

Dynamic virtual infrastructure benchmarking: DynaViBe

R. Sitzenfrei, S. Fach, M. Kleidorfer, C. Urich and W. Rauch

ABSTRACT

In environmental engineering, identification of problems and their solutions as well as the identification of the relevant processes involved is often done by means of case study analyses. By researching the operation of urban drainage and water distribution systems, this methodology is suited to evaluate new technologies, strategies or measures with regard to their impact on the overall processes. However, data availability is often limited and data collection and the development of new models are both costly and time consuming. Hence, new technologies, strategies or measures can only be tested on a limited number of case studies. In several environmental disciplines a few virtual case studies have been manually developed to provide data for research tasks and these are repeatedly used in different research projects. Efforts have also been invested in tackling limited data availability with the algorithmic generation of virtual case studies having constant or varying boundary conditions. The data provided by such tools is nevertheless only available for a certain instance in time. With DynaViBe (Dynamic Virtual Infrastructure Benchmarking), numerous virtual case studies are algorithmically generated with a temporal development of the urban structure (population and land use model) and infrastructure. This provides a methodology that allows for the analysis of future scenarios on a spatio-temporal city scale. By linking a population model with DynaViBe's infrastructure models, socio-economics impacts on infrastructure and system coherences can be investigated. The problematic of limited case study data is solved by the algorithmic generation of an unlimited number of virtual case studies, which are dynamic over time. Additionally, this methodology can also be applied on real world data for probabilistic future scenario analysis.

Key words | socio-economic impacts, stochastic scenario analysis, total urban water cycle, virtual case studies

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INTRODUCTION

Analyses of case studies are a well-known instrument to identify problems and interactions of processes. In the field of urban drainage and water distribution systems this methodology is suited to evaluate new technologies, strategies or measures with regard to their impact on the overall processes. However, data availability is limited and hence, new technologies, strategies or measures can only be tested in a limited number of case studies, because data collection and the development of new models are both costly and time consuming.

For the research of urban drainage systems the following examples give a glimpse into the numerous applications of virtual case studies in the field. Rauch *et al.* (2003) used a virtual case study to investigate the dynamics of urine production of single toilettes, to optimize the human wastewater stream with regard to effluent concentrations of the wastewater treatment plant and discharge concentrations in case of storm events. Achleitner *et al.* (2007) followed a similar strategy to test urine separation approaches on a simplified single catchment and a

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real-world case study, the results of which showed similarities among these. A variation of simplified virtual catchments with varying boundary conditions and ranges according to literature were used in [De Toffol *et al.* \(2006\)](#) to compare the cost effectiveness of combined sewer systems with that of separate sewer systems. Due to specific boundary conditions and system properties of only a few single case studies, results can hardly be generalized or transferred to other systems.

For the research of water distribution systems, case studies are used to test software and methodologies e.g. optimization algorithms. Benchmark networks were introduced and used such as the New York City Tunnels ([Olsson *et al.* 2009](#)), the Hanoi network ([Dandy *et al.* 1996](#); [Savic & Walters 1997](#)) and the “Anytown” network ([Walters *et al.* 1999](#)). Two single virtual case studies for water distributions systems Micropolis ([Brumbelow *et al.* 2007](#)) and Mesopolis have been presented to provide case study data for analysis and research tasks and are used for various applications ([Rasekh *et al.* 2010](#); [Shafiee & Zechman 2010](#)).

[Sitzenfrei *et al.* \(2010c\)](#) presented the WDS Designer which generates water distribution systems with varying characteristics (e.g. looped or branched layout) based on GIS (geographic information system) data. Although this approach could be applied to different GIS data (representing different states in time), the WDS Designer cannot consider dynamic change as each system generated is independent from previous generations. [Möderl *et al.* \(2007\)](#) developed the modular design system (MDS), which is a stochastic approach to generating a multitude of virtual water distribution systems with an interface to the hydraulic solver Epanet 2 ([Rossman 2000](#)) for stochastic hydraulic performance evaluations. For research on combined sewer systems [Möderl *et al.* \(2009\)](#) developed the case study generator (CSG), which allows for the generation of a number of dendritic virtual drainage systems (the amount of which is limited by computing power) for a stochastic performance evaluation with the hydraulic solver SWMM ([Rossman 2004](#)). Both stochastic approaches (MDS and CSG) are based on a very simplified urban structure and network systems with only low complexity and are therefore only partly comparable with real world case study data. [Ghosh *et al.* \(2006\)](#) presented an “Artificial Network Generator” (ANGel), which was used to generate artificial

sewer networks based on a Tokunaga fractal tree and can be applied on an existing coarse network structure or existing land use data. But with ANGel, no interface to hydraulic solvers is available and only network layout can therefore be generated.

[Sitzenfrei *et al.* \(2010a\)](#) presented VIBe (Virtual Infrastructure Benchmarking), which algorithmically generates complex virtual case studies (VCSs) at a city scale for urban water systems including sewer systems ([Urich *et al.* 2010](#)) and water distribution systems ([Sitzenfrei *et al.* 2010b](#)). The parameters of the virtual case studies are stochastically varied in ranges extracted from real-world case studies and literature to cover a broad range of possible system properties. As a result, VIBe generates input files for simulation software such as Epanet 2 ([Rossman 2000](#)) for water distribution simulation, SWMM ([Rossman 2004](#)) for sewer simulations or GIS (geographic information system) data files for spatial evaluations and visualisations with GIS software. With algorithmic generation, numerous simulations can be performed and the results benchmarked and analysed stochastically at a city scale. Thereby, the understanding of real world systems can be increased and the potential of measures applied to the infrastructure evaluated. The data provided by VIBe and therefore its analysis are only applicable to one certain point in time. In geographical and social research, the application of combined agent-based cellular automata for modelling the spatiotemporal transition of urban structure is state-of-the-art ([Batty *et al.* 1999](#); [Batty 2005](#); [Torrens 2000](#)). In environmental engineering research, the urban simulation model UrbanSim ([Waddell 2002](#)) was used to estimate future water demand based on the spatial distribution of land use and population densities including income and other demographic indicators ([Polebitski & Palmer 2010](#)). This model however does not generate detailed water system network data nor is it linked to a water distribution system or a sewer system model.

The focus of this paper is to present the methodology of DynaVIBe (Dynamic Virtual Infrastructure Benchmarking), which combines the stochastic engineering approaches for generating complex virtual case studies with urban simulation models like UrbanSim. With DynaVIBe, the VCSs are generated with combined agent based cellular automata development algorithms, which represent the temporal

development of the urban fabric and infrastructure. The development algorithms take into account change processes in the urban environment, initiated by population growth or decline, changes of connected areas to the sewer or the influence of new legal standards. Hence, DynaVIBe can constitute the temporal dynamics of a new technology, strategy or measure for the simulated period of time. Consequently, stochastic future scenario analysis at a city scale can be performed and socioeconomic impacts on infrastructure investigated.

METHODS

DynaVIBe is a further development of the software VIBe. In VIBe, the following technologies from different scientific fields were combined into an innovative approach (Sitzenfrei *et al.* 2010a; Urich *et al.* 2010; Sitzenfrei *et al.* 2010b): (a) Combined agent based cellular automata modelling for urban structures (Batty 2005) and (b) Stochastic approaches for urban water management (Ghosh *et al.* 2006; Möderl *et al.* 2007, 2009). However, the full potential of agent based cellular automata modelling in combination with stochastic approaches for urban water management is regarded as more extensive as realized in VIBe. DynaVIBe allows the full potential of dynamic urban models for the simulation of urban structure to be utilized. In the following, the various aspects of the methodology are described.

Cellular automata modelling

Cellular automata are dynamic grid-based computer models. The cells of the grid can be of a common shape. To simplify matters, they are mostly constricted to quadratic cells. Each cell can capture different states from a predefined range of values. By transition of the cell states for discrete time steps, the system sustains a characteristic, which is dynamic over time. The transition of the cell states is controlled by transition rules, which can be flexibly modified. A transition rule has to be applied for each cell. Depending on the present state of its neighbouring cells, the cell's state for the next time step can be evaluated. The visible neighbourhood of a cell is defined by the kind of local neighbourhood adopted (Moore or von Neumann

neighbourhood (Batty 2005)) and thereby locally restricted to only a few adjacent cells. Using this bottom-up approach, where actions take place at a local scale, emergence of a complex system will result. Grid based analysis of urban systems is state-of-the-art (raster data in geographic information systems). Applications of cellular automata are also numerous in the investigation of urban phenomena. Various alternative approaches for urban development and growth have been developed and presented (Alkheder & Shan 2005; Wilson 2008a,b) including socio-economic aspects (Ward *et al.* 2000; Liu & Phinn 2003; Crooks *et al.* 2007) and infrastructure modelling (Wittmann *et al.* 2006; Schwarz & Ernst 2007). Urban sub-systems and processes are well described by diverse models; an integrated approach for the whole system to generate a major variety of virtual case studies with variable boundary conditions and infrastructure has however yet to be developed.

With the application of cellular automata for urban systems the transition rules represent processes in urban systems. For example, the cell attribute "land price" can be described with a transition rule containing parameters such as *distance from city centre, recreation area, population density et cetera*. Therefore, procedures, such as flow of traffic, land use change, historical and future urban/population development can be locally simulated and analysed. The transition rules remain comprehensible and the simulation is not based on a black box model (Torrens 2000).

Agent based modelling

Batty (2005) identifies two approaches to demonstrate urban changes. In this context agent based modelling can be applied for modelling hydrological processes as shown by Reaney (2008) or to represent socio-economic processes in urban structures. Whereas the cells are considered as immovable spacious base elements in a grid, agents have the ability to move through the grid and occupy individual cells. Decision trees are used by the agent to alter its position in each time step. These decision trees are based on the states of the cell grids and other agents in the immediate neighbourhood. The information about the neighbourhood is derived partly from the cellular automata grid and partly from the state of other nearby agents.

In an agent based model, various different types of agents can operate. The agents can communicate among each other to determine for instance how many of the same type are in the immediate neighbourhood. The population of other types of agents in that same neighbourhood can conversely be used as an inhibitory factor. Due to the fact that agents have a limited radius of action, their mobility is also determined by the cells in the grid, which are not occupied by other agents. With this approach, complex social behaviour can be modelled. In combination with cellular automata, modelling an agent based approach can be included in the transition rules of the cellular automata. For example, the transition rule of the cell attribute “land price” described in the previous section can be enhanced by a parameter “class of population” where different classes of population are represented by specific agents. For each member of a population class, other members of the same class can be seen as a providential factor. With this approach, social and ethnic segregation or household income of the predominant population class can be included in the transition rules and consequently in the simulation model.

Stochastic approaches for urban water management

Möderl *et al.* (2007) developed the Modular Design System (MDS) for an algorithmic generation of water distribution systems. The MDS has different elements including junctions, pipes and reservoirs, which can be combined to various modules of arbitrary size. Each module presents different sections of water distribution systems and furthermore these modules can be combined to design different water distribution systems consisting of tree or loop networks. In the generation process, the urban structure is realized by the varying population density and therefore by the variation of demand per junction. Apart from a spatial population distribution, the urban water demand is generated in a simplified manner based only on the structure of the water distribution system. With a simplified dimensioning process, all pipe diameters are designed. With the great number of generated water distribution systems a stochastic approach for performance evaluation is presented, which supports or even substitutes the evaluation of real-world systems.

Another stochastic approach for urban water management is presented in Möderl *et al.* (2009). The developed Case Study Generator (CSG) generates virtual urban drainage systems. The algorithm generates tree layouts based on a Galton Watson branching process adapted for urban drainage systems. This algorithm allows for the generation of combined sewer systems with varying boundary conditions. In the tree layout, the nodes of different levels are defined as generations whereas in case of sewer systems the children nodes of each generation are located upstream. The layout of the sewer system is defined by the number of generations in the tree layout and the probability of children nodes in each generation. Furthermore, the location of children nodes is determined by a stochastically generated elevation and with the requirement to secure drainage. Related to the MDS, the urban structure is realized by varying population density and therefore a variation of dry weather flow. Additionally, virtual sub catchments of different size are allocated—based on the tree layout—to determine the impervious area and hence the wet weather flow. Pipe diameters are determined with a simplified conduit design process. With the variety of generated virtual urban drainage systems, a stochastic approach for hydraulic performance is given.

Virtual infrastructure benchmarking (VIBe)

In VIBe, ranges of parameters (e.g. percentage of land use classes, population densities, population equivalents, relief properties, etc.) from real world case studies (CS) and from literature can be evaluated (Figure 1). With a variation of these parameters within the extracted ranges, numerous VIBe case studies of urban structure are generated in the urban structure module. For each urban structure data set the sewer module and water distribution system module (WDS module) generate infrastructures with different system properties. Examples for the virtual infrastructure generated are shown in Figure 2 (left: virtual sewer system; right: virtual WDS topography and land use).

In Sitzenfrei *et al.* (2010a), an application of the urban structure module for alpine areas is shown. The Inn river in the Inn valley, Austria (between the towns of *Innsbruck* and *Kufstein*) was selected. In the work presented, 1,000 virtual case studies (VCSs) for urban structures in an alpine region were generated with ranges of parameters evaluated

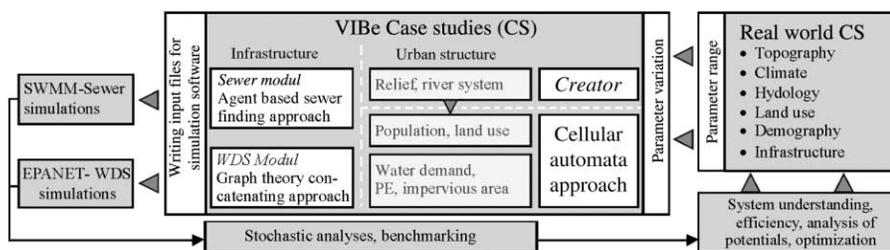


Figure 1 | Procedural method for generation of the virtual urban structure (Sitzenfrei et al. 2010a).

from the two towns *Innsbruck* and *Schwaz* (both in the valley). For the purpose of validation, the data from the case study of the town of *Hall* was evaluated. It was shown that properties (percentage of land use, population DWF, impervious area) of the real-world cities lie within the ranges of the 1,000 VCSs generated.

In Urich et al. (2010), an application of the sewer module was shown. Therein, urban structure data of virtual case studies corresponding with real world data for *Innsbruck* was used as a basis for the generation process of virtual sewer systems (layout of a single combined sewer system, see Figure 2, left side). These virtual sewer systems were compared with the real world sewer system of *Innsbruck* taking into account system properties (e.g. impervious area, sub catchment areas), layout properties (conduit length, cumulative distribution function of cross section areas of entire sewer system) and hydraulic performance indicators (flooding efficiency, combined sewer overflow efficiency).

Sitzenfrei et al. (2010b) presented the water distribution module of VIBe. In this paper the module for the generation of water distribution systems (WDS) was presented (layout of a single WDS projected on its digital elevation map—see

Figure 2 right side). In total, 75,000 virtual WDS were generated (with different properties and characteristics) and investigated systematically. As an example evaluation, the impact of mesh degree on hydraulic performance, water quality performance and cost was investigated. The generated WDS were compared with a real-world system. An example evaluation of the used pipe sizing algorithm with the set of 75,000 WDS is also shown in order to determine a cost effective factor for prospective demand and an economic design flow velocity taking into account hydraulic performance and quality performance.

Hence, it is revealed that VIBe provides a methodology to test new technologies, strategies and measures on numerous case studies with different properties to obtain case unspecific results. Furthermore, detailed data of VCSs is provided allowing for the analysis water systems at a city scale.

Enhancement of VIBe to DynaVIBe

A further enhancement of VIBe by DynaVIBe is to complement case study conception with algorithms for

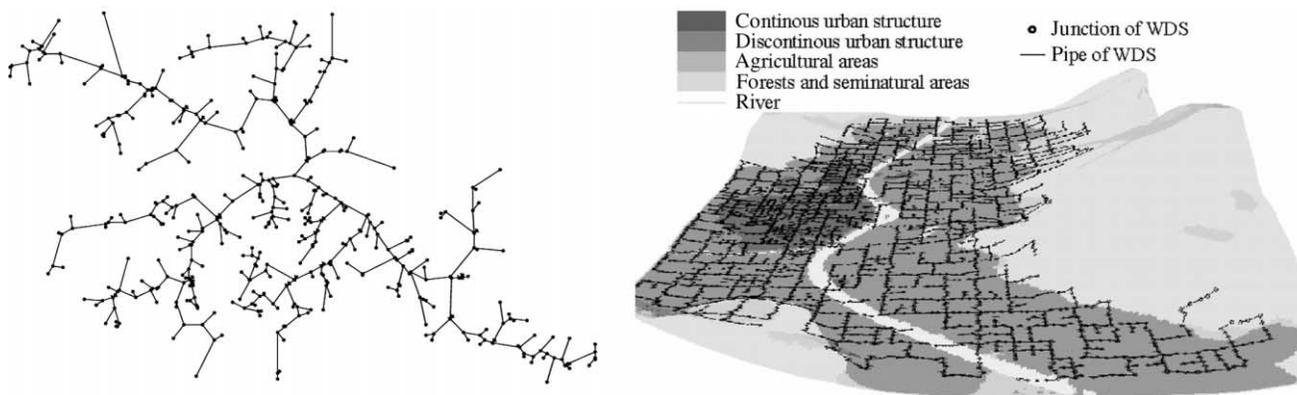


Figure 2 | Infrastructure generated with VIBe; left side: virtual sewer system; right side: elevation map with land use and virtual water distribution system.

temporal development. These development algorithms model change processes in urban fabric and infrastructure. Therefore, the methodology will be enhanced for dynamics. The complexities of the virtual case studies generated in DynaVIBe have to be increased compared to VIBe. Especially in VIBe, neglected components of the infrastructure generation process have to be included in the new approach (e.g. valves, tanks pumps in the WDS module; e.g. pump systems and additional cross-section shapes for the conduits in the sewer module).

In the initialization phase, an initial urban structure is generated based on the generation algorithms (see Figure 3, enhanced urban structure of VIBe). On the basis of this structure, the infrastructure is designed. Because the development of urban structures is a long-lasting historic process too complex to simulate, the generation algorithms in the initial phase are only partly comparable with realistic processes of urban development. With the generation algorithms starting from a partly random state (Figure 3, Genesis A) a virtual urban structure is created that closely resembles reality (Initial state B). The structure between states A and B has no relation to reality. However, as the simulation approaches initial state B, the urban structure begins to better resemble the real world.

In the validation phase the development algorithms can be calibrated and validated with indicators describing the urban structure. In DynaVIBe, these algorithms model

the urban structure relevant for the regarded infrastructure and therefore the impact of changing urban structure to the infrastructure. Beyond, the development of the infrastructure meeting the requirements of growing population for example is also implemented in the development algorithms. For state C in Figure 3, a model state is provided comparable to the actual state in 2010. In the prognosis phase the calibrated model can be applied to test new technologies, strategies or measures on the entire system.

RESULTS AND DISCUSSION

In the following section, an exemplary analysis with DynaVIBe is demonstrated and the benefits of the methodology are discussed. Additional potential applications are mentioned.

Exemplary analysis with DynaVIBe

In order to highlight the analysis with DynaVIBe, two example case studies A and B are discussed. The objective of these case studies is to evaluate the impact of a new real time control strategy. Case studies A and B shall be two urban structures with comparable boundary conditions and system properties. However, for case study A, the impact of the measure regarded with the indicator parameter can

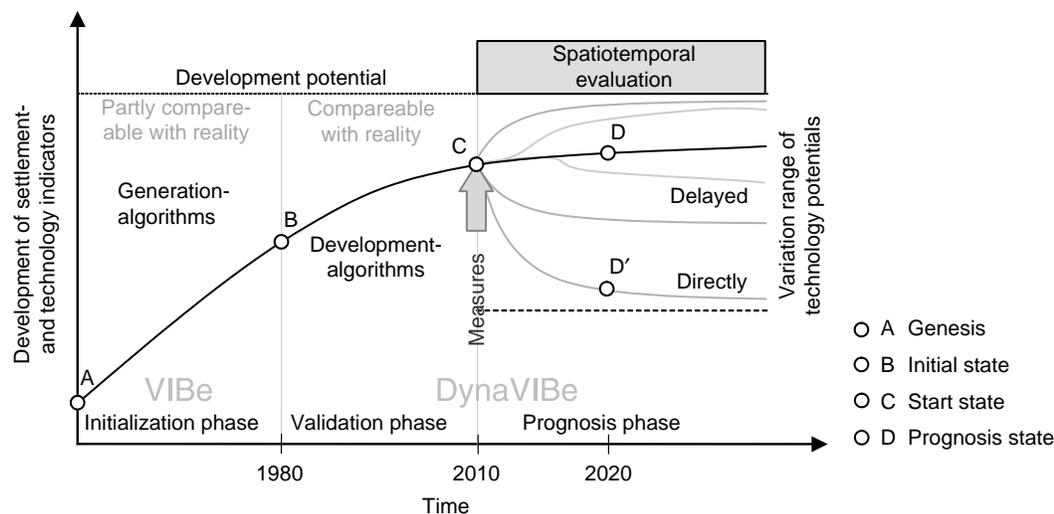


Figure 3 | Procedural method evaluation with DynaVIBe.

be quantified with +4%, whereas for case study B, -18% percent can be stated (Figure 4 left side). Although the boundary conditions are regarded as comparable these two single values represent the properties of two very specific systems. For another urban structure with similar boundary conditions it is not possible to conclude if the impact of the measure will be positive or negative. Furthermore it is not reasonable to transfer single value results onto different boundary conditions. A stochastic evaluation of normally distributed results with DynaVIBe provides a probability density function as output of the analysis. Hence, results are not constricted as single values (e.g. +4% or -18%), but in fact as standard deviation σ , expectation value μ and probability of occurrence p for intervals, which can be used to describe the impact more precisely. For the measure discussed above, the evaluation with DynaVIBe reveals a standard deviation $\sigma = 9\%$ and an expectation value $\mu = -11\%$ as outcome. The impact of the measure on the indicator parameter is, with a probability of 68%, situated between minus 2% and minus 20% (interval within $[\mu \pm 1\sigma]$). Alternatively, with a probability of 95%, the impact of the measure on the indicator parameter is less than plus 4% (case study A). With this stochastic evaluation, a more precise assessment of the impact of this new real

time control strategy is possible with the added benefit of allowing uncertainties to be quantified. Such information is essential for decision makers to decide on which measures to emphasize in planning policies.

Besides this stochastic assessment, DynaVIBe allows the temporal development over the simulated period of time to be examined. Standard deviation, expected value, probability of occurrence and other statistical evaluations can be calculated for each discrete time step simulated. For the impact of a measure on the indicator parameter, the outcome applies to a specific point of time, such as ten years after implementation (Figure 4 right side). Especially in the context of evaluating the success and shortcomings of planning measures and novel technologies, this feature is both innovative and of practical interest. Here, not only the dynamics of the system are taken into account, but also the effect of the measure on the system itself (i.e. the promotion of rainwater infiltration as primary drainage option would eventually lead to a stagnation in drainage capacity of the pipe network, as dual systems cannot be maintained economically). On the other hand, this reduced drainage capacity would be influential under changing boundary conditions due to the impacts of climate change.

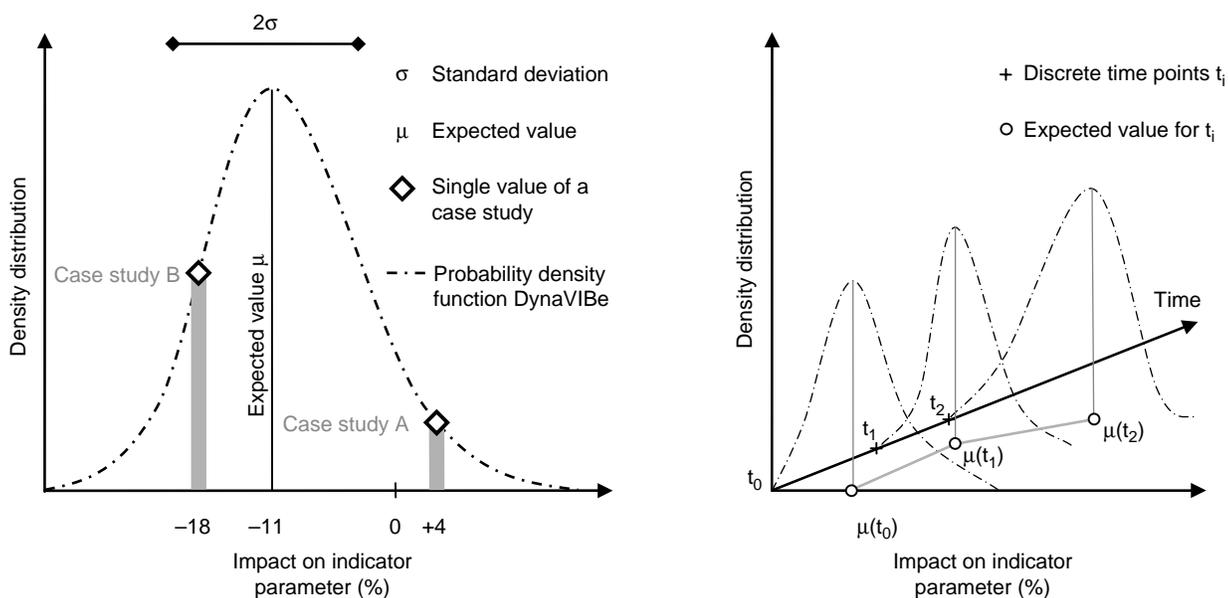


Figure 4 | Exemplary evaluation of measure to reduce substantial impact to urban waste water with two case studies and DynaVIBe.

Potential applications

Although the DynaVIBe approach is applicable to virtually any infrastructure, an application for water infrastructure is intended here. This encompasses an integrated perception of the urban water cycle, which includes the sewer system (hydraulic efficiency and efficiency towards pollution retention of the sewer system, emission and immission based/ambient water quality investigations), the water distribution system (hydraulic performance, water quality, availability of sources, ground water wells and vulnerability) and interactions of these infrastructures among each other with respect to the socio-economic aspects of population, water efficiency and sustainability.

Uncertainty and sensitivity analysis of environmental models is essential to estimate predictive uncertainties as models can never perfectly represent reality due to different sources of uncertainties in the modelling process (Beck 1999; Deletic *et al.* 2009). Much work has been done on the analysis of uncertainties in environmental modelling, but most studies mainly focus on uncertainties of modelling of large natural watersheds or concentrate on a specific source of uncertainty. Uncertainties in urban water modelling have in recent years attracted increasing attention of scientists and are still often neglected in non-scientific practical projects. Despite different methods of uncertainty analysis available including Generalized Likelihood Uncertainty Estimation (GLUE), Markov Chain Monte Carlo simulation (MCMC) for Bayesian inference or the Bayesian Total Error Estimation (BATEA) framework, all of these suffer from the same problem of data-availability (Kleidorfer 2010). Additionally, Deletic *et al.* (2009) report that not all methods are appropriate for use with urban water models. With DynaVIBe, available methods for uncertainty analysis can be tested and compared more comprehensively as data availability is not the limiting factor. As a result, conditions can be identified under which only certain methods are applicable.

A further application of DynaVIBe related to uncertainty analysis in urban water systems is the analysis of predictive uncertainties of a model. Especially as water systems change continuously due to building measures, land-use change and urbanisation (leading to population growth and increasing catchment imperviousness),

rehabilitation measures for sewer systems and water supply systems, the questions of how accurate a model calibrated for the current/past state, is able to predict future system behaviour, is asked. Therefore, case studies with a comprehensive dataset (input data and calibration data) over a long time period and data of system structure (system layout, building measures, pipe roughness) and boundary conditions (population density, water consumption and paved area) for different states in time (e.g. every 10 years) would be required. As this data is often limited, new strategies and modelling approaches can only be tested on a few case studies. By using DynaVIBe methodologies, such research can be conducted and additionally impact of environmental change scenarios (e.g. climate change) with respect to the dynamic change of the system due to aging and upgrades can be analysed.

In addition, DynaVIBe can provide data with different levels of detail (up to a raster resolution of 20 m × 20 m) for evaluating the impact of model structure uncertainties. Different questions related to the issue of model structure uncertainty can be investigated (e.g. what is the required spatial resolution of a model or in other words how many sub-catchments can be considered as one to represent an urban drainage system). For water distribution systems, the issue of skeletonization can also be investigated by identifying skeletonization rules/recommendations based on evaluations of numerous virtual case studies.

CONCLUSIONS

In urban water management research, the availability of case study data is a crucial issue. Approaches have been developed to tackle the problem of limited data availability with manual or algorithmic generation of case studies. Only with the algorithmic generation of numerous virtual case studies with varying boundary conditions can general conclusions be made. But approaches for the algorithmic generation of case studies so far neglect the changes of the systems over time and are therefore not useful to evaluate problems such as climate change effects or climate change adaptation strategies over time. DynaVIBe provides numerous virtual case study data-sets, which can be used for such evaluations.

Additionally with DynaViBe, a tool is provided, which combines population and land use models with infrastructure models. The impact of the population and its influence on the infrastructure can thus be investigated. This approach can also be applied to real data if available. Stochastic future scenario analysis of real case studies can therefore be performed with DynaViBe.

The entire DynaViBe approach is exposed to uncertainties and hence systematic investigation for the quantification and identification of parameter dependencies are necessary. Especially for the analysis of predictive model uncertainties, DynaViBe can provide the relevant data for estimating uncertainties in model structure due to spatial resolution.

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