al., 2016).

The **scenario manager** is a smart tool which leads the user through a step-by-step process to select the different options for the drivers described above. A color-coded progress bar supports the user to keep track which drivers have already been managed. Due to interdependencies of the drivers, the scenario manager has to pre-select and provide only meaningful options in later drivers. All selected options (such as legal framework choices) and internally calculated values (such as derived values depending on the water demand development) are stored as a scenario.

The scenarios are integrated into the **optimization model** as input parameters (Baron et al., 2016). In order to determine an optimized transformation strategy of urban drainage systems, a mathematical model based on mixed-integer linear programming (MILP) is used. In this chosen approach, a set of binary variables model the decisions to build, rebuild, or close down a specific entity of the wastewater system in a specific year while real-valued variables model the flows of rainwater and wastewater at each point in time as well as the costs of a candidate solution to the mathematical problem. In order to guarantee the technical feasibility of the system, a large number of linear constraints are defined which, e.g., restrict the flows in each conduit to cohere to lower and upper technical limits. Based on the demographical model described above, these variables and constraints are defined for each of the future years in order to obtain a transformation path for the upcoming 50 years. In order to evaluate and compare different possible solutions, the system uses the user-specific evaluation criteria costs, ecological impact, water balance, flexibility, water recycling, resource recovery, energy efficiency and acceptance. A special feature of the model is the simultaneous consideration of each of these eight evaluation criteria as a weighted sum. All implemented measures influence the degree to which each individual criterion is achieved on the basis of their deposited properties. In order to make the individual criteria comparable and thus be able to produce an optimized compromise solution of the multi-criteria optimization problem, a uniform scaling of the criteria (here values between 0 very good and 1 very poor) is necessary.

The results of the optimization are presented in the **interpretation tool**. This tool supports the user to analyse and interpret the proposed transformations in an intuitive way. Therefore, the principle of multiple coordinated views has been applied; a map-based view serves as key component in this tool. The user is able to navigate freely in the 3D-map by panning, rotating, tilting, and zooming. As can be seen in the figures 2 and 4, all geo-referenced data including the sewers and the connected infrastructure as well as newly introduced measures are shown directly on the map. For each element on the map, its relations to other elements can be shown by semantic highlighting. Popups and connected views provide details on demand. To traverse through time (transformation period which has been calculated in the optimization) the tool provides a time slider. Pre-defined settings enable quick views on the map, e.g. show different sewer types directly color-coded in the overall infrastructure. Following the overview-and-detail approach, next to the map, a panel is visible that provides statistical data and distributions.

Fig. 2*. Display in demonstration model: Existing sewers in selected residential areas in the year 2060. Graphic: University of Kaiserslautern*

More details of the transformation strategy proposed by the optimization that have no geospatial references (e.g. costs) are provided in further reporting views. The “overview” view provides a general summary of the scenario and its results. Radar plots enable to compare the user-specific evaluation criteria with their degree of achievement which allows the user to rate the optimization results. The “financial” view let the user inspect the costs in different levels of detail, from an overall overview of the development of costs in the whole optimized area to a detailed view of costs per inhabitant in a certain year of a certain transformation area. Transformation strategy means that there are in general adaptations in the sewer system, e.g. change of material, change size of sewers, etc. The “measures” view gives a list of all proposed actions, grouped by transformation areas and year. Additionally, details about emissions per sewer are given. All items that appear in those reporting views and that have geospatial reference are connected. Whenever the user is interested in such an item, he can click on it and the tool directly jumps to the item's representation on the map.

Results and Discussion

The optimization system has been applied to two municipalities for a time period of 50 years. In consultation with the representatives of the municipalities, scenarios were prepared and the weighting emphasis of the evaluation criteria was discussed. It was determined that the three scenarios of the development of rural settlements are the focus of the investigation. Furthermore, the effects of climate change had to be considered. For this purpose, the design rainfall intensity was increased in the scenario manager. It was decided that the impact of each individual evaluation criteria for a small model community should be considered in a first step. The results of the transformation were evaluated in detail with planning consultants and the representatives of the municipality. For the individual optimization results, the cost values for future investments are shown in figure 3. It can be seen that for the model community, a significant cost increase is caused by a high weighting of the evaluation criteria flexibility, local water balance, ecological impact and water recycling. In contrast the different scenarios have very little influence.

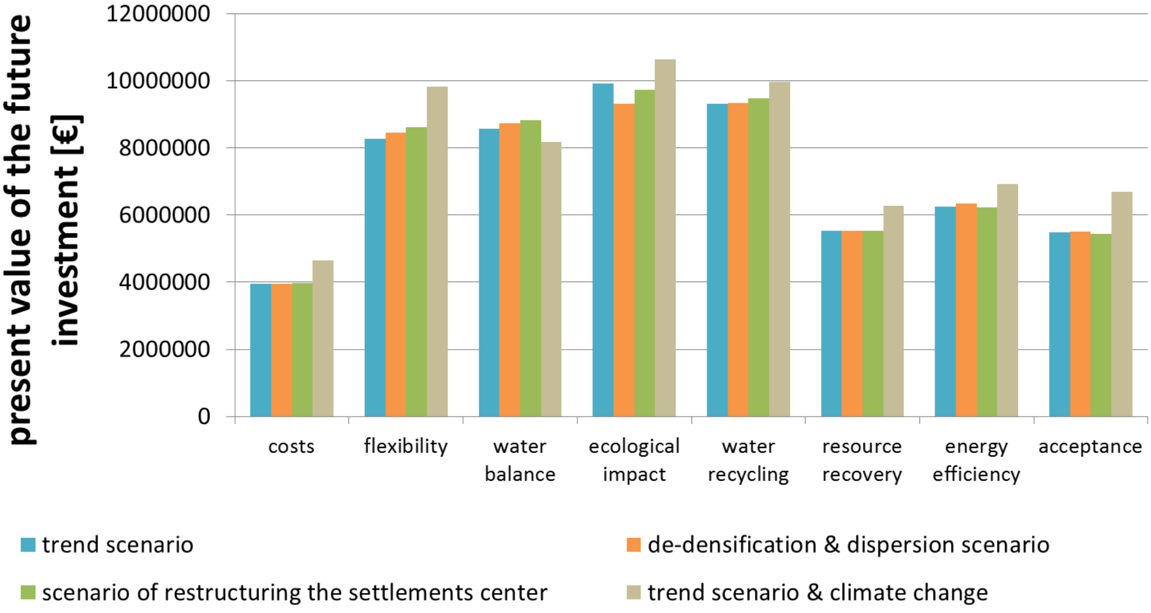

Fig. 3. *Present value of the future investment for the individual consideration of each evaluation criteria. Graphic: University of Kaiserslautern*

The next step included the optimization for the entire catchment area of the wastewater treatment plant of the model communities. Different levels of importance given to the evaluation criteria have been analyzed and the effects of different scenarios on the transformation processes can be shown. Primarily a broad spectrum of different transformation scenarios of wastewater infrastructure in rural areas under the influence of demographic change have been generated and evaluated. The model application demonstrates that "optimal decisions" are significantly influenced by the level of importance given to the single evaluation criteria. Decentralized measures for the separation of material flow with separated blackwater and greywater treatment and the establishment of decentralized wetlands are selected in cases in which both flexibility and the conservation of resources are predominantly focused (Figure 4).

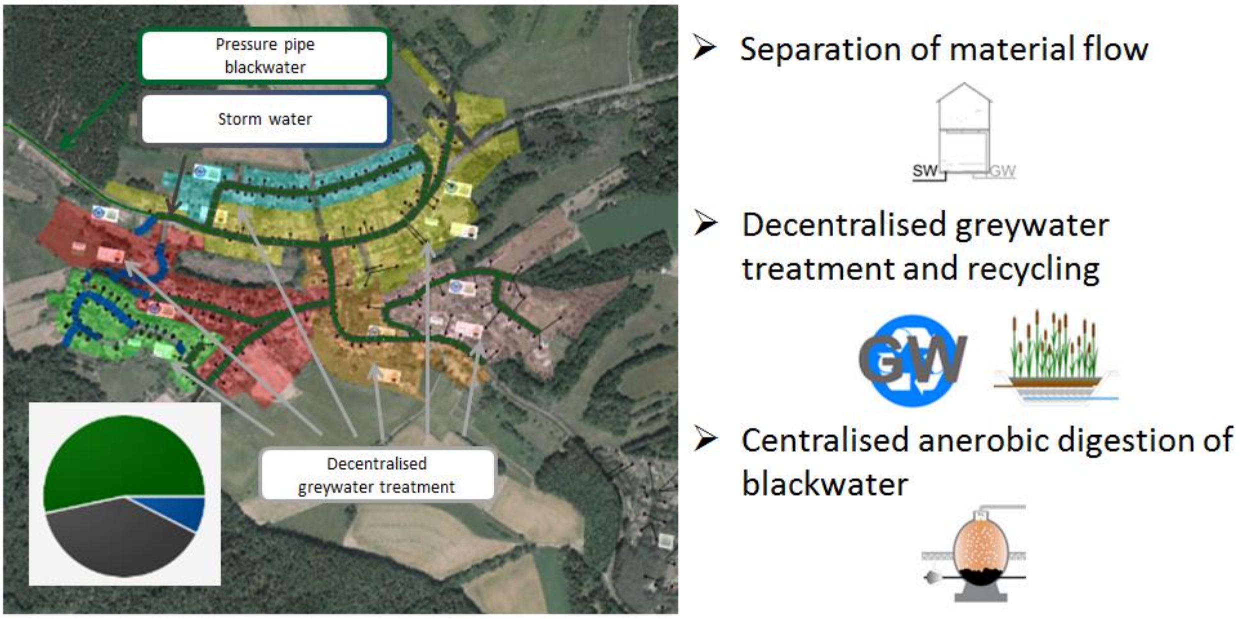

Fig. 4. *Optimization solution with decentralised measures for the separation of material flow with separated blackwater and greywater treatment. Graphic: University of Kaiserslautern*

A standard level of importance given to cost, on the other hand, leads to the preservation of centralized systems. The implementation of decentralized stormwater management measures is supported by the criteria of water balance, cost, ecological impact and flexibility in equal measure (Figure 5).

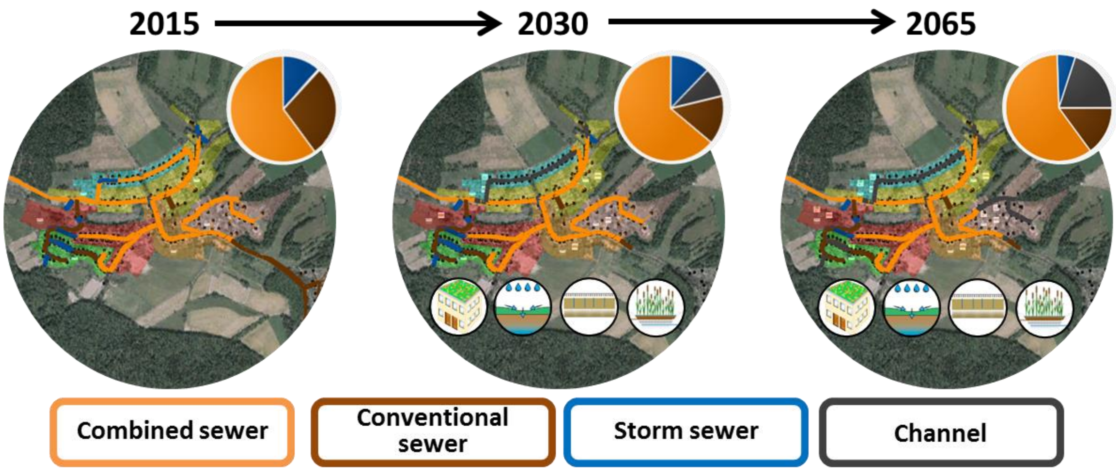

Fig. 5. *Exemplary transformation path for an optimization with the priority on water balance and cost. Graphic: University of Kaiserslautern*

Concerning the context of demographic decline in peripheral rural regions, it appears necessary to define strategies of structural shrinkage in respect to infrastructural measures. One possible approach is the step-wise decentralization of water infrastructures especially of settlements subdivisions on the fringe. In respect to the uncertainties of future structural and demographic decline, which can be associated with a regionally differing intensity, the perspective of a necessary consolidation of the settlements structure, e.g. deconstruction programs on the settlements fringe, should be considered in the decentralization and transformation process of water infrastructures.
The study has shown that implementation of innovative sanitation systems to the existing infrastructure or decentralization of the waste water infrastructure would further increase the pressure to adapt the central system. It is expectable that new or other waste water treatment

methods (e.g. anaerobic treatment) can also be relevant at central locations by implementing a separation of grey- and blackwater.

Conclusions

In the past, and to a large extent also in the current application practice, evaluations are made on the rehabilitation requirements of pipes and sewers according to aspects of the constructional state, possibly in combination with hydraulic requirements as a result of pipe network and sewer network calculations. This results in repairing, renovation or renewal of pipes and sewers without taking into account new methods and technologies. Regarding the entire lifecycle and renewal of sewers, decentralization of wastewater disposal especially in the peripheral location of settlements or settlement units should be taken into consideration especially concerning their medium and long-term advantages. In case of a renewal or renovation of sewers, it should be taken into account whether a reduction of the sewer cross-section or the implementation of decentralized stormwater management measures are possible. Measures for stormwater management appear to be particularly advantageous in terms of improving the local water balance as well as saving money. The comparative assessment of centralized and decentralized concepts and facilities for wastewater treatment must take into account the reduced treatment performance of small wastewater treatment plants (in particular with natural methods like constructed wetlands). This results in higher emissions of pollution loads into the water bodies. A large-scale introduction of a separate greywater treatment and reuse appears to be ineffective in rural areas, as it would further decrease drinking water consumption and the water flow in drinking water networks - at least under the cost assumptions underlying SinOptiKom. (Schmitt et al., 2016)

The general adaptation strategies for wastewater systems can be formulated as a sequence of individual work steps (Schmitt et al., 2016):

1. Problem analysis
2. Analysis of the future population and settlement development
3. Identification and analysis of influencing factors for water infrastructure
4. Selection and weighting of evaluation criteria
5. Generation of development scenarios
6. Analysis of generated development scenarios
7. Decision about alternative solutions

The presented method and general adaptation strategies can be applied to settlement areas facing the same challenges. Even though the project has been focused on rural areas several key aspects, like scenario generation and management, selection of evaluation criteria and general recommendations might be applied to more densely populated urban settlements and inceasing population as well. The demonstration and visualization of different solutions for an expedient future transformation of wastewater infrastructure facing high uncertainty in its major impact factors is a great benefit for planners, engineers and political decision-makers.

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