Comprehensive scenario management of sustainable spatial planning and urban water services

Silja Baron, Jannis Hoek, Inka Kaufmann Alves and Sabine Herz

ABSTRACT

Adaptations of existing central water supply and wastewater disposal systems to demographic, climatic and socioeconomic changes require a profound knowledge about changing influencing factors. The paper presents a scenario management approach for the identification of future developments of drivers influencing water infrastructures. This method is designed within a research project with the objective of developing an innovative software-based optimisation and decision support system for long-term transformations of existing infrastructures of water supply, wastewater and energy in rural areas. Drivers of water infrastructures comprise engineering and spatial factors and these are predicted by different methods and techniques. The calculated developments of the drivers are illustrated for a model municipality. The developed scenario-manager enables the generation of comprehensive scenarios by combining different drivers. The scenarios are integrated into the optimisation model as input parameters. Furthermore, the result of the optimisation process – an optimal transformation strategy for water infrastructures – can have impacts on the existing fee system. General adaptation possibilities of the present fee system are presented.

Key words | demographic and spatial development, development water demand, scenario management, transformation of water infrastructures

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INTRODUCTION

In the INIS joint research project 'SinOptiKom – Cross-sectoral optimisation of transformation processes in municipal infrastructures in rural areas', funded by the German Federal Ministry of Education and Research, a software-based decision support and optimisation model for long-term transformations of urban water infrastructures is developed. The overall structure of the optimisation system consists of a pre-processing tool with a database and a scenario-manager, a mathematical optimisation model and an interpretation tool for the visualisation of results. The optimisation model determines adaptation strategies for existing water supply and wastewater systems, based on the implemented objective functions and shows their implementation over a specific period of time (Baron *et al.* 2015). The model is tested in two rural municipalities in the southwest of Germany.

Special attention has to be paid to the increasing uncertainty of future constraints and impact factors (Pearson *et al.* 2010; Stojanović *et al.* 2014). A realistic prognosis for different dynamic drivers including their interdependencies has to be examined to produce representative solutions within the model. Scenarios are required to generate quantitative dynamic input and evaluation data for the period of investigation. A characteristic of future water systems are the long capital commitments of central water infrastructures for time periods of 50 to 80 years and challenges like demographic, climate and socioeconomic developments. The development of consistent scenarios requires the cooperation of water management and town planning.

Different scenario management techniques are effectively applied in the business world and the scenario approach is increasingly used in the context of spatial planning (Andrienko *et al.* 2003; Krawczyk & Ratcliffe 2006; Myers & Kitsuse 2009; Stojanović *et al.* 2014) and the development of future urban water infrastructures (Lienert *et al.* 2006; Nowack & Günther 2009). One approach is the generation of future scenarios with the engagement of stakeholders (e.g. Truffer *et al.* 2010; Lienert *et al.* 2014). A multi-stage procedure with stakeholder interviews results in the definition of mostly three to four scenarios. This

doi: 10.2166/wst.2015.578

approach supports infrastructural planning processes but the selection of stakeholders is very crucial even with a systematic approach. Stakeholders have a subjective point of view about current conditions and a likely future. In general the development of three or four scenarios or storylines is highly dependent on the quality of assumptions and projections (Urich & Rauch 2014). In other projects only a limited number of drivers are included in scenarios, for example a combination of population growth and spatial development scenarios (e.g. Mikovits *et al.* 2014). For policy examples complex approaches based on participatory, computer-assisted approaches using algorithms are explored (e.g. Bryant & Lempert 2010).

This paper presents the development of a scenario management approach for the generation of scenarios by combining different drivers. It is designed for the integration of a large range of important drivers of future water infrastructures with the aim of generating an optimised transformation strategy of urban water systems. Since several different factors influence transformation strategies simulations with only three to four scenarios cannot take all important developments of each driver into account. Simulations with more scenarios are important for generating robust transformation strategies and exploring the underlying uncertainties. Stakeholders are involved in the identification of drivers of water infrastructures. The user of the model, an expert, then arranges the drivers to scenarios. In the project several rural municipalities are considered and therefore the transferability of the method is important.

In this paper, methods for the prediction of each identified driver are described and for some drivers their development in the context of a model municipality is illustrated. The terms scenario, driver and influencing factor are subject matter. In this paper a scenario is defined as a consistent combination of prognoses of different drivers. The development of each driver is affected by divers influencing factors.

IDENTIFYING DRIVERS OF WATER INFRASTRUCTURES

Drivers that influence the development of water infrastructures have to be identified and predicted for future planning and management of water supply and wastewater systems. The development of each driver has to be shown over a period of at least 50 years due to the long lifespan of central water infrastructures (DWA 2012). The following drivers have been chosen based on the project scope examining rural areas and comprise engineering and spatial factors (see Figure 1). On the one hand local demographic developments, as well as their impact on the settlement structure, have to be examined. On the other hand technical aspects, such as the development of water demand, prices for water and energy supply as well as costs of the technical equipment, have to be predicted. Changes in the legal framework, for example modifications of legal limits or amendments as well as changes of local precipitation intensities caused by climate change are implied.

The scenarios are developed on three decision and modelling levels: macrolevel, mesolevel and microlevel. On the macrolevel, the development of the settlement in general, the institutional and legal framework, energy prices and effects of climate change are considered for an association of municipalities. In Germany, an association of municipalities is a local authority which consists of neighbouring municipalities. The fee system is also designed on the macrolevel. For every municipality (mesolevel) the development of population, settlement and water demand is explored. The microlevel considers units of municipalities, e.g. street sections or neighbourhoods. On this level the population and settlement development is presented in detailed scenarios.

The different methods and techniques of predicting each identified driver are presented below. The future development of the drivers ‘demographic and spatial development’ as well as ‘water demand’ is illustrated for a rural model village within the project’s case study region (mesolevel,

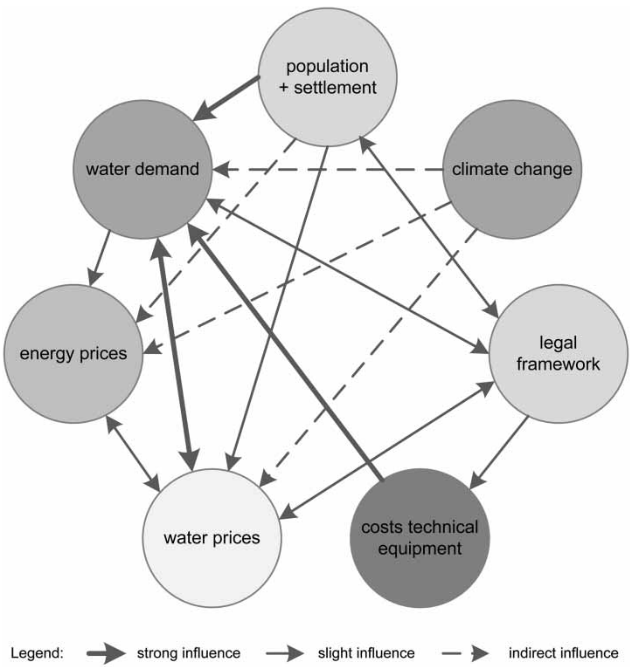

Figure 1 | Interconnections of the identified drivers of water infrastructures.

microlevel). The model village has about 800 inhabitants with a specific water demand of 115 L/(C·d) at present. A central combined sewer system is installed and the wastewater is treated in a wastewater treatment plant together with the wastewater of three neighbouring villages. The future developments of the other drivers are illustrated for the rural case study region in the project (macrolevel).

Demographic and spatial development

The development of rural settlements and the number of their inhabitants are major drivers for the transformation of water infrastructures. Scenarios are being generated in order to analyse the spatial and demographic development of rural settlement structures over the period of consideration. For this purpose a cross-impact-analysis (cf. Heinecke & Schwager 1995), combining major influencing characteristics of settlement development and a stakeholder interview (e.g. political decision makers) is used to generate consistent qualitative scenarios of future structural developments for rural model associations of municipalities (cf. Siedentop *et al.* 2011). The scenarios are then combined with official regional statistics of the demographic development. As a next step, spatial planning concepts are developed in cooperation with the municipal authorities, in order to ensure a participative approach as well as an integrated and sustainable result (see Figure 2). The spatial planning concepts consider the settlements' structural state based on detailed municipal data as well as the development of public services, technical, and social infrastructures with regard to official regional statistics of demographic developments. The spatial concepts are prepared in three variants, in analogy to the official demographic statistics.

Furthermore, spatial concepts regarding the association of municipalities' structural state and development on the macrolevel are concretised on the mesolevel in different variants, in order to synthesise the development of the single municipalities. The final step towards the integrated municipal spatial planning scenarios is their implementation into a geographic information system (GIS). Here, detailed data as the status quo of demographic structure, the inhabitants' milieu, building occupancy or condition is geo-referenced. Depending on the demographic prognoses and factors as the economic development or strategic decisions on infrastructures and public services, the municipal development is synthesised. The synthetic spatial development refers to the spatial development concept in order to assess changes in land use, building activity or spatial transformation, e.g. the revitalisation of municipal centres.

The definition of the microlevel is based on an analysis of the settlement structure regarding the structure and age of buildings, the local milieus and water infrastructures. Figure 3 illustrates settlement units for the model village. The defined units of the settlement (microlevel) form as homogenous entities as possible and are the spatial basis for the demographic scenarios. The demographic scenarios consider detailed factors, e.g. the status quo of the local age and gender structure, the regional birth- and mortality rate and they are influenced by probable internal and external migration rates. The internal migration is specified by family migration, labour and educational migration as well as the migration of younger and older seniors and differs between males and females. The probabilities are based on a monitoring of fluctuations in the residential sector, building condition and occupancy, and demographic information, e.g. the milieu or the residents' age structure. The generated microsimulations are flexible and can react on changes in, e.g. the association of municipalities' labour market situation. For example, the economic collapse of a major employer in the considered area would affect the migration probabilities, which then needed to be adapted for the reference interval. This approach offers a realistic and detailed basis, which is implemented into the pre-processing tool in different variants. The output microsimulations represent the spatial and demographic basis for the transformation of water infrastructures.

Development of water demand

Different methods can be used for the prediction of the water demand, e.g. trend analysis or econometric models (cf. Schleich & Hillenbrand 2009). As the water demand in Germany has been declining since the mid-1990s, a trend analysis could result in unrealistic small water demands for a time horizon of 50 years. In the presented project the scenario technique (Dönitz 2009; Nowack & Günther 2009) is used to identify the future development of water demand. This approach allows an integration of important influencing factors and their uncertainties (Lienert *et al.* 2006). Previously presented developments of population and settlement are integrated in the approach.

First, the situation and challenges of the considered municipality have to be identified in an initial analysis. Influencing factors on the water demand are determined, prioritised and arranged in categories (Figure 4).

Based on a literature review (cf. Schleich & Hillenbrand 2009; Roth *et al.* 2011a, b; Tränckner *et al.* 2012) and site-specific data, development trends for each influencing

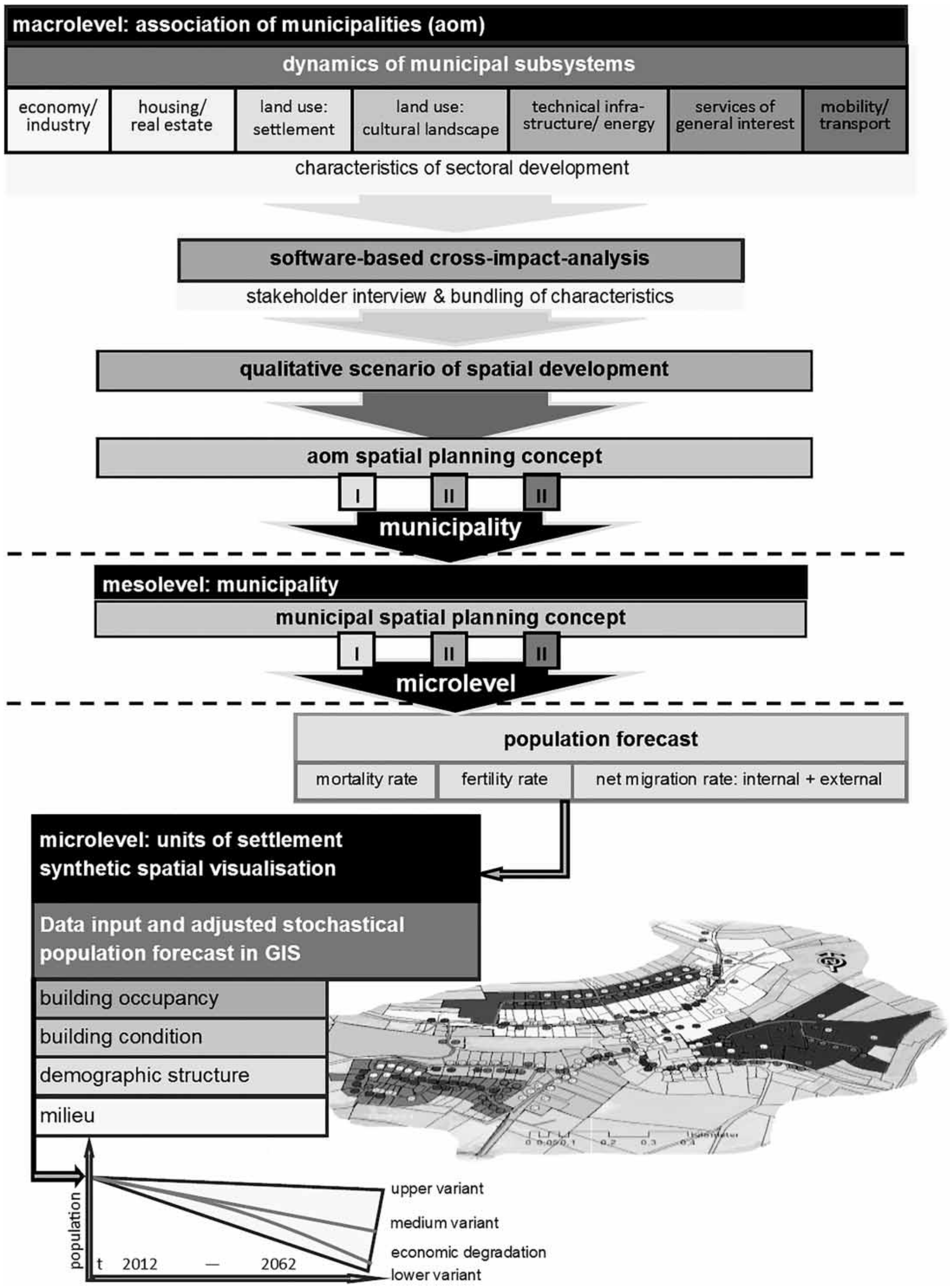

Figure 2 | Generation of demographic and spatial developments (Hoek & Herz 2015).

factor are investigated. In a next step, conflicts and synergies are determined for the different developments of the influencing factors with a consistency matrix. Prognoses of the future water demand are generated by bundling consistent future developments of the influencing factors. The generated prognoses and underlying assumptions are discussed with project partners from the model municipalities and engineering offices. The possible range of the water demand per capita and three calculated projections for the model village are shown in Figure 5. Besides, the development of the water demand over the last 20 years is shown. The underlying combinations of future developments of influencing factors are described for each projection to facilitate the users' decision.

The total water demand comprises the water demand of households, commerce and industry, public institutions, own needs of water supply companies as well as losses in the water supply network. For the determination of the

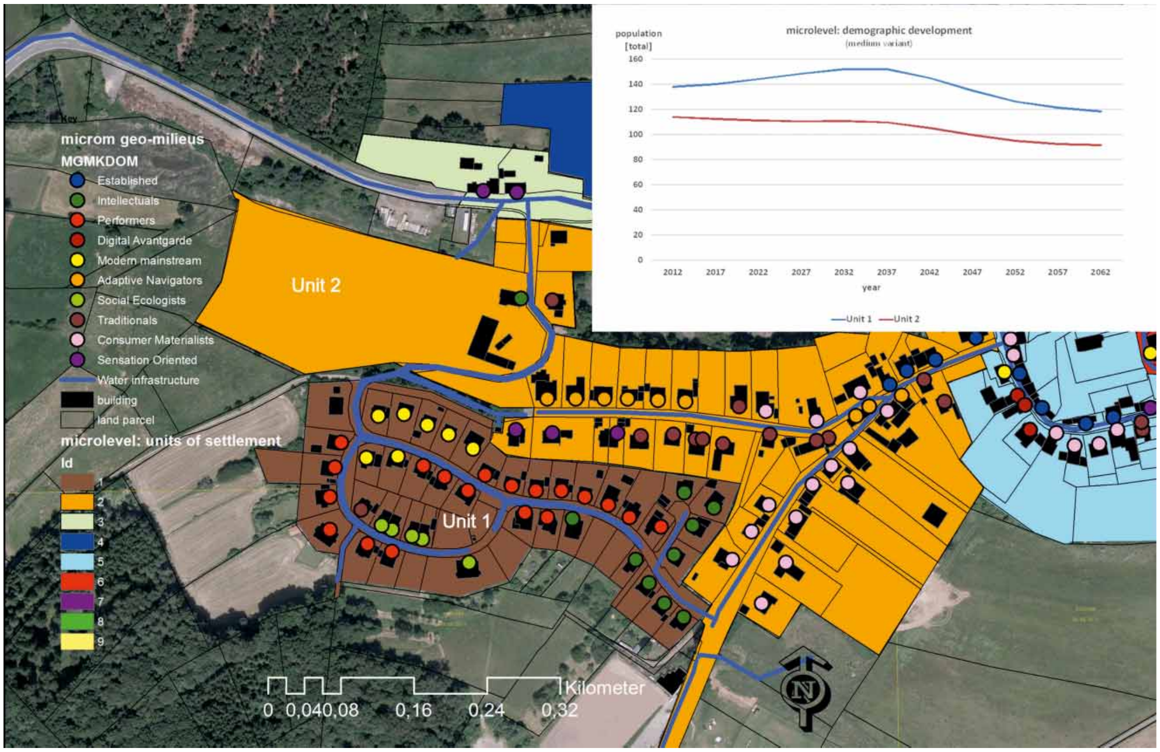

Figure 3 | Generation of the microlevel: units of the settlement for a model village (Hoek & Herz 2015).

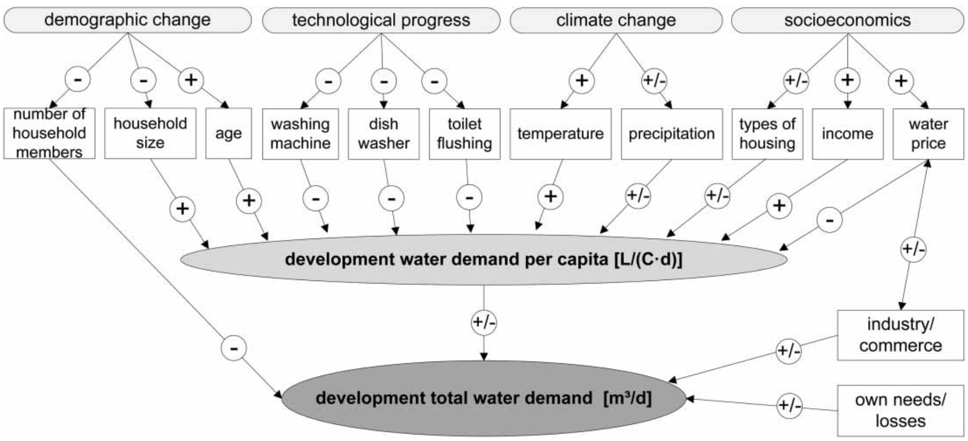

Figure 4 | Influencing factors on water demand per capita and total water demand (Baron 2015).

total water demand, the above presented developments of inhabitants and settlement structure are integrated.

Development of energy prices

The future development of energy prices is very complex. Therefore, the project focuses on electricity prices. The development of electricity prices depends on national funding programs and legal developments, the development of the share of renewable energies, or formation of power grids. Since the presented project is not focusing primarily on energy, future development possibilities are derived from the literature (e.g. SRU 2011; UBA 2012; Öko-Institut 2015) and from results of the funding program ERWAS

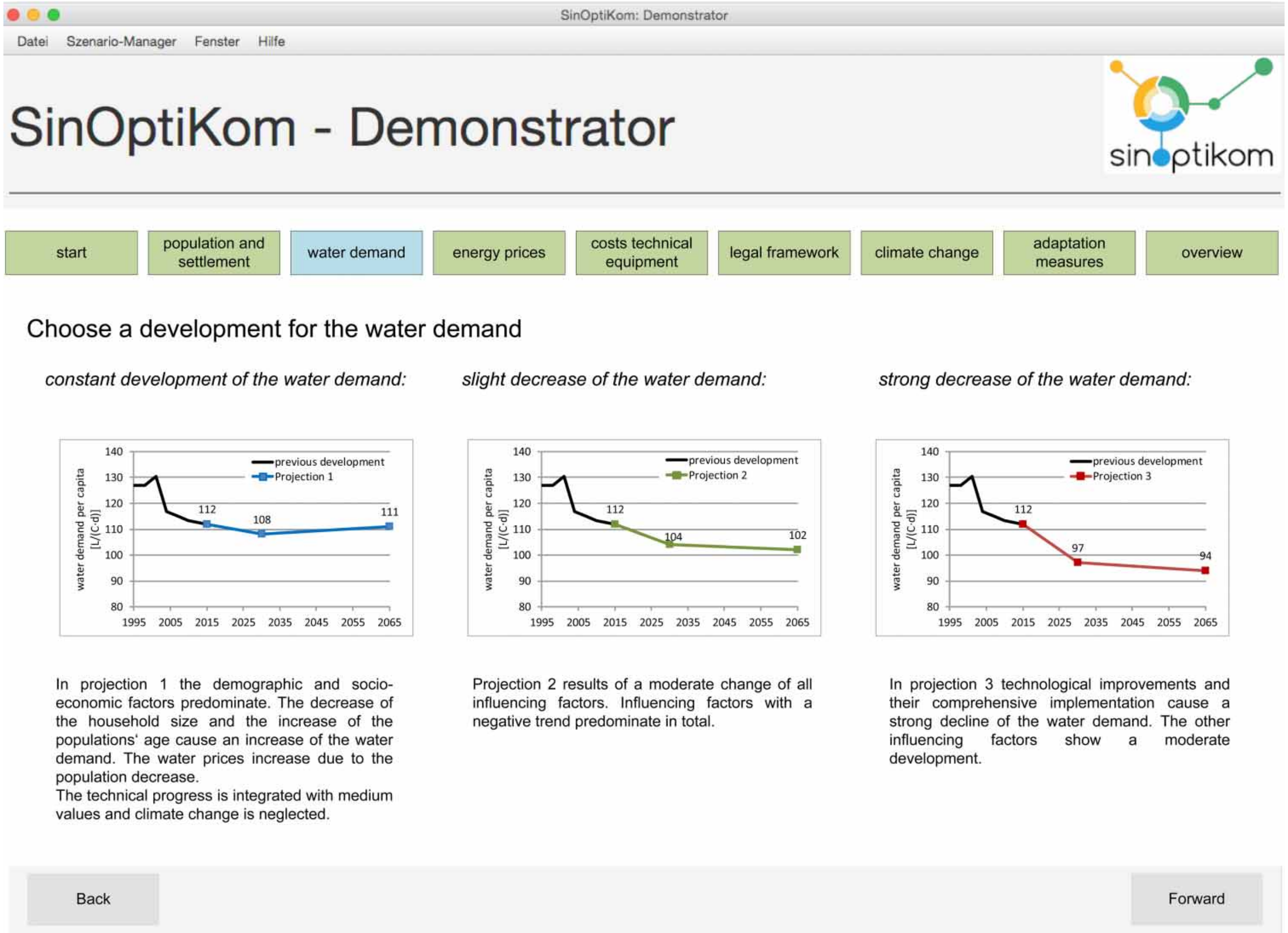

Figure 5 | Screenshot of the scenario-manager showing three projections of the water demand for the model village (Schöffel *et al.* 2015).

(Future-oriented Technologies and Concepts for an Energy-efficient and Resource-saving Water Management) of the German Federal Ministry of Education and Research (Table 1).

Development of costs of the technical equipment

The investment and operational costs of water infrastructures, especially of new and innovative technologies, might change in the future. Therefore, two alternatives of cost development are considered. In the first version present prices of technologies of water supply, wastewater discharge and treatment as well as rainwater management are assigned with a medium rate of price increase of 3%.

The second version includes larger variations of current investment and operational costs. Investment costs can be divided into costs of well-established and comprehensively installed facilities like conduits and in new and innovative technologies like greywater treatment. Costs for well-established technologies will similarly remain in the future. However, expensive costs of new technologies might change significantly with wider dissemination and use. In addition, the implementation of new technologies benefits with a price reduction. Increasing personnel costs and maintenance efforts of facilities, e.g. flushing of conduits might affect the operational costs. For the quantification of cost developments of new technologies the concept of 'production learning curves' is applied. The concept indicates that with every duplication of the accumulated production

Table 1 | Projections of electricity prices (SRU 2011; UBA 2012; Öko-Institut 2015)

Projection	Electricity price	2015	2050
1	Constant	10 ct/kWh	10 ct/kWh
2	Decrease	10 ct/kWh	7 ct/kWh
3	Increase	10 ct/kWh	12 ct/kWh

Table 2 | Examples of values of learning curves for new technologies in the water sector (Baron 2015)

Technology	Present field of application	Future field of application	Estimated cost reduction
Small WWTP (<50 inhabitants)	In some very rural areas	In more rural areas because of a decreasing population	40–60%
Nutrient recycling	Initial application	Wider dissemination because of limited P reserves	40–80%
Decentralised heat recovery with greywater reuse	Research and demonstration projects, mainly in development areas	Wider dissemination with the integration in existing buildings	50–70%

volume the total costs for a product decreases with a constant percentage. This reduction of costs is called learning rate. The concept is known from other sectors (e.g. chemical industry) and there are only few applications in the water sector (e.g. Zhou & Tol 2005; Hillenbrand 2009). Learning curves are designed for the implemented new technologies in the project and in Table 2 possible ranges of cost reduction for three examples are presented. The values were derived for Germany, but they might differ in other countries.

Development of the legal framework

This driver allows the inclusion of future modifications of legal limits or amendments. These are increasing discharge limits of nutrients for wastewater, the introduction of thresholds for micropollutants or the introduction of rates for recycling of phosphorus. Another important change will be the withdrawal of the use of sewage sludge in agriculture in Germany. Currently, a large part of sewage sludge in rural areas is used locally as fertiliser in agriculture. Alternatives for the utilisation, like incineration, are integrated and costs for storage and transportation to larger incineration plants are considered. Moreover other methods for the recirculation of nutrients into the soil are examined.

Climate change

Climate change will cause changes in rain patterns and temperature. In the project the impacts of climate change on heavy rainfall events are integrated. For rainwater simulations the local precipitation intensity according to the KOSTRA-DWD-2000 (DWD 2005) is used. In the simulations the precipitation intensity for the design rainfall for rural areas with a duration of 15 minutes and a recurrence interval of one year is applied. In the climate change version the precipitation intensity is adapted to the next recurrence interval. Thus, for a rural area the value for a recurrence interval of two years is used. In the model municipality the corresponding local precipitation intensity is 125 L/(s·ha) at present and 161.4 L/(s·ha) in the climate change version.

Adaptation of the fee system

Adaptations of water infrastructures can have an impact on the existing fee system of water supply and wastewater discharge and treatment. Depending on the transformation strategies calculated by the model, which, e.g. can imply a change from central to more decentralised water infrastructures, institutional changes, e.g. in the fee system might be required (Bellefontaine *et al.* 2010; Duffy & Jefferies 2011). Fees are not considered as a driver in the presented scenario management approach, because thereby the selection of adaptation strategies could be influenced or limited. Rather, a compatible fee system for the optimised solution can be determined. Adaptation possibilities of the present fee system can be deduced for the calculated transformation strategy and generalised as recommendations for the adaptation of a future water fee system.

The modifications can be an implementation of base fees and per unit used fees, one time payments for modernisation, or subsidies. The adaptation of the fee system depends on the effects of demographic change and has to take social fairness into consideration. A flat rate for potable water can be an option for securing the functional capability of the water supply network. Wastewater fees are calculated based on the consumption of potable water. They may no longer be suitable when innovative sanitary systems are implemented and the consumption of potable water is reduced further. Then, other factors like nutrient and energy content of wastewater or the type of treatment will be of importance and have to be taken into consideration in the fee system. If the existing urban drainage system is transferred to a decentralised system the ownership structure is of importance for the fee system. The owner and the operator of decentralised facilities on private properties can be the municipality or the private person. General adaptation possibilities of the fee system and the application for a model municipality are presented in Breitenbach *et al.* (2015).

SCENARIO MANAGEMENT APPROACH

The above presented future developments of different drivers are combined in a software-based scenario-manager. In the scenario-manager probabilities of (co-)occurrence are assigned to the different prognoses for each driver and the interdependencies of the drivers are integrated.

In the scenario-manager calculated prognoses can be chosen for each driver successively and if there are correlations to the pre-selected drivers they are shown. Figure 5 and Figure 6 show screenshots of the visualised scenario-manager. In the upper part of the figures the drivers are shown in the sequence where the user can choose between them. The user has to choose one of the presented projections of each driver and can then proceed to the next driver. In Figure 6 a list of possible adaptation measures for the optimisation process is shown. Adaptation measures that are not reasonable or technically feasible for the generated scenario are marked in grey. For example, for a scenario with a strong decrease of population and water demand and a de-densification of the settlement a central combined sewer system is not a feasible measure and it will not be integrated in the modelling process. If in another scenario thresholds for micropollutants are introduced and legal limits for nutrients are tightened, only wastewater treatment measures that fulfill the new requirements are integrated in the modelling process. Moreover, the user can choose which adaptation measure should be integrated in the optimisation process. Thus, the number of adaptation measures and the computation time of the model can be reduced. At the end an overview of the chosen

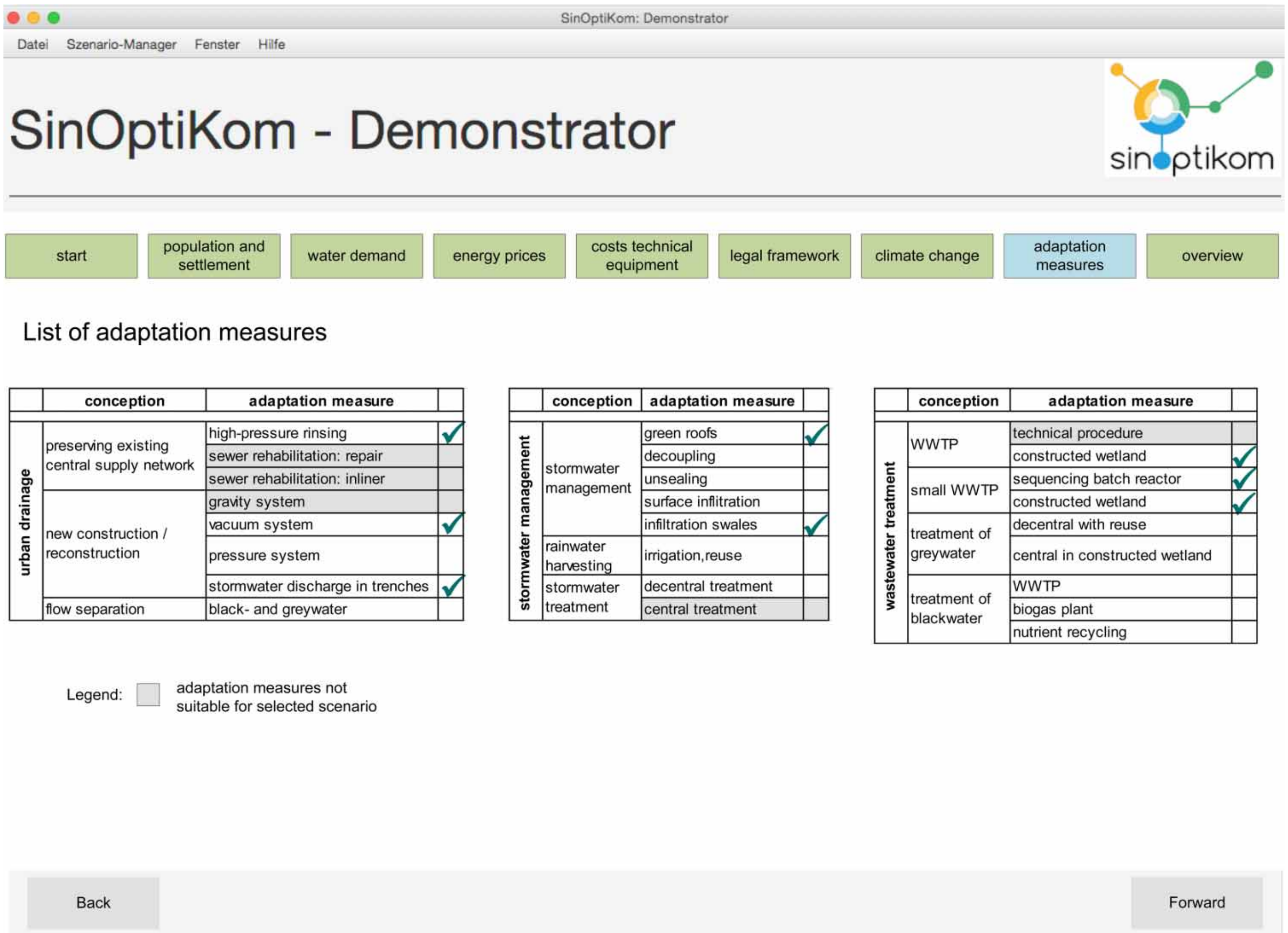

Figure 6 | Screenshot of the scenario-manager showing the selection of adaptation measures (Schöffel *et al.* 2015).

Table 3 | Three selected scenarios for the model village

	Moderate scenario	Doom scenario	Ecological scenario
Population	Slight decrease	Strong decrease	Medium decrease
Settlement	Stable settlement	De-densification	Consolidation
Water demand	Constant	Strong decrease	Slight decrease
Energy prices	Constant	Increase	Increase
Costs technical equipment	Price increase of 3%	Price increase of 3%	Decrease of costs for new technologies
Legal framework	Prohibition of sewage sludge use in agriculture	Prohibition of sewage sludge use in agriculture	Introduction of thresholds for micropollutants and P-recycling rates
Climate change	No influence	Has influence	Has influence

developments of each driver is given. The generated scenario is then processed to the optimisation model.

The scenario-manager is integrated into the database management system of the decision support and optimisation model. The user interface of the scenario-manager allows a clear selection and arrangement of scenarios. The underlying network and site-specific data for the optimisation model are processed for different time steps. In the next step objective functions are selected and weighted for the optimisation process (Schmitt *et al.* 2014). The optimisation model calculates adaptation possibilities and transformation strategies for water infrastructures, showing their chronological and spatial implementation over the considered period of time (Baron *et al.* 2015). Besides, the visualisation of model results, the underlying scenario with the developments of the selected drivers, e.g. demographic developments, is visualised in the interpretation tool.

The arrangement of different drivers to different scenarios allows a comprehensive illustration of future states. Sensitivity analyses will be undertaken with the optimisation model for different scenarios in order to examine the sensitivity of results and thus the robustness of transformation strategies.

For the presented model village three scenarios were defined and will be tested (see Table 3).

CONCLUSIONS

Scenarios are an important input for the decision support and optimisation tool. They have a big influence on the calculated transformation strategy. For the determination of developments of each driver different adequate methods were presented and illustrated for a model municipality. The presented scenario management approach bundles the different drivers' developments and ensures a realistic modelling. The approach includes a wide range of drivers and therefore differing scenarios covering a wide spectrum of factors can be derived. The specification of scenarios by the user has the advantage that the expertise of the user is included. The specification of scenarios can reduce the number of possible adaptation measures. Sensitivity analyses can then be undertaken for different scenarios in order to examine the robustness of calculated transformation strategies. Thus, the uncertainties in the modelling process can be reduced.

The scenario management approach is applied on two model municipalities in the project, but general recommendations for rural areas facing the same problems can be derived. The approach of combining spatial developments with population prognoses and connecting them to water infrastructures, especially enables an integrated scenario management. Formulating new recommendations for the fee system can support or even enable the implementation of innovative wastewater technologies.

ACKNOWLEDGEMENTS

The INIS joint research project 'SinOptiKom – Cross-sectoral optimization of transformation processes in municipal infrastructures in rural areas' is funded by the German Federal Ministry of Education and Research and is conducted by a research consortium of ten cooperation partners. Their contributions to the project's progress and diffused input to the paper are highly appreciated.

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First received 8 July 2015; accepted in revised form 28 October 2015. Available online 12 November 2015