# Cross-sectoral optimization and visualization of transformation processes in urban water infrastructures in rural areas

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## ABSTRACT

Predicted demographic, climatic and socio-economic changes will require adaptations of existing water supply and wastewater disposal systems. Especially in rural areas, these new challenges will affect the functionality of the present systems. This paper presents a joint interdisciplinary research project with the objective of developing an innovative software-based optimization and decision support system for the implementation of long-term transformations of existing infrastructures of water supply, wastewater and energy. The concept of the decision support and optimization tool is described and visualization methods for the presentation of results are illustrated. The model is tested in a rural case study region in the Southwest of Germany. A transformation strategy for a decentralized wastewater treatment concept and its visualization are presented for a model village.

**Key words** | innovative decentralized water technologies, optimization, transformation processes, visualization

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## INTRODUCTION

Adaptations and transformations of urban water infrastructures will be required due to predicted climatic, demographic, and socio-economic developments. In large parts of Europe, central urban drainage and water supply systems predominate, which have grown over the last century. They do not meet the increased requirements of resource efficiency and sustainability anymore. Especially in those rural areas, where population will decline, the new challenges will affect the functionality of existing central supply and disposal systems and demand flexible adaptations or even long-term transformations (cf. Comas *et al.* 2003; Tscheikner-Gratl *et al.* 2014).

Previous scientific approaches for the adaptation of existing infrastructures have aimed at the evaluation of urban drainage systems and the comparison of alternative solutions (cf. Meinzinger 2010; Bach *et al.* 2013) or on the development of decision support frameworks (cf. Dockhorn & Dichtl 2006; Pearson *et al.* 2010; Duffy & Jeffries 2011; Lienert *et al.* 2013; Scholten *et al.* 2014). Approaches for chronological and spatial sequencing of transformation processes are rarely investigated (cf. Schiller 2010; Kaufmann Alves 2013; Boelee & Kellagher 2015). The transformation process should comprise innovative wastewater technologies as well as resource efficiency and nutrient recovery (cf. DWA 2014; Singh *et al.* 2015). Moreover, the cross-sectoral connections of water, wastewater, and energy infrastructure have to be considered (cf. Sitzenfrei & Rauch 2014). The large number and the complexity of decisions to be made, as well as the interrelation of their outcomes, require the application of a sophisticated optimization and decision support system. Partners from universities, planning and consulting firms, as well as communities and supply and disposal companies, have participated in the joint research project *SinOptiKom* presented here.

The main objective of the project is the development of an innovative software-based optimization and decision support system for long-term transformations of existing infrastructures of water supply, wastewater, and energy. The model analyzes and evaluates possible future scenarios and intelligent system structures, and it deduces optimal strategies for planning, technical, and political processes aiming at sustainable urban water infrastructures. The

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identification of stakeholders and their influence on the model development are presented in Schmitt *et al.* (2014). They are grouped in stakeholders directly related to the IT-system under development (system developer direct and indirect system users) and stakeholders with an indirect interest or influence regarding the supply and disposal systems (supply and disposal provider; political decision maker; planner/consultant; user; high-level influencer). This paper presents the structure and results of the optimization and decision support tool for the wastewater system. Approaches for the visualization of simulation results with the scalability for different stakeholders are shown.

## OPTIMIZATION AND DECISION SUPPORT TOOL

The overall structure of the software-based optimization system consists of and integrates three components (see Figure 1). These components are mainly a pre-processing tool with a database and a scenario-manager, a mathematical optimization model and an interpretation tool. The interpretation tool will be used by persons directly planning and working with the optimization and decision support model as well as indirectly by decision makers relying on the produced results and their visual representation.

### Pre-processing tool

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) is applied. All input data for the investigated settlement are implemented in the database. Thereto belong water supply and disposal infrastructure data, the variable input parameters inhabitants, drainage area (types, runoff coefficient and categories of pollution), water demand as well as sewage dry weather flow (e.g., greywater, blackwater) and their contaminants (e.g., nutrients, energy content). These data should be provided by the local supply and disposal providers and the planners and consultants.

To integrate possible future changes, scenarios are generated by combining developments of population, settlement structure, water and energy demand, changes of the legal framework, costs as well as climate. The approach is described in Worreschk *et al.* (2015). These scenarios are developed on three decision and modelling levels. On the macro level, the development of the settlement in general, as well as of the institutional and legal framework for an association of municipalities, is considered. In Germany an association of municipalities is a local authority, which consists of neighboring municipalities. For every village (meso level) the development of population, settlement and water demand is considered (cf. Notaro *et al.* 2014). In addition, the functionality of the sewer network is examined and the need for action is shown. The micro level considers smaller parts of a village, e.g., parts of the network or groups of buildings. On this level, the settlement development in detail is presented and the implementation of adaptation measures is performed.

To illustrate and select scenarios, a software-based scenario-manager referring to the database is developed. In the scenario-manager, a calculated prognosis can be chosen for each driver successively and here interdependencies of the drivers are shown.

Figure 2 presents the adaptation measures implemented in the presented project. The cross-sectoral connections of water supply, urban drainage, stormwater management, wastewater treatment and reuse as well as energy recovery are shown. Adaptation measures are assigned to each sector and divided into general and detailed measures. The arrows show the influence of one sector on another sector. For example, if a central sewer system is changed to a system with a separation of greywater and blackwater and a reuse of greywater, the central sewer system has to be adapted, heat recovery of greywater is possible and the central water supply system is influenced through the strong decline of water demand due to the reuse of greywater.

Depending on the selected scenario, different adaptation measures for water infrastructures are chosen by the mathematical optimization model, because not every adaptation measure is reasonable or technically feasible for every scenario. Then the number of adaptation measures as input parameters is reduced and so the computation time of the optimization model decreases.

### Optimization model

In order to determine an optimized transformation strategy of urban drainage systems, a mathematical model based on integer linear programming (ILP) is used (cf. Worreschk *et al.* 2014). The model is based on hydraulic and material flow principles.

The present and the future states of the urban drainage system are modelled with a directed graph. For each conduit in a central sewer system, and the connected households and real estates, different adaptation measures are investigated for each time step. A binary decision variable is

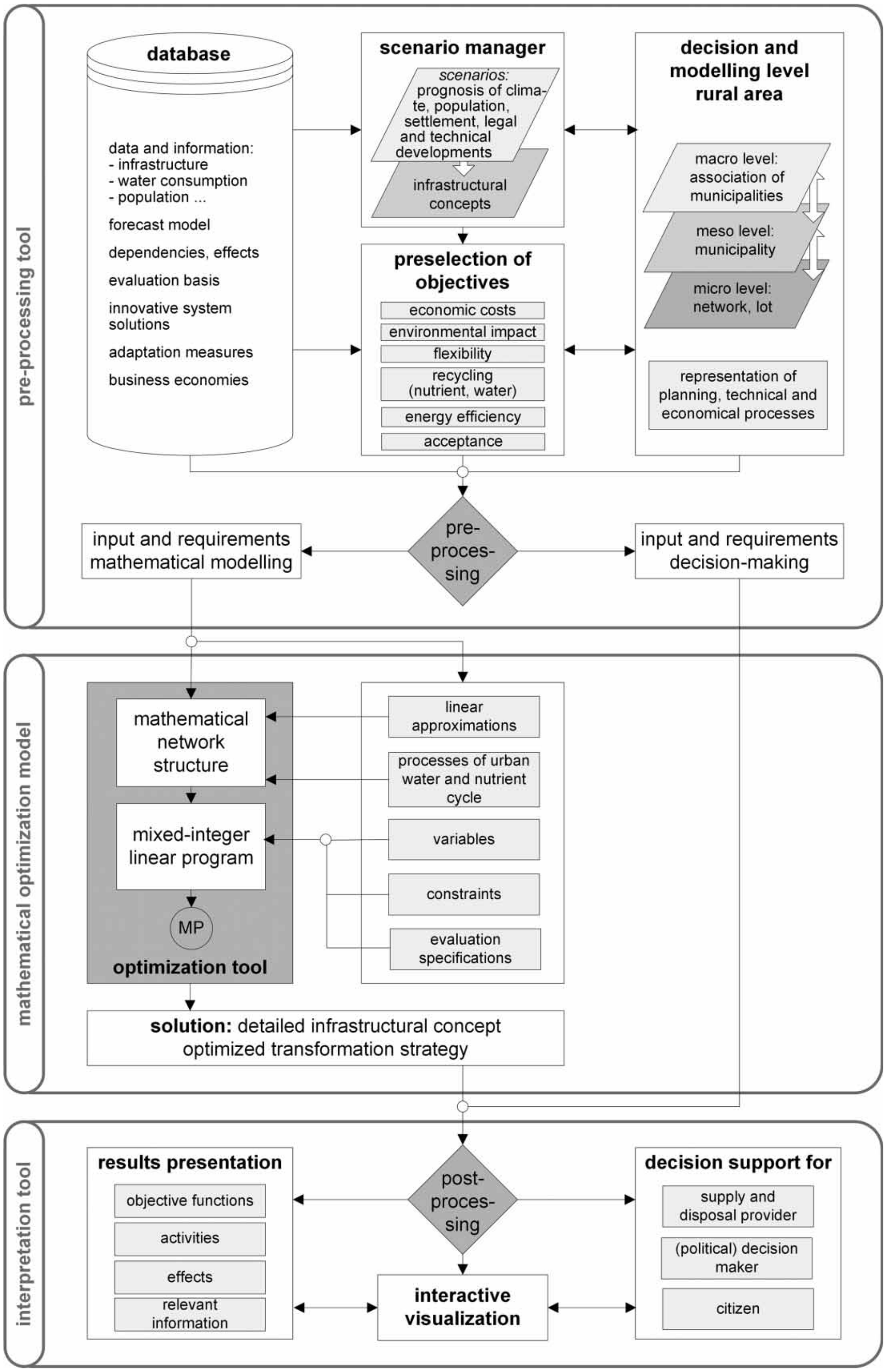


**Figure 1** | Concept of the optimization and decision support system.

introduced to decide whether the measure should be taken at this time step. Adaptation measures are shown in Figure 2 and comprise not only changes of pipe diameters or flushing intervals but also the installation of decentralized facilities like small wastewater treatment plants (WWTPs) or a separation of greywater and blackwater.

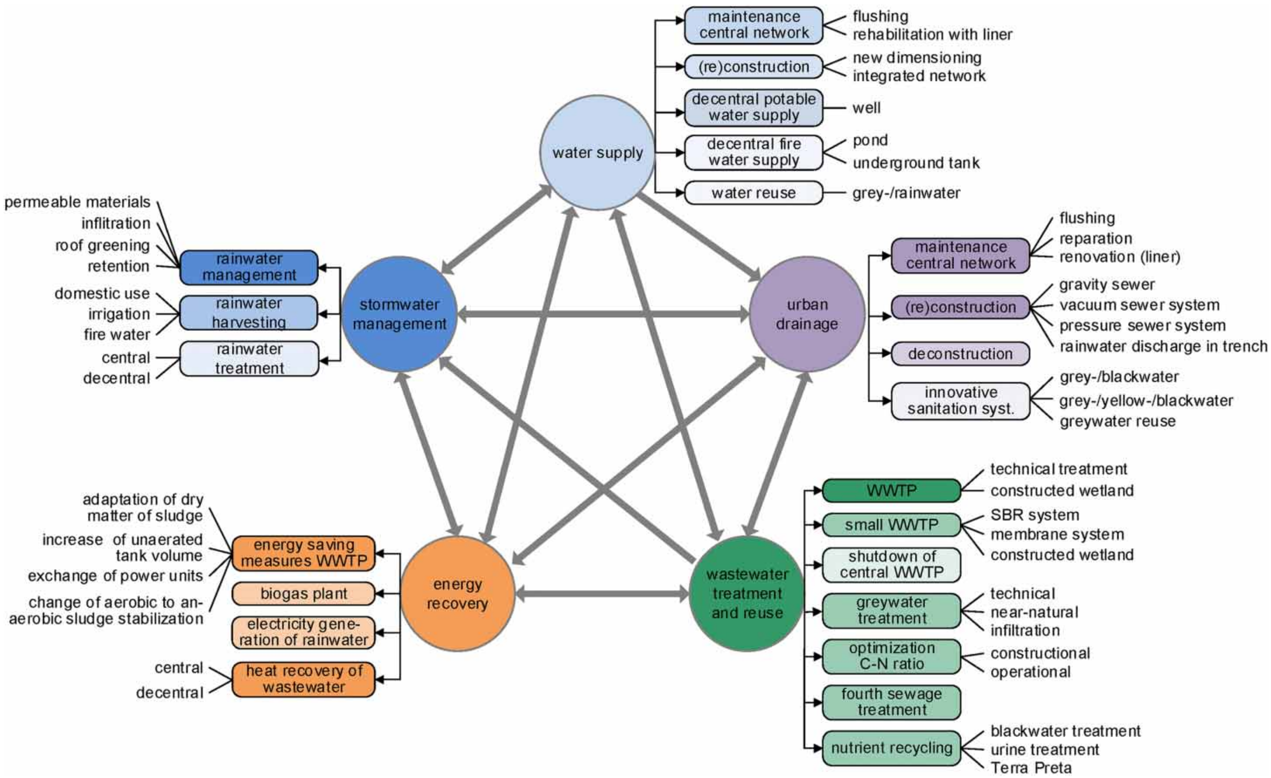


**Figure 2** | Excerpt of concepts with implementation options for water supply, urban drainage, stormwater management, wastewater treatment and reuse as well as energy recovery.

Moreover, a dynamic network flow model with flow variables and appropriate side constraints is used to model the flows through the wastewater networks and ensure feasibility of the systems at each time step. This network flow model analyzes technical functional limits for the present state and the chosen scenario for different time steps.

For example, for sewers the functional limit for underutilization is determined with the parameters shear stress and corrosion. Thus, problems in the sewer system can be located and the need for action is shown.

The model calculates optimized adaptation measures and transformation strategies considering the weighting of objective functions. The objective function of the ILP model consists of a weighted sum of the different objectives that are to be optimized. These objective functions are economic costs, environmental impacts, flexibility, recycling of water and nutrients, energy efficiency and acceptance (see Table 1). The weights to be assigned to the objectives can be determined by the user of the model. Hence, each user can specify their own preferences with respect to the importance of economic, environmental, and social aspects. Since the objectives are all measured in different units, they are scaled between 0 (= very good) and 1 (= very poor).

The results of the optimization model are detailed infrastructural concepts and optimized transformation strategies which show the spatial and chronological sequencing of adaptation measures for the considered period of time.

## Interpretation tool: visualization of results

Besides the development of optimized transformation strategies, an interactive visualization of scenarios, processes, dependencies, and results is of high importance (e.g. Niederer *et al.* 2007). The visualization tool forms a functional cross section of the overall model and provides full interaction possibilities for all stakeholders, i.e. planners, decision makers, and users. The visualization and interaction concept focuses on an attractive, scalable design adapted to the different user requirements and devices. To support collaborative work (Schöffel *et al.* 2014) and to provide maximum flexibility, especially for the decision makers, the visualization tool is available for tabletops (large multi-touch displays) as well as for common mobile smart devices (e.g. Apple iPad and Android-based devices). Furthermore, each user group (e.g. planners and decision makers) needs the results of the optimization process presented in an appropriate level of detail, e.g.

**Table 1** | Objectives for the modelling process and their evaluation

| | Objectives | Evaluation | Scaling between 0 and 1 |
|---|---|---|---|
| Economic criteria | costs (investment costs, operational costs, maintenance costs, sunk costs, earnings) | average present value of capital costs | 0 = capital value of project costs is 0<br>0.5 = average capital value of project costs (in Germany) |
| | flexibility | lifetime, minimum size, expandability, modular design and robustness of each technology | evaluation of each adaptation measure with scores between 1 and 10 |
| Ecological criteria | water balance | distance between current and natural rate of runoff, infiltration and evaporation | 0 = natural rate<br>1 = rate of covered area |
| | emission in environment (through WWTPs, combined sewer overflows, stormwater discharge) | balance of emission (on different discharge points) | 0 = no emissions<br>1 = compliance of legal minimum standards |
| Resource efficiency | recycling of water<br>recycling of nutrients<br>energy recovery | percentage of recycled water<br>percentage of recycled nutrients<br>percentage of recovered energy | 0 = 100% recycling<br>1 = 0% recycling |
| Social criteria | acceptance | user-friendly handling, operating expenses, odour, noise, social environment, financial issues, required space of each technology | evaluation of each adaptation measure with scores between 1 and 10 |

the mayor is in general not interested in the diameter of a new sewer pipe but in the total cost of the adaptation measures.

The visualization tool illustrates and visualizes the following criteria: sequencing of the transformation process, cost effectiveness, financial feasibility, energy efficiency, nutrient recycling, as well as political requirements and legal modifications. For visualizing changes in time, different techniques are applied. According to Ware (2012), color as well as shape coding can be used to visualize changes.

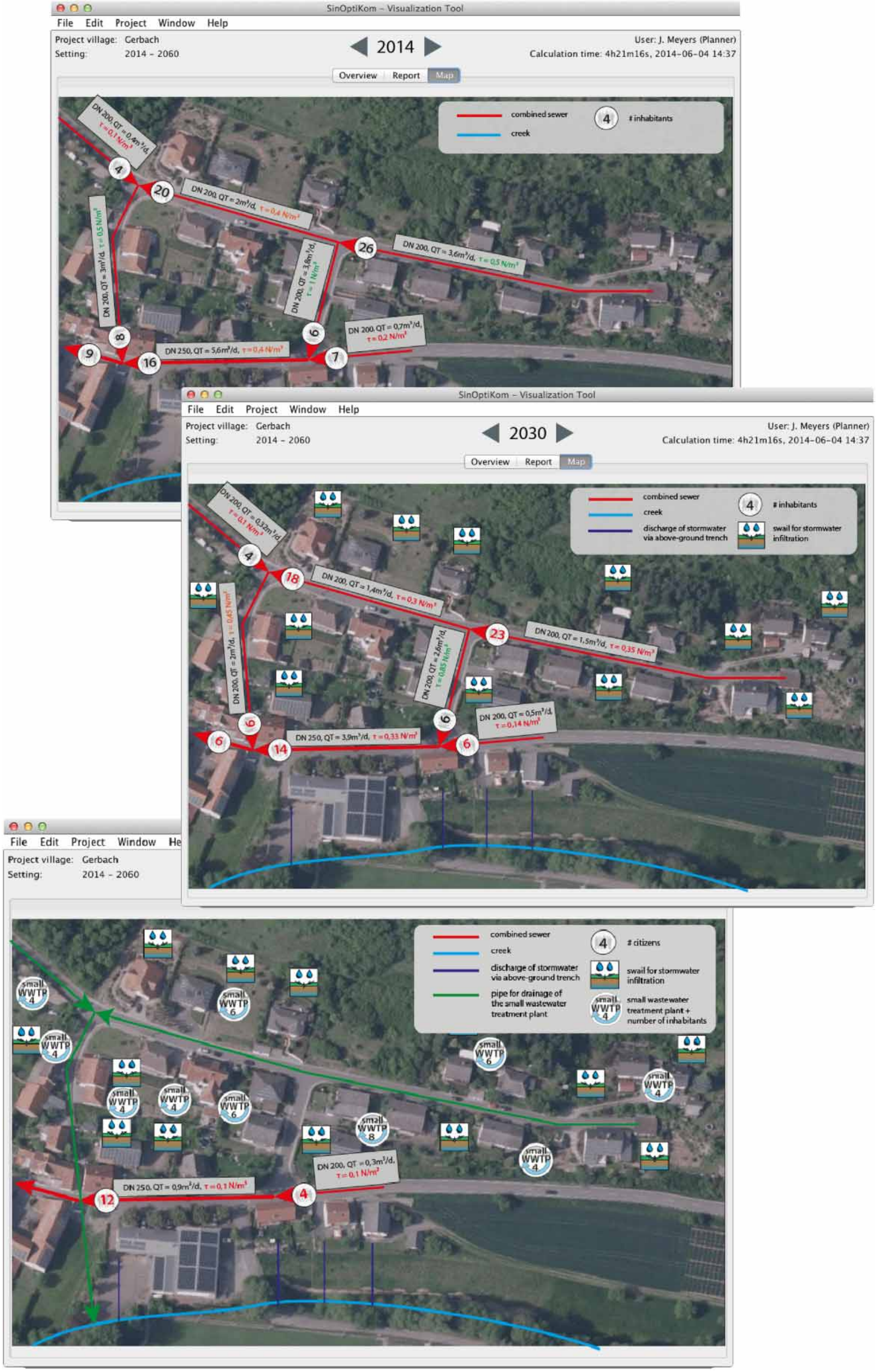
The tool consists of three main modules: overview, detailed report, and map view. The overview provides the user with a short textual report and a summary graph of the optimization results, e.g. total costs, environmental impacts, etc. In the detailed report, the user can find more information concerning the necessary adaptation measures and additional facts provided by the mathematical optimization model, e.g. construction year, material, diameter, etc. The core component of the visualization tool is the map view. Here, a geographical information system (GIS) is integrated, which is based on the open-source and platform-independent NASA World Wind Java SDK framework (NASA 2014). This framework can easily be adapted to different users' needs.

## IMPLEMENTATION AND RESULTS

A first design of the prototype of the optimization and decision support system is tested and evaluated in a rural case study region in the Southwest of Germany. The two model municipalities have a wide range of settlement structures and face different challenges for the future design of urban supply and disposal systems. They are representative for numerous municipalities in rural areas in other parts of Germany as well as in other countries.

Results for a selected model village are presented. They are based on a scenario with a medium population decline of 12% until 2030 and 32% until 2060 (Statistical State Office of Rhineland-Palatinate 2010, 2012). The development of the specific water demand is identified with the scenario technique which comprises the development of the major influencing factors (Nowack & Günther 2009). The specific water demand is 100 litres per capita and day at present and in the chosen scenario it will decrease to 80 in 2030 and 75 in 2060. The objectives for recycling of nutrients and water as well as flexibility are more strongly weighted in the objective function. A system change is suggested due to the decline of population and water demand: transformation of the current central sewer network to a combination of small wastewater treatment plants and a central sewer for the center of the village.

At present a central combined sewer system exists and the wastewater is treated in a wastewater treatment plant together with the wastewater of neighboring villages. The shear stress in some sewers is very low ($<0.5\ \mathrm{N/m^2}$), this indicates that short flushing intervals are needed which will cause higher operational costs. On the other side,



Project village: Gerbach
Setting: 2014 - 2060
User: J. Meyers (Planner)
Calculation time: 4h21m16s, 2014-06-04 14:37

Project village: Gerbach
Setting: 2014 - 2060
User: J. Meyers (Planner)
Calculation time: 4h21m16s, 2014-06-04 14:37

Project village: Gerbach
Setting: 2014 - 2060

**Figure 3** | Prototype of the visualization tool (map view) for a model village for 2014, 2030 and 2060.

surcharges of manholes in a design rainfall event cause hydraulic problems. The presented system transformation recommends the implementation of measures for the retention and infiltration of stormwater until 2030. The real estates are large enough for the installation of swales for stormwater infiltration. If they are close to the creek the rainwater is discharged via aboveground trenches. Thereby, the rainwater in the combined sewer system can be reduced and the infiltration supports the natural water balance. Since the population and the water demand decrease, the shear stress decreases also. In 2060, the shear stress is very low and the economic lifetime in some sewers is reached. Therefore, for parts of the village, small wastewater treatment plants are implemented. The treated wastewater is discharged into the creek via a sewer. For the center of the village the combined sewer is maintained because more inhabitants live there. The combination of central and decentral elements make the system more flexible and easily adaptable to future changes. The recycling of nutrients takes place on the central wastewater treatment plant in 2060. It is assumed that the technological progress makes recycling of nutrients cost effective until 2060.

In Figure 3, a prototype of the visualization tool with the results of the transformation is shown. The figure presents three different time steps of the resulting optimal adaptation strategy for a small part of the selected model village. The user can see the wastewater system (pipes, stormwater infiltration, and small wastewater treatment plants) with important data (diameter, dry weather flow and shear stress $\tau$) and additional information about the population (i.e. number of inhabitants connected to the pipe at different points). Important parameters are visualized color-coded to perceive critical and changed values in an intuitive way. Shape coding is used to enable easy distinction between different types of information. For example, parameters concerning the pipes are shown in a transparent grey text box, while swales for stormwater infiltration and small wastewater treatment plants are presented as small intuitive icons.

In Figure 4, the investment and operational costs for the maintenance of the central sewer system are compared with the costs of a system with a combination of small wastewater treatment plants and a central sewer. The more decentralized concept is slightly cheaper than the central system. Even though there is no significant cost difference, the second concept has more advantages. It is more flexible because it comprises technologies with a lifetime < 20 years. Technologies with lower lifetimes can be adapted more easily to demographic changes. Moreover, nutrient recycling is implemented and thereby it is possible to earn money, for example with the sale of fertilizer. Possible proceeds are not integrated in Figure 4; they would have a positive effect on the cost comparison.

## CONCLUSIONS

This paper presents the design and development of an optimization and decision support system for long-term strategies in the transformation of wastewater infrastructure. The benefit from the model is the calculation of optimal adaptation measures and strategies for urban drainage systems, taking into account weighted objective functions. A clear and interactive visualization of results and information relevant for decision-making is necessary and important for all stakeholders. The main requirements for the development of the optimization and decision support tool have been:

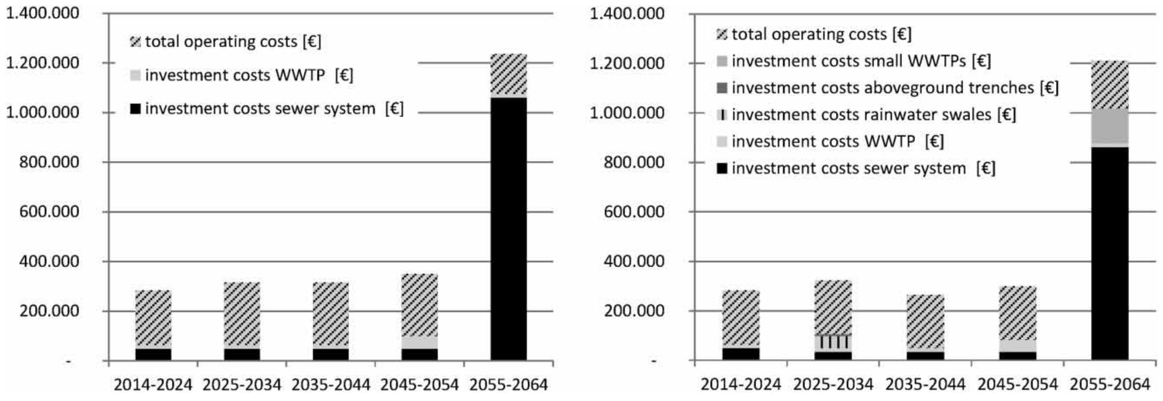


**Figure 4** | Comparison of costs for the maintenance of the central sewer system (left) and the transformation to a combination of decentralized and central elements (right) in the model village.

- early involvement of relevant stakeholders (task oriented requirements engineering)
- knowledge of decision-making requirements and levels
- knowledge of relevant processes and interdependencies in urban water supply and disposal infrastructures as well as in decision-making
- focusing on crucial information for decision support.

The presented results for a selected model village showed one option for the adaptation of a central sewer network over a long time period. The current prototype of the visualization tool for analyzing the results of the optimization steps uses state of the art concepts for visualizing the results in an intuitive and scalable way for different user groups. The next step will be further development, testing and evaluation of the optimization and decision support tool in the model region for different scenarios and weighting of objectives.

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## REFERENCES

Bach, P., McCarthy, D., 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.

Boelee, L. & Kellagher, R. 2015 ADAPT–A Drainage Analysis Planning Tool. Result of the EU-Project TRUST – Transition to the urban water services of tomorrow. http://www.trust-i.net/downloads/index.php?iddesc=117.

Comas, J., Alemany, J., Poch, M., Torrens, A., Salgot, M. & Bou, J. 2003 Development of a knowledge-based decision support system for identifying adequate wastewater treatment for small communities. *Water Science and Technology* **48** (11–12), 393–400.

DWA 2014 *Guideline DWA-A 272: Grundsätze für die Planung und Implementierung Neuartiger Sanitärsysteme (NASS) (Principles for Planning and Implementation of New Sanitation Systems)*. Arbeitsblatt, Hennef, Germany.

Dockhorn, T. & Dichtl, N. 2006 A decision support tool for implementing resource management in the sector of municipal wastewater treatment. In: *2nd IWA Leading-Edge Conference on Sustainability in Water-Limited Environments, Water, Environment Series No. 10* (Beck, M. B. & Speers, A., eds). IWA Publishing, London, UK.

Duffy, A. & Jeffries, C. 2011 A new framework to guide urban water transitioning. In: *Proceedings of the 12th International Conference on Urban Drainage*, Porto Alegre/Brazil, 10–16 September 2011.

Kaufmann Alves, I. 2013 A mathematical approach to find long-term strategies for the implementation of resource orientated sanitation. *Water Science and Technology* **67** (7), 1442–1454.

Lienert, J., Schnetzer, F. & Ingolt, K. 2013 Stakeholder analysis combined with social network analysis provides fine-grained insights into water infrastructure planning processes. *Journal of Environmental Management* **125**, 134–148.

Meinzinger, F. 2010 Resource Efficiency of Urban Sanitation Systems: a Comparative Assessment Using Material and Energy Flow Analysis. PhD thesis, Institute of Wastewater Management and Water Protection, No. 75, University of Hamburg, Germany.

NASA 2014 World Wind Java SDK. http://worldwind.arc.nasa.gov/java/ (accessed 13 June 2014).

Niederer, S., Kriz, K. & Pucher, A. 2007 Development of a spatial decision support system for sustainable water management. In: *Proceedings MEDA WATER International Conference, Sustainable Water Management*, *Tunis*, *21–24 March 2007*.

Notaro, V., Fontanazza, C. M., La Loggia, G. & Freni, G. 2014 Identification of the best flood retrofitting scenario in an urban watershed by means of a Bayesian decision network. In: *Urban Water II* (Mambretti, S. & Brebbia, C. A., eds). WIT Press, Southampton, UK, pp. 341–352.

Nowack, M. & Günther, E. 2009 Scenario planning: managing the effects of demographic change on East German wastewater companies. In: *Water: Economics and Management of a Key Resource.* German Institute for Economic Research, Berlin, Germany.

Pearson, L. J., Coggan, A., Proctor, W. & Smith, T. F. 2010 A sustainable decision support framework for urban water management. *Water Resources Management* **24** (2010), 363–376.

Schiller, G. 2010 Kostenbewertung der Anpassung zentraler Abwasserentsorgungssyteme bei Bevölkerungsrückgang (Evaluation of costs and adaptation of central wastewater systems to demographic change). PhD thesis, Leibniz Institute of Ecological Urban and Regional Development, No. 51., Rhombos Verlag, Berlin, Germany.

Schmitt, T. G., Worreschk, S., Kaufmann Alves, I., Herold, F. & Thielen, C. 2014 An optimization and decision support tool for long-term strategies in the transformation of urban water infrastructure. In: *Proceedings of the 11th International Conference on Hydroinformatics, HIC 2014*, *August 17–21*, New York, NY, USA.

Schöffel, S., Schwank, J. & Ebert, A. 2014 MuGIS: multi user geographical information system. In: *Proceedings of Mobile HCI 2014*, *September 23–26, 2014*, Toronto, Canada.

Scholten, L., Scheidegger, A., Reichert, P., Mauer, M. & Lienert, J. 2014 Strategic rehabilitation planning of piped water networks using multi-criteria decision analysis. *Water Research* **49** (2014) 124–143.

Singh, N., Kazmi, A. & Starkl, M. 2015 A review on full-scale decentralized wastewater treatment systems: techno-economical approach. *Water Science and Technology* **71** (4), 468–478.

Sitzenfrei, R. & Rauch, W. 2014 Integrated hydraulic modelling of water supply and urban drainage networks for assessment of decentralized options. *Water Science and Technology* **70** (11), 1817–1824.

Statistical State Office of Rhineland-Palatinate 2010 *Rhineland-Palatinate 2030 – Third Local Population Forecast for Municipalities 2010 Statistical State Office of Rhineland-Palatinate*, Bad Ems, Germany.

Statistical State Office of Rhineland-Palatinate 2012 *Rhineland-Palatinate 2060 – Third Regional Population Forecast (Base Year 2010). Statistical Analysis No. 25*, Bad Ems, Germany.

Tscheikner-Gratl, F., Mikovits, C., Rauch, W. & Kleidorfer, M. 2014 Adaptation of sewer networks using integrated rehabilitation management. *Water Science and Technology* **70** (11), 1847–1856.

Ware, C. 2012 *Information Visualization: Perception for Design*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.

Worreschk, S., Kaufmann Alves, I., Schmitt, T. G. & Thielen, C. 2014 Optimization of transformation processes of drainage systems in rural areas. In: *Proceedings of the 13th International Conference on Urban Drainage, 7–12 September 2014*, Kuching, Sarawak, Malaysia.

Worreschk, S., Hoek, J., Kaufmann Alves, I., Bellefontaine, R. & Herz, S. 2015 Comprehensive scenario management of sustainable spatial planning and urban water services. In: *Proceedings of the Cities of the Future Conference, 28–30 April 2015*, Mühlheim an der Ruhr, Germany.

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