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Stochastic Generation of Urban Water Systems for Case Study Analysis

DISSERTATION

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ABSTRACT

Analysis with case studies is a well known instrument to identify problems and interactions of processes. Therefore, analysis of urban water systems is not feasible without case studies. But preparing a model for a case study e.g. for a water distribution or urban drainage system is time and resource intensive. The expenditure of time to build a detailed model of the water infrastructure of a mid-size city (about 150,000 inhabitants) can be quantified with several man-months. Therefore, for research tasks, case studies are often only available in a limited number. Analyses based on a limited number of case studies are very case-specific and the results can be hardly transferred to other boundary conditions. Further, it is difficult to determine case-unspecific system coherences and to obtain general results.

Since the mid of the 1990s, synthetic or semi-synthetic case studies were used in numerical studies to demonstrate applicability of new approaches or to outline the effects investigated. With investigations on systematically created, but very simple case studies, it was attempted to obtain case-unspecific results. More recently, approaches were developed for the stochastic generation of case studies with different characteristics which can be used further for systematic investigations. But case studies generated with these approaches are still very simplified and conceptual.

The aim of this PhD project is to develop tools for stochastic generation of complex case studies for urban water systems. In this thesis, case study models for water distribution systems, urban drainage systems and geothermal energy utilisations are stochastically generated by means of newly developed tools. Further, comparisons of the generated with real world case studies are provided, in order to demonstrated the accuracy of the developed tools. The subsequent systematic investigations of numerous case studies are based on extern and well-known numerical models which are used for the design-process, but also for performance assessment.

KURZFASSUNG

Fallstudien stellen ein bewährtes Instrument in der Forschung dar, um Probleme und Interaktionen von Prozessen zu identifizieren. Die Forschung an städtischer Wasserinfrastruktur ist stark gekoppelt an solche Fallstudien. Jedoch kann der Zeitaufwand für das Erstellen eines Simulationsmodells eines Wasserversorgungs- oder eines Siedlungsentwässerungssystems einer mittelgroßen Stadt (in etwa 150,000 Einwohner), mit mehreren Mannmonaten veranschlagt werden. Gerade für Forschungszwecke steht dadurch nur eine beschränkte Anzahl von Fallstudien zur Verfügung und die gewonnenen Resultate sind daher sehr fallspezifisch und können kaum auf andere Randbedingungen übertragen oder allgemein gültige Zusammenhänge abgeleitet werden.

Bereits Mitte der neunziger Jahre des letzten Jahrhunderts wurden synthetische oder halbsynthetische Fallstudien erstellt mit dem Zweck die Anwendbarkeit von neuen Ansätzen darzustellen, beziehungsweise um die möglichen Auswirkungen der untersuchten Sachverhalte aufzuzeigen. Desweiteren wurde versucht mit systematisch erstellten, jedoch sehr vereinfachten Fallstudien, fallunspezifische Resultate zu erhalten. Gerade in den letzten Jahren wurden Werkzeuge zur computerbasierten, stochastischen Generierung von einfachen Fallstudien mit unterschiedlichen Charakteristiken entwickelt. Jedoch werden in diesen konzeptionellen Fallstudien wichtige Elemente und Zusammenhänge vernachlässigt.

Das Ziel dieser Dissertation ist es neue Werkzeuge zur stochastischen Generierung von komplexen Fallstudien städtischer Wasserinfrastruktur zu entwickeln. Im Zuge dieser Arbeit werden Fallstudien für Wasserversorgungs-, Siedlungsentwässerungssysteme und Wärmelastpläne für geothermische Grundwassernutzung für weitere Untersuchungen stochastisch generiert. Desweiteren werden Vergleiche mit realen Fallstudien aufgezeigt, um die Güte der entwickelten Werkzeuge zu demonstrieren. Mittels Schnittstellen zu bewährten Modellierungswerkzeugen wird die Leistungsfähigkeit dieser Systeme anschließend untersucht und dies ermöglicht auch ein einfaches Einbinden dieser Vielzahl von generierten Fallstudien in anschließende, weitere Untersuchungen.

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Sitzenfrei, R.; Möderl, M.; Rauch, W. (submitted-b): WDS Designer - Generator of Water Distribution Systems using GIS Data. Submitted to: Environmental Modelling & Software.

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Paper VIII

Sitzenfrei, R., Urich, C.; Möderl, M.; Kinzel, H. Rauch, W. (in preparation): Stochastic Generation of Urban Water Systems with VIBe for Case Study Analysis. will be submitted to: Environmental Modelling & Software.

Paper IX

Sitzenfrei, R.; Fach, S.; Kleidorfer, M.; Urich, C.; Rauch W. (2010): Dynamic Virtual Infrastructure Benchmarking - DynaVIBe. In: In: Water Science and Technology: Water Supply. Vol. 10(4), p. 600 – 609

In addition to the papers listed above which are integral parts of this cumulative thesis, the following publications also derived in the course of this PhD project. These following papers are not integral parts of this thesis but they also provide valuable additional information for readers of this thesis.

Sitzenfrei, R.; Fach, S.; Rauch, W. (2008): Impact of simplifications in the assessment of Combined Sewer Overflow discharge, quo vadis, Poleni? (in german: Auswirkungen von Vereinfachungen bei der Bestimmung von Mischwasserentlastungsmengen- quo vadis, Poleni?). In: Wiener Mitteilungen 2008, Vol. 209

Fach, S.; **Sitzenfrei, R.**; Rauch, W. (2008): Assessing the relationship between water level and combined sewer overflow with computational fluid dynamics. In: Proceedings of the 11th International Conference on Urban Drainage, Edinburgh, Scotland, 31. October - 5. September 2008.

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Sitzenfrei, R.; Möderl, M.; Urich, C.; Rauch, W. (2009): Assessment of thermal regeneration for improved groundwater management. In: Proceedings of the Water & Energy, Copenhagen, Denmark, 29.-31. October 2009.

Urich, C.; **Sitzenfrei, R**.; Möderl, M.; Rauch, W. (2009): Assessment of the technical usable shallow geothermal potential of an aquifer. In: Proceedings of the Water & Energy, Copenhagen, Denmark, 29.-31. October 2009.

Möderl, M.; **Sitzenfrei, R.**; Rauch, W. (2010): Empirical Equation for Spacing of Ground Water Heat Pump Systems. In: Proceedings of the World Environmental and Water Resources Congress 2010: Challenges of Change; Section: Groundwater Council - 8th Symposium on Groundwater Hydrology, Quality and Management, Providence, Rhode Island, United States, May 16-20, 2010.

Sitzenfrei, R.; Möderl, M.; Urich, C.; Rauch, W. (2010) (in german): Erforderliche Abstände für die thermische Grundwassernutzung - Nachschlagewerk als Bemessungsbehelf. In: Proceedings of the 10. Internationales Anwenderforum, Oberflächennahe Geothermie, Erdgekoppelte Wärmepumpen und unterirdische thermische Energiespeicher, Regensburg, Deutschland, 19.-21. April.2010

Sitzenfrei, R.; Möderl, M.; Urich, C.; Rauch, W. (2010): Thermal regeneration of aquifers for sustainable resource management. In: Proceedings of the 1st IWA Austrian National Young Water Professionals Conference, Vienna, Austria, 9-11. June 2010.

Urich, C.; **Sitzenfrei, R.;** Rauch, W. (2010): Stochastic Design of Urban Areas for Benchmarking Energy Strategies. In: Proceedings of the AAG (Association of American Geographers) 2010 Annual Meeting, Washington, United States, 14. – 18 April 2010

1 INTRODUCTION

Case studies of infrastructure systems are an integral part of research in urban water management. This PhD thesis focuses on this issue and in particular faces the problem of limited availability of case study data for research tasks. Therefore, in course of this PhD project, tools and approaches are developed for the stochastic generation of urban water systems for case study analysis.

In this chapter, an introduction to case study research in the context of philosophy of science and urban water management is given (sub-chapter 1.1). In sub-chapter 1.2, case studies in urban water management are characterised and problems in regard of data availability are discussed in order to outline the aim and scope of this thesis. The scope of this thesis is specified and defined in more detail in sub-chapter 1.3 and the structure in context with the annexed papers is described.

1.1 Case Study Research

Research is driven by advancement of knowledge to enhance the understanding of phenomena. In philosophy of science, Kuhn (1970) defined different phases of progress in science. For that reason, the term “paradigm” (Kuhn, 1977) was introduced for sciences that describes an issue which is broadly accepted in a research community. Depending on the existence of such a “paradigm”, three different phases of science progress can be defined. The first phase is the “proto-science” without paradigms or consistent theory. The second phase is the “normal science” with established paradigms. With existence of such paradigms, an incremental, but in-depth science progress is enabled. If there is a raising number of inexplicable phenomena, established paradigms may be replaced by new ones. This describes the third research phase: “revolutionary science”.

Case study analysis is a valuable research strategy for all phases of science. Especially for “proto-sciences”, case study research based on data is essential. Even if there are just a few cases available, in order to get an idea of parameters and coherences in the investigated system, case study analysis is crucial. But also for progress in “normal science”, development of new or incremental enhancement of existing theory, case study data is important not only for theory building, but also for testing of new hypothesis. If phenomena observed in case study data cannot be described with established theory, the replacement of the existing paradigms is enforced. Therefore, science is strongly linked to observations and analysis based on case study data.

Analysis with case studies is a research strategy that involves data (Yin, 1981). Therefore, this particularly suits for the development and building of new theory (Eisenhardt, 1989; Eisenhardt and Graebner, 2007) which is empirical valid (Meredith, 1998). In principal, a single case study provides data for provable evidence of phenomena, but generalisation is often difficult (Easton, 2010). Multiple case studies, in contrast, suit for theory building and generalisation of findings (Siggelkow, 2007).

A major advantage of theory building based on case studies is that there exists a high probability that the new theory is valid due to the determined empirical coherences. A disadvantage is that an extensive utilisation of empirical arguments can result in overly complex theory. Also, without clearly defined research aims, a flood of information can lead to “*death by data asphyxiation*” (Pettigrew, 1990).

1.2 Urban Water Management and Case Studies

In urban water management, case studies of infrastructure systems are used to identify system coherences, build theories and for testing of new technologies, strategies or measures. Data, which describes such an infrastructure system based on data collection and measurement campaigns, represents a case study in the sense of philosophy of science. In urban water management a model for e.g. a software, which is based on data, is often also referred to as a case study (e.g.: Willems and Berlamont, 2002, Kleidorfer et al., 2009a). Although, according to Eisenhardt (1989) this would be a theory/model. Therefore, a case study in the context of urban water management can also be a model for simulation software (mathematical model) of a water infrastructure (e.g. urban drainage system or water distribution system).

Although for research in urban water management, case study data is crucial, the development of a case study (model of simulation software) is a time and cost consuming task. Starting with data collection, digitalisation, model development, calibration and validation (Refsgaard and Henriksen, 2004), the entire process for setting up a detailed model for e.g. a mid-sized town takes several man-months. But even if such a model is available, for research tasks and publication of the work the case study data may contain sensible data (e.g. water supply data which can be target for terrorist attacks). Therefore, there is only restricted access to data or dissemination (which is crucial for a researcher) is prohibited.

Due to the limited data availability for research tasks (like model/hypothesis/software testing, evaluation of potential of management strategies, technical measurements et cetera), investigations are often based on a single or a small number of case studies and so the obtained results can hardly be generalised or transferred to other boundary conditions. The issue of limited availability of case studies (case study data and models for simulation software) is addressed in this PhD project. This is done by developing new tools for the algorithmic generation of case studies. The generated case studies can be further used for research tasks and can help generalising the obtained results.

1.3 Scope and Structure of this Thesis

In order to tackle the problems of case study availability for research tasks (see 1.2) this thesis focuses on the development of tools for the algorithmic generation of case studies in urban water management. Further, it is demonstrated how these generated case studies can be used for systematic investigations and how obtained results were improved by the proposed methodology. In this chapter, the aim and scope of this PhD thesis is specified in detail. This is done in order to give an overview of the structure of this thesis and to show the relation to the annexed papers which are an integral part of this dissertation. The aim of this PhD project is not only to summarise the annexed papers, but to present additional results, discussion and critical reflection and to give a holistic overview of the entire context.

In Chapter 2 it is highlighted how synthetic case studies are already widely applied in urban water management research. Furthermore, it is described in which way the utilisation of synthetic case studies improved the quality of the results of the investigations. In addition, in Chapter 2 existing approaches for the systematic generation of case studies are discussed to gain an overview of related work in this context. One of these methodologies from literature is systematically applied for the generation of a large number of conceptual water distribution networks which is linked to Paper I.

In Chapter 3 and Paper II, the newly developed software WDS Designer is presented which is capable to algorithmically generate water distribution systems based on given GIS (geographic information system) data. Beyond providing case study data for research tasks, potentially this tool can also be applied in practice to get a preliminary design for growth corridors and to estimate costs and performance of new water distribution systems. This application bridges the gap between this research work and potential application in practice. As a research application of case studies generated with the WDS Designer, in Paper III it is determined how many network sources are required in water distribution systems.

A key method of this thesis is the developed software tool VIBe (Virtual Infrastructure Benchmarking). VIBe generated case studies for urban water systems including all necessary data for investigations. In Chapter 4 (Paper IV and Paper VIII) the architecture and general modelling concepts of VIBe are described. VIBe consists of several modules. At first, cities are generated with the urban structure module (Chapter 5, Paper IV). Subsequent, for the generated cities, the infrastructure modules algorithmically generate sewer systems (Chapter 6 and Paper VI) and water distribution systems (Chapter 7 and Paper V).

In addition, the VIBe approach is also applied to assess the potential of geothermal energy utilisation of shallow aquifers for different types of housing patterns. This is discussed in Chapter 8 and also presented in Paper VII.

The conception of VIBe and therefore, the generated case studies lack temporal development. E.g. neglected aspects are: the urban development over time in the urban structure module, the consideration of different pipe ages and pipe rehabilitation in the water distribution system module or the sewer module or the change in heat insulation standards and renewing rates of buildings for the geothermal energy module. Thus, the conception of DynaVIBe (Dynamic Virtual Infrastructure Benchmarking) which takes into account a temporal development for the generated cases studies is outlined in Paper IX and set in context with existing approaches (Chapter 9).

2 VIRTUAL INFRASTRUCTURE IN URBAN WATER MANAGEMENT

In the research field of urban water management, the application of mathematical (numerical) models is well known. Amongst others, for the sub-fields (which are also investigated in this thesis): urban drainage modelling (Rauch et al., 2010), water distribution modelling (Strafaci and Walski, 2003) and groundwater modelling (Refsgaard et al., 2010; Fairley et al., 2010) for geothermal energy utilisations (Rauch et al., 2009a; Hecht-Méndez et al., 2010); mathematical models are state-of-the-art. Therefore, for research tasks, as well as for practical engineering applications, numerical models are widely applied.

To verify hypotheses or new modelling approaches with mathematical models, it is crucial to test these on case studies in order to outline effects. If there is no case study data available, these new approaches can only be tested on synthetic/virtual case study data. Synthetic case study data can be created manually or generated systematically by means of algorithms. In this context, case study data, which are created for a particular investigation, are referred to as “synthetic” case studies for infrastructure systems. The algorithmically/ systematically generated case studies, which are created in order to provide data for other investigations, are in this thesis referred to as “virtual” case studies.

In the following sections, research applications of synthetic infrastructure case studies are shown for urban drainage research and water distribution system analysis (2.1). Further, a literature review on existing methods for the systematic generation and applications of these virtual case studies is provided in chapter 2.2 and 2.3. In chapter 2.4 a systematic generation and investigation of a set of 2,280 virtual water distribution systems is discussed. In Paper I, the systematic generation process is presented which is an integral part of this thesis.

2.1 Applications of Synthetic Infrastructure Systems

In the following paragraphs, an assortment of research works in which hypotheses and models were tested with synthetic case studies and benchmark systems is shown. Benchmark systems are introduced and used in order to make findings of different research group more comparable. In urban drainage systems research, the application of benchmark systems is much less common compared to e.g. research on waste water treatment plants or water distribution system analysis.

In this literature review a brief description of established benchmark systems is given. Therein, the focus is on network-based analysis. Further, the application of synthetic case studies is described and how and with which complexity these synthetic case studies are created and how they are used for investigations. Finally, the complexities and purposes of the synthetic case studies in the different investigations are compared among each other.

In chapter 2.1.1 synthetic case studies of urban drainage systems research are discussed and an overview on benchmark systems for waste water treatment plant is given. In chapter 2.1.2, benchmark systems from water distribution systems analysis are discussed.

2.1.1 Urban Drainage Systems Research

In urban drainage system research, only a few benchmark systems were introduced (e.g. Schilling, 1989, Schütze et al., 1999) and used for other investigations (e.g. Rauch and Harremoës, 1999, Zacharof et al., 2004). Especially to make control strategies of waste water treatment plant more comparable, simulation-benchmark models were introduced (e.g. Spanjers et al., 1998; Pons et al., 1999). This model was enhanced in various studies (e.g. Rosen et al., 2004; Jeppsson et al., 2006; Zaher et al., 2007) and is well-established and widely applied in that research field (e.g. Nopens et al., 2009; Flores-Alsina et al., 2010; Flores et al., 2007).

In urban drainage systems research, the application of many different synthetic case studies is more common. Since the mid of the 1990's, synthetic case studies were used in investigations. These investigations focused e.g. on integration of sub-models to an integrated urban drainage model (Rauch et al., 1998; Meirlaen et al., 2001) or to determine real time control potentials (Schutze et al., 2002; Borsanyi et al., 2008). The created integrated case studies were very simplified and were used to show the applicability of the new models and to outline the effects of new modelling approaches. The synthetic or semi-synthetic test cases were created but these have rarely been used in other studies.

In the following, only an assortment of used synthetic case studies are discussed and compared regarding their complexities. E.g. Rauch et al. (2003) investigated a stochastic model for urine separation on a very conceptual synthetic catchment without spatial reference. Alike, Achleitner et al. (2007) followed a similar strategy to test urine separation control strategies, but applied the approach to a more complex synthetic catchment. The single combined sewer catchment, used in the investigations in Achleitner et al. (2007), were, in contrast those in Rauch et al. (2003), designed according to national guidelines with an over the catchment uniform distributed urine production. Further, in Achleitner et al. (2007) the results of the synthetic case studies were compared with results based on a real world case study and both showed the same resulting trends. Sitzenfrei et al.

(2008) used very simplified catchments with design storm events to give a glimpse on the impact of the new rating curve for combined sewer overflow discharge. In that work, a hydrodynamic model was used to compare run-off rates and therefore, spill flow volumes based on simulated water levels and compared traditional weir equation with the newly developed ones. Borsanyi et al. (2008) designed synthetic case studies according to national guidelines. Although no systematic generation of case studies was done in the synthetic catchments, complex components like pumps, slides weirs, storage tanks and pipes were implemented.

Additional complexity was introduced by the synthetic catchments used in De Toffol et al. (2007). This was done in that study by using sub-catchments instead of larger catchments and variations of population densities, impervious area and different rainfall characteristics. Beyond outlining the effect of an measure (Rauch et al., 2003; Achleitner et al., 2007), in De Toffol et al. (2007) case unspecific results were obtained by means of parameter variations in defined parameter ranges and by investigating an entire set of synthetic case studies. Alike, Schutze et al. (2002) used a set of 64 hypothetical instances to test two paradigms of real-time control in order to get case unspecific results.

The discussed applications of synthetic or semi-synthetic case studies are only an assortment of work done in this field. It was shown, how these synthetic case studies were created and how they are used for investigations. Further, different complexities of synthetic case studies were discussed and pointed out, starting from a catchment without spatial reference to sets of synthetic case studies to obtain case unspecific results. In addition, it was discussed how the application of the synthetic case studies improved the work, respectively, that the work was only possible by using synthetic case studies.

2.1.2 Water Distribution Systems Analysis

Since almost 3 decades, modelling of water distribution systems is a research field of high interest. For research tasks as design optimisation (e.g.: Gupta et al., 1999; Ostfeld and Tubaltzev, 2008 di Pierro et al., 2009), water quality assessments (May et al., 2008; Tamminen et al., 2008; Wu et al., 2009a) or performance assessments (Ramos et al., 2009) only a few or one single case study were used. Furthermore, these case studies for investigations are synthetic case studies or benchmark systems.

In numerous studies, example network provided with the hydraulic solver Epanet2 (Rossman, 2000) were used. The three case studies (Net1, Net2 and Net3) were applied in Rossman (1994) to present example applications of the Epanet program. Net1 (Figure 1, left) was used to illustrate how Epanet can model chlorine decay. With Net2, a fluoride tracer analysis was shown and Net 3 was utilised to trace back source feed into the system.

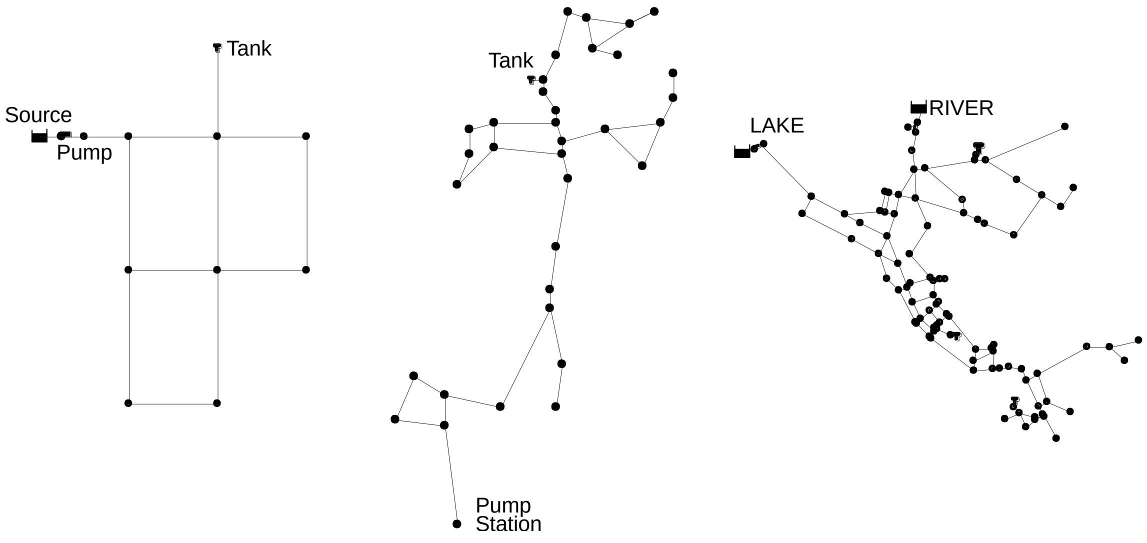


Figure 1: Example networks provided with Epanet

To make approaches more comparable, benchmark water distribution systems were introduced (see Figure 2 to Figure 5). E.g. the water distribution system New York City Tunnels was established by Schaake and Lai (1969). This system consists of 20 nodes and 21 pipes and a reservoir with an elevation of 91.33 metres (see Figure 2). All nodes are at elevation zero.

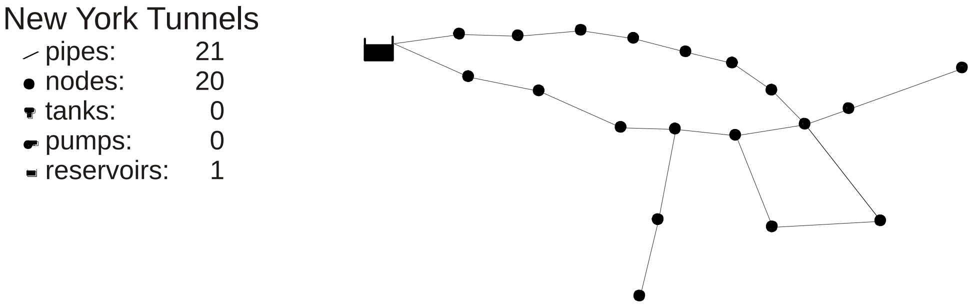


Figure 2: Benchmark system: New York Tunnels

The Two-Loop System was introduced by Alperovits and Shamir (1977). The system is based on a regular grid and therefore, all pipes have the same length of 1,000 metres. Further, it is fed in from one reservoir with 210 meters head (Figure 3).

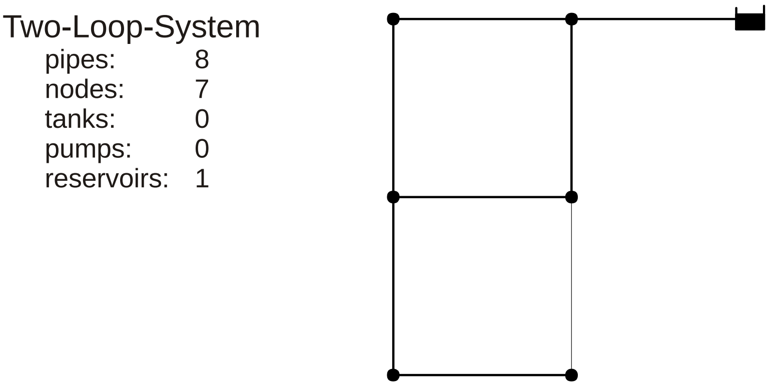


Figure 3: Benchmark system: Two-Loop

The Anytown network (see Figure 4), established by Walski et al. (1987), consists of 40 pipes and 22 nodes (16 demand nodes and 6 non-demand nodes). There are two tanks and one pumping station in the Anytown network. Another benchmark water distribution system (see Figure 5) was presented by Fujiwara and Khang (1990). The Hanoi system consists of 32 nodes and 34 pipes. There are three loops and in the system and no pumping station is considered. The head of the source has a fixed value of 100 metres.

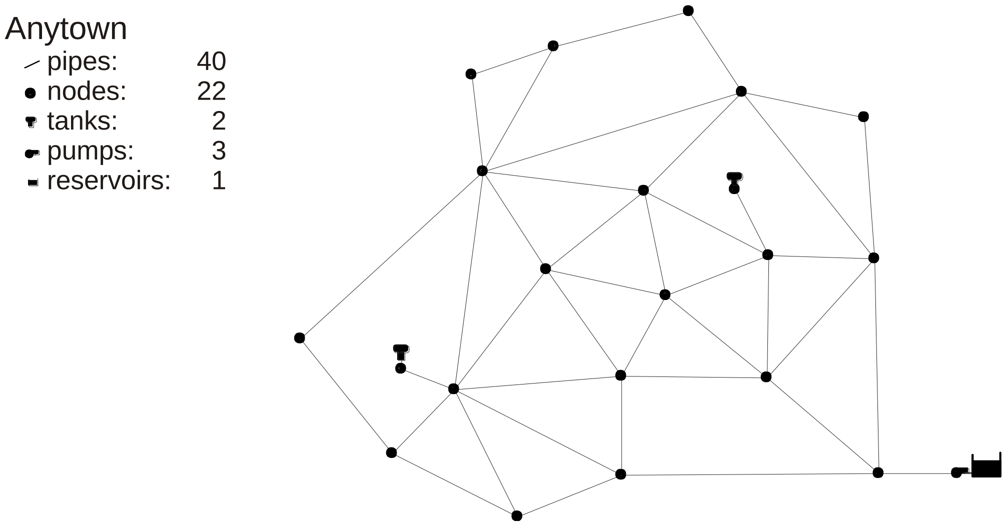


Figure 4: Benchmark system: Anytown

Various studies used one benchmark system to apply their approaches: among others Dandy et al. (1996), Babayan et al. (2007) and Chu et al. (2008) applied the New York Tunnels network; Walters et al. (1999), Farmani et al. (2006) and Behzadian et al. (2009) the Anytown network and Todini (2000) and Kalungi and Tanyimboh (2003) the Two-loop network.

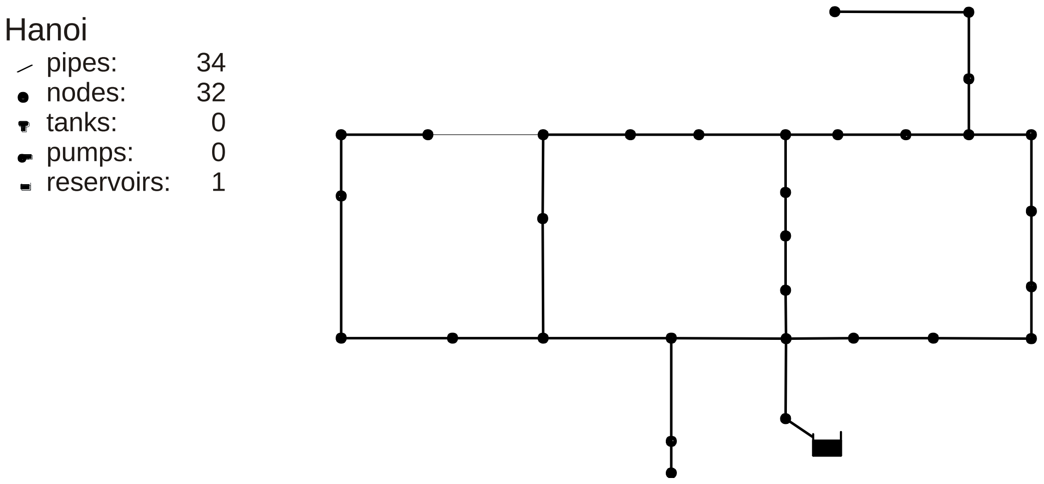


Figure 5: Benchmark system: Hanoi

Numerous studies used two or more benchmark networks for their investigations (Savic and Walters, 1997;Cunha and Sousa, 1999; Maier et al., 2003; Eusuff and Lansey, 2003; Zecchin et al., 2006; Gomes et al., 2009;

Olsson et al., 2009). Anyway, for their investigations only very few single case studies were utilised and generalising the results is still difficult.

Anyhow, e.g. optimisation tasks require comprehensive simulation efforts (simulation runs). Due to this, with currently available computer power, these modelling tasks can only be applied on systems with a restricted number of elements (nodes and pipes), respectively on a limited number of case studies. Therefore, these approaches can be applied to numerous case studies not until available computation power allows to.

2.1.3 Summary and Conclusions

For urban drainage system research application of synthetic case studies with varying complexities were shown. It was demonstrated how they are created and how they were used for investigations.

Also, for water distribution system analysis, the application of synthetic case studies is a common technique to test approaches and algorithms. Especially, in water distribution analysis, benchmark studies were used to compare findings and provide data for case study research. But still, the results obtained by the investigated approaches remain very case specific. This is due to the fact that there are only very few benchmark case studies available and the results can hardly be generalised or transferred to other boundary conditions.

2.2 Virtual Sewer Systems

In this section two approaches for systematic generation of virtual drainage systems are shown (ANGel, see 2.2.1 and CSG, see 2.2.2). Virtual case studies generated with the CSG approach were used in numerous further studies. An overview of these studies is given in chapter 2.2.3. In chapter 2.2.4 the different approaches discussed before are compared and advantages and disadvantages of the approaches are pointed out, in order to formulate the requirements of a new, enhanced generation tool.

2.2.1 *Artificial Network Generator ANGel*

River networks can be described by means of fractals (Veltri et al., 1996). Ghosh et al. (2006) adapted this idea for sewers and presented an “Artificial Network Generator” (ANGel). The approach was developed to generate artificial sewer networks, based on a Tokunaga fractal tree, for city-scale analyses. Different generations in the fractal tree represent different levels of network resolutions. For that purpose, in ANGel for the fractal branches the Strahler stream order (Strahler, 1952) is used. ANGel can be applied to an existing coarse network structure or existing land use data. But with ANGel, no interface to a hydraulic solver is available and therefore, only the layout of networks can be generated. Ghosh et al. (2006) outlined possible applications for a tool which generates sewer systems with an interface to a hydraulic solvers like SWMM (Rossman, 2004):

- for older cities: instead of manually developing a time consuming digital representation of the sewer network
- for analyses of future scenarios based on planning variables
- for research tasks: identifying system coherences and interactions
- for understanding scaling effects (coarse-scale, fine-scale)

Ghosh et al. (2006) outlined that the major aim of further work is to run hydraulic simulations, but this goal has not been achieved from that research group yet.

2.2.2 *Case Study Generator*

Möderl et al. (2009a) developed a stochastic approach for automatic generation of virtual case studies for urban drainage systems. With the developed algorithm, an unlimited number of dendritic virtual drainage systems can be generated. In this approach an interface to the hydraulic solver SWWM is implemented and therefore, stochastic performance evaluations of the generated systems are enabled.

For the generation process, it was assumed that the generated drainage systems have a tree layout and that there are no loops in the drainage systems (dendritic or branched systems). Therefore, the developed software tool Case Study Generator (CSG), generates tree layouts based on a Galton Watson (Pitman, 1998) branching process, which was adapted to meet the requirements of urban drainage systems. With this adapted algorithm, combined sewer systems can be generated with different boundary conditions as input (e.g. slope of catchment surface, etc).

The layout of the generated urban drainage system consists of nodes and pipes. The nodes are determined by different generations in the branching process or in other words: a node has a probability of children (different branches). The children nodes of each generation are located upstream and each children node is connected to its parent node via a pipe. The number of generations and therefore, the degree of branching, is an input parameter for the CSG algorithm.

The elevation of each node is a random process, taking into account an average elevation gradient. The average elevation gradient is an input parameter. Starting with the Waste Water Treatment Plant as first node and the assumption that every children node is located upstream of its parent node, the capability of drainage is secured. To each node (except from the Waste Water Treatment Plant), a sub-catchment is connected, taking into account elevation difference and placement of storage nodes to determine the impervious area and therefore, the rain weather flow. With a stochastic variation of population densities in the sub-catchments, dry weather flow is added to the virtual case study in a simplified manner. For the design process of the conduits, a simplified approach using design fall intensity is applied. Therein, with a flow balance and an assumed flow velocity in the pipes of 1 m/s, the diameters are determined.

As a systematic example evaluation, Möderl et al. (2009a) assess the hydraulic system performance regarding surface flooding. Further, based on these evaluations, the approach is calibrated with the results of two real world case studies (alpine and semi-alpine). With the variety of generated virtual urban drainage systems, a stochastic approach for hydraulic performance assessment is given and the applicability is shown.

2.2.3 Applications of the Case Study Generator

The Case Study Generator (CSG) is a free available Matlab-based software tool. An unlimited number of case studies for combined sewer systems are therefore, available for the public. In this chapter, the aims of studies in which the CSG was used, are discussed. Further, it is discussed how the application of sets of virtual drainage systems improved the findings of the studies. Two of them (Kleidorfer et al., 2009b; Möderl et al., 2009b) were produced with co-operations in course of this PhD project. Although, these papers are not integral parts of this thesis, they provide valuable background information in context of this thesis.

Impact of Climate Change effects on Combined Sewer Systems

Urban drainage systems have to be designed not only in order to cope with present conditions, but also with future conditions. The lifespan of drainage systems amounts to several decades. Due to this fact, it is a challenging task for the design engineer to predict future conditions (Ashley et al., 2005) or to adapt existing systems (Arnbjerg-Nielsen and Fleischer, 2009).

In Kleidorfer et al. (2009b) an approach is presented which aims to estimate the impact of long-term environmental changes on the performance of combined sewer systems. To obtain more general conclusions, a set of 250 virtual case studies generated with the Case Study Generator (Möderl et al., 2009a) and one real world case study were used and systematically analysed. For the hydraulic analysis the hydrodynamic model SWMM (Rossman, 2004) was used. In total, 30,000 simulation runs were analysed.

The used virtual case studies and the real world case study showed similar behaviour to long-term environmental effects. These long-term environmental effects are e.g. changes in rainfall characteristics due to climate change (climate change factors applied to rainfall intensities, Arnbjerg-Nielson, 2008), changes in impervious area and changed dry weather flow due to future development (increase or decrease).

The systematic investigations showed e.g. that an increase of rainfall intensities of 20% has the same impact on the investigated performance indicators for flooding and emission performance, as an increase of 40% of impervious area. And the same increase of rainfall intensities can be compensated by a reduction of impervious area of 30%, initiated for example by infiltration measures. By using the 250 virtual case studies and one real world case study, the obtained results were more general. Therefore, general suggestions for the design process of sewer system under consideration of future conditions can be made.

Identifying weak points in urban drainage systems

To ensure the operation of urban drainage systems, not only under regular but also under critical conditions, the weak points of the systems have to be identified. Möderl et al. (2009b) presented the software tool VulNetUD. This software tool provides spatial referenced vulnerability maps of system performance of urban drainage systems. Therewith, GIS-based identification of vulnerable sites in drainage systems is provided to support e.g. decision makers in the development of rehabilitation strategies.

VulNetUD mimics hazardous impacts on the urban drainages system on different components by assuming that to fail. Subsequent, the tool evaluates the resulting impact on the system performance by means of the hydrodynamic solver SWMM (Rossman, 2004) and spatially references this impact at the position of the component failure. By repeating this procedure systematically for all components, vulnerable sites can be identified in spatially referenced vulnerability maps.

The VulNetUD approach was applied to a real world case study and additional, to a set of 250 case studies generated with the Case Study Generator (Möderl et al., 2009a). The 250 virtual case studies were used for software testing and to determine the ranges of possible impacts on drainage systems. It was revealed that the results of the real world case study are within the ranges of the virtual case studies and the ranges of the possible effects were outlined.

Generic Performance Assessment of Combined Sewers

In Möderl and Rauch (2010) a set of 250 virtual case studies generated with the Case Study Generator (Möderl et al., 2009a) was used to analyse, how system characteristics influence the system performance (e.g. emission and flooding performance). Therefore, sensitive and meaningful characteristics of the set of virtual case studies were identified and separated in character groups. It was found that characteristics, which have a positive impact on emission performance, have a negative impact on flooding performance and vice versa.

2.2.4 Summary and Conclusions

The two approaches for the generation of virtual case studies presented in chapter 2.2.1 (ANGel) and chapter 2.2.2 (CSG) assume a fully branched urban drainage system (fractal layout and layout based on Galton Watson branching process). This also reflects the typical layout of sewer systems described in Butler and Davies (2004) and is related to layouts of natural drainage networks in rural hydrology (Hjelmfelt Jr., 1988; Puente and Castillo, 1996). In the layouts generated with ANGel, existing pipes can also been taken into account. This provides an application for the generation of semi-virtual case studies by supplementing unknown data. The aim of the CSG approach (chapter 2.2.2) is different. With the Galton Watson branching process, it is only intended to generate entire layouts of urban drainage systems (including pipe-sizing and an interface to a hydraulic solver).

The major weakness of the ANGel approach is that no pipe-sizing and no hydraulic simulations are included. In the CSG approach, the hydraulic simulations and the stochastic performance evaluations are the major innovations. The weakness in the CSG approach is that the layout of the sewer system is generated at first (determined by the branching process) and in a second step is the basis for the urban catchments. Therefore, this does not reproduce real circumstances, because real world sewer systems are designed to meet the requirements of the urban environment (consisting of different catchments). Resulting, in the CSG approach the urban environment reflects the branching process. Or in other words the layout of the urban environment is driven by the sewer layout. To face this shortcomings, an approach is needed which generates infrastructure based on a virtual/real urban environment (GIS data) or which takes an existing parts of infrastructure into account.

The applications of the virtual case studies, generated with the CSG (chapter 2.2.3), significantly improved the quality of the discussed studies. In each study a set of 250 virtual case studies was used. On the one hand the systematic investigation of the set was used to obtain more general conclusions and to outline the impact of the investigated effects on systems (Kleidorfer et al., 2009b; Möderl et al., 2009b). On the other hand the set was also used for software testing (Möderl et al., 2009b). In both applications, it is reported that the virtual and the real case studies similarly respond to the investigated measures and approaches and ranges of effects could be outlined.

Another approach was followed in Möderl and Rauch (2010). Different groups of system characteristics of the set of 250 case studies were defined in order to get an idea of how different impacts on the system performance can be traced back to system characteristics. Although this is an encouraging approach, it cannot be ensured that the coherences found, reflect the generation process (Galton Watson branching process). For this study, a significant improvement can be achieved if the generated drainage systems are based on primarily generated urban environments with varying characteristics.

Concluding, the advantages of using numerous virtual case studies is shown in two studies (Kleidorfer et al., 2009b; Möderl et al., 2009b) and an encouraging approach for generic performance assessment of sewer systems (Möderl and Rauch, 2010) is discussed. The approach for generic performance assessment should be further investigated, regarding the impact of the generation process. Overall, the application of virtual case studies in research of urban drainage systems can be considered as valuable. But the assumptions and simplifications in the generation approaches have to be addressed in further investigations.

2.3 Virtual Water Distribution Systems

In this chapter, two virtual cities which were created for research tasks are discussed (chapter 2.3.1). In chapter 2.3.2, an approach for the systematic generation of water distribution systems is shown. In chapter 2.3.3, the presented approaches are compared and discussed in order to identify their advantages and weak points.

2.3.1 Virtual Cities for Water Distribution System Analysis

To face the problem of limited case study availability and to conserve infrastructure security (publishing sensible data and fear of terrorist attacks), Brumbelow et al. (2007) proposed the development of a library of virtual cities. The idea is to provide a free available library of virtual cities for research tasks. Therefore, by presenting research results based on evaluations of these virtual cities, no confidential or critical data (e.g. regarding safety) has to be published. Currently, two virtual cities have been developed: “Micropolis” and “Mesopolis”.

Virtual City Micropolis

With Micropolis, one single virtual city is presented, which has 5,000 residents. Micropolis is fully described in GIS and as Epanet2 model. A historical timeline of 130 years is implemented in the virtual city, trying to replicate the “organic nature” of infrastructure systems. This is done by adding spatial markers to guide the design process of the infrastructure. The

Epanet2 model has 1,236 nodes, 575 mains and 486 connection pipes. There are 434 residential demand nodes and 24 industrial/commercial nodes. The average daily consumption is 681l/d per capita and a total daily demand of 4,540m³/d. The main sources for water supply are groundwater wells and a reservoir outside the city. For the demand, different diurnal demand curves were used representing demands for residential or industrial areas, schools, grocery stores and restaurants. In the developmental process, the authors tried to consider imperfections similar to real world water distribution systems (Torres, 2006). Anyhow, the layout of the water distribution system is based on an equally spaced grid with a grid size of 1,000 feet (approximately 305 metres). But for the pipe-sizing, imperfections have been taken into account. As an example application of Micropolis, an investigation of fire flow under system damage is shown (Brumbelow et al., 2007).

Torres et al. (2009) presented a risk classification for attempted contamination of the water distribution system under uncertainty propagation and applied it to the Micropolis water supply system.

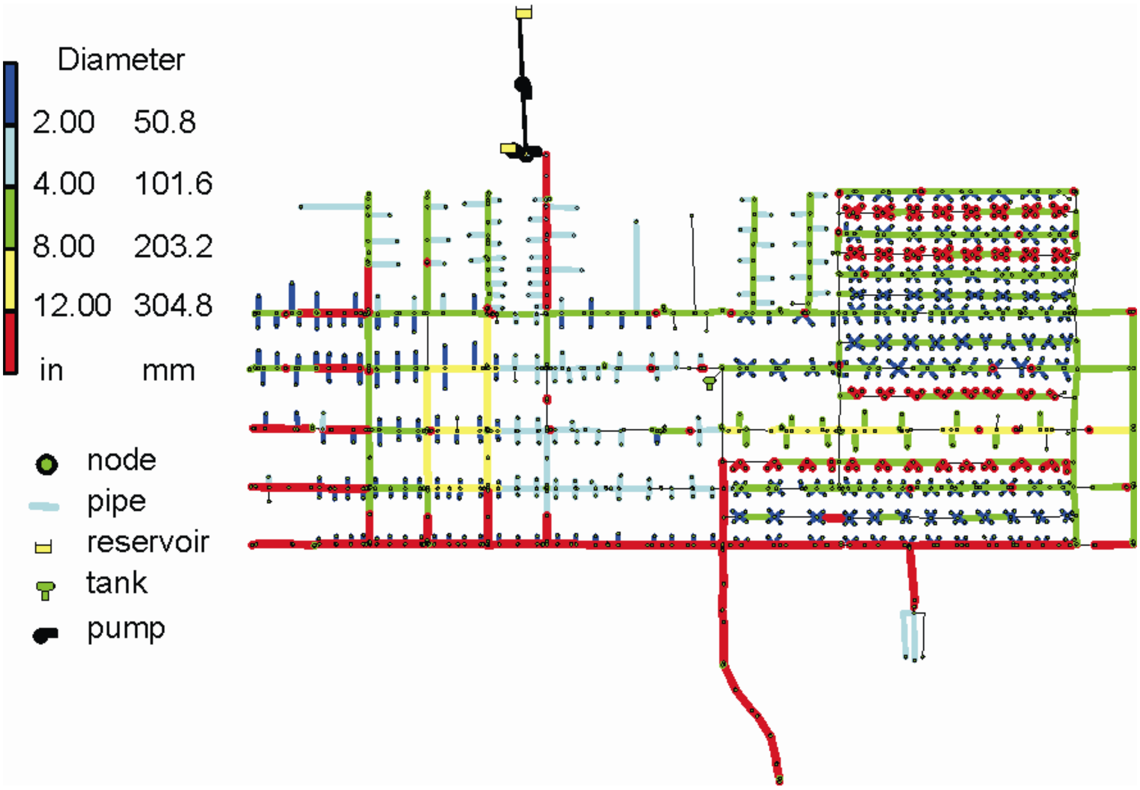


Figure 6: Water Distribution System of Micropolis

Kumar et al. (2010) present an approach to indentify reactive contaminant sources in a water distribution system. The approach was applied to the Epanet2 (Rossman, 2000) example network 3 (see 2.1.2) and to the water distribution system of the virtual city Micropolis. With the application of the approach to these two case studies, it was concluded that therewith the search for nodes as contamination source is narrowed down to a small group of potential nodes.

Virtual City Mesopolis

Mesopolis is a virtual city with a population of 140,000. The city was set-up for research tasks. Geographic data of Mesopolis is built in the software ArcGIS and the water distribution system in Epanet2. In the water distribution system, the network layout with pipes and different pipe materials, pumps and tanks are regarded. A diurnal demand pattern as well as a seasonal demand change is taken into account.

Anyhow, the virtual city Mesopolis has been used for several academic investigations. Shafiee and Zechman (2010) presented a modelling framework for simulation of contamination events in water distribution systems and applied it to the virtual city Mesopolis.

Although the virtual cities Micropolis and Mesopolis and their application for research tasks demonstrate the potential of such virtual case studies, the limiting factor is still the availability of case study data with different characteristics. Further, the manual construction process is time consuming and comparable with the construction process of a real world case study or even longer. But no security risk by publishing the system data arises, because the two case studies are no real world systems.

2.3.2 Modular Design System

In Möderl et al. (2007) the Modular Design System (MDS) is presented. With the MDS, a framework for systematic investigations of network structures is presented. Network structures like energy supply network, district heating networks or water distribution networks can be organised, administrated and represented by means of graph theory. An application of the MDS approach for water distribution systems was presented in Möderl et al. (2007).

In the MDS, the layout graph of a network structure is represented by a graph matrix (see also chapter 2.4). Parts of water distribution systems (blocks or modules, see Figure 7) of different sizes and characteristics can easily be connected to entire water distribution systems. Reservoirs can be added with the MDS, and with an interface to the hydraulic solver Epanet2 (Rossman, 2000) and simple pipe sizing algorithms, entire water distribution systems can be generated. A stochastic performance evaluation of 2,280 water distribution systems was shown in Möderl et al. (2007) and proved the proposed methodology.

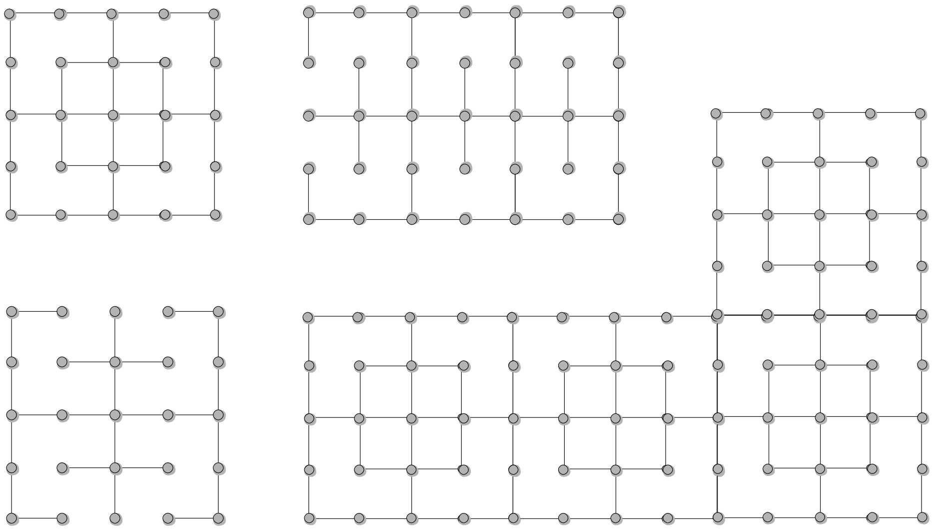


Figure 7: Four example blocks/modules generated with the MDS

A detailed description of the method and the systematic application of the MDS are shown in chapter 2.4 and in Möderl et al. (submitted) which is an integral part of this thesis (Paper I).

2.3.3 Summary and Conclusions

In chapter 2.3 two approaches were discussed which aim to provide virtual case study data for research tasks. With the approach in chapter 2.3.1, the development of a library of very specific virtual cities is intended. In contrast, the approach discussed in chapter 2.3.2 aims to provide a method to systematically generate virtual water distribution systems. Therefore, the MDS approach can be considered as a more generic approach to face the setting of the task. Another advantage of the MDS is that the number of provided case studies is only limited by computer power.

On the other hand, the water distribution systems of the virtual cities Micropolis and Mesopolis better resemble real world case studies and also include GIS data for buildings, land use and roadmap. In contrast to the MDS approach, in which there are significant simplifications and assumptions for the network structure (e.g. no pumps, tanks or valves), the water distribution system in Micropolis and Mesopolis are more complex.

2.4 Systematic Application of the Modular Design System

The development of software tools for the systematic generation of virtual infrastructure systems is an integral part of Möderl (2009). For network systems like energy supply network, district heating networks or water distribution networks, the Modular Design System (MDS) was developed. With the MDS the systematic generation of entire sets of virtual case studies is enabled.

In this chapter the systematic generation of virtual case studies for water distribution systems by means of the MDS is discussed. This topic is related to Paper I, but delivers also insight in the generation process of the set of 2,280 virtual water distribution systems in more detail. In addition, it provides some additional results, discussions and critical reflections. Paper I is an integral part of this thesis.

2.4.1 Virtual Water Distribution Systems in the MDS

The MDS is a free available Matlab-based software tool (free available at http://www.hydro-it.com/extern/IUT/mds/). With the MDS approach, amongst others, water distribution networks can be organised and represented by means of graph theory. In the following paragraphs, the graph-based network representation and the data administration of the MDS is illustrated.

Graph based data administration

For water distribution systems, the demand junctions are points in the MDS grid. The grid of the MDS and therefore, the coordinates of the junctions, are in this study for simplicity considered as rectangular (for example Figure 8 left). But with the MDS, the coordinates of the grid can be transformed to any other shape, e.g. circular arrangement (see Figure 8 right).

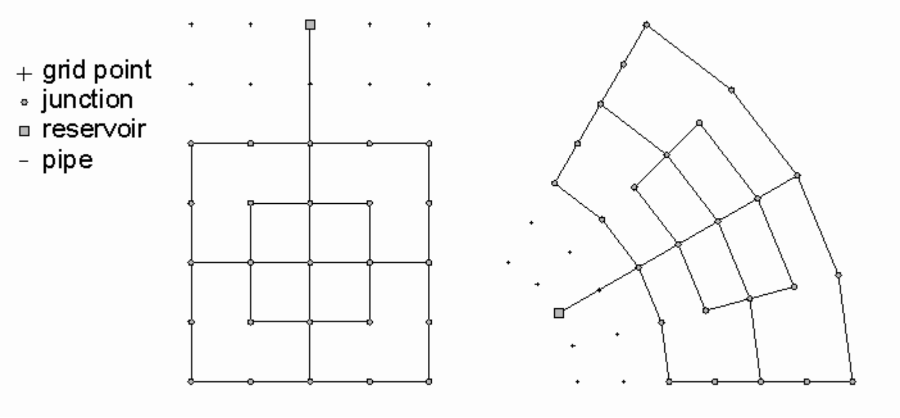


Figure 8: Different coordinates for MDS grid

The MDS has the limitation that there is a maximum of four pipes connected to a junction. This assumption is in good agreement with the network examples shown in the previous chapters (Figure 2, Figure 4 to Figure 6). With this assumption, the number of pipes connected to a junction and in which direction the pipes are connected to the junction (four cardinal directions) can be binary coded by means of a graph matrix.

Each junction is represented by an element in the graph matrix containing binary coded information about the connections (east=2^0, north =2^1, west =2^2, south =2^3). By summing up the values for the existing connections, the values in the graph matrices range from 0 ($0 \cdot 2^0 + 0 \cdot 2^1 + 0 \cdot 2^2 + 0 \cdot 2^3 = 0$) for no connections to 15 ($1 \cdot 2^0 + 1 \cdot 2^1 + 1 \cdot 2^2 + 1 \cdot 2^3 = 15$) for four connections. This explicitly indicates in which directions pipes are connected to the junction. For each junction additional information (e.g. coordinates, elevation, demand, type properties (reservoirs, demand nodes)) is stored. Also for the pipes, properties like roughness or diameter can be administrated within the MDS approach.

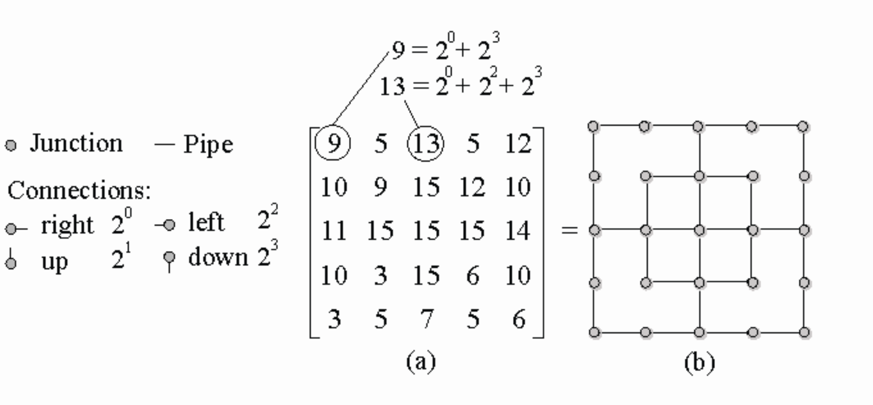


Figure 9: Graph matrix and example blocks

As an illustrative example, in Figure 9 (a) the graph matrix of the water distribution block of Figure 9 (b) is shown. For two circularly marked elements in the matrix, a detailed description of the value in the graph matrix is shown. For example the value 13 in the graph matrix represents connections to right (2^0), left (2^2) and lower (2^3) neighbouring junctions (Figure 9 (b)).

Concatenation operator

In Matlab, it is very easy to concatenate two matrices. This concatenation operator was adapted in order to concatenate the graph matrices (representing water distribution blocks) and to get the correct binary coded value in the boarder columns of the graph matrices (Möderl et al., 2007). With this modified concatenation operator, entire water distribution systems can be concatenated with graph matrices of smaller entities. This enables the user to concatenate different blocks with simple generation algorithms in order to form entire virtual water distribution systems (see chapter 2.4.2).

Data interface

In the MDS approach, an interface to the well known hydraulic solver Epanet2 (Rossman, 2000) is implemented. If there is a need for another hydraulic solver e.g. a pressure driven solver (Todini, 2003; Giustolisi et al., 2008; Möderl, 2009) for analysis of critical conditions, an interface to other hydraulic solvers with text-based input files can easily be added or the Epanet2 input file can be converted, respectively.

2.4.2 Generation of a Set of Virtual Water Distribution Systems

For the generation process, different characteristics of water distribution systems have to be defined and varied. In this chapter, these variations are summarised and it is described how virtual water distribution systems can be generated by means of the MDS approach and provided additional functions.

The generation process is based on the concatenation of different water supply blocks to form an entire complex water distribution system. Following the idea of simple building blocks in complex network systems (Milo et al., 2002), two different types of blocks were used, representing looped and branched structures (see Figure 10). The two block types have the same number of nodes, but different numbers of pipes.

How these two basic blocks are created, is described in detail in Paper I. Additionally, there are free available Matlab functions (www.hydro-it.com/extern/IUT/mds_app/) in order to document the generation process of the blocks more explicit.

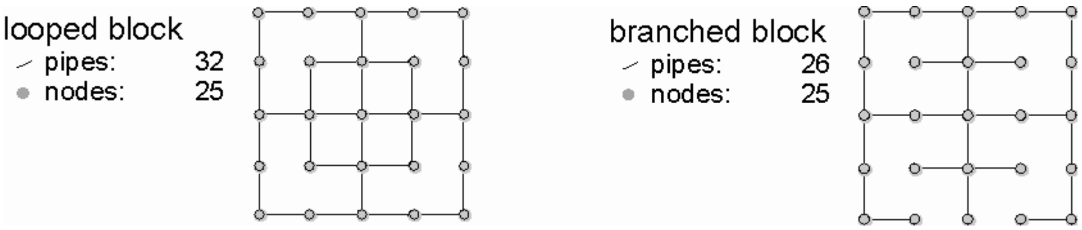


Figure 10: Looped block layout (left), branched block layout (right)

The two block types (branched and looped) represent different layout characteristics of water distribution networks. The differences of looped and branched network structure were analysed in various studies (e.g. Kalungi and Tanyimboh, 2003 or Babayan et al., 2007). In branched blocks, there is less over capacity (Fujiwara and Tung, 1991) or supply redundancy (Setiadi et al., 2005) in case of e.g. pipe breakage. But the construction costs of a looped system is in general higher (Strafaci and Walski, 2003, Sitzenfrei et al., in press).

Variations overview

In order to generate an entire set of virtual water distribution systems, variable parameters and ranges have to be defined. In this generation process, properties like pipe roughness, are set accordingly to default values (Rossman, 2000), but can also be set by means of algorithms and stochastic variations. In this set, for all reservoirs (network sources), an elevation of 100 metres is assumed and for demand junctions 0 metres. In total, the generated set consists of 2,280 virtual water distribution systems with a combination of following parameters (abbreviations used in Paper I and in the Matlab functions in brackets):

- demand variations for junctions (de1, de2, de3): 0.1 l/s for villages, 1 l/s for cities and 5 l/s for metropolises; additional an uniform distributed random factor within the range of 0.75 – 1 is applied
- variation of spatial expansion (di1, di2, dic): one-dimensional expansion in valleys (1 to 60), two-dimensional expansion in plain areas (1 to 11) or a complex expansion with separate municipalities of different sizes with connection pipes
- variation of sources which feed into the system (so1, so2, so3, so4): one to four sources per complex
- variation of network structure (ne1, ne2): looped network structure or branched network structure (see also Figure 10)
- variations of linking structures (li1, l2): with integrated pipes (one strong pipe) and connecting pipes (several small pipes, see Figure 12)
- variations of size (co1, co2, co4, co6): number of complexes used for a system (see see Figure 12 upper side: 4 complexes)
- variations of intermediate distance between complexes (in1, in2, in3): distance between the complexes of 1 km, 5 km and 10 km

The one-dimensional expansion leads to 1,440 variations (3 demand variations, 60 spatial variations, 4 source variations and 2 network structure variations). The two-dimensional expansion leads to 264 scenarios (3 demand variations, 11 spatial variations, 4 source variations and 2 network structure variations). The complex spatial expansion leads to 576 variations (3 demand variations, 3 distance variations, 4 variation for the number of complexes, 4 variations of complex size and 2 network structure variations). In total there are 2,280 different virtual water distribution systems.

Matlab Functions for the Generation Process

The free available Matlab functions were scripted in order to help the user to get started with the MDS and to be adapted by the user for user-defined purposes. All water distribution systems, shown in the figures of Paper I, can be recreated with these Matlab function by simply typing their abbreviations to the Matlab console (e.g. “li1” for a linking type with an integrated pipe, Figure 11).

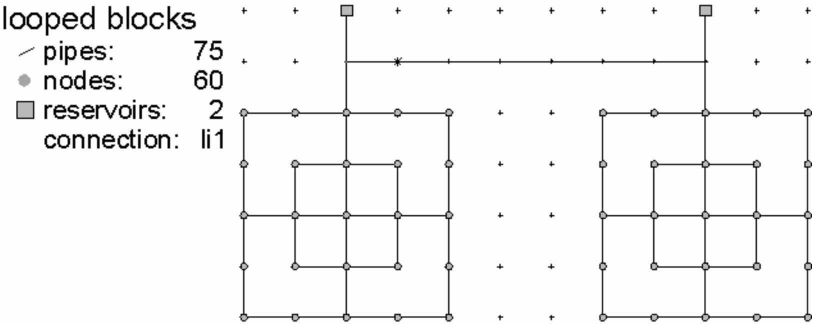


Figure 11: Result for function “li1” according to Paper I

For the systematic generation, more generic functions were scripted in order to decrease efforts for an algorithmic creation of a set of virtual water distribution systems. A detailed description of each function is available in its documentation (available at: http://www.hydro-it.com/extern/IUT/mds_app/). In the following paragraphs, the creation of two example networks is shown. In Figure 12 upper side, a water distribution system with 364 pipes and 365 nodes is shown. For the creation process of this system 6 parameters were used:

- linking type: integrated pipe

- number of complexes: 4
- distance between the complexes: 4
- spatial expansion 2
- network structure branch
- demand variation (l/s) 0.1

Integrated connected systems can be generated with the function call *li*. This function has 5 call parameters. Following the Matlab syntax by calling the commands below in the Matlab console (parameters are in the same order as in the list above):

```
>> WDS = li(4,4,2,’branch’,0.1);

>> plotmds(WDS);

>> printmds(WDS, ‘EpanetInputFile.inp’,
‘options.inp’)
```

the virtual water distribution system shown in Figure 12 upper side is created. With the command *plotmds* a figure is plotted and with *printmds* the water distribution system is exported via the Epanet2 interface to the file *EpanetInputFile.inp*. The commands *plotmds* and *printmds* and the file *options.inp* are provided with the MDS software tool.

- linking type: connecting pipes
- number of complexes: 3
- distance between complexes: 2
- spatial expansion 3
- network structure loop
- demand variation (l/s) 1

Systems with connecting pipes can be generated with the function call *in*. By calling in the Matlab console (parameters are in the same order as in the list above):

```
>> WDS = in(3,2,3,’loop’,1);

>> plotmds(WDS);

>> printmds(WDS, ‘EpanetInputFile.inp’,
‘options.inp’)
```

the virtual water distribution system shown in Figure 12 lower side is created, plotted and exported to Epanet2.

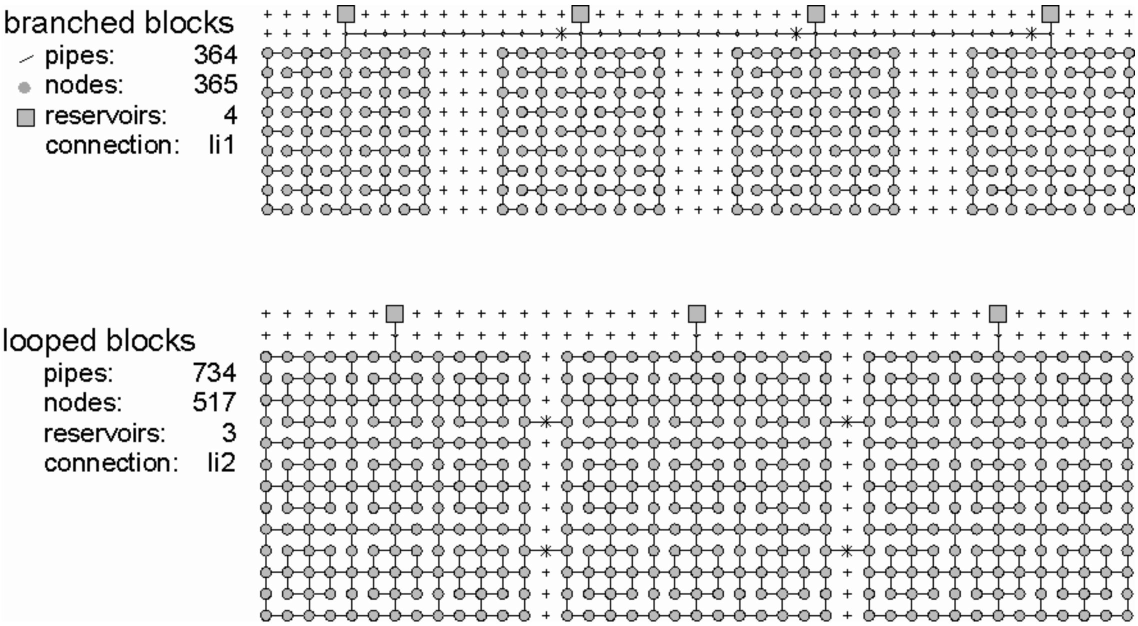


Figure 12: Examples created with generic functions

A further description in more detail and additional descriptions of the generation functions is available in the file *download_figure_description.m* which is provided with the entire download (free available at: http://www.hydro-it.com/extern/IUT/mds_app/).

Set Generation Procedure

To generate the entire set of 2,280 virtual water distribution systems, the generic functions and the variations described above were systematically applied. The generation procedure of each virtual water distribution system follows three steps. Firstly, the layout of the virtual water distribution system is generated by means of the layout/properties variations and default values listed above. In a second step, the system is pipe-sized with the approach described in chapter 2.4.3. Finally, each pipe-sized water distribution system is exported as Epanet2 input file for further investigations.

2.4.3 Auto Pipe-sizing and Hydraulic Analysis

For pipe-sizing of the generated virtual water distribution systems, the Epanet2 Programmer’s Toolkit is used. The Epanet2 Programmer’s Toolkit is a free available (http://www.epa.gov/nrmrl/wswrd/dw/epanet.html) dynamic link library (DLL) which allows customising the Epanet2 engine. For example, the Epanet2 engine can be used in the Matlab environment by directly addressing functions, values and results.

The objective of this pipe-sizing algorithms is to obtain diameter distributions, comparable with real world systems and not an optimised design as shown in various studies (Savic and Walters, 1997; Maier et al., 2003; di Pierro et al., 2009). The virtual water distribution systems can be of extensive size (several thousand nodes and pipes), and for a systematic generation process, numerous virtual case studies have to be pipe-sized. Real water distribution systems are not optimised systems. Usually, there are even errors in the design process incorporated in the systems. For example in a transport pipe without demand junction, there can be a restriction in the diameter. Hence, the aim of the used algorithm is to have little computation time and to conserve over capacity (without the risk of resulting excessive security, Tillman et al., 2005) in the network to obtain a realistic design. Therefore, it is not an optimisation, but a simple pipe-sizing algorithm which also leads to design errors.

With the pipe-sizing algorithm, initially all diameters are set to the smallest available diameter (in this case 80 mm). The algorithm iteratively determines flow velocities in the entire system by means of the hydraulic solver Epanet2 (with the Epanet2 Programmers toolkit) and incrementally (i.e. 80, 100, 125, 150, 200, 250, 300, 350, 400, 500, 600 mm) augments pipe diameters in which the actual flow velocity exceeds defined economic flow velocity of 1 m/s (according to Trifunovic, 2006). This results in 11 iterations for each virtual water distribution system for the entire pipe-sizing algorithm.

2.4.4 Results and Discussion

In Paper I network statistics, statistics of total demand and demand per source and a comparison of these data with three real world systems are provided. A hydraulic application example was also included to demonstrate the value of the methodology. Therefore, an increase of water demand of 50%, due to e.g. climate change effects and higher population densities, was investigated. It was shown that for the network statistics, as well as for the hydraulic application example, the set behaves similar as the investigated real world case studies.

In this chapter further results are presented. First, an example evaluation of one single case study is shown. Subsequently, the characteristics of the generated set are discussed in more detail.

Single Example for Hydraulic Analysis

As a single example for a hydraulic performance evaluation, in Figure 13 simulation results calculated by applying the software Epanet2 are shown. The flow velocity is symbolised for links. Darker gray of the pipes indicates higher velocities. The gray scale in the junctions indicates the pressure i.e. also head losses. Such evaluations can be made for each of the generated water supply systems without any additional work.

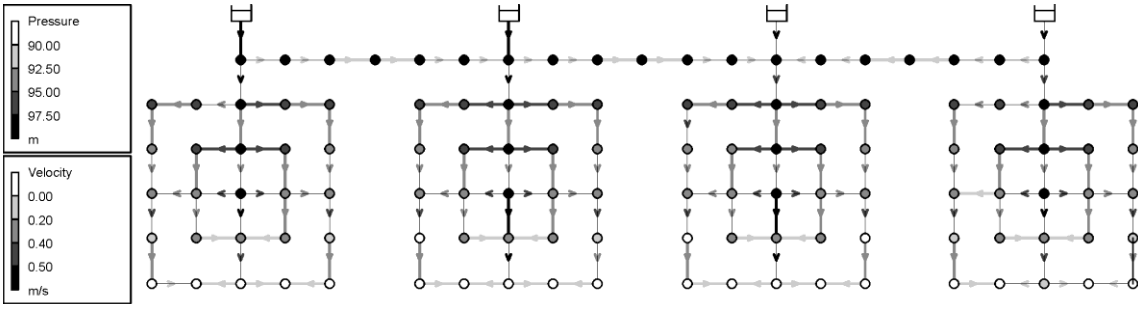


Figure 13: Results for pressure and velocity simulated with Epanet2

Set Characteristics

As a description of the generated set of 2,280 water distribution systems, in Figure 14 and Figure 15 statistics are shown. Thereby, Figure 14 specifies the number of nodes (left) and number of links (right). Most of the systems consist of not more than 1,000 nodes and 1,000 links. Approximately, 40 % and 36 % of the graphs consist of less than 500 nodes and 500 links, respectively.

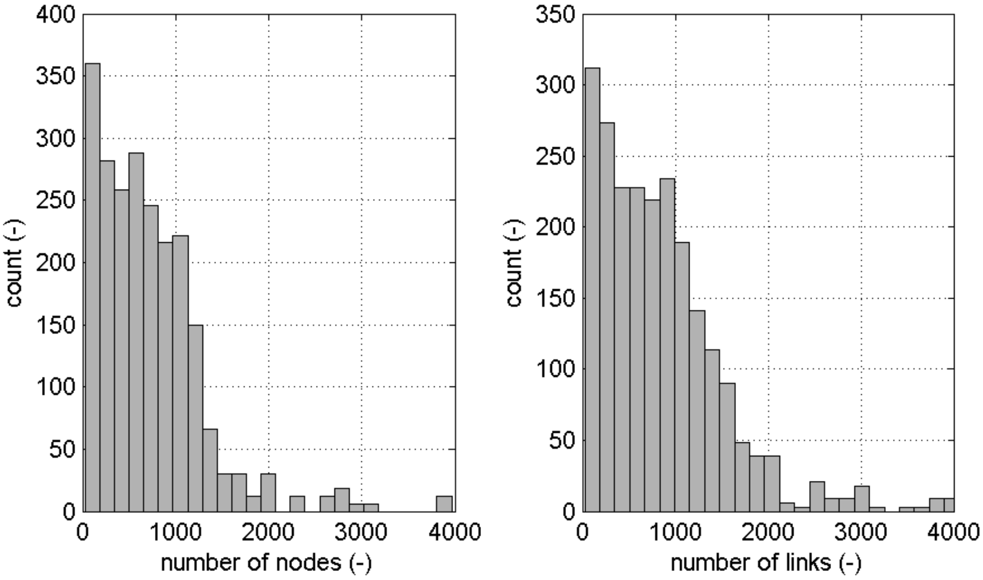


Figure 14: Histogram of left: number of nodes and right: number of links of systems generated

Figure 15 (left) shows the bar plots of systems and the total demand. Figure 15 (right) shows the bar plots of systems and total demand per source. Most of these systems deliver a total demand less than 1,000 l/s and approximately 30 % of the systems deliver a total demand lower than 200 l/s.

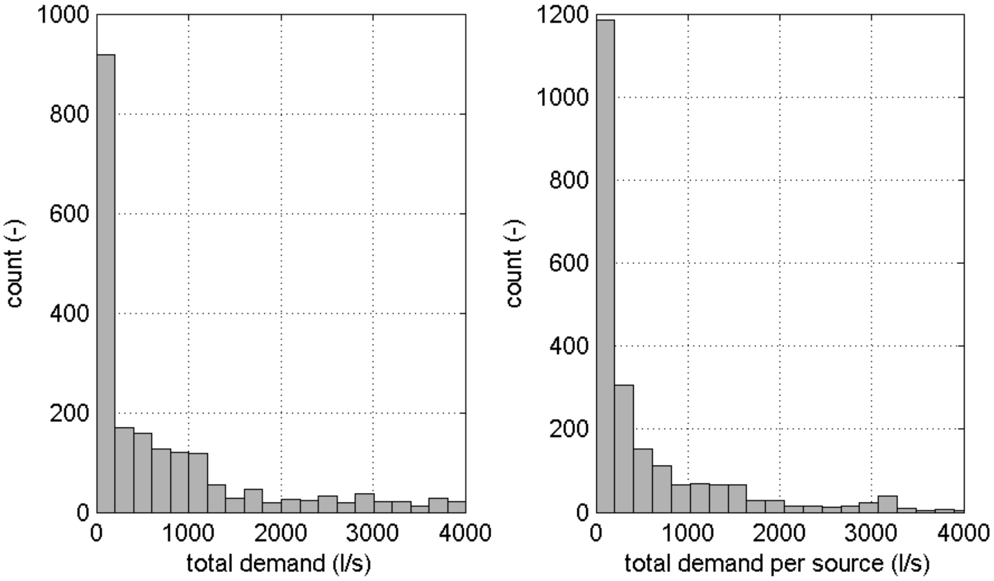


Figure 15: Histograms of total demand (left) and total demand per source (right) of WSSs generated

Special attention has to be drawn to the characteristics of the set, due to the fact that the generation process is the controlling factor. Therefore, the frequency of different size of water distribution systems does not represent the frequency in e.g. an alpine valley. Or in other words, the number of small, medium and large virtual water distribution systems represents the generation process (variations of parameters) and not the agglomeration of real systems in e.g. an alpine valley.

To obtain results for a specific region, the generation procedure has to be adapted in order to sustain the same characteristics as the investigated area. An investigation of different groups with systems with similar size and according performance characteristics is reasonable (like the generic performance assessment for urban drainage systems proposed in Möderl and Rauch, 2010; see chapter 2.2.3).

2.4.5 Summary and Conclusions

Paper I presented the systematic generation of virtual water supply systems by means of the Modular Design System, and it successfully demonstrates the benefits of the proposed method for water distribution system analysis. In this chapter, Paper I was summarised and an overview of the used methods was given. Examples of the systematic generation process following the Matlab syntax were shown to illustrate the application of the generic generation functions.

In addition, results not presented in Paper I were shown and further discussions of the systematic generation process and the resulting set characteristics were provided in this chapter.

3 WDS DESIGNER

In this chapter the software tool Water Distribution Systems Designer (WDS Designer), which was developed in course of this PhD project is discussed. With the WDS Designer, a tool for the algorithmic generation of water distribution systems based on GIS (Geographical Information System) data is presented and discussed.

In this chapter, summary and additional information to Paper II is given and further results are presented. In chapter 3.1, the objectives and aims of the developed software tool are discussed. In chapter 3.2, an overview of the methods used in the WDS Designer is given. Special emphasis is given on the case study data description and the data modification. Further, the calibration process of the generation procedure is discussed in more detail in that chapter. In chapter 3.3, the graphical user interface is shown and its application is outlined. Finally, in chapter 3.4, an application of the WDS Designer is shown (Paper III). Paper II and Paper III are integral parts of this thesis.

3.1 Motivation

Numerous studies in water distribution system analysis only use one or a few case studies or benchmark systems to test their approaches and hypothesis (see chapter 2.1.2). Often, in these studies, the impact of the specific network layout is neglected. The aim of the WDS Designer is to provide a tool for the algorithmic generation of water distribution systems based on GIS data with different network characteristics (mesh degree). In contrast to the systematic generation of very conceptual water distribution systems in Möderl et al. (submitted) (see Paper I and chapter 2.4), with the WDS Designer water distribution systems which are more complex and based on real world GIS data can be generated. These systems can be used for e.g. improved hydraulic understanding of systems (factor for prospective demand, economic flow velocities); evaluating the impact of loops in systems; cost estimations of a new water distribution system for growth corridors; et cetera.

The created water distribution systems can be classified (according to the notation in this thesis, see chapter 2.1) on the one hand as virtual case studies (for research tasks), but also as preliminary design of a real world case study (for practical applications). This bridges the gap from the research application of the developed tool to a potential field of application in practice (cost and performance evaluation for new water distribution systems for growth corridors).

3.2 Methods overview

The approach is based on GIS data as input. Input data for the WDS Designer are elevation data, population and housing densities (see Figure 16 a chapter 3.2.6). With blocks from a database (see 3.2.2), networks are generated (following the idea of network motifs, Milo et al., 2002). The selection process of blocks from this database is driven by the Input GIS data. Therefore, the GIS data has to be rasterised to a resolution which represents the block size (see chapter 3.2.7). This has to be done in order to obtain the desired pipe length distribution and the available junction density (see Figure 16 b and chapter 3.2.7).

From the block database (Figure 16 c, each block is administrated by means of the Modular Design System, Möderl et al., 2007) for each GIS raster cell a block is chosen in order to meet the requirements of the urban environment (Graph Concatenation Approach (GCA), Figure 16 d). Therewith, an entire water distribution system is formed with numerous concatenated blocks from the block database.

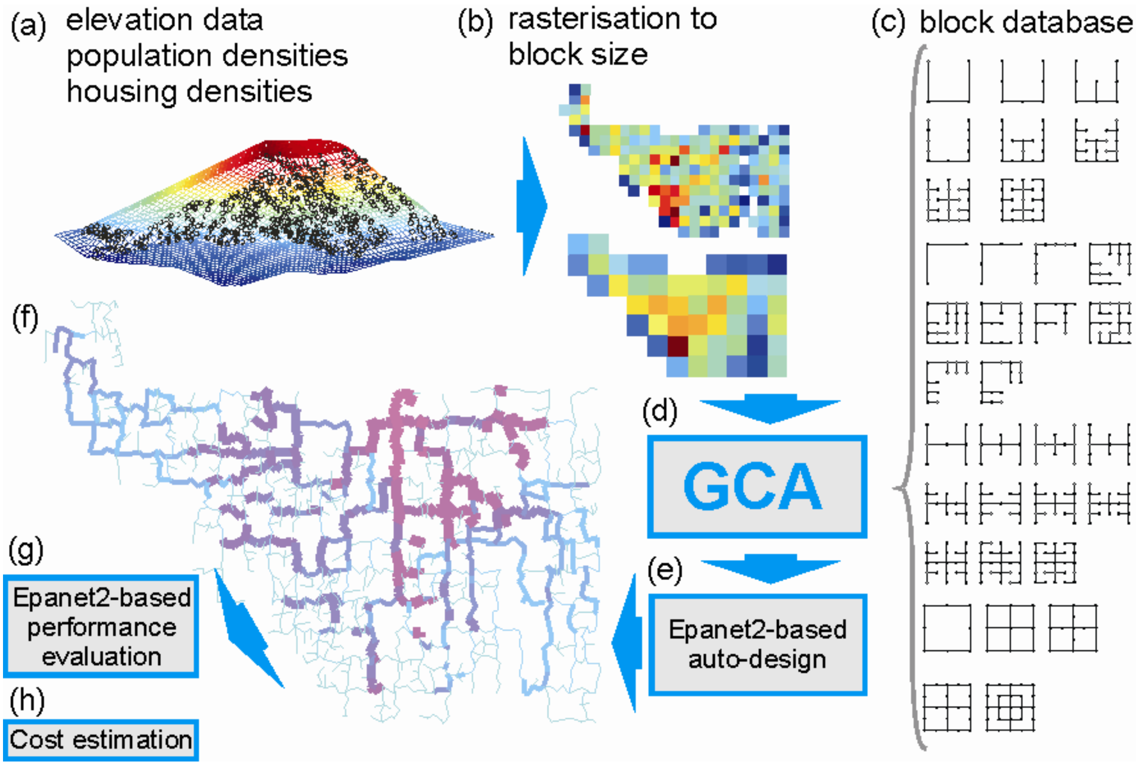


Figure 16: Overview methods of the WDS Designer

The constructed water distribution system is subsequent auto pipe-sized, based on economic flow velocities determined with Epanet2 (Figure 16 e, chapter 2.4.3 and 3.2.3). As result of this procedure a pipe-sized water distribution system is created (Figure 16 f) which can be evaluation regarding hydraulic performance (Figure 16 g, see chapter 3.2.4) or which can be used for cost estimations with default or user-defined construction costs (Figure 16 h, see chapter 3.2.5).

3.2.1 Data Administration

For data administration of the blocks and of water distribution systems generated, the Modular Design System (MDS, Möderl et al., 2007) is used. With this approach the water distribution system can be organised by means of graph theory (chapter 2.4.1).

3.2.2 Block Database and Graph Concatenating Approach

In Paper I, two blocks with different characteristics concerning network redundancy were introduced. The two blocks represent entities of looped and branched water distribution networks. The concatenation of theses blocks to entire water distribution systems was done without taking into account any additional GIS-data.

In Paper II, this approach was further developed in order to meet requirements of GIS data. To meet the requirements of housing densities a database of 35 different blocks with 4 general layout characteristics and up to 11 additional block variations was developed. The layouts of the entire database can be looked up in Paper II.

Population densities were implemented in the approach by intersecting the GIS map for the required water demand with the water distribution network (adding the required water demand to the junctions). Further, the digital elevation map is used to project the junctions on it (in contrast to Paper I in which there is a constant elevation of 0 meters for all junctions)

3.2.3 Auto Pipe-Sizing

Similar to chapter 2.4.3, in this pipe-sizing process the flow velocities are sequentially determined and if the actual flow velocity exceed the economic flow velocity the diameter is incrementally augmented. But instead of a fixed economic flow velocity of 1 m/s, this can be user-defined for each diameter. By default, economic flow velocities according to Gujer (2002) are used, distinguishing between long-distance, transport and service pipes.

The available diameters for the incremental augment can also be user-defined. By default the same diameters as in Paper I or the same diameters which occur in the real world case study (Wolf-Codera Ranch model, described in chapter 3.2.6) can be used in the pipe-sizing process.

A user-defined factor for the design demand, taking into account prospective demand (Zhou et al., 2002; Alvisi et al., 2007; Ghiassi et al., 2008) or demand peaks (Diao et al., 2010), can be regarded in the auto pipe-sizing by multiplying the actual demand with this factor. Also to take into account population decrease or water saving strategies, a demand factor below 1 can be applied.

3.2.4 Performance Evaluation

For performance evaluations normalised performance indicators for hydraulic performance (sufficient pressure), quality performance (sufficient water age) and an overall performance (taking into account hydraulic and quality performance) according to Möderl (2009) are used. A detailed description is given in Paper II.

Due to e.g. a strong impact on sufficient water pressure by topographic boundary conditions (Trifunovic, 2006; Chung et al., 2009), the limits for the sufficient performance can be user-defined. By default, the limits for the performance assessment are 100 metres as upper limit and 40 metres as lower limit. Therefore, a hydraulic pressure between these two limits is regarded as sufficient.

3.2.5 Cost Estimation

Besides operational costs, the construction costs for pipes are the major costs of a water distribution system. For a rough estimation the investment cost of the pipes are approximately 70 % of the total investment costs (Möderl, 2009). By knowing the costs per running meter pipe (e.g. from Mutschmann and Stimmelmayr, 1999), the total investment costs (investment costs for pipes and construction cost) can be assessed by multiplying the investment costs for pipes with 1/0.7. If available, user defined values (obtained from e.g. construction experience) can also be defined and used in the approach.

3.2.6 Case Study Data

For a comparison with real world data, the water distribution system Wolf-Codera Ranch (discussed in Lippai, 2005) is used (free available: centres.exeter.ac.uk/cws). It is a part of the Colorado Springs Utilities, but for a region with expected future development. The layout of the Epanet2 model is shown in Figure 18 left. The original data consists of about 2,000 pipes and 1,800 junctions.

The utility standards for pipe-sizing of that model require a minimum diameter for distribution lines of 200 mm and for cul-de-sacs 150 mm. Therefore, in the original data, almost 90% of the pipes have a diameter of 200 mm or smaller (see Figure 17). The cumulative distribution function of the lengths of pipes is shown in Figure 17 left. Approximately 80% of all pipes have a length of 100 metres or shorter (thick dashed gray line). Noticeable, all pipe lengths of the smallest diameters (150 mm) are below 21 metres and over 90% are even below 10 metres (thin solid black line). These small pipes significantly impact the cumulative distribution function of all pipes, because about 34 % of all pipes have a diameter of 150 mm (see Figure 17 right).

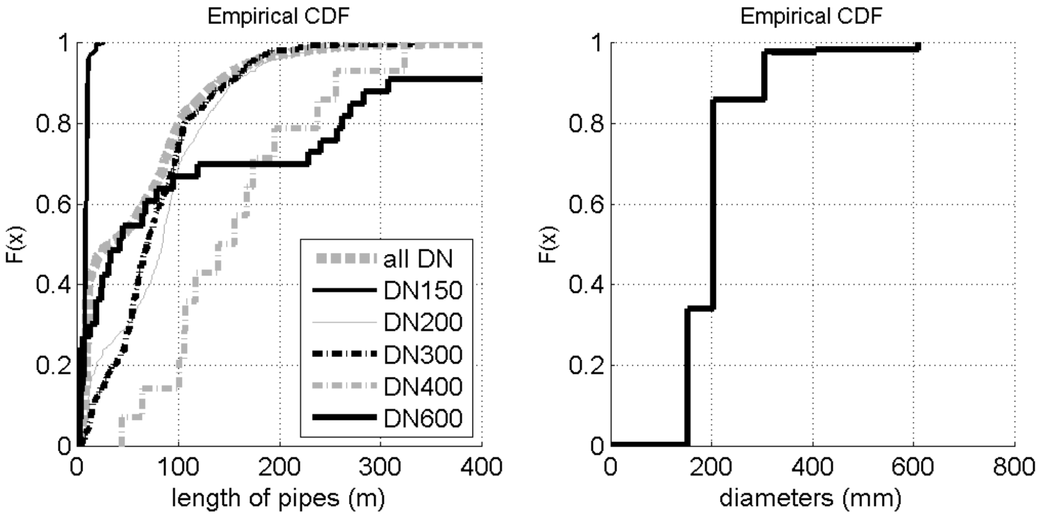


Figure 17: Lengths of pipes and diameter distribution in the Wolf-Codera Ranch model

To evaluate the importance of the pipes with diameter 150 mm, i.e. cul-de-sac pipes, in regard of the layout of the entire system, the demands of the junctions at the end of the cul-de-sac pipes are investigated. In Figure 18 the junctions of the network are coloured according to their amount of demand. The colour scale is logarithmic. In total, there is a demand of 524 litres per second. Taking a closer look to a part of the system marked with the box with the dashed blue line in Figure 18 left reveals that there are cul-de-sac pipes in this system without demand (dark blue junctions, Figure 18 right).

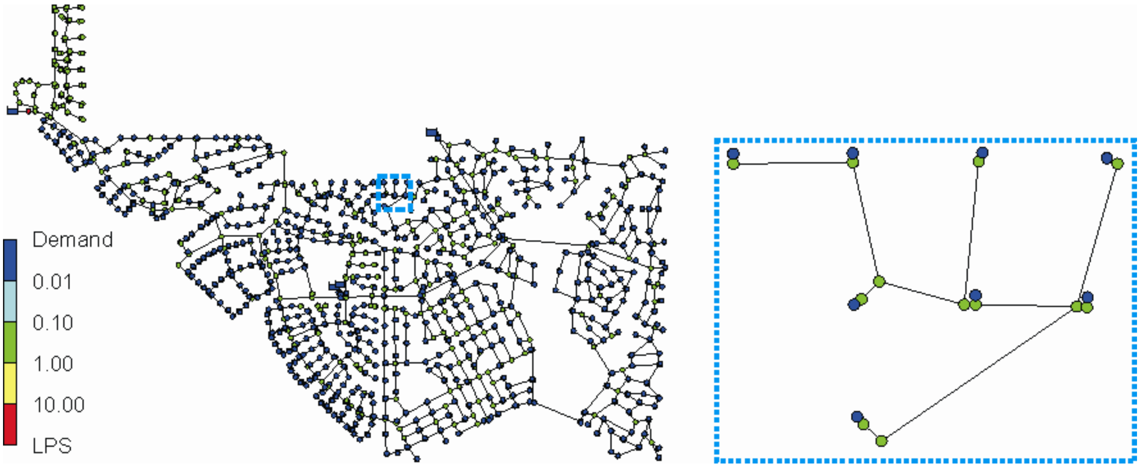


Figure 18: Wolf-Codera Ranch model with original demands

A statistical evaluation of the system elements revealed that 37 % of all nodes are without demand (see Figure 19 left) and 31.5 % are with 0.254 or 0.532 litres per second, respectively. One node has a demand above 1 litre per second (82.7). This single node represents industrial usage which is less than 0.06 % of all nodes.

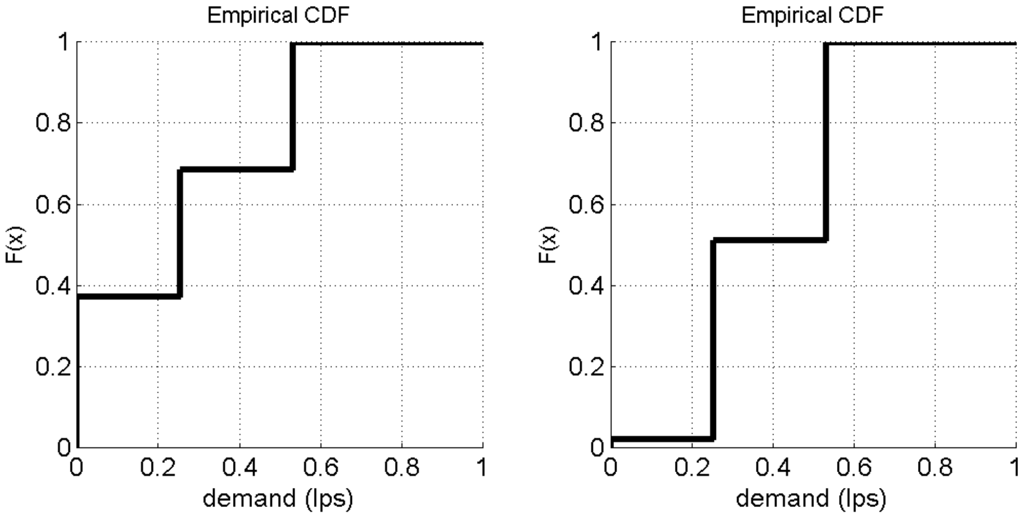


Figure 19: Wolf-Codera Ranch model, distribution models: original and modified data

As an additional scenario, the nodes without demand and no connecting task are removed (see Figure 19 right). This was done following the principles of skeletonisation by removing the dead-end branches (Strafaci and Walski, 2003).

In this modified scenario, there are about 1,150 nodes and 3% of the pipes have a diameter of 150 mm. Especially for the median value of the lengths of all pipes (see Figure 20 left, thick dashed gray line), there is a change from 32 metres for the unmodified data to 80 metres for the modified data. In the following chapters, the data with the removed pipes and nodes without demand which are dead-end branches is denoted: modified data in contrast to the original data.

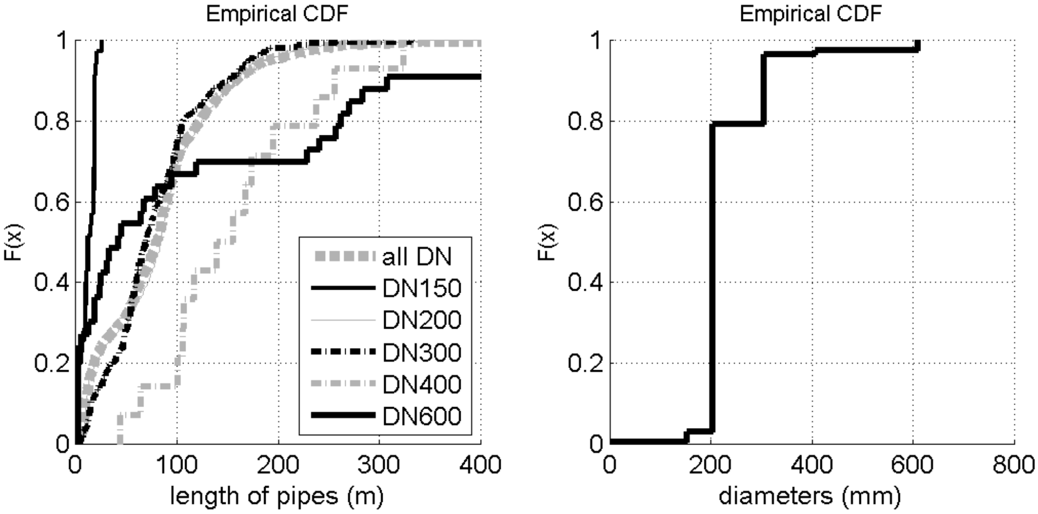


Figure 20: Lengths of pipes and diameter distribution in the modified Wolf-Codera Ranch model

The elevation model of the Wolf-Codera Ranch model is shown in Figure 21 with 5-times vertical exaggeration. From the Epanet2 model only elevation data for the junctions was available; therefore, additional mesh points were interpolated between these points.

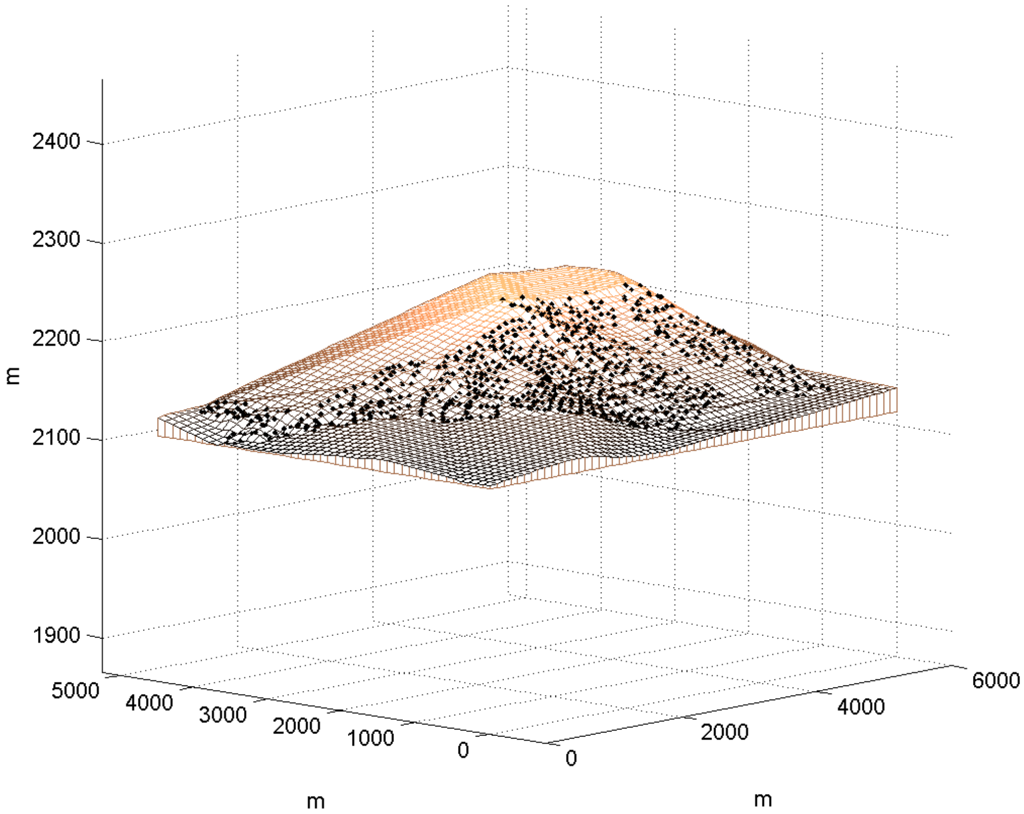


Figure 21: Elevation map of Wolf-Codera Ranch model

The junctions of the generated virtual water distribution system do not match exactly with those of the Wolf-Codera Ranch. This can lead to difficulties (no values available) when projecting them on the elevation map, especially at the boarders. Therefore, at each of the four vertices, an additional point with the same height as the corresponding vertex and a horizontal offset was added and used for the triangulation of the elevation map (see Figure 21).

3.2.7 Calibration of the Generation Process

For the calibration of the generation process, there are two parameters: the cell size of the blocks with according ranges of required junction densities and the distribution of pipe lengths.

Block Size

The GIS data for housing density is assumed to be the junction density of the Epanet2 model of the Wolf-Codera Ranch model. In each raster cell, a block has to be placed. Therefore, the cell size of the blocks indicates to which resolution (i.e. with which cell size) the GIS data has to be rasterised. Determining the required number of junctions in each cell, the distribution of junction densities of the entire area can be assessed.

Figure 22 shows the maximum numbers of junctions in a cell for different cell sizes (50, 100, 150, 200, 250, 300, 350, 400, 450, 500 metres). The blocks in the database are based on a 5 times 5 raster. Therefore, at maximum a block with 25 junctions (Figure 22 gray dashed line) is available (see database Paper II).

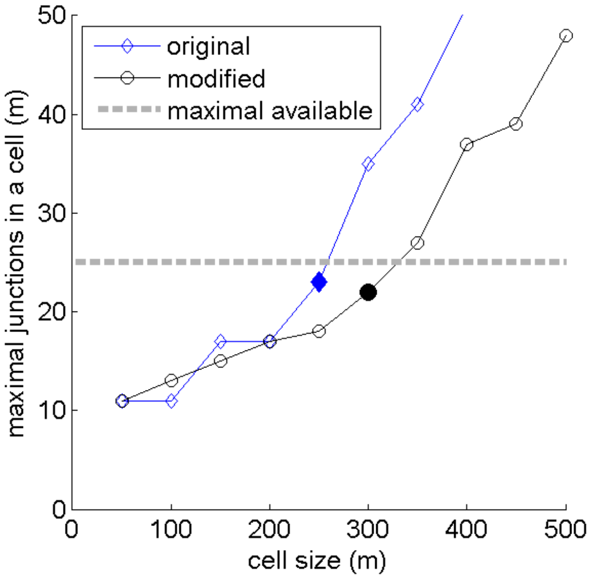


Figure 22: Determining cell size modified and original data

In the database, there are blocks obtainable with 3 to 25 junctions (gray area in Figure 23). Investigating original GIS data and a cell size for the blocks of 250 metres, 90 % of the GIS data cells can be represented with a block from the database. With a cell size of 300 metres, 88 % of the cells are within the range of available blocks. For the modified data, with a cell size of 300 metres, 89% of the GIS data cells can be represented by a block from the database and 83 % with a cell size of 350 metres. For the other resolutions investigated, the percentages within the block range in the database are smaller and therefore, they are shown in light gray lines.

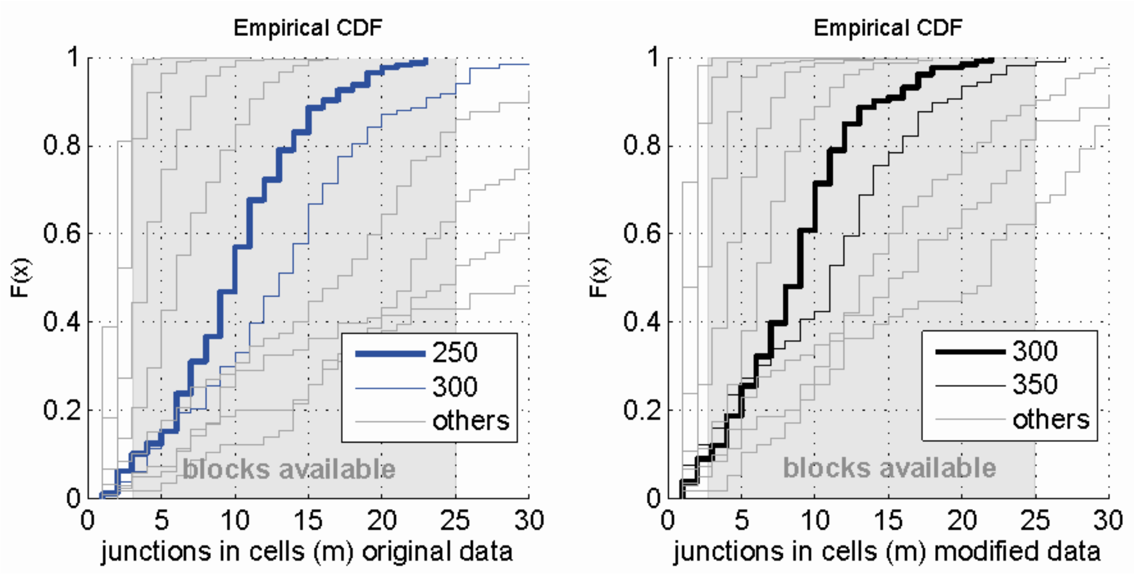


Figure 23: Junctions in cells, original data (left), modified data (right)

With cell sizes of 250 metres (original data) and 300 metres (modified data) respectively, the cells which are not within the range of the database are those which require one or two junctions. It is assumed that these can be approximated with a block with 3 or 4 junctions.

Pipe Lengths and Diameter Distributions

With the determined cell sizes of the blocks, the entire water distribution systems can be formed. A detailed description of the concatenating procedure is given in Paper II. The pipe-sizing is done according to chapter 3.2.3.

To obtain the same diameter distribution (cumulative distribution function of diameters) as for the Wolf-Codera Ranch model, a calibration of economic flow velocities for the different corresponding diameters is done for both: the original data and the modified data, respectively. In Paper II, the calibration process for the modified data is presented. Additionally, in this chapter the calibration process for the virtual water distribution systems based on the original data is shown.

In Figure 24 left side, the pipe distribution in context with the pipe distribution of the generated water distribution systems is shown. In solid gray, the cumulative distribution function of all diameters (DN150 - 600) and in dashed gray for all pipes without cul-de-sac pipes (DN200 – 600) is presented. A comparison of the original data with two generated networks with different layout strategies (grid deviation see chapter 3.3.1 and Paper II) for the MDS grid is shown in Figure 26 left (DNvWDS, r=0; DNvWDS, r=60; for a detailed discussion of parameter r see 3.3.1). It is revealed that 85 % of the pipe lengths of the virtual systems are close to the original data distribution.

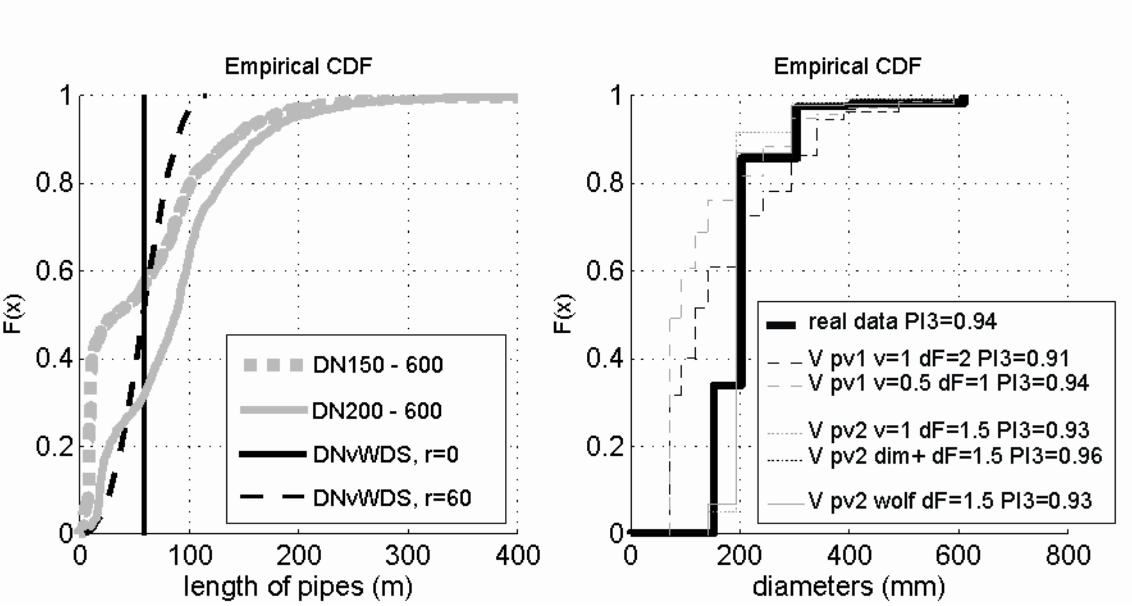


Figure 24: Original data in context with virtual data, length of pipes and diameter distribution

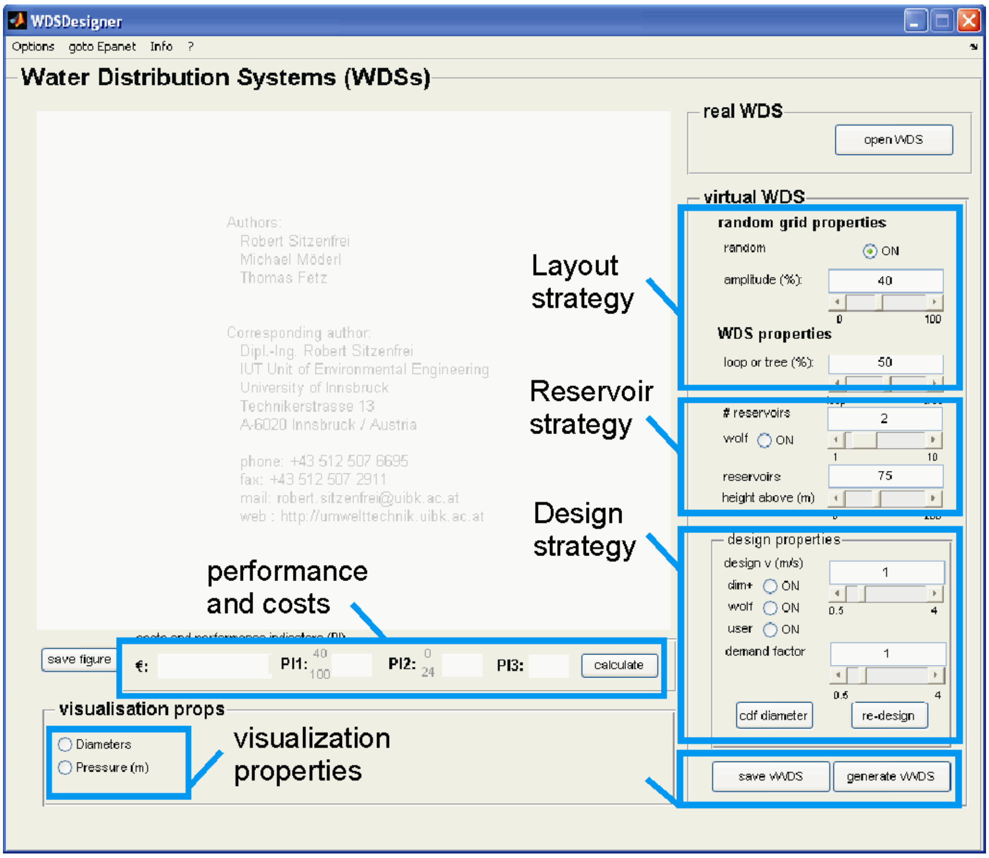
Figure 24 right shows the cumulative distribution function of diameters of virtual water distribution systems with different design strategies (V: virtual; pv: used pipe vector; v: economic flow velocity or flow velocity mode; dF: demand factor; PI3: overall performance indicator indicating sufficient overall performance, see also Paper II). In addition, the original Wolf-Codera Ranch model (Figure 24 right, black solid line) is shown.

Analyses of the diameter distribution were done for varying flow velocities and the different factor for prospective demand. These investigations have the aim to identify values for these parameters, in order to attain a similar diameter distribution for the generated water distribution systems as in the Wolf-Codera Ranch model. A factor for demand was evaluated and for each diameter a flow velocity was determined. Therefore, this parameter set for the design mode was denoted as wolf mode (Figure 24 right, gray solid line, see Paper II).

With this design mode for diameters above DN150, there is a good fitting between the real world data and the virtual water distribution system designed with the wolf mode. Anyhow, the number of pipes with diameter DN150 is significant lower in the virtual water distribution system than in the real world water distribution system. This is due to the fact that the utility's standards require DN200 minimum diameters for distribution lines and DN150 for cul-de-sacs. This issue cannot be reproduced with this simple auto pipe sizing algorithm.

3.3 Graphical User Interface of the WDS Designer

In this chapter, features of the Graphical Interface (GUI) of the WDS Designer are illustrated. A description of a subset of different parameters and how the different parameters have an impact on the resulting networks is shown and discussed.



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random ● ON
amplitude (%): 40
loop or tree (%): 50
reservoirs: 2
wolf ○ ON
reservoirs height above (m): 75
design v (m/s): 1
dim+ ○ ON
wolf ○ ON
user ○ ON
demand factor: 1
○ Diameters
○ Pressure (m)

Figure 25: GUI of the WDS Designer

In Figure 25, the GUI of the WDS Designer is presented. The blue boxes mark different classes of parameters, which are exemplarily discussed in the next paragraphs. In addition, there are features like an export interface to Epanet2 for the real and virtual systems (see also WDS Designer manual, Sitzenfrei, 2010).

3.3.1 Layout Strategy

For the layout strategy, three different parameters are available. The first parameter is a factor which determines the range of stochastic deviation from the regular MDS grid (see chapter 2.3.2). With the second parameter, the available database can be composed by default block sets and user-defined block sets. By default, the database is divided into two main sets: looped and branched blocks. The last parameter determines the probability of selecting a block out of these two main sets.

Maximum variation amplitude for grid deviation

The junctions and pipes are based on a graph matrix and therefore, on a regular grid (see chapter 2.3.2 and 2.4.1). On this regular grid, a stochastic variation can be applied by defining the variation amplitude in percentage of the maximal deviation r (the maximal deviation is the cell size). In Figure 26, the layouts with four different maximum deviations r= 0, 33, 67 and 100% are shown.

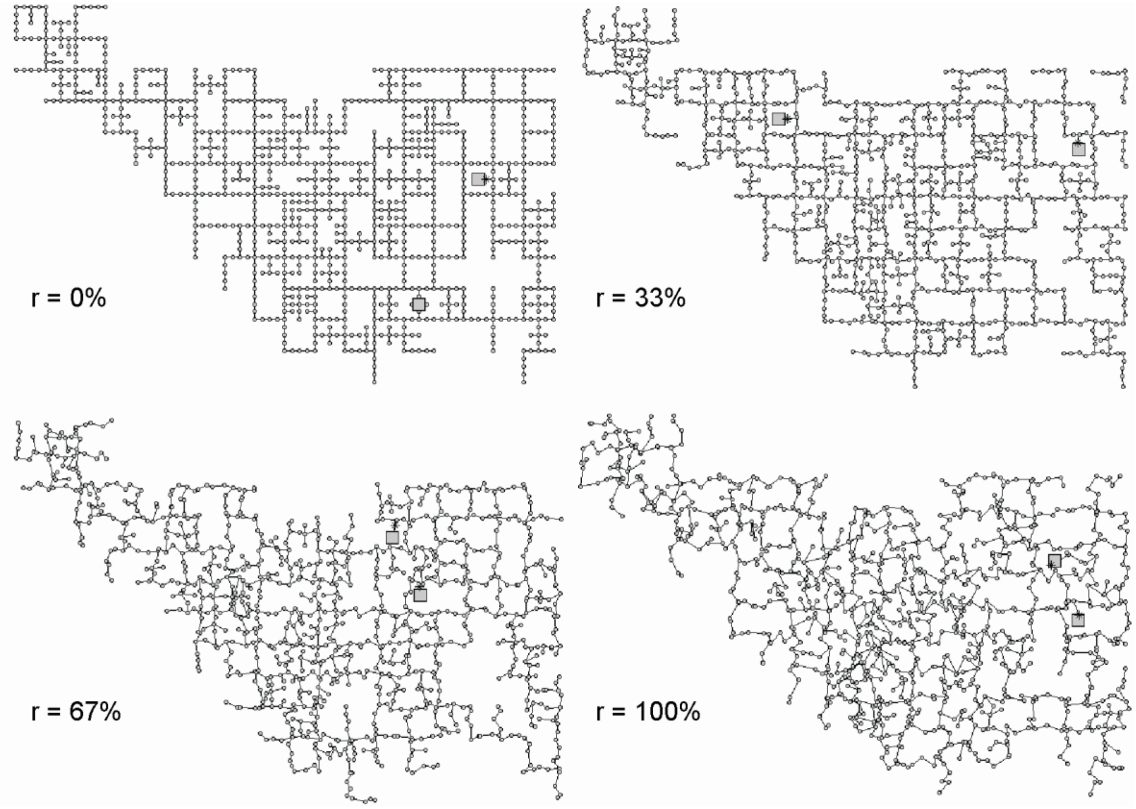


Figure 26: Layouts for different percentages of maximum deviation r

The cumulative distribution functions of the pipe lengths in the systems of the four different water distribution systems of Figure 26 are shown in Figure 27. A constant pipe length for all pipes results from r= 0%. With increasing deviation r, there is a horizontal deformation in the length distribution. In addition, in Figure 27 the pipe lengths distribution of the Wolf-Codera Ranch model are shown (WCR: original data, WCR_{mod}: modified data). The major discrepancy can be observed for the pipe lengths below the cell size. This issue could e.g. be addressed by adding short cul-de-sac pipes to the blocks in the database. Anyhow, in this study this has not been implemented yet. Pipes of the Wolf-Codera Ranch model, which are longer than the pipes in the generated virtual water distribution systems, are implicitly included in the approach by means of fractional pipes.

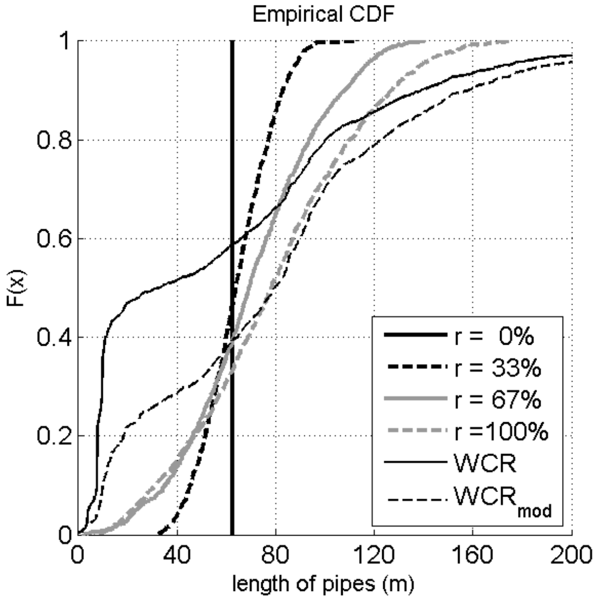


Figure 27: Distribution of pipe lengths with different deviations r

Probability of Set Selection

In the database, there are two main sets: looped and branched blocks (see Paper II). In the GUI, there is a layout factor which indicates the probability of selecting a block out of these two main sets. A layout factor of 0 means that only looped blocks and a factor of 100 that only branched blocks are used. For interim values, there is random selection weighted with the layout factor. Example layouts are shown in Figure 33 left and right.

Definition of the block database

The two main sets are, by default, composed of the O-Set for the looped main blocks and of the L-, H- and U-Set for the branched main blocks (see Paper II). The different sets are characterised by the layout of their appearance. In one set, there are blocks with a low number of junctions (e.g. 3 junctions) to a high number of junctions (25 junctions) included. The user can also exclude different sets (see Figure 28) or also include user-defined sets if they are described in files following the notation described in Sitzenfrei (2010).

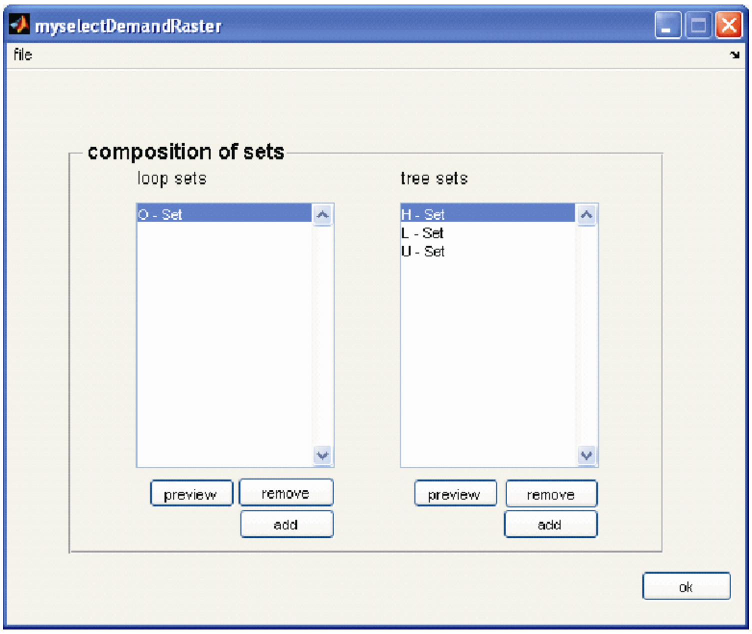


Figure 28: Block Selection GUI

In Figure 29, two generated water distribution systems are shown. On the left side, only L-blocks and on the right side only H-blocks were used for the generation process. Although the densities of the junctions are the same, it can be observed that by using only the L-blocks the junctions are concentrated in edges of the blocks, whereas by using the H-blocks there are also junctions within the blocks.

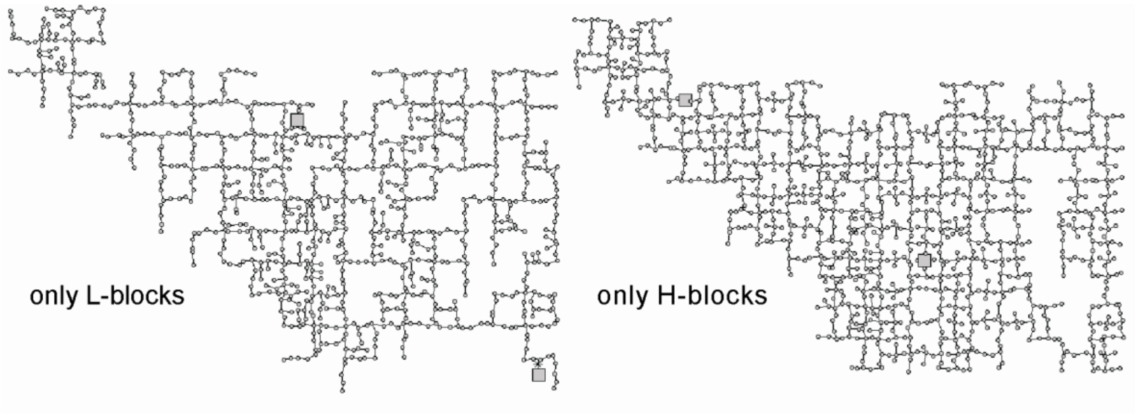


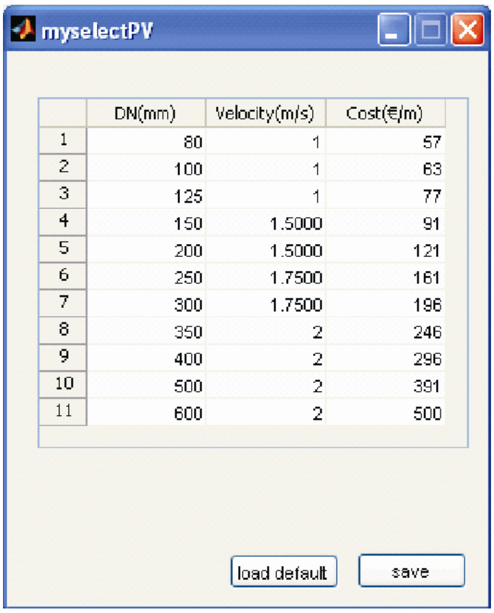
Figure 29: Generated systems with L-blocks (left) and with H-blocks (right)

3.3.2 Reservoir Strategy

The reservoirs of the water distribution system generated with the WDS Designer are placed corresponding with the positions and height in the Wolf-Codera Ranch model (with modifications described in Paper II). In addition, a specified number of randomly set sources can be used instead. If the placement is random, the number of sampled source is an input parameter which can be determined with the GUI. Another input parameter is the elevation over surface of the reservoirs. Hence, this parameter represents the pressure heights in the sources for feed-in. Different reservoir positions are shown in Figure 26 and Figure 29.

3.3.3 Design Strategy and Costs

The implemented pipe sizing algorithm is described in chapter 2.4.3. It is based on economic flow velocities for different diameters. For a user-defined pipe-sizing, the available diameters (pipe vector) and the corresponding economic flow velocities, can be defined with the GUI via the option menu in the main menu bar (Figure 30). To consider prospective demands (Ghiassi et al., 2008) and demand peaks (Diao et al., 2010), a factor applied on the demand is another input which can also be defined via the GUI in the design section (Figure 25).



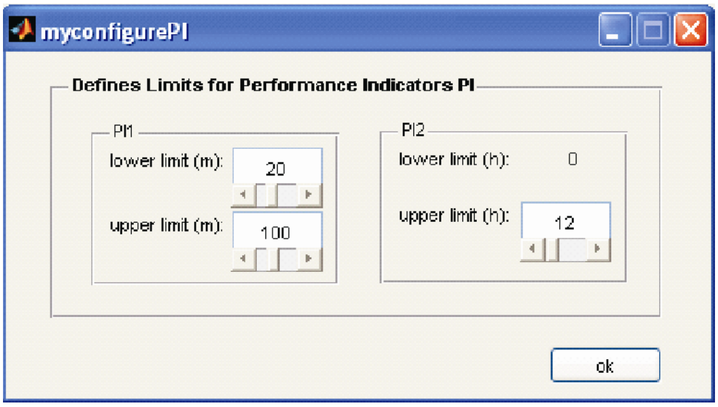
	DN(mm)	Velocity(m/s)	Cost(€/m)
1	80	1	57
2	100	1	63
3	125	1	77
4	150	1.5000	91
5	200	1.5000	121
6	250	1.7500	161
7	300	1.7500	196
8	350	2	246
9	400	2	296
10	500	2	391
11	600	2	500

Figure 30: GUI to define pipe vector, economic flow velocity and costs

To evaluate costs of the water distribution systems, user-defined costs per running meter pipe can be defined in the same mask. Respectively, the implemented default costs are used (see Paper II).

3.3.4 Performance Assessment

The performance indicators (PI) are described in Möderl et al. (2007) and Möderl (2009). The normalised hydraulic performance indicator (PI1) indicates how much water is delivered with sufficient water pressure (within the lower and upper pressure limit). The normalised water quality performance indicator (PI2) indicates how much water is delivered with a water age below a defined limit. Because the limits for sufficient performance strongly depend on topography and regulatory standards, the limits for these two performance indicators can be user-defined with the GUI via the option menu in the main menu bar (Figure 31).



Defines Limits for Performance Indicators PI

PI1
lower limit (m): 20
upper limit (m): 100

PI2
lower limit (h): 0
upper limit (h): 12

Figure 31: Configure limits for performance indicators GUI

For an overall performance evaluation, another performance indicator is used (PI3). This performance indicator is calculated as product of PI1 and PI2. In Figure 25, the button to calculate all performance indicators and the text boxes which report them are highlighted.

3.4 Applications of the WDS Designer

In this chapter example evaluations with generated systems are shown, highlighting that the WDS Designer can also be used to redesign real world systems represented by Epanet2 files. In addition, two virtual example layouts are discussed which are based on the original Wolf-Codera Ranch model data.

As another research application, the number of required sources in water distribution networks with different loop characteristics is determined. These investigations are also addressed in Paper III which is an integral part of this thesis.

3.4.1 Network Examples

Besides the generation of virtual water distribution systems, the WDS Designer can also be used to visualise, analyse and redesign real world water distribution systems represented by Epanet2 files.

Redesign of Real World Networks

In Figure 32 left, the Wolf-Codera Ranch model is shown with colour and width of lines indicating their diameters. Cost estimations and the performance indicators (PI1, PI2 and PI3) of real water distribution systems can also be calculated with the WDS Designer (Figure 32 and Table 1). Figure 32 right, shows the same network layout but with the pipe sizing of the WDS Designer applied to. Due to regulatory standards in the original data, there are no diameters below 150 mm (DN150). In the redesigned system, there are smaller diameters (80 mm; 100 mm; 125 mm).

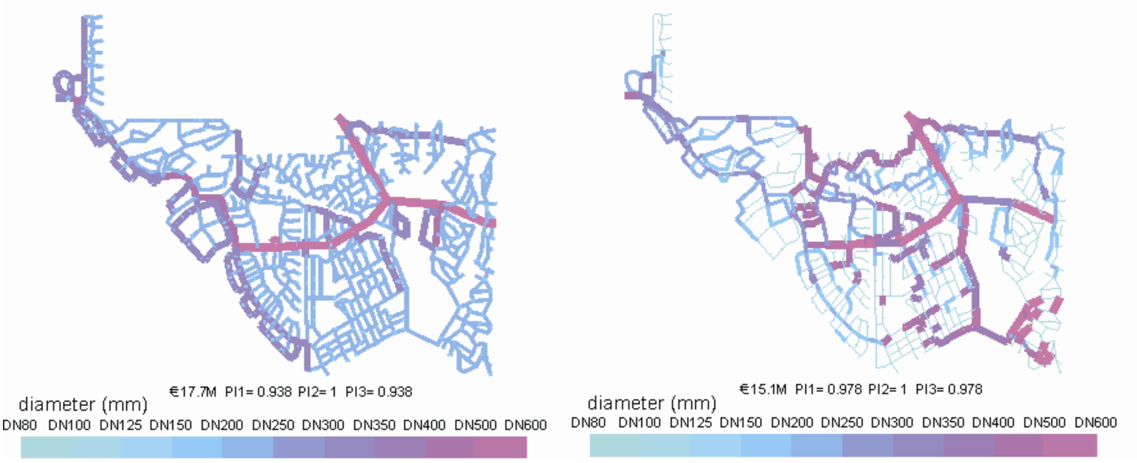


Figure 32: Wolf-Codera Ranch model, original (left) and redesigned (right)

The hydraulic performance under regular conditions is better for the redesigned network. But in the pipe sizing process, redundant capacity (e.g. backbone connections between reservoirs) is not yet included. Therefore, under critical conditions (e.g. failure of one reservoir) the virtual system would hydraulically perform worse than the real world system.

Examples of Virtual Water Distribution Systems

In Figure 33, two virtual water distribution systems generated with the WDS Designer are shown. The system on the left side is an entirely looped system which is pipe-sized with the same regulatory standard as the Wolf-Codera Ranch model (no diameters below 150 mm, DN150). The system shown in Figure 33 right side, shows a branched layout which is pipe-sized with the algorithm used in Möderl et al. (2007).

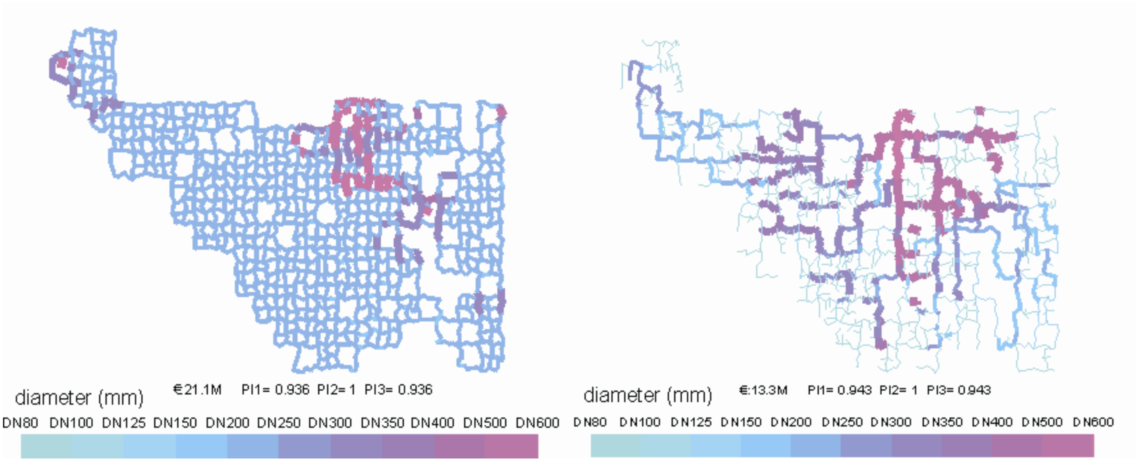


Figure 33: Generated water distribution systems, looped (left) and branched (right)

Other network examples which are based on the modified data of the Wolf-Codera Ranch model are presented and discussed in Paper II.

3.4.2 Cost Estimations

In Table 2, the sum of construction costs for several water distribution systems determined with the WDS Designer are summarised. The assessments are in contrast to Paper II (which is based on the modified data) based on the original data (see chapter 3.2.6). The estimated costs for the Wolf-Codera Ranch model are within the range of the two generated water distribution systems. In comparison with the estimated costs used in Lippai (2005) of $ 28.8 million (€ 19.23 million, exchange rate from 23.11.2009), which were based on utility experience, the generated water distribution systems and the real world water distribution system are in good agreement.

Table 1: Sum of costs for WDS and vWDS

Description	Figure	Costs (M €)
Wolf-Codera Ranch model	Figure 32 left	17.7
Wolf-Codera Ranch model, redesigned	Figure 32 right	15.1
Virtual water distribution system completely looped	Figure 33 left	21.3
Virtual water distribution system completely branched	Figure 33 right	13.3

In Paper II, it is shown that also for the modified data as input, the generated virtual water distribution systems are in good agreement with the real world data.

3.4.3 Number of Network Sources

The water distribution systems, generated with the WDS Designer, are used to determine the number of required network sources in a water distribution network. This investigations are presented in Möderl et al. (2010b) which is an integral part of this thesis (Paper III).

This study aims to answer the question, how many network sources are required to ensure supply in water distribution systems, taking into account layout characteristics (mesh degree) and hydraulic simulations with Epanet2.

For this study, the Wolf-Codera Ranch model was used. In addition, 3 networks, generated with the WDS Designer, were included in the investigations. Further, the set of 2,280 water distribution systems presented in Paper I, were used for a systematic investigation of the number of required network sources and their impact on system performance.

Two different approaches were applied to the investigated systems. One approach was applied to the 3 systems generated with the WDS Designer and the Wolf-Codera Ranch. In this approach, a Monte Carlo approach applied with Latin hyper cube sampling of possible locations of network sources was performed. Different numbers of sources with different characteristics (different amount of delivery, source type see Paper III) were placed and systematically investigated under regular conditions.

In the second approach, the set of 2,280 virtual water distribution systems was systematically investigated. The number of sources in these systems is determined by the generation process (see chapter 2.4). In contrast to the first approach, the performance analyses for this set were performed under critical conditions.

By means of this generic and stochastic approach, it was found that the number of network sources for regular conditions, but also under critical conditions is three sources. This means that the performance increase of supplying the network with 3 sources compared to more sources is marginal.

3.5 Summary and Conclusions

In this chapter, the tool WDS Designer was presented. With this tool, water distribution systems can be generated based on GIS-data for housing and population densities and a digital elevation map. For this purpose, the graph concatenation approach was developed which constructs water distribution systems with network motifs (blocks). These blocks are predesigned and therefore, a database for the generation process was developed. Out of this database, blocks are selected and subsequent concatenated to entire networks meeting the requirements of given GIS-data.

The approach was applied to the Wolf-Codera Ranch model. Special focus of this chapter was therefore on the calibration of the generation process (determining the cell size of the blocks). In addition, in this chapter, the functionalities of the graphical user interface of the WDS Designer were outlined. It was found that the generated water distribution systems resemble the characteristics of the real world system.

The advantage of the proposed method is to generate water distribution systems based on GIS-data with different layout characteristics (mesh degree, pipe-sizing, number of sources, et cetera). The networks with different layout characteristics represent valuable data for research applications.

As applications examples, water distribution systems with different characteristics were generated, analysed and compared with the real world system. As another application example, three water distribution systems generated with the WDS Designer were used to determine the number of required network sources for sufficient hydraulic performance. It was found that in general, three network sources ensure sufficient hydraulic performance under regular conditions.

3.6 Outlook

The concatenation approach and therefore, the WDS Designer is the first step in developing a tool for algorithmic generation of water distribution systems based on GIS-data. Therefore, potential for further enhancement of the approach is given. Anyhow, there are already potential applications for this approach in research, as well as in practice.

Further Development

A weakness of the WDS Designer is that in the current graphical user interface, only the set of GIS-data for the Wolf-Codera Ranch (elevation map, population and housing densities) is implemented. Anyhow, the graph concatenation approach can also be applied to other GIS-data (see chapter 7). Therefore, a further development will include a varying GIS-data.

With these varying GIS-data, it is also intended, that the concatenation approach can be applied to defined growth corridors. Therefore, a part of a new water distribution system can be connected to an existing one. The definition of such GIS-processing features does not require changes in the graph concatenation approach. Mainly, this is a programming task, enhancing the graphical user interface.

The pipe-sizing process will also be enhanced respectively, and another model will be implemented. Further, additional crucial elements of water distribution systems which are at the current state of development neglected (pumps, tanks, valves, et cetera), are intended to be implemented in the next version of the WDS Designer.

Potential Practical Applications

The practical application of the WDS Designer is the cost and performance evaluation for new water distribution systems. This can be valuable for new cities, but also for construction of new water distribution systems (for e.g. growth corridors) which are connected to an existing one.

4 VIRTUAL INFRASTRUCTURE BENCHMARKING – VIBE

The discussions in the previous chapters 1, 2 and 3, formulate the requirement of an integrated tool for the algorithmic generation of case studies for urban water systems. In order to cope with the posed requirements, the software tool VIBe (Virtual Infrastructure Benchmarking) was developed. In this chapter, the motivation and aim are formulated, respectively summarised from the previous chapters. Furthermore, in this chapter an overview of the modelling principles of VIBe is given and the architecture of the module-based VIBe approach is presented.

The architecture of VIBe and the modelling principles are also addressed in Paper IV and Paper VIII. The three different infrastructure modules are presented in detail in Paper V, Paper VI and Paper VII, respectively in chapter 6, 7 and 8 of this thesis.

4.1 Motivation and Aim of VIBe

For all disciplines of science, case study analyses are a valuable research approach (see chapter 1.1). But with increasing complexity of case studies, availability is limited. Therefore, in research disciplines the stochastic generation of data is common practice. The generation of rain series based on statistical data is since several decades state of the art (for a detailed review see Wilks and Wilby, 1999). Also, stochastic weather generators are widely applied (e.g. Chen et al., 2010; Birt et al., 2010; Caron et al., 2008; Flecher et al., 2010; Mezghani and Hingray, 2009). These models generate time-series based on statistical data with the same statistical properties. The advantages of generated long times series are that there is no missing data and the statistical properties can be changed for e.g. climate change scenario analysis (e.g. Xia, 1996; Semenov and Barrow, 1997; Dubrovsky, 1998). The approach of weather generation can also be enhanced for multi-site data generation. Brissette et al. (2007) presented a stochastic generator of multi-site synthetic precipitation data and Wang (2008) presented an approach for multi-site generation of missing data in flow series.

In the field of urban water management, a stochastic generation of emission time-series for pollutant release in urban areas was presented by De Keyser et al. (2010). The approach encompasses structured storage of emission patterns, retrieving spatial emission source data based on GIS data, coupling emission patterns with emission source data and generating pollutant release time-series for dynamic sewer modelling. The release patterns are based on a stochastic data generation. This was done by linking priority pollutant source GIS data and dynamic models of urban environment. From literature, generic emission data was extracted and stored in a central database as default release patterns. This default release patterns were used if no better knowledge/data was available.

In chapter 2, the application of generated, synthetic case studies of infrastructure systems with varying complexity is discussed. Further, it was shown how the results of investigations were improved by means of these synthetic case studies. Also, for water distribution systems analysis, the use of synthetic case studies and benchmark systems is a common technique. Anyhow, the analyses are still based on a few case studies and the findings are difficult to generalise or can hardly be transferred to other boundary conditions.

Recently, encouraging approaches were developed to face data availability in urban water management by means of stochastic approaches and the algorithmic generation of case studies and infrastructure systems (see 2.2, 2.3 and 2.4). Anyhow, the generation process in these approaches is driven by the layout of the infrastructure and not by the urban environment (2.1.3 and 2.2.4). In chapter 3, the WDS Designer is presented. This approach generates water distribution systems based on GIS data and therefore, based on the urban environment. Anyhow, at the current state of development of the WDS Designer, one single urban environment is implemented for the generation process.

Coupling models for human systems with their environment or nature obtains rising awareness, due to the potential simulation of dynamic interactions. In city simulation games (e.g. SimCity; ElectronicArts, 2005) this feature is often included. Adams (1997 and 1998) described SimCity as a teaching tool to get an idea of urban processes. Gaber (2007) outlined SimCity as a pedagogical tool and Tanes and Cemalcilar (2010) investigated the potential of SimCity in training informed citizens. But to obtain valuable results, the included processes have to realistically represent environmental processes. D'Artista and Hellweger (2007) investigated hydrology in the simulation game SimCity4. Although the implemented hydrologic cycle includes groundwater, water supply and water treatment, the technical functionality and the interactions of the sub-systems are implemented in an unrealistic manner. Anyhow, it was concluded, that there is still potential to adapt the implemented models in order to include a more realistic urban water cycle.

Following the idea of urban hydrology in a computer game (D'Artista and Hellweger, 2007), the combination of urban models with stochastic engineering approaches exhibits potential applications. The aim of VIBe is to combine these approaches and to provide an integrated approach for the generation of entire virtual cities. In these virtual cities, realistic infrastructure based on the state-of-the-art, is included, as well as the urban environment (land-use, population et cetera).

In addition, interfaces to well known simulation software for performance assessment of the generated infrastructure systems are implemented. The stochastic generation of numerous integrated case studies is an innovative approach. But besides, this modelling technique carries potential to investigate the impact of development of urban structure on wastewater infrastructure (Doglioni et al., 2009) or water quality (Fu et al., 2009), but from an more integrated point of view. Also, the impact of population (socio-economic impact) on infrastructure can be modelled and systematically investigated. A further advantage of the propose methodology is that all generated data match (same cell size, same spatial reference, et cetera).

4.2 Modelling Concepts of VIBe

The modelling concepts of VIBe are outlined in Sitzenfrei et al. (2009b). Basically, to improve/combine the conception of the stochastic engineering approaches for water distribution systems (Möderl et al., 2007) and urban drainage systems (Möderl et al., 2009a), an urban environment is required (Figure 34). Subsequent, the infrastructure generation in VIBe has to be based on a generated urban environment. Hence, the generated infrastructures have to meet the requirements of the generated urban environment.

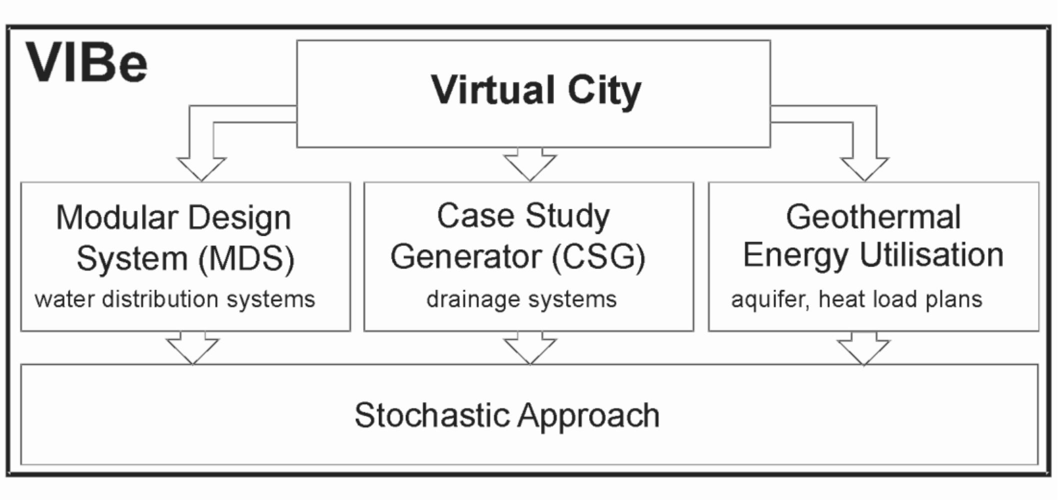


Figure 34: Aim of VIBe

VIBe is a module-based software tool. Each of the modules is an enclosed tool. Therefore, without a lot of effort, modules can be replaced or new modules can be added to the approach.

At the current state of development of VIBe, there is one urban structure module, providing data for elevation, population density, land-use, et cetera. Based on the city data, generated with the urban structure module, the infrastructure modules generate the water networks, respectively water management and heat load plan for geothermal energy utilisation. To provide city data and infrastructure data for modelling software, visualisation software and GIS-processing, data interfaces are also implemented and outlined in this chapter.

4.2.1 Urban Structure Generation

To generate cities, input parameters for the urban environment are required. For alpine cities, these input parameters were determined in Sitzenfrei et al. (2009b), respectively in Sitzenfrei et al. (2010a). The input parameters encompass values for average slopes, maximal height difference in the elevation model, size of the river, width of valley floor, attaining population densities, land-use mix, et cetera.

Starting with generating the river system and an elevation model, the basic characteristics of the generated urban environment are defined. Subsequent, an initial land-use, main transport routes and population are added to the city. Based on a multi-cellular automata model, the initial land-use mix and the initial population distribution are modified, in order to obtain the required land-use mix, distribution of population densities and the total population.

The urban structure module basically generates GIS-data (and topological data) which are further used by the infrastructure modules or for GIS-processing.

4.2.2 Water Infrastructure Generation

The water infrastructure modules encompass at the current state of development of VIBe three modules:

- water distribution system module
- urban drainage system module
- geothermal energy utilisation module.

The water distribution system module of VIBe is a further development of the WDS Designer (chapter 3). In this module, the approach of the WDS Designer was enhanced, in order to generate water distribution systems for varying (stochastic generated) GIS data.

The urban drainage module of VIBe follows the idea of the Case Study Generator (see 2.2.2). But while the Case Study Generator algorithm is based on a branching process, starting from the waste water treatment plant (most downstream junction in the system), the algorithm in the urban drainage module starts from the most upstream junctions in the system (dead end pipes). Like in a gravity driven flow routing process for run-off concentration, the water is collected and transported to the waste water treatment plant. The water collection process is adapted in order to represent the functionality of urban drainage systems and therefore, follows the state-of-the-art guidelines for construction of sewer systems (minimum slopes, depth below surface, et cetera). Agent-based modelling techniques suit to model this processes, because there are a numerous starting points for the collection process (represented by different agents), and the collection process is basically an attraction of flow (communication between agents).

The geothermal energy module generates heat demand and water management plans for settlement areas. Compared to the generated networks in the other modules, the generation process is less complex. The placement of geothermal heat pump systems has to follow the placement guidelines, avoiding hydraulic or thermal interaction of the systems.

Each of the infrastructure modules generates the according infrastructure systems. The generation process is based on data, provided by the urban structure module. Basically, the infrastructure generation is based on the GIS data as input. Therefore, the infrastructure modules can also be applied for other purposes. E.g. it is feasible to automatically construct new infrastructure for new development based on real GIS data. Or to complement unknown data in real infrastructure systems based on stochastic scenario analysis.

4.2.3 Data Interfaces and Hydraulic Simulations

The implemented data interfaces in VIBe provide on the one hand the possibility to utilise GIS systems for data visualisation and GIS-processing. On the other hand interfaces are provided which write according input data files for simulation software. The simulation and GIS-processing software was chosen to use well known mathematical models which are preferably free. But, if required, interfaces to any other simulation software (preferable based on text input files) can be implemented to the VIBe approach.

GIS (Geographic Information System)

For GIS-processing an interface to the widely known, but costly ARCGIS software was implemented. In addition, a data interface to a free GIS system

(GRASS GIS) is implemented. The preferred data format in which the data is represented is raster files, but also vector based data can be exported from VIBe.

SWMM (Strom Water Management Model)

The Storm Water Management Model of the US Environmental Protection Agency (Rossman, 2004, 2009) is a dynamic rainfall-runoff model. It is a free available tool for running hydrological and hydraulic simulations, as well as water quality simulations (Gironás et al., 2010). SWMM is widely applied for hydrodynamic sewer modelling (e.g. Aad et al., 2010; Barco et al., 2008; Kipkie and James, 2000; Tsihrintzis and Hamid, 1998). To demonstrate the potential of the VIBe sewer module, an interface to SWMM is implemented, writing according input files.

EPANET

EPANET is a free available modelling tool of the US Environmental Protection Agency (Rossman, 2000) for simulation of hydraulics and water quality in pipe networks. Alike SWMM, EPANET is a well known tool (Kovalenko et al., 2010; Shang et al., 2008). Anyhow, for special application this solver is not adequate,e.g. for analysis of critical conditions in a pipe network a pressure driven solver (Todini, 2003; Chandapillai, 1991; Gupta and Bhave, 1996) would be more accurate. Nevertheless, an interface to this widely applied solver was implemented to the water distribution system module of VIBe. But again, interfaces to any other software with text based input files can be added, without changing the approach.

Database based on HST3D (Heat and Solute Transport Simulator)

The Heat and Solute Transport Simulator of the US Geological Survey (HST3D, Kipp Jr., 1997) is a free available simulation source code. HST3D simulates ground water flow and associated solute and heat transport by means of a 3dimensional numerical model. It is a widely applied model (Dickinson et al., 2009; Xin et al., 2003), but for stochastic scenario analysis, the computational complexity leads to too time consuming simulations.

Therefore, a pre-simulated database was implemented in the geothermal energy utilisation module of VIBe. The database was developed by Sitzenfrei et al. (2010f) by means of a simulation cluster and includes results for common configurations of geothermal heat pump systems in this context.

4.3 Architecture of VIBe

In the architecture of VIBe, from real world case studies and from literature, parameter ranges and characteristics have to be evaluated, respectively defined. Increasing knowledge on a parameter precisely indicates the parameter ranges and therefore, narrows it down. Vice versa, little knowledge on a parameter requires a comprehensive range of the parameter. After defining the parameter ranges, data sets with a variation of these parameters are generated. The algorithmically generated case studies encompass all necessary spatial data for further investigations. The number of generated case studies is only limited by computer power. Interfaces to external software provide according input files for further analysis.

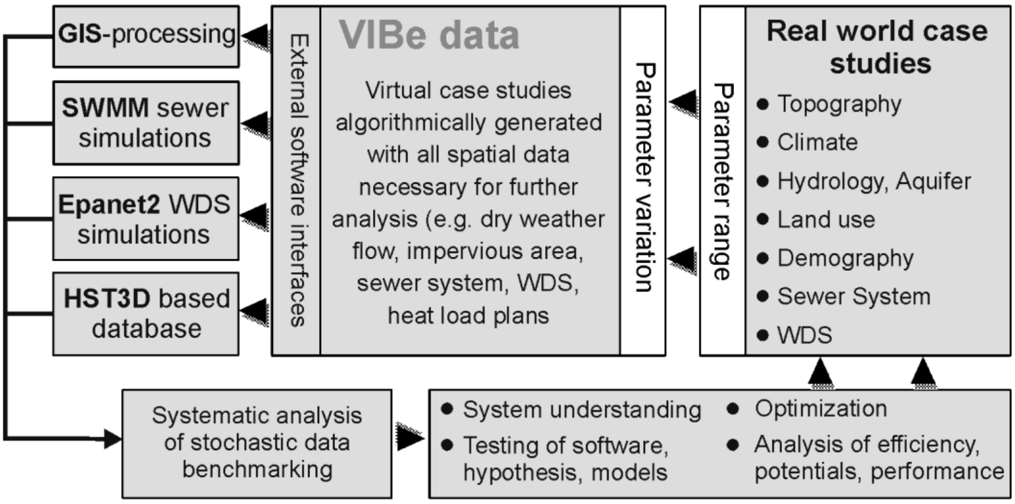


Figure 35: VIBe architecture

Based on further analysis, system understanding of the real world systems can be enhanced. In addition, with the generated virtual case studies, data is provided for testing of software, hypothesis, models and optimisation (example case study see Figure 36). Furthermore, data for analysis of efficiency, for determining potentials and generic performance studies are provided. From this extended knowledge, research and real world case studies can benefit.

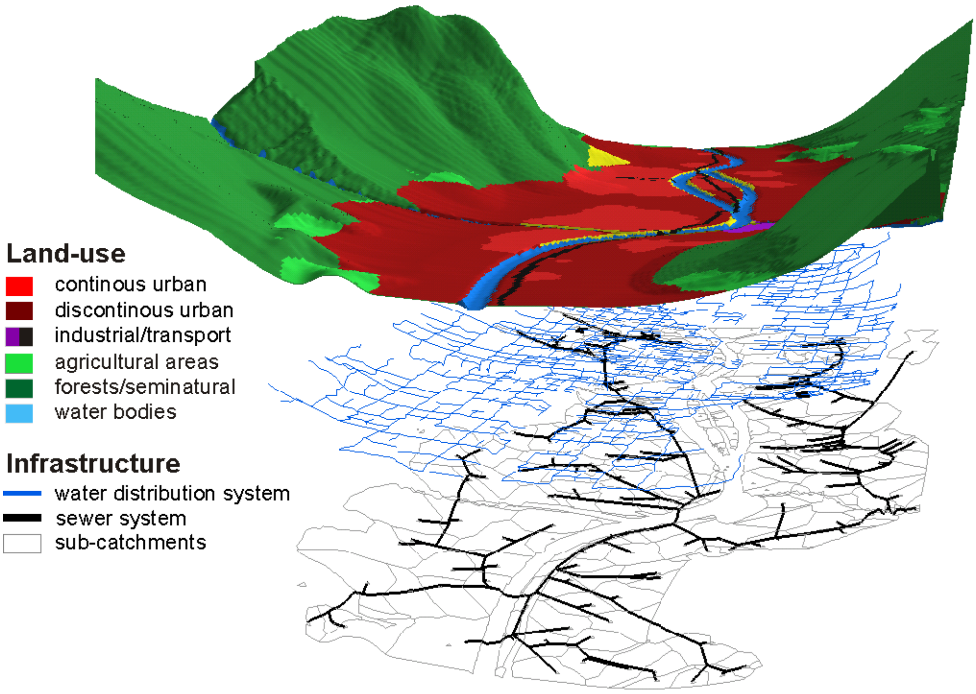


Figure 36: Example virtual case study generated with VIBe

In the following three chapters, the three different infrastructure modules are presented and discussed.

5 URBAN STRUCTURE MODULE OF VIBE

The urban structure module of VIBe generates entire cities, but without infrastructures (see chapter 4). Compared to the stochastic engineering approaches for urban water systems (Case Study Generator and Modular Design System) described in Möderl (2009), the key enhancement of VIBe is this urban structure module (see also Figure 34). All infrastructures are based on these generated cities (therefore, based on GIS-data). To generate these infrastructures, the existing stochastic approaches for infrastructure generation (Case Study Generator and Modular Design System) have to be adapted, respectively new approaches have to be developed.

The generation process of the urban structure in VIBe is presented in Sitzenfrei et al. (2010a). In this chapter, compared to Paper IV, a more extensive discussion of the generation process is presented. Starting with an introduction to urban modelling, it is shown, how all elements of the virtual city are generated (elevation model, river system, land-use, population and main transport system).

Besides a summary of Paper IV, special emphasis is placed on the calibration process of the population and land-use model. Therefore, the real world case studies which were used for calibration are shown, in order to provide a deeper insight to the key principles of the process. The results of

VIBe applied to alpine case studies are presented in Paper IV. In the results and discussion section in this chapter, the key results are discussed and a critical reflection of the entire generation process is provided.

5.1 Urban Modelling

Urban modelling focuses on the simulation of urban processes. Usually, these urban processes are complex and dynamic. To model an urban process (numerical simulation), a discretisation of the urban environment is required. A common way to digitally represent urban areas is a raster-based description. Although, due to the discrete cells, a loss of spatial information occurs (Yeh and Li, 2006). To modify these cell-based data (in order to represent e.g. urban processes), cell-based models, like the cellular automata models, are favourable.

Cellular automata are dynamic, cell-based models. Transition rules within these models, describe how the states of cells are modified through time. Traditionally, a transition rule takes into account the states of the neighbouring cells at the actual state and determines the future state of this cell (O'Sullivan and Torrens, 2001). Such a transition rule is applied to each cell in the investigated area. Anyhow, the transition rules and therefore, the entire cellular automata model remain understandable (Torrens and O'Sullivan, 2001) and it is not a black-box model.

A simple transfer rule for one single data layer is visualised in Figure 37. This simple transfer rule only contains cell states of 0 and 1. A cell state for a future time i+1 is set to 1, if the sum of states of the neighbouring cells (at the current time i) is equal or more than 4 (else wise 0). By sequentially applying this transfer rule to all cells, all new states for time i+1 can be calculated. In complex, multi-layered cellular automata, these states are e.g. the actual settlement, the settlement probability, population densities, et cetera (see also Paper IV), and the transfer rules take into account the states of several layers.

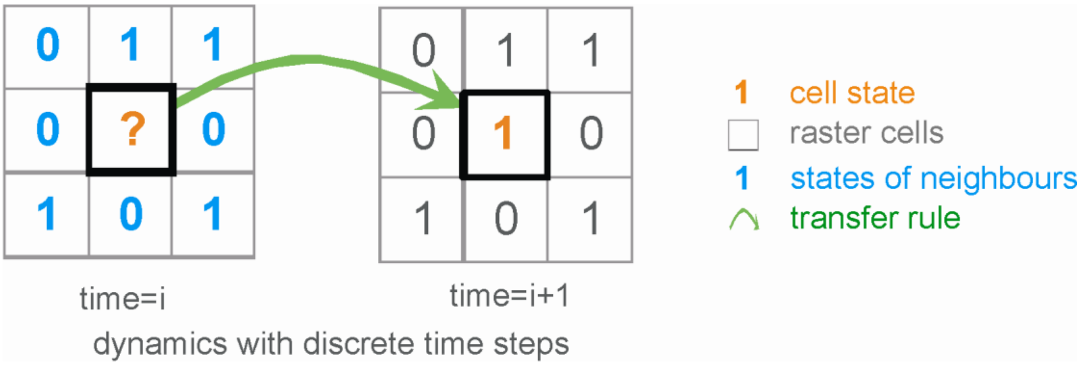


Figure 37: Simple transfer rule in a cellular automaton

Cellular automata models are therefore, widely applied in geography and architecture to model urban processes (Santé et al., 2010). The first approaches were developed for hypothetical applications (Couclelis, 1997). With increased comprehension of the models and increasing computer power, these models were also applied for real world analysis (e.g. Loibl and Toetzer, 2003; Chen et al., 2006). In literature, a lot of tools are available to model these urban processes (Clarke et al., 1997; Stevens et al., 2007; Batty, 2005; Waddell, 2002).

In VIBe, the representation of the virtual city (without infrastructures) is raster-based and therefore, a discretisation of the city with quadratic raster cells. The aim of the urban structure module in VIBe is to generate a diversity of virtual city realisations. For this purpose, a land-use and population model is required. Thus, the cellular automata approach fulfils these requirements. With implementation of stochastics in the generation process, a diversity of virtual cities can be generated with different characteristics regarding land-use mix and population densities.

5.2 Generation Process

The generated data are mainly raster based data (organised in data layers). A raster resolution of 20m times 20m was chosen for all data layers. This choice was made in order to allow representing structures like streets but also in regard of the amount of data (computer capacity). Therefore, with this resolution, the modelling aim (basically, to create urban drainage and water distribution system with accurate level of detail) can be achieved. If sufficient, also lower data resolutions can be used without changing the modelling approach. Anyhow, in that case, the results of the calibration processes cannot be transferred to different resolutions.

Before the land-use and population can be generated, the “topographical boundary conditions” have to be generated. These boundary conditions basically encompass the elevation model and the river system. The initial land-use and population are generated (initial state) based on these topographical boundary conditions. The implemented population and land-use model is subsequent applied, to modify the initial state to the finial state. While the initial state is a conceptual city, the aim of the final state is to resemble real world cities. In the following chapters, each of these steps is described.

5.2.1 Elevation and River System

Typically, cities evolve due to a favourable location (in bay, at river, crossing of important transportation routes). It was assumed that the location in this context is in an alpine valley, close to a river. But the entire generation process has only to be marginal adapted for, e.g. low land and location in bay.

River

Initially, vector-based models - starting with random walk models (Ferguson, 1976) - are used to obtain the layout of meandering rivers. But recently, numerous complex models were developed (e.g. Coulthard and Van De Wiel, 2006; Duan and Julien, 2010). In VIBe, a very simple vector-based model is implemented for the generation of the river course. This model could be substituted with a more complex one if necessary (e.g. for investigations of river hydraulics). But for the current applications of VIBe, this model fulfils the requirements.

All generated case studies are orientated in a plane Cartesian coordinates system, and it is defined that the river in general flows in positive x-direction. At the minimal and the maximal x-coordinate is an inflow and outflow to area of investigation, respectively. The positions of these inflow and outflow points at the edges are randomly selected. These two points constitute the initial river axis (Figure 38). Following this river axis, random steps are made starting from the river inflow point. From each of these points on the river axis, a lateral dislocation is applied and new river points are obtained (Figure 38). The obtained points represent the new and complex river axis.

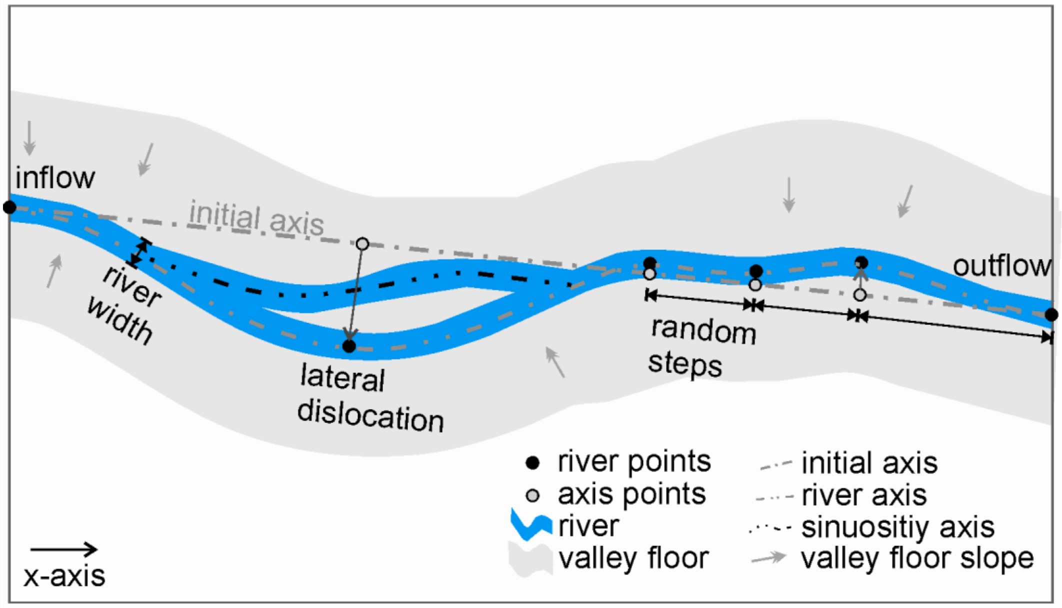


Figure 38: River generation

Rabelo et al. (2007) described cubic spline as suitable description of river paths. Therefore, the points on the new river axis are connected with a cubic spline. Additional sinuosities and river branches are added to obtain a more realistic layout of the river system (Figure 39). The width of the river continuously increases with the flow path. The average width of the river, the slope of the river and the average elevation below surface of the bottom of the stream are input parameters. In the generation process, on these input parameters stochastic variations are applied.

Valley floor and Slopes

The width of the valley floor (light gray area, Figure 38) is determined with an input parameter. This width of the valley floor was evaluated from the digital elevation map of the Inn valley. A stochastic variation applied on this width, results in the valley floor shown in Figure 38. The valley floor is characterised by low slopes (fluvial sediments). The direction of the slope in the valley floor is, in general, to the river axis (gray arrows, Figure 38).

Alpine valleys are characterised by their U-shaped form. Therefore, starting from the borders of the valley floor, heightening is added with variations (representing different angles of internal friction; Thinh, 2001) and U-shaped characteristics. The input parameter for the hillsides is the maximum height difference at the borders of the investigated areas (see Figure 39).

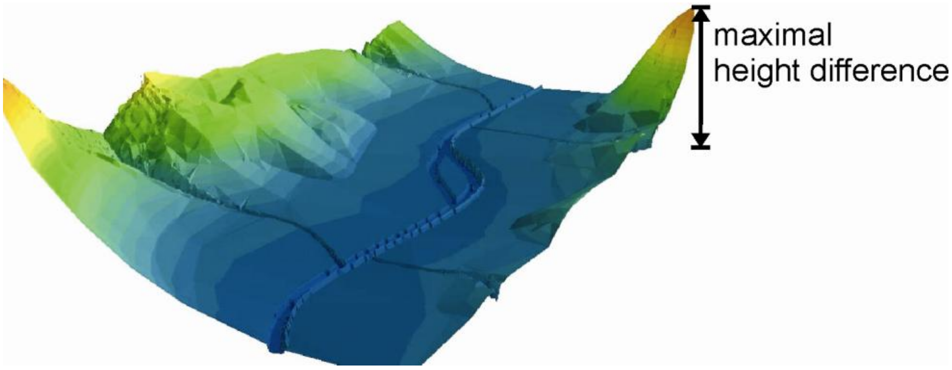


Figure 39: Valley generation, elevation map

In Figure 40, a generated valley floor (slopes below 5%) is shown in comparison to a real world case study. It can be seen, how the river meanders in this area in both, the generated and the real system.

Besides the valley floor, in the real system, there are more small areas with slopes below 5%. For this purpose, in the generated systems, hills are added to the elevation map outside the valley floor (see Figure 39). The number of hills and their height therefore, the lumpiness of the elevation map, are input parameters of the approach. In the generation process, to the input parameters, for each generated hill, stochastic variations are applied.

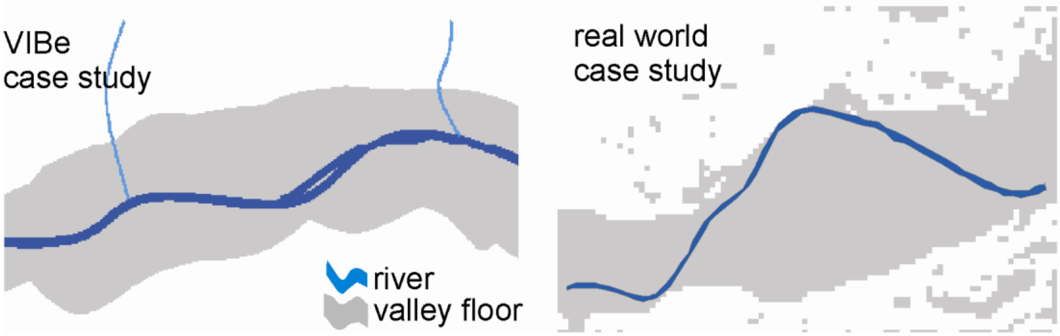


Figure 40: Valley floor, generated (left), real (right)

5.2.2 Initial Land-use and Population

The development of a city is a complex historic process. For the city generation in VIBe, this processes are too complex to model, respectively it is an unreasonable effort for this purposes to do so. Therefore, the idea is to create an initial city (land-use and population densities) which is based on conceptual city layouts and modify these layouts with cellular automata in order to obtain realistic city layouts.

Land use

A conceptual city layout was used, following the idea of a city structure model in Heineberg (2001). Therein, different circular city centres and sub centres are enclosed by concentric circles of residential area and suburbs.

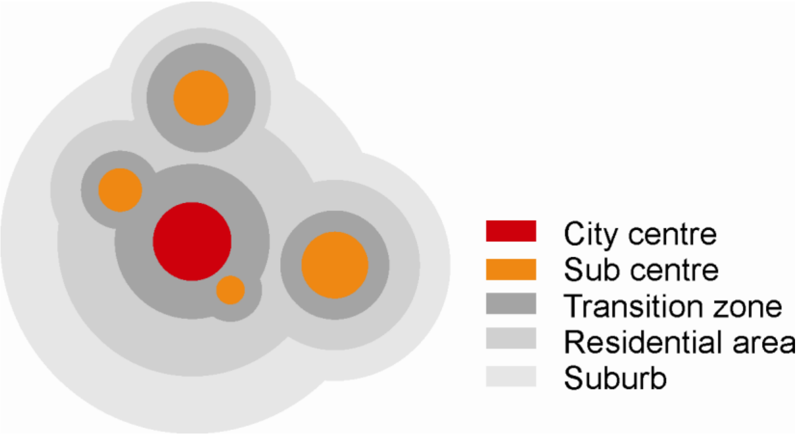


Figure 41: Conceptual city structure

To use well known land-use classes, the CORINE (Coordinated Information of the European Environment) land cover nomenclature was used (CEC, 1994). In total, there are 44 classes included. The level of detail in these 44 classes is not necessary in this study. Therefore, 8 different land-use/land-cover classes of the CORINE nomenclature were implemented in VIBe with a higher level of detail for urban areas. The city structure model (shown in Figure 41) was adapted to the CORINE land-use classes. The city centres and sub centres (according to Figure 41) are regarded as continuous urban fabric; the transition zone, residential areas and the suburbs as discontinuous urban fabric (Figure 42).

For the generation process, city centres and sub centres are centrally placed in the valley floor (see Figure 42, continuous and discontinuous urban fabric). Areas outside the urban fabric with slopes below 18% are regarded as agricultural areas and above 18% as forests and semi-natural areas. The areas for the river system are water bodies. In addition, into the urban fabric area, industrial zones are placed.

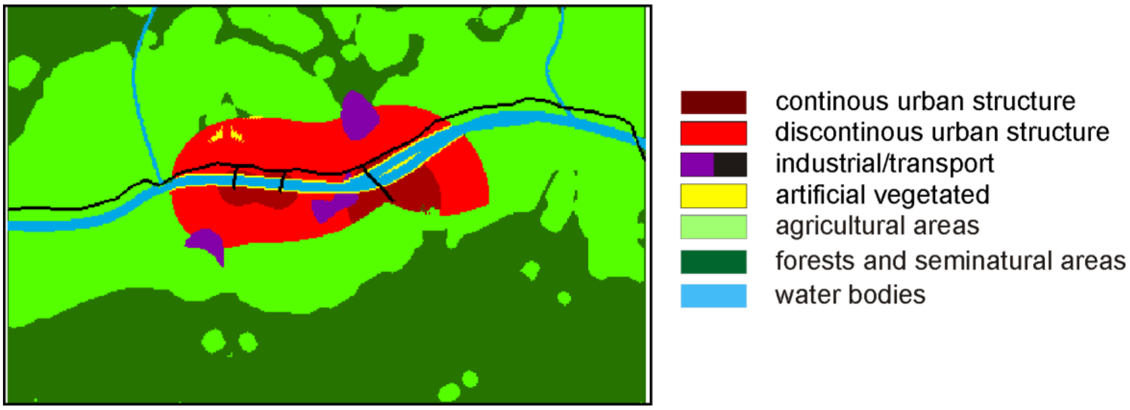


Figure 42: Initial land-use

Population Densities

The initial population densities are generated on basis of the initial land-use classes: continuous and discontinuous urban fabric and agricultural areas. It is assumed that agricultural areas, with a population density above a critical value, can be rededicated to discontinuous urban fabric. Therefore, within these land-use classes, “population hotspots” are randomly set within these land-use classes. Starting from these hotspots and given values for population densities (for each different land-use class), the values exponentially decreases from the hotspots, substituting lower values. The values for population densities are set according to the corresponding land-use classes and critical values. These critical values for each land-use class are input parameters. For the land-use distribution shown in Figure 42, this results in an initial population map (shown in Figure 43).

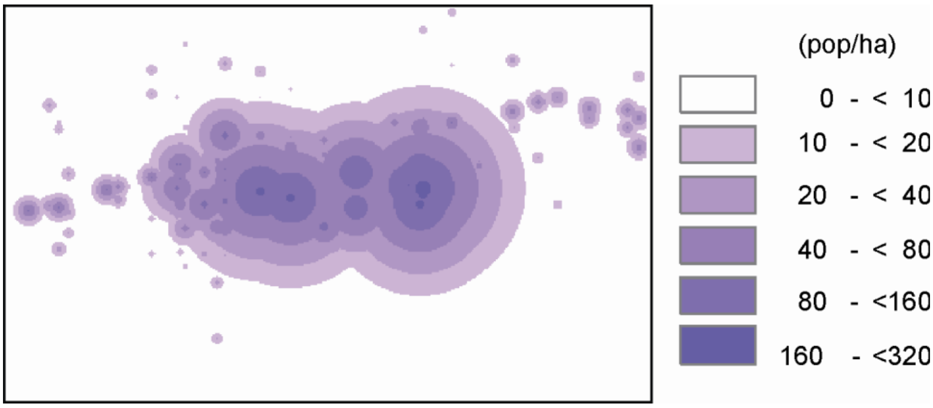


Figure 43: Initial population densities

5.2.3 *Main Transport System*

In Figure 44, the main and minor transport systems of the city Innsbruck are shown. It is revealed that the entire system is orientated on the river system. The main transport system in VIBe is generated, based on the city centres of the initial land use and orientated on the river system (see Figure 42).

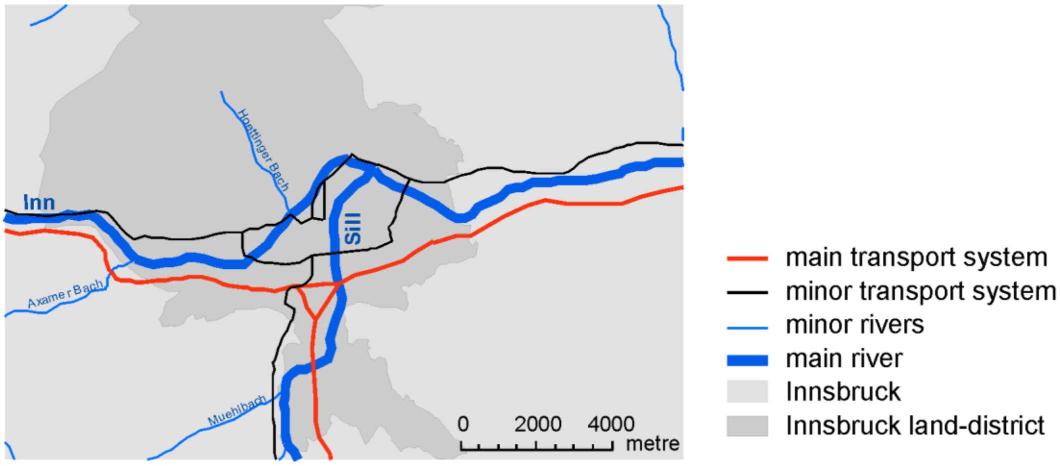


Figure 44: River-orientated transport system

The algorithm for the generation of the main transport system in VIBe has the aim to follow the river course, connecting the two borders of the investigated area. Alike the generation of the river system itself, linear random steps are set besides the river. If there is a change of angle above a limit value (default 15°), the river is approximately orthogonally crossed. Additional, the city centres are connected to this main transport system (see Figure 42).

5.2.4 Land-use and Population Model

Although, a lot of urban simulation models have already been developed, most of them are too complex for the required task. Therefore, a model was developed which exactly meets the requirements of VIBe in this context.

Anyhow, the modelling concepts of existing tools were taken into account (e.g. Clarke et al., 1997). A detailed description of the land-use and population (in particular the transfer rules) is available in Paper IV. In Figure 47 left, exemplarily, the land-use of a generated case study is shown.

5.2.5 Calibration of Land-use and Population Model

For calibration and validation process, the land-use and population densities of three alpine case studies in the Inn valley were determined. As described in more detail in Paper IV, the two case studies Schwaz and Innsbruck were used for calibration of the land-use and population model. With the two obtained parameter sets, parameter ranges were defined. Within these parameter ranges, values were randomly sampled. The third city Hall was used for validation. The three cities are described and characterised in Paper IV.

In the urban structure model of VIBe, the generation processes are stochastic. Therefore, a calibration is only reasonable in a comparison with numerous generated case studies. Hence, for each calibration state, 100 samples are generated and investigated. In the following paragraphs, the calibration data for land-use and population model is shown and discussed in more detail and therefore, provides additional information to Paper IV.

Real World Case Study Innsbruck

In Figure 45 right, the calibration for the land-use mix for the city Innsbruck is shown. Population densities for different land-use classes were extracted from this data and used as input parameters for the urban structure module. The land-use and population model was calibrated, in order to achieve a similar land-use mix and to obtain the same amount of total population.

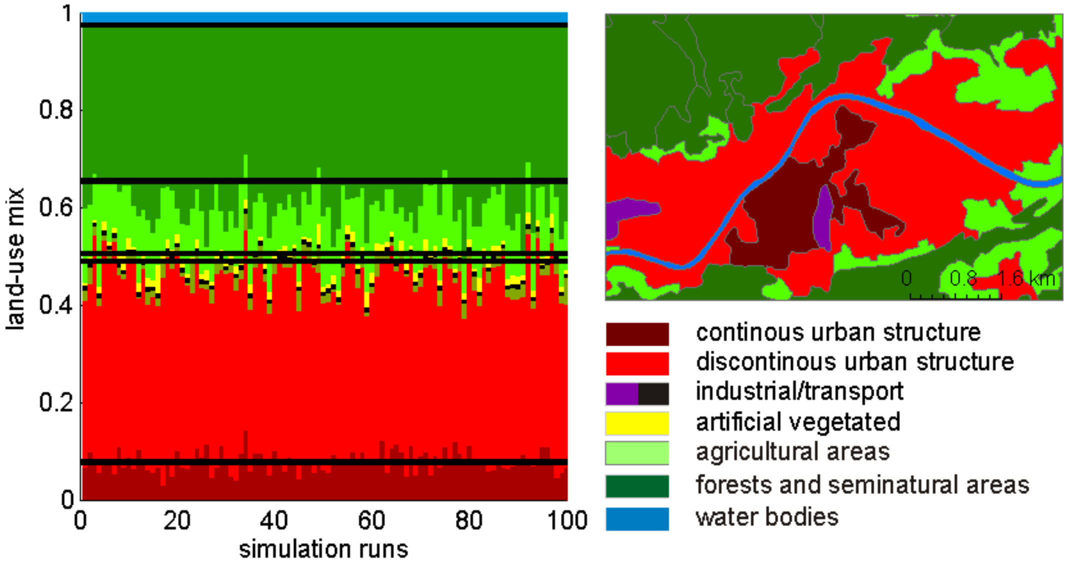


Figure 45: VIBe calibration data, Innsbruck

In Figure 45 left, the land-use mixes of 100 VIBe cities are shown. The black lines indicate the percentage of land-use of the real system. Based on visual comparison of the generated and real data, the calibration parameters were obtained.

Real World Case Study Schwaz

Alike as for the city Innsbruck, for the city Schwaz the population densities and the land-use mix were determined. Figure 46 left, shows the land-use mix of 100 VIBe cities with the calibration parameters of Schwaz. Again, a visual comparison of the generated data with the virtual data was used to obtain calibration parameters.

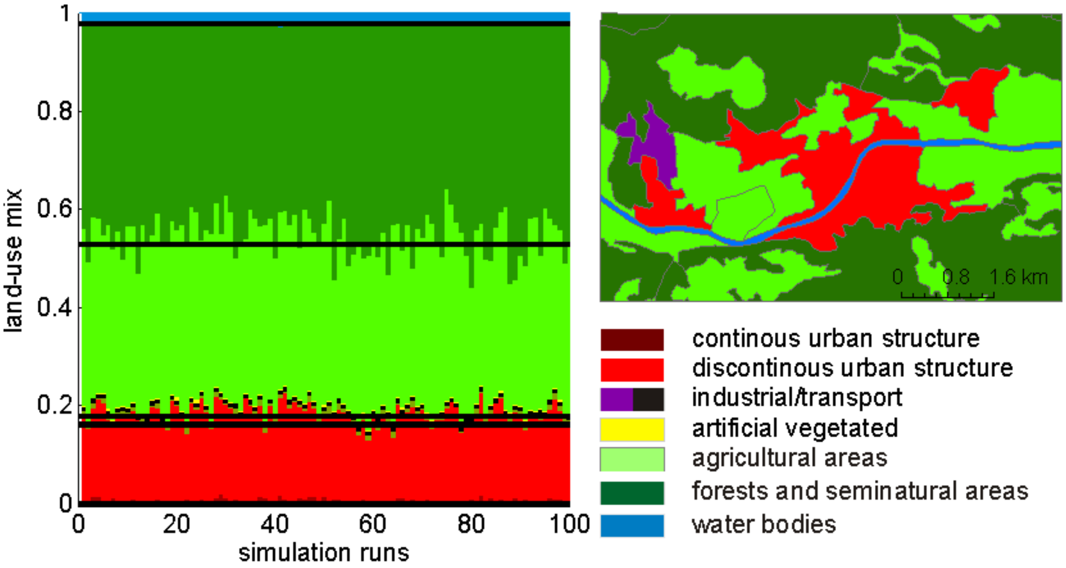


Figure 46: VIBe calibration data, Schwaz

Comparison of the Generated Case Studies with Real Case Studies

In Paper IV, 1,000 virtual cities, within the determined parameter ranges (by calibrating the approach on Innsbruck and Schwaz), are generated and systematically evaluated. It is revealed, that the characteristics of the three real world systems (Innsbruck, Hall, Schwaz), for all investigated parameters, are in the ranges of the generated 1,000 virtual case studies (see also Paper IV).

Impervious Area

Two approaches from literature were combined, in order to calculate the spatial distributed coefficient of impervious area. With a linear regression (Chabaeva et al., 2004) with population density, the coefficient of impervious area is assessed for agricultural areas and discontinuous urban fabric (maximum coefficient of impervious area 50%).

For the continuous urban fabric and industrial areas, coefficients of impervious area are set according to Butler and Davies (2004) between 50% and 90% with stochastic variation for each cell. To obtain areas with the same amount impervious area, a cellular automata for clustering of data is applied (Batty, 2005). In Paper IV, it is shown that the impervious area of the generated case studies resembles the investigated real world data of the city Innsbruck (i.e. approximate 32%).

Dry Weather Flow and Water Demand

With parameter ranges from literature and values obtained from the investigated case studies, the value ranges for the generation process were defined. The dry weather flow was determined according to ÖWAV-RB 11 (2009). To obtain the spatially distributed dry weather flow, based on the population density and the values ranges for dry weather flow from literature, for each cell the actual amount is determined. The sums of dry weather flow of the generated virtual cities were in good agreement with data from the investigated real world system (Paper IV).

The water demand was determined on basis of the population densities, respectively on basis of the case study data and literature review. The sums of water demand as well as the water demand per capita of the real systems are in good agreement with the generated ones (see Paper V).

5.3 Results and Discussion

In Paper IV, the results of the application of VIBe for alpine case studies are shown. Detailed information about the results can be sustained in Paper IV. Summarising the results, it can be concluded that with the urban structure module of VIBe, virtual case studies can be generated which resemble real world quiet well and are therefore, comparable with real world systems. Hence, applying the VIBe approach provides numerous case study data for investigations to obtain case unspecific results. Exemplarily, a virtual city generated with the characteristics of the real world city Innsbruck is shown in Figure 47. Therein, the land-use mix is plotted on the elevation map.

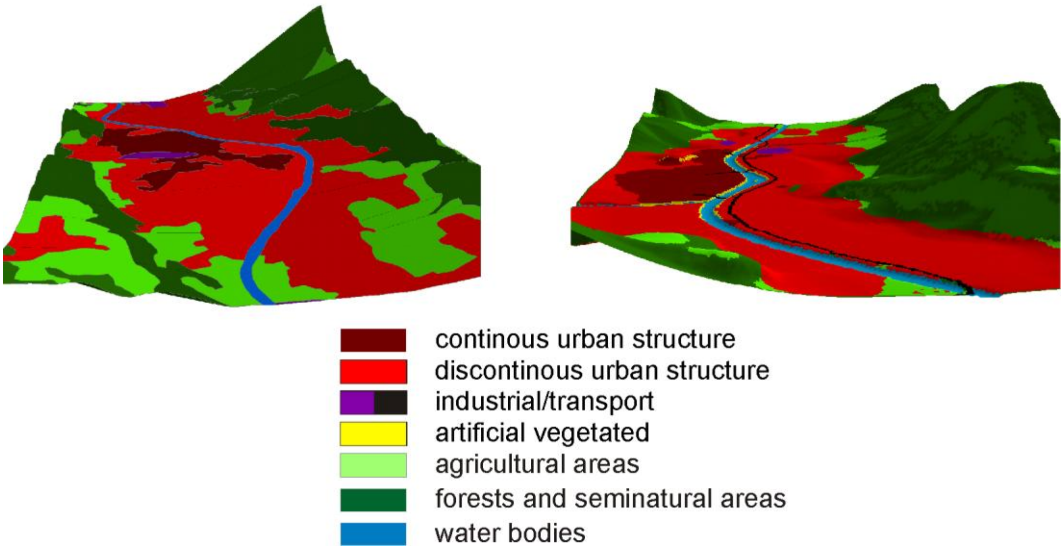


Figure 47: Land-use and elevation of Innsbruck (left) and results of VIBe (right)

As mentioned in Paper IV, there are several assumptions, simplifications and neglected issues in the urban structure module of VIBe. E.g. the generation process of the topographic boundary conditions is partly based on observed data and empirical coherences. Detailed analysis and literature reviews are required to reliably determine, respectively approve these method.

The land-use and population model also needs to be analysed in more detail, e.g. regarding uncertainties and errors. Especially, the simple transfer rules have to be investigated, because the definition of these rules is affected by the researcher’s understanding of the process (Yeh and Li, 2006). Also, analysis concerning the different neighbourhood models is proposed, e.g. the impact of different neighbourhood models, the impact of scale (cell resolution) and the impact of the time steps on the obtained results (Batty, 2005).

The calibration process of stochastic model needs special attention (Maria de Almeida et al., 2003). The calibration process of the empirical land-use and population algorithms is difficult. Especially, the visual comparison for the calibration of the land-use and population model is proposed to be investigated in more detail, e.g. with sensitivity analysis of the parameters.

5.4 Outlook

It is intended to substitute several simple models with more accurate models in order to reduce the neglected issues. Additional complexity (additional data layers) is to be added to the approach, e.g. pollutant concentrations (build up, wash-off rates). The urban structure module strongly impacts the infrastructure modules. Therefore, the impact of parameter uncertainties and error propagation is intended to be investigated in more detail, addressing the issues outlined in chapter 5.3. In addition, a climate and weather generator is intended to be implemented in the VIBe approach.

Regarding the conception of VIBe, it is intended to develop an integrated model for water distribution and waste water (linked via spatial population). E.g. both water infrastructure models are at the same horizontal location (thus under a road system). This integrated model would have potential to investigate the urban water cycle from a new point of view and would enable to investigate e.g. sustainable water management strategies (reuse of waste or gray water and the impact on both, water distribution and urban drainage system, et cetera; see also chapter 9).

Further, the consideration of dynamics in the system is aspired, including dynamics in the land-use and population model (future scenarios) and models for the development of infrastructure over time (see chapter 9).

6 SEWER MODULE OF VIBE

Following the aim and conception of VIBe (see chapter 4), the generated infrastructure is based on virtual cities. Therefore, for VIBe, new approaches for the generation of infrastructure based on GIS-data of virtual/ real cities are required. For the generation of combined sewer systems with VIBe, the sewer module was developed in course of this PhD project and the master thesis of Urich (2009).

The sewer module of VIBe is an enclosed tool. Therefore, this approach can also be applied to real world data, in order to e.g. complement inadequate data or unknown data of real world case studies. Anyhow, in this chapter, an application for virtual data (generated with the urban structure module of VIBe) is discussed.

The modelling principles of the sewer module of VIBe are outlined in Sitzenfrei et al. (2009b) and Paper VI. Paper VI is an integral part of this thesis. In the following chapters, an introduction to urban drainage is given (chapter 6.1) in order to give an idea of the requirements of urban drainage systems in this context and how they can be modelled. The sewer module of VIBe is based on agent based modelling technique. Therefore, a short introduction to this technique is given (chapter 6.2) to provide a better insight into the generation process (chapter 6.3). In the results and discussion section (chapter 6.4), merely an overview of the results provided in Paper VI is given, to provide a complete picture of this study in this thesis. Finally, in chapter 6.5 ideas of further work and further investigations are outlined.

6.1 Urban Drainage

With increasing urbanisation, artificial water ways (man-made urban drainage system) are required to drain urban areas (Butler and Davies, 2004). For urban drainage systems, there are, in general, two tasks: protection of human being from nature (flooding, et cetera); protection of nature from anthropogenic impacts (emissions, et cetera).

The technical design of drainage systems has to be done in a predictive way, taking into account, among others, statistical evaluation of rain data and return periods, future developments of the urban areas (ATV-A 128E, 1992) or climate change effects (see also chapter 2.2.3). But also following technical principles like ensured hydraulic functionality under different conditions, operation safety and cost-effectiveness, regarding construction and operation (ÖWAV-RB 11, 2009). With these principles, the design of urban drainage systems is specified to protect nature from human beings and vice versa in an economical maintainable way.

The technical design of urban drainage systems encompasses two major aspects: first, the spatial layout of the sewer systems and second, the pipe-sizing process. Usually, the spatial layout of the sewer system is manually determined by engineers, taking into account the requirements and opportunities in the cities (areas to drain, connection to existing pipes, available space for sewer pipes e.g. in streets, elevation map, et cetera).

For the pipe-sizing process of the urban drainage system, traditional simplified empirical or analytical approaches (with “paper and pencil”) are used (Rauch et al., 2010). With increasing computer power, numerical simulations gained importance over the last decades (ATV-DVWK-M 165, 2004). In contrast to the simplified approaches, with the numerical approaches, the dynamics of rain weather can be considered in the technical design process.

This issue is also taken into account in the development of new legal regulations and guidelines e.g. in contrast to the former Austrian guideline

ÖWAV-RB 19 (1987) for the design of single combined sewer overflow structures which is based on simplified approaches, the new guideline ÖWAV-RB 19 (2007) considers numerical simulations with long time series to determine combined sewer overflow emissions and immissions for the entire sewer system.

To determine the spatial layout of the sewer systems in VIBe, an agent-based approach was used (see chapter 6.2 and 6.3). The pipe-sizing process of the sewer system in VIBe is based on simplified analytical approaches which are algorithmically applied to the entire sewer system. These approaches were used, because an iterative design process, based on a numerical model is considered as to time intensive. Respectively, the development of such a design algorithm was regarded as to complex for the current state of development of the sewer module in VIBe. For the performance evaluation of the sewer system, anyhow, numerical models are used.

6.2 Agent Based Modelling

Batty (2005) described two principles to model urban processes. Besides, describing processes of the investigated area with raster-based models (cellular automata, see 5.1), urban processes can also be modelled with mobile objects. These objects operate on raster grids, but they are mobile (they can move in the grid) and can modify raster data. The movement of these objects is driven by movement rules. Because these objects can communicate directly or via communication data layers, this approach represents swarm intelligence (Meng et al., 2007). These modelling principles are also referred to as agent based modelling technique (Crooks et al., 2007).

In hydrology, algorithms are used to determine water ways. E.g Tarboton (1997) investigated different approaches to assess the impact of models to determine flow directions based on digital elevation data. Reaney (2008) adapted agent based modelling techniques to determine the spatial and temporal origin of channel flow. In that study encouraging results were obtained for a semi-arid catchment.

In the sewer module of VIBe, agent based modelling techniques are used, in order to combine flow routing (basically driven by gravity) from hydrology with technical urban drainage principles. In the context of finding a sewer layout based on GIS-data, the movement paths of agents represent water ways (sewer pipes) of urban drainage. Therefore, it is a water flow routing which is not only driven by gravity, but also by technical design guidelines (vertical alignment, et cetera). In addition, it is driven by already existing nearby water ways (existing sewers) which are used by other agents (communication of the agents, knowledge transfer). These movement rules can be implemented to control movements of the agents. The agents mark the path of their movement and therefore, after applying several generations of agents, possible sewer layouts are obtained.

6.3 Generation Process

The virtual cities, generated with the urban structure module (chapter 5), are the input for the sewer module (chapter 6.3.1). The generation process of the sewer layout consists of two models. The first model places the waste water treatment plant and generates a branched main sewer network which ensures drainage from the city centres (chapter 6.3.2). The second model constructs the minor sewer system which connects the remaining parts to the main sewer system (chapter 6.3.3). Paper VI focuses on the second model. The discussion in this chapter focuses on model 1 of the sewer module. After generating the layout of the combined sewer system with the two models, it is pipe-sized. The concept of the pipe-sizing process is outlined in chapter 6.3.4.

6.3.1 Urban Structure

For the generation process, GIS-data of cities are required. In the context of this study, cities generated with VIBe are used which have the same characteristics as the real world city Innsbruck. A description of these characteristics can be obtained in Paper IV and Paper VI.

The required GIS-data for the sewer module are the digital elevation map, the land-use map, population densities and impervious area. Further, for sewer model 1, data of the city centres and the river course is required.

In real world cities, the street network is an important issue to determine the spatial layout of the sewer system. At the current step of development of VIBe, the streets network are currently not implemented in the urban structure module and hence, also not implemented in the sewer module. But this important issue will be implemented in the next development steps of the urban structure module. For the sewer module, a consideration of streets can be implemented with low effort. Therefore, the agent movements have to be restricted to streets only respectively most likely in streets.

6.3.2 Sewer Model 1

Sewer model 1 generates a branched main sewer layout. This main sewer layout connects the city centres with the waste water treatment plant considering the course of the river.

Waste Water Treatment Plant

At the most downstream area of the generated case study (outflow of the river, see chapter 5.2.1), a waste water treatment plant (WWTP) is placed close to the main river (see Figure 48or Figure 49).

Main Sewer

The algorithm for generating the main sewer, takes into account the position of the WWTP, the positions of the city centres (including sub-centres) and the river course. Starting with the most upstream city centre (Figure 48, city centre 1), sewer segments are placed along the river course, in order to connect to the WWTP. The direction and distance to the WWTP is indicated with a “connection field” around its location. The intensity of the connection field decreases with increasing distance from the WWTP.

These sewer segments have a default length of 200m (with a stochastic variation applied on it). The spacing of the manholes in sewer system is usually shorter, anyhow Butler and Davies (2004) reported that the spacing of manholes may be increased up to 200m for larger pipes. It is assumed that the pipe-sizing process of these main sewer segments results in larger pipes and therefore, 200m for spacing of manholes is accurate.

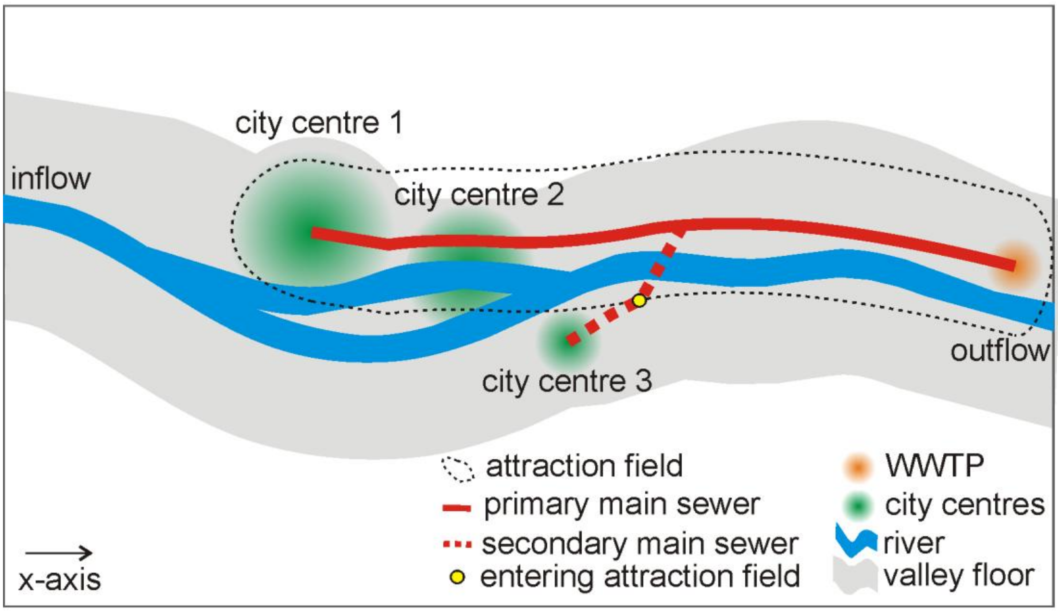


Figure 48: Generating main sewer system

After the most upstream city centre is connected to the WWTP, an attraction field is placed (Figure 48 and Figure 49), indicating an existing main sewer. In a next step, at the most upstream but unconnected city centre, it is started to place sewer segments. If this city centre is already in an attraction field of an existing main sewer (e.g. Figure 48, city centre 2), no sewer branch is constructed. If the regarded city centre is not in an attraction field, sewer segments are place until the WWTP is reached or an attraction field is entered. This procedure is repeated until all city centres are connected to the WWTP, respectively connected to the primary main sewer.

Every time before a sewer segment is placed, the angle between the direct connection to the WWTP and the sewer segment following the river course (Figure 49, angle α) is determined. If this angle α is more than a limit value (default value 15°) the river is approximately orthogonally crossed (culvert, see also Figure 49).

If a sewer segment is placed in an attraction field, an entering point occurs (e.g. Figure 48, city centre 3). This sewer branch is connected to the already existing main sewer (secondary main sewer branches in Figure 48 and Figure 49).

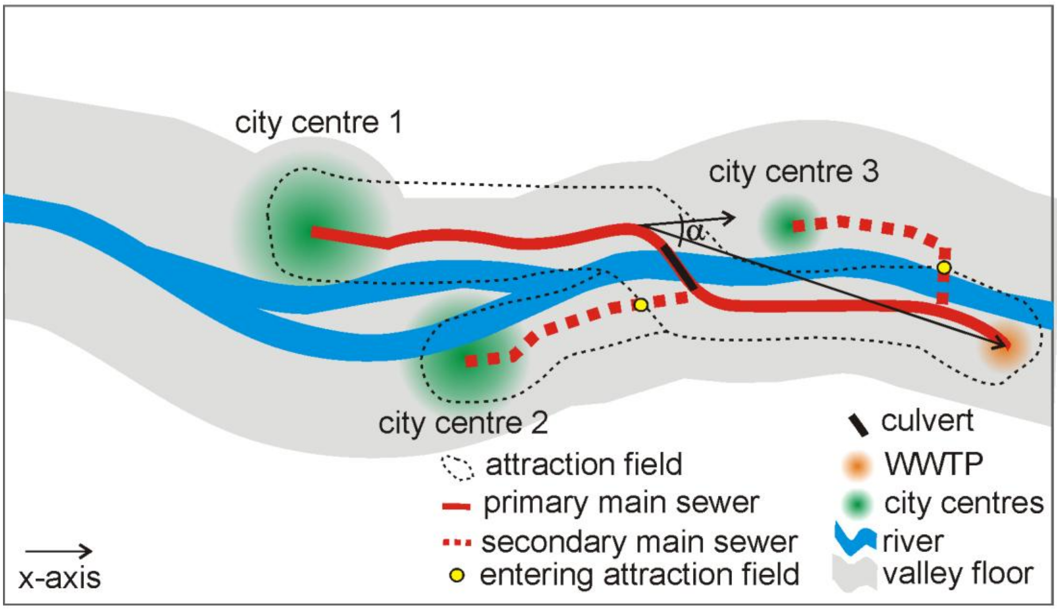


Figure 49: Attraction fields main sewer

For all city centres and sub-centres, it is ensured that they are connected to the WWTP. Due to the downstream location of the WWTP, gravity driven drainage is, as well, ensured.

This algorithm can be described as simple agents who “walk” along the river course, following additional rules (angle for direct connection to the WWTP, connection to already existing sewer branches). This approach is not limited to one WWTP only. Also more WWTP can be used, connecting the city centres to the closest WWTP (indicated by the “connection fields”)

6.3.3 Sewer Model 2

Sewer model 2 generates the remaining sewer branches based on a more complex agent model. The input data for this model are the land-use map, elevation map, population densities, impervious area and the main sewer system generated with sewer model 1.

The starting points of the agents and therefore, the inlet nodes of the drainage systems, are determined with the land-use map. For continuous and discontinuous urban fabric and agricultural areas, agents (inlet nodes) are placed. In different generations, the agents try to find the WWTP or the main sewer system.

Extensive discussion of how this agent based model works is provided in Paper VI. Condensed, it can be described as gravity driven flow routing process based on agents, which takes into account technical design principles (vertical alignment, et cetera) and already marked water ways which have been used by other agents. The determined water ways (agent paths) are applied to place the remaining sewer layout. As a result, all urbanised area is connected to the WWTP.

6.3.4 Pipe-sizing

For the design process of sewers, usually two criteria are used: design discharge for high flow and sewers should be free from sediment deposits also under dry weather flow conditions. Deposits in sewers reduce hydraulic capacity and increase the roughness of the sewers. Usually, criteria for flow velocity (e.g. 0.6 m/s) or minimal bed shear stress criteria are used. In Vongvisessomjai et al. (2010), a review of these self-cleansing design criteria for sewers is shown.

For the pipe-sizing algorithm in the sewer module of VIBe, the time area method is used (Butler and Davies, 2004). To place the combined sewer overflow structures, the idea of Ghosh et al. (2006) was followed and the branches of the sewer network (tree layout graph) were indicated by the

Strahler stream order (introduced by Strahler, 1952). In case of a sewer layout, this order indicates the “sewer branch order”. This sewer branch order was used to determine locations for combined sewer overflow structures and storage tanks. A detailed description of this process can be found in Paper VI, respectively also in Sitzenfrei et al. (2009b).

6.3.5 Real World Case Study Data

The sewer module is applied to 100 virtual cities generated with the urban structure module of VIBe. Generation characteristics were applied to obtain virtual case studies which are comparable with the real world city Innsbruck (see Paper IV and Paper VI).

For the city Innsbruck, also case study data of the sewer system as SWMM (Rossman, 2004) model is investigated. The results of the sewer generation and the pipe-sizing process were compared with this case study data.

6.4 Results and Discussion

For each of the 100 virtual cities, 12 virtual sewer systems were generated. The obtained 1,200 combined sewer systems were evaluated regarding system properties (number of sub-catchments, sub-catchment areas, impervious area, cumulative distribution of conduit lengths and cross section areas) and compared with the real world case study Innsbruck. In Paper VI, it is revealed that results for the real world case study are within the results range of the virtual case studies

To estimate the hydraulic performance of the generated sewer systems, an interface to the hydraulic solver SWMM (Rossman, 2004) was implemented (see also chapter 4.2.3). For performance evaluation, two system performance indicators (according to Möderl, 2009) were used. One normalised indicator describes the combined sewer overflow efficiency and the second one the surface flooding. The determined performance indicators of the real world system are in the same range as those of the generated 1,200 virtual systems (Paper VI).

With the sewer module of VIBe a generic tool was developed which allows generating combined sewer systems. The required data for the generation process is basically GIS-data and therefore, the sewer module can also be applied to real world data. It was shown in Paper VI that layout characteristics as well as hydraulic performances of the generated system are in proper agreement with the investigated real world system.

6.5 Outlook

Several improvements can be added to sewer module. In the generation process, besides the alpine case studies, also e.g. low-land case studies should be generated and analysed. Low-land case studies may require pumps in the urban drainage system (Korving and Ottenhoff, 2008) and therefore, an implementation of that issue in the pipe-sizing process, respectively in the generation process, should be intended. Also different cross section shapes for the pipes (e.g. noncircular shapes like egg-shaped) should be implemented in the approach.

Regarding the layout of the urban drainage system, investigations should be made, on the subject of the importance of loops in the drainage system. Further, the conception of the generation process should be enhanced to generate separate sewer systems. Also, an application of the proposed method to generate sewer systems for real world data would be a valuable investigation to proof the proposed methodology.

Anyhow, the sewer module of VIBe in combination with the urban structure module provides valuable data for research tasks. E.g. different level of details (alike skeletonisation in water distribution analysis; Strafaci and Walski, 2003) and how these levels impact the obtained results can be systematically investigated. This could e.g. contribute to uncertainty research for urban drainage systems (Refsgaard et al., 2007; Kleidorfer, 2009), answering the question of e.g. model structure uncertainties.

7 WATER DISTRIBUTION MODULE OF VIBE

The water distribution module of VIBe is a further enhancement of the approach developed for the WDS Designer (chapter 3, graph concatenation approach). But in contrast to the WDS Designer, this approach is based on stochastically generated GIS-data for virtual cities. The enhancements of the approach were developed in course of this PhD project.

Alike the other infrastructure modules implemented in VIBe, the module for the generation of water distribution systems is an enclosed tool. Therefore, it can also be applied to real world data for e.g. cost estimation for construction of water distribution systems for new development. Anyhow, in this chapter, the application of this approach to virtual data, derived from the urban structure module of VIBe, is discussed.

The water distribution module of VIBe is presented in Sitzenfrei et al. (2010d) which is an integral part of this PhD thesis (Paper V). In the following chapters, an introduction to water distribution is given in the context essential for this study (chapter 7.1). Because the implemented graph concatenation approach is based on graph theory, it is also outlined, how water distribution systems can be described by means of graph theory and how graph theory can be used for investigations (chapter 7.2). Further, an overview on the generation process of the water distribution systems in VIBe is given (chapter

7.3) and substantial points of the results and discussions of Paper V are described (chapter 7.4). Finally, a detailed outlook of the next steps in the development of the water distribution module of VIBe is given (chapter 7.5).

7.1 Water Distribution

The basic purpose of water distribution systems is to deliver water from a source to costumers (Strafaci and Walski, 2003). Historically, increasing demand due to urbanisation caused that the water has to be transported over longer distances which requires water distribution networks.

The technical design process of these water distribution networks has to consider several requirements. Taking into account factors for peak flows and future water demands (ÖNORM B 2538, 2002), it is ensured that costumers are supplied with water with accurate quantity (also in future, peak or critical conditions). Especially under critical conditions (e.g. pipe burst or source failure), the redundancy of important pipe connections is essential, but has to be considered with regard to water quality (insufficient water age due to over-capacity and low flow velocities). Also, regarding economic requirements, an efficient utilisation of capital expenditure has to be ensured for both, construction and operation of the water distribution networks.

Compared to hydrodynamic simulations of sewer networks, the mathematical formulation and solution of the flow and pressure equations in the water distribution networks can be formulated and solved in a less calculation intensive way. Anyhow, increasing complexity of water distribution systems also increases the calculation efforts. Therefore, the manual calculation of flow and pressure conditions in such a system is virtually impossible. Consequently, the simulation (mathematical representation) of water distribution networks for design, management and planning is, since several decades (e.g. Donachie, 1974), standard practice for hydraulic and environmental engineers.

The simulation tools for water distribution networks are therefore, capable of simulating networks of extensive size with maintainable calculation effort. For the investigations on network systems, steady state simulations (static conditions) are used to calculate certain operating points. To evaluate e.g. tank filling, varying demand conditions et cetera, extended period simulations are required (Strafaci and Walski, 2003).

In the water distribution system module of VIBe, in contrast to the sewer module of VIBe (see chapter 6.1 and 6.3.4), a simulation tool is used for the pipe-sizing process. This is feasible because of the marginal computation time of the state-of-the-art simulation tools (e.g. Epanet2, Rossman, 2000). With iterative steady state simulation with Epanet2, the entire generated networks are pipe-sized. For hydraulic performance evaluation and water quality evaluation, the Epanet2 hydraulic solver is used (see chapter 7.3.4). This pipe-sizing approach can be applied with short calculation time (less than 5 seconds) to mid-size cities. But, e.g. for mega cities, the application of this approach would anyhow be very time consuming.

7.2 Graph Theory

Pipe networks consist of pipes, nodes, pumps, valves, storage tanks and reservoirs (Rossman, 1994). Water distribution systems can be described by means of graph theory and network graphs consisting of nodes (sources and sinks) and links. Thus, existing mathematical methods can be applied to evaluate the graphs of water distribution networks. Various studies used graph theory for their investigations in water distribution networks. E.g. Rahal (1995) used graph theory to reduce the size of the original governing equation for hydraulic steady state simulations in water distribution systems by means of co-trees. Demšar et al. (2008) used graph theory to identify critical locations in networks systems, amongst others, also for water supply networks. These studies used graph theory to mathematically describe the network structure and used existing theory (overview of this theory is provided e.g. in Diestel, 2006) for their studies and investigations on water distribution networks.

Möderl et al. (2007) used graph theory to binary code the connections of links in nodes of infrastructure networks and therefore, represent the entire network with a graph matrix (see chapters 2.3.2 and 3.2.1). This was developed, in order to generically describe recurring block motifs in networks (Milo et al., 2002) and systematically concatenate these blocks to entire network systems (see chapter 3.2.2).

In the water distribution module of VIBe, this graph theory based description was used and the graph concatenation approach presented in Paper II and chapter 3 was enhanced. The enhancements encompass that the graph concatenation approach can be applied to varying GIS-data. In context of this study, this GIS-data is stochastically generated with the urban structure module of VIBe. Therefore, the placement of water source (compared to chapter 3) has to be improved. These improvements include a graph-testing routine which determines if the network graph is coherent or not, respectively, if all demand nodes are connected to a network source. If the network graph is not coherent, the consideration (strategic placement) of groundwater wells in the systems to ensure water supply, in regard of economic construction principles, is applied.

7.3 Generation Process

For the systematic generation process in the water distribution system module, 1,000 virtual cities generated with the urban structure module of VIBe were used as input data (see 7.3.1). For each of the cities, the graph concatenation approach (enhanced for an application in VIBe) was applied with 3 different layout strategies (see 7.3.2). This was done by applying the source strategy which was developed for alpine environments (see 7.3.3). For pipe-sizing, for each of the generated systems (3,000), 25 different parameter scenarios were used (demand factor, economic flow velocity) and the resulting 75,000 different water distribution systems were systematically analysed by means of hydraulic simulations and system performance indicators (see 7.3.4). Further, the 75,000 generated water distribution systems were set in context with the characteristics of a real world system (7.3.5).

7.3.1 Urban Structure

The urban structure was generated with the urban structure module of VIBe applied to alpine environments. As input parameters, the value ranges obtained in Paper IV were used. The generation process resulted in 1,000 virtual cities with total population between 8,000 and 800,000.

These stochastic generated virtual cities have diverse characteristics and properties. Besides generating a multitude of water distribution systems, by applying the module to 1,000 different cases, this process is also a software test of this module.

7.3.2 Graph Concatenation Approach

In order to obtain the network structures of the virtual cities, the graph concatenation approach developed for the WDS Designer can be applied. But enhancements and additional features have to be implemented.

Layout Generation

The database of water distribution blocks, presented in Paper II, is used to generate the layout of the water distribution networks. But the GIS data of the urban structure module have to be adapted in order to represent housing densities. This was done based on GIS-data of land-use and population densities.

In addition, the river course has to be considered in the concatenation approach. Therefore, a parameter was introduced which indicates the probability of placing a block in river in order to connect by the river divided network parts.

According to the parameters for the layout generation in the WDS Designer (chapter 3), three different layout strategies were used in this study: entirely looped, intermediate and entirely branched.

Cell Size of the Blocks

Investigations on the impact of cell sizes of the network blocks on the distribution of pipe lengths is provided in chapter 3.2.7. It that chapter, it was determined that a cell size of 250m is appropriate. Based on these findings, for the generation process presented in Paper V, and based on the raster resolution in the urban structure module of VIBe (20m), a cell size for the networks block of 240m was used in this study (multiple of raster resolution).

7.3.3 Sources Strategy

According to alpine situations, two types of sources for the water supply networks were used in this study. On the one hand groundwater wells and on the other hand hillside springs were regarded. In Paper III, it was determined that three network sources are enough to ensure supply even under critical conditions. Therefore, initially 3 hillside sources are regarded in a generated water distribution system. Taking into account construction costs, groundwater wells are also used to supply urban areas which are not connected to hillside springs. To determine whether an area is supplied or not, an evaluation of the graph matrix (representing the entire water distribution system) is used. With this evaluation, unconnected areas can be identified with marginal computation time by means of graph theory.

Hillside Springs

The supply with hillside springs is usually gravity driven. Urban areas can be supplied with hillside springs without using any additional energy for pumping or at least with minimal energy requirements due to the elevated locations of the springs.

In alpine areas, due to the elevated location of these hillside springs, the water is, besides water supply, also used for energy generation with turbines. But these issues are neglected in this study.

Groundwater Wells

Usually, alpine valleys are affected by a river. Former glaciers formed deep valleys which are now filled with fluvial sediments. Usually, these sediments form groundwater reservoirs. Therefore, availability of groundwater in alpine valleys is ensured. For the placed groundwater wells, additional pressure heights (due to a pump) are regarded in the generation process, respectively in the pipe-sizing process. The groundwater table was considered as constant and the dropping due to wells was neglected.

7.3.4 Pipe-Sizing and Performance Evaluation

For pipe-sizing, the approach presented in Paper II was used. This approach takes into account economic flow velocities and a demand multiplier (representing peak factor and factor for future demand). To show an application example of the water distribution module of VIBe, the pipe-sizing approach (see chapter 2.4.3) was systematically investigated. For the systematic investigation and performance evaluation, performance indicators, described in Paper II, are used. Also, for cost estimations, the standard values presented in Paper II are considered in the water distribution module of VIBe.

7.3.5 Real World Case Study Data

To compare the generated water distribution system with real data, the characteristics of the real water distribution system of the city Innsbruck were used. The values for average residents, daily consumption per capita and daily average water flow were compared. The water distribution system of Innsbruck is mainly delivered from hillside springs. Groundwater wells are used for supply in case of accidents or catastrophes. Detailed data and discussion on this topic can be obtained from Paper V.

7.4 Results and Discussion

In Paper V the generated water distribution systems are statistically evaluated in regard of diverse characteristics (mesh degree (loops in the systems), total pipe lengths, construction costs, diameter distributions, hydraulic performance and water quality). With available data from the real world case study, the generated systems were set in context and it was shown that the real system is within the range of the generated.

As application example of the 75,000 generated water distribution systems, a systematic investigation of the used pipe-sizing algorithm, taking into account hydraulic performance and water quality, was performed in this study. Detailed results are presented and discussed in Paper V.

7.5 Outlook

It was shown that the water distribution module of VIBe can be a valuable tool to provide case study data for water distribution systems analysis. The generated systems can also be used for software testing. Therefore, further steps in the development of this module will include the systematic investigation of other pipe-sizing algorithms or even optimisation algorithms (in case of accurate computation time for a set of 3,000 systems). Further, it is intended to investigate skeletonisation approaches and to develop e.g. generic skeletonisation rules. Another intended application is to compare pressure driven solver with demand driven solver under regular and critical conditions in order to point out the differences and the applicability of the different solvers.

The water distribution module of VIBe is the first step in a new and innovative way of investigating water distribution systems. Therefore, at the current point of development of this module, there is a lot of potential for enhancement of the implemented models and approaches. E.g. to add stochastics to pipe-sizing (small intended errors) could help to investigate the linking of errors and their impact on the entire system. Also the implementation of demand patterns can contribute to better resemble reality and to allow additional types of systematic investigations (taking into account tank filling and emptying, et cetera).

For the implemented pipe-sizing process, the assumption was made, that the entire generated water distribution systems are in one single pressure zone. This simplification is intended to be faced in further developments of the water distribution modules of VIBe by adding valves and pressure zones to the design process. This is an important issue, because especially for alpine situations, pressure zone with pressure reducing valves are required. Further, the entire conception of this module is intended to be applied not only for alpine situations, but also to e.g. low land situations. This can be done by adding elements like tanks and pumps to the systems and to consider them in the pipe-sizing process.

For the generation process of further sets of water distribution systems, it is intended to include regional statistics of urban agglomerations in the generation process e.g. Inn valley characteristics (frequencies of different city sizes). Therefore, generic performance assessment, taking into account regional conditions, could be provided. Also, more complexity can be added to the pipe-sizing process, taking into account requirements regarding reliability and redundancy of important main pipes. Also the rectangular layout of the system can be enhanced with irregular grids. This can be done with the consideration of e.g. potential theory for transformation of coordinates. Therefore, with this enhancement the approach is capable to take into account a river orientated grid (alignment of housing blocks with different orientations along the river course).

Further, research has to be done in order to compare the generated systems with real world case studies. But data availability of these infrastructure case studies is still limited. Also, studies of coupling water distribution systems and urban drainage system with available data for road systems can contribute valuable knowledge on city infrastructure. Therefore, e.g. with the skeletonisation of street maps, possible layouts of water infrastructures can be obtained. Therewith, due to the same horizontal alignment of the infrastructure, coupled water infrastructure can be generated, enabling to set-up an integrated water cycle with e.g. reuse of rain water for water distribution, gray water reuse et cetera.

8 GEOTHERMAL ENERGY MODULE OF VIBE

The utilisation of geothermal energy as a renewable energy source has potential to reduce emissions from fossil energy consumption and therefore, to counter climate change (Fridleifsson, 2003; Bilgen et al., 2004; Fridleifsson, 2008). E.g. for heating and cooling of buildings sustainable geothermal energy could be used instead of non-renewable fossil energy. The potential of geothermal energy utilisation in this context is often assessed based on energy or mass balances. But how much energy demand for heating and cooling can effectively be substituted in highly populated areas cannot be assessed without taking into account technical aspects like housing structure, building standards, technical design guidelines or regional groundwater hydraulics.

As a practical example of the application of VIBe, the technical potential of the geothermal energy utilisation is determined. In contrast to a theoretical potential which is based on mass and energy balances, the determined technical potential also takes into account design-guidelines (technical design of wells and ground water heat pumps), numerical simulations and the housing strucutre. This is done by means of the VIBe-approach and stochastic scenario analysis (Paper VII).

In the following chapter, a brief introduction to geothermal energy utilisation and an overview of Paper VII and Sitzenfrei et al. (2010f) is given. In addition to the information presented in Paper VII, the implementation of the technical aspects of design-guidelines (ÖWAV-RB 207, 2009) and results which are based on numerical experiments presented in Sitzenfrei et al. (2010e , 2010f), Möderl et al. (2010a) are discussed. For the method to assess the theoretical potential of Paper VII, parameter sensitivity respectively the impact of model selection is investigated in this chapter. In addition, a critical reflection of the assumptions and neglected aspects of Paper VII is provided.

8.1 Geothermal Energy

The shallow geothermal energy is a renewable energy source which is primarily based on thermal regeneration from the sun and marginal from radioactive decay processes in the earth core (Sitzenfrei, 2007). But it has to be utilised in a sustainable way in order to conserve water quantity, temperature and therefore, also quality. To quantify the potential of geothermal energy utilisation different potentials have to be determined. On the one hand, there is the theoretical potential which can be determined with water and energy balances on a regional basis (Rauch and Stegner, 2004). On the other hand, there is a technical potential which takes into account available utilisation technologies, boundary conditions (e.g. settlement structure, building standards) and the impact of technical design guidelines and interactions and interdependencies of systems.

8.2 Ground Source Heat Pumps

There are different systems to utilise geothermal energy. E.g. with geothermal heat pump systems energy can be extracted (for heating purpose) or injected (for cooling purpose) in the ground or the groundwater in order to substitute energy consumption from non-renewable energy sources. This technology can be applied for shallow geothermal energy utilisation.

The temperature regime in the ground (in regard of shallow aquifers) can be utilised for buildings primarily for low temperature heating (Milenic et al., 2010) with heat pumps or for direct cooling. This means that primarily buildings with good building standards, accurate heating system and thermal insulation should be used for geothermal heating utilisation (ÖWAV-RB 207, 2009). Ground and groundwater temperatures are impacted by fluctuating surface temperature (which corresponds with air temperature) to a depth of about 10 to 15 m (Taylor and Stefan, 2009). This is also denoted as buffer zone for the atmospheric temperature fluctuations (Figure 50). Below this depth and in regard of shallow geothermal energy there is approximately a constant temperature.

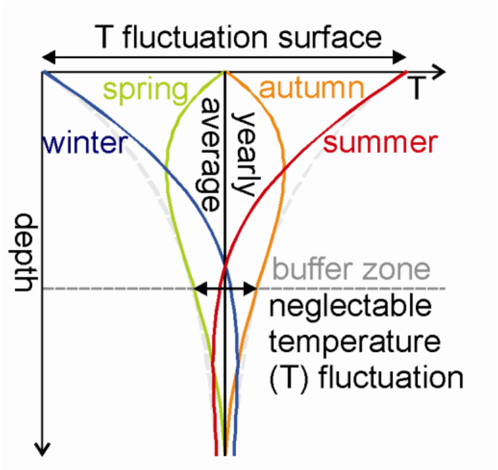


Figure 50: Temperature (T) fluctuation/distribution in ground and groundwater

In temperate climate zone the yearly average of the surface temperature is about 10 to 15°C. Therefore, by installing the system below certain depth (below the atmospheric buffer zone), water or the soil with the constant temperature of the yearly average can be utilised for heating in winter (with a heat pump) and cooling in summer (Polyzakis et al., 2008). In regard of utilisation of deep aquifers the geothermal gradient (temperature rise with increasing depth, approximately 3K/100m) has to be considered.

8.2.1 Systems for Geothermal Energy Utilisation

There are different systems for geothermal energy utilisation with ground source heat pumps (for a detailed overview see e.g. Omer, 2008 or Lund et al., 2005). On the one hand, there are ground coupled heat pumps (closed-loop heat pumps) which utilise the temperature in the soil (e.g. Bernier, 2006; Yang et al., 2010). On the other hand there are ground water heat pumps (open-loop systems) which extract groundwater from an aquifer (with a production well) and re-inject the utilised water in the aquifer (with an injection well). Such systems require groundwater flow respectively enough distance between production and injection well to provide unaffected groundwater. Otherwise the thermally utilised water is re-circulated in the system which leads to a hydraulic/thermal short-circuit (Möderl et al., 2009c and see Figure 51).

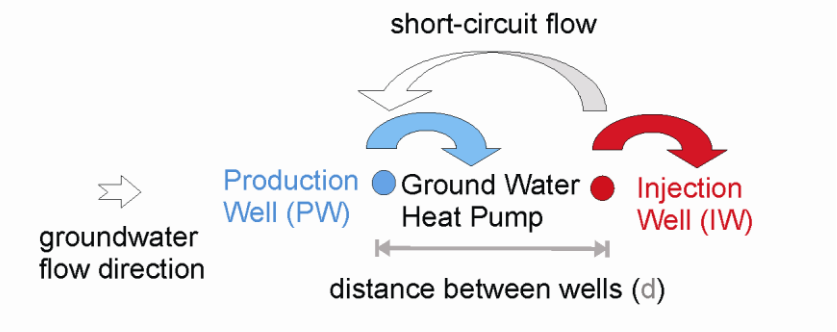


Figure 51: Schema of a groundwater heat pump and short-circuit

8.2.2 Temperature Anomaly in Groundwater

In order to determine the thermal impact of geothermal energy utilisation on the temperature regime in the ground, numerical groundwater modelling is state of the art (Ozgener and Hepbasli, 2007; Rauch et al., 2009a; Fairley et al., 2010). Anyhow, depending on the national guidelines there are different approaches applied with varying complexity to determine the temperature anomaly (Rauch et al., 2009b) in order to ensure a functionality and efficiency of systems and also to preserve groundwater quantity and quality.

The impact of a ground water heat pump on the temperature regime of the groundwater declines approximately exponentially with increasing distance from the injection well. In regard of a geothermal utilisation of the groundwater, a change in groundwater temperature of e.g. 0.1°C is insignificant. Therefore, to identify/determine a temperature anomaly as technically not negligible, a tolerable temperature difference to the unaffected groundwater has to be defined (Figure 52). This temperature tolerance has a significant impact on the expansion of temperature anomalies (critical reflection of the temperature tolerance see Sitzenfrei et al., 2010f). In this study a temperature tolerance according to Austrian guideline ÖWAV-RB 207 (2009) of 1°C is used (Figure 52).

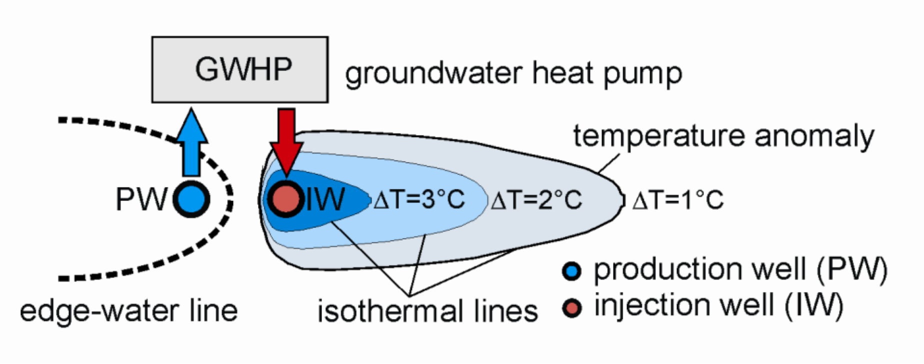


Figure 52: Definition of a temperature anomaly

8.2.3 Numerical Models to Determine Temperature Anomalies

To determine the spatial extension of such a temperature anomaly different approaches are used:

- standard values (e.g.: Sorensen S. N. et al., 1985; US-EPA, 1999)
- simple analytical equations (e.g. Kobus H. and Mehlhorn, 1980; Sorensen S. N. et al., 1985; Rauch, 1992)
- iterative semi analytical models (Ingerle, 1988)
- 2-dimensional models with simplified decoupled hydraulics (Kinzel et al., 2007), with enhanced but decoupled hydraulics (Rauch and Kinzel, 2009) or empirical consideration of third dimension (Sitzenfrei et al., 2010c)

- complex 3-dimensional numerical models with coupled consideration of water and heat transport (e.g. Kipp Jr., 1997; Diersch, 1996).

But application of a complex numerical model often is (especially for small geothermal systems) an unreasonable effort. This can lead to inefficient energy exploitation of the small geothermal systems (Sitzenfrei et al., 2009a). These effects can occur due to poor placement strategy, poor system spacing (Möderl et al., 2010a) or interactions and interdependence of systems (Sitzenfrei et al., 2010e). For that purpose, a database of thermal plumes is developed in Sitzenfrei et al. (2010f) in order to provide results of a complex model also for small geothermal systems.

In Sitzenfrei et al. (2010f), thermal plumes based on the results of simulations with the 3dimensional mathematical model HST3D (Kipp Jr., 1997) of a set of 864 different configurations (parameter variations) are determined. Subsequent, the results are systematically analysed in order to develop a database for small geothermal systems. In addition, the results are compared with results following approaches in guidelines (ÖWAV-RB 207, 2009; US-EPA, 1999) and suggested standard values (Sorensen S. N. et al., 1985). It was shown that especially for small systems (thermal plumes shorter than 100m) there is a significant underestimation of the thermal plumes with the method proposed in ÖWAV-RB 207 (2009).

8.3 Generation Process

The aim of this systematic investigation is to determine the effective potential of geothermal energy utilisation, taking into account the state-of-the-art design rules, varying boundary conditions and housing patterns. The study focuses on open-loop geothermal systems for alpine areas with a fast flowing aquifer (filtration velocities between 5 – 50 cm/d; pore velocities between 25 – 250cm/d).

8.3.1 Placement of Open-loop Heat Pump Systems

A general requirement for new open-loop heat pump systems is that all water supply utilities have to be unaffected. Especially to ensure water supply in case of catastrophes, deep groundwater storey have to remain unaffected (ÖWAV-RB 207, 2009). Therefore, only the groundwater storey closest to the surface can be used for open-loop heat pump systems. Besides these general requirements, the open-loop geothermal systems need to be properly spaced inside the systems (distance between production and injection well, denoted spacing in systems) and between entire systems (intersystem spacing).

Intersystem Spacing

Before installing new groundwater heat pump systems the resulting temperature anomaly has to be determined. According to the Austrian guideline, a restriction of existing systems is forbidden (ÖWAV-RB 207, 2009) or in other words: water rights are giving according to first-come, first-served principles, already installed systems have to remain unaffected. A new system can be placed in the thermal affected area (therefore in a temperature anomaly) of an existing system, but this is in case of same operation mode (in this case heating) inefficient.

If a system (subsequent system in Figure 53) is placed at the end of a temperature anomaly (defined with the temperature tolerance of 1°C), it uses water which is affected (1°C) by the upstream system. The Austrian guideline ÖWAV-RB 207 (2009) demands that the injected water has to have an absolute temperature of at least 5°C (anyhow for such cold temperature the operation of a heat pump system is hardly efficient). Therefore, if both systems (upstream and subsequent system) utilise the same temperature difference (e.g. 3K and an unaffected groundwater temperature of 10°C) the temperature after the first system is 7°C, at the end of the first temperature anomaly 9°C (which is also the temperature at second production well). The unaffected groundwater temperature is defined as the temperature in the production well and therefore this effect sums up.

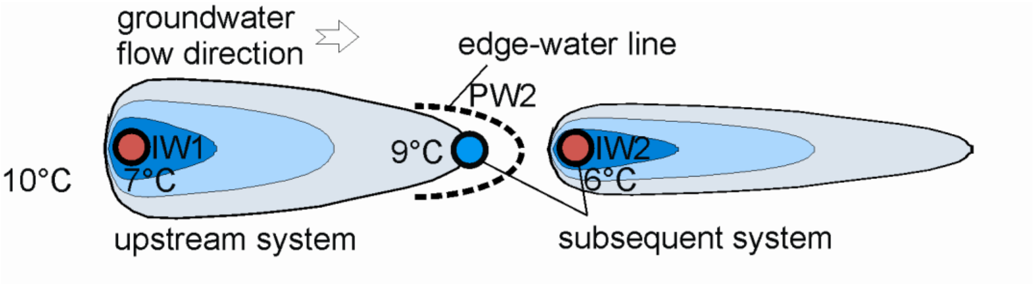


Figure 53: Subsequent open-loop systems

Following this idea, the next subsequent system has an injection temperature of 5°C and the next system cannot utilise the temperature difference of 3K. This effect only occurs in densely populated areas but in the course of this study, this has to be considered.

Another effect is caused by the change of hydraulic flow regime due to placement of a new system. Usually, the temperature anomaly of an upstream system is determined with an unaffected flow regime. If, at the end of a determined temperature anomaly, another production well is placed, the existing temperature anomaly is long drawn-out in flow direction (change in flow regime)

Therefore, to cope with these two effects in this study, the heat pump systems are designed with a temperature difference of 3K, but the temperature anomaly is determined with a temperature difference of 5K.

To assess the intersystem spacing (length and width of temperature anomaly) the database presented in Sitzenfrei et al. (2010f) for small geothermal systems is used (864 configurations). In addition, this database is enhanced with mid-size and large geothermal systems (in total 3456 configurations).

Spacing in Systems

An open-loop heat pump system consists of a production well and an injection well (Figure 52). The capacity of both wells is determined by the aquifer properties and the length of the filter pipe. In a complete well, the length of the filter pipe is equal to the aquifer height. If the filter pipe is shorter, the well is an incomplete well. With the required heat demands, the well flows can be determined and further, with the well flows the lengths of the filter pipes can be designed.

If the production well and the injection well are placed too close together, a hydraulic respectively a thermal short-circuit may occur. Möderl et al. (2010a) presented an empirical equation to determine the spacing between injection and production well. In this study the empirical equation is used.

Another distance requirement is that the two required wells of the system fit to the available building lot. The sizes of the building lots are assessed based on the different housing structures (see 8.3.2).

8.3.2 Scenario Definition

To investigate the impact of housing structure and housing standards on the technical usable geothermal potential, analyses based on stochastic scenarios were performed.

The efficiency of open loop systems is higher than with closed loop systems (high specific heat capacity of water can be utilise with the wells). But to install open loop systems, an aquifer with sufficient convective flow (water yield) is required due to technical design principles (well spacing, groundwater level dropping, et cetera). In this study, Alpine case studies with convective groundwater flow in the valley floor are investigated.

Housing Structure

Settlement areas of 1,000m times 1,000m with different housing densities were investigated (see Paper VII). In total 5 different housing densities for monotone housing (single-family houses (2 different types), multi-family houses, and 2 types of for rows of houses) and 2 mixed housing forms were investigated.

The settlement area is divided into city blocks of about 120m times 120m with different building lots according to the housing densities. For the settlement areas different buildings standards and therefore, with different thermal insulations and energy consumption for heating were investigated. Different building standards and power demand per area for heating were chosen according to the Austrian guideline (ÖWAV-RB 207, 2009). For old buildings (75W/m²), new buildings (40W/m²) and passive house standards (15W/m²) were chosen. With a heating period of 2,000 hours per year and standard values for usable living area, the required energy consumption for each building lot is determined.

Heat Pump Design

With the required energy demand the open-loop heat pumps systems for each building lot can be designed (amount of well water and temperature spread). In addition scenarios were defined in which the energy requirements of building lots were centralised supplied. Therefore variations in grouping factors (between 0 and 100%) for systems were used indicating how much of building lots in a city block are supplied with a centralised heat pump system.

Aquifer Properties

The assumption that the investigated area is in an alpine area was made. Variations in the thickness of the surface and aquifer layer were neglected. Therefore, constant thicknesses for the surface layer of 5m and for the aquifer layer of 25m were assumed. Also the groundwater slope was assumed to be constant (0.001 m/m) without changing flow direction. Variable flow directions and changes in flow direction over year (due to e.g. different water levels in surface water) have significant impact on which areas are affected by temperature anomalies. The assessment of the geothermal potential is based on the evaluation of area which is occupied by groundwater anomalies and therefore, the changes in flow direction only have marginal impact on the regional geothermal potential. Hence, in this context variable flow directions can be neglected.

The longitudinal dispersion of modelling task of this modelling scale can be assessed with 10m (Gelhar et al., 1993). All parameters for thermal properties of the ground and groundwater are set to standard values recommended in the Austrian guideline (ÖWAV-RB 207, 2009). The hydraulic conductivity is varied with two sampling points: 0.005m/s and 0.0005m/s and the ratio of horizontal to vertical conductivity is assumed to be 2(-), which is close to isotropic conditions.

Scenarios

In the first part of this study, the impact of building densities, building standards and hydraulic conductivity are investigated. For each of the 7 building densities, 3 different building standards and 2 different values for hydraulic conductivity the placement strategy (following the rules defined in chapter 8.3.1) is applied. To ensure that the sequence of placement does not impact the results, the placement strategy is applied 100 times with random starting for each scenario. In total there are 7 x 3 x 2 x 100 = 4,200 samples for this investigation.

The second part of the investigation includes the impact of grouping of single systems to centralised systems. For the 5 monotone building densities, 3 different building standards, 2 different values for hydraulic conductivity were investigated with 1,000 random samples for the grouping factor. The grouping factor determines how much building lots in a city block are supplied with a centralised geothermal system. In total there are 5 x 3 x 2 x 1,000 = 30,000 samples for this investigation.

8.3.3 Determining the Theoretical Potential

In addition to Paper VII a sensitivity analysis of the method to determine the theoretical potential is shown in this chapter. The theoretical potential can be determined by balancing the volume flux with the corresponding temperatures and therefore the energy flux over a control volume (Figure 54). There are two controlling energy fluxes regarded in this context: the convective flow which is determined with inflow to and outflow from the control volume (inflow with the unaffected groundwater temperature (T_{IN}) and outflow with temperature T_{OUT}, neglecting volume storage) and the energy inflow to the system due to solar radiation (solar regeneration). In the context of this study, infiltration and exfiltration of surface water (e.g. from a river) are neglected. Also rain water infiltration is not regarded in this context.

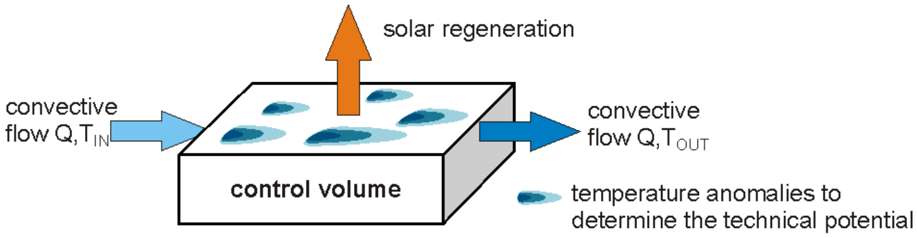


Figure 54: Regarded control volume, energy and mass balance

The energy flux introduced by the sun can be described with the unsteady 1dimensional differential equation for heat transfer. Under several assumptions this can be described with an approximation for the steady heat transfer (see Sitzenfrei, 2007). With this model, two boarder cases can be described: an approximation for the solid heat transfer and an approximation for the fluid heat transfer (Figure 55). In Rauch (1992), a bilinear approximation is proposed for geothermal applications (Figure 55) and anisotropic ground characteristics. In the fluid model, there is the assumption that there is a mixture of water with different temperatures to an overall temperature. The mixture is ensured if the ground characteristics are isotropic.

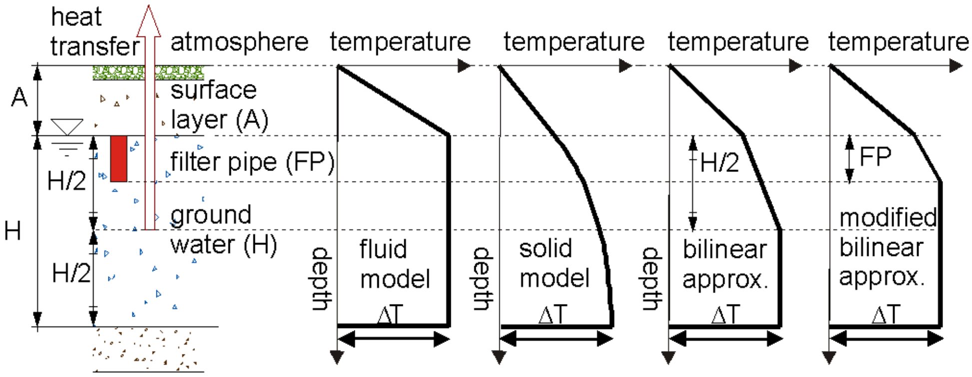


Figure 55: Approximations for heat transfer model

For anisotropic ground characteristics (horizontal to vertical conductivity), the mixing of the groundwater is not correct. In that case, the solid heat transfer model provides better results. In that study a combination of both models would be accurate. Rauch (1992) proposed to use the bilinear approximation. In Paper VII, a combination of the fluid model and the bilinear approximation was used (Figure 55, right). Consecutively, a sensitivity analysis of the different heat transfer models is shown.

To determine a regional potential, an average temperature difference to the unaffected groundwater temperature of the entire region has to be used. Following the idea of Rauch and Stegner (2004) of a exponential decline of the temperature difference with increasing distance from the injection well, a substitution area with a constant temperature is used (Figure 56). With the temperature spread T_i in the injection well and a tolerable temperature difference ΔT the averaged temperature difference T_a for the substitution area can be calculated with

$$T_a = \frac{(\beta - 1)}{\ln(\beta)} \cdot T_i \text{ and } \beta = \Delta T / T_i$$

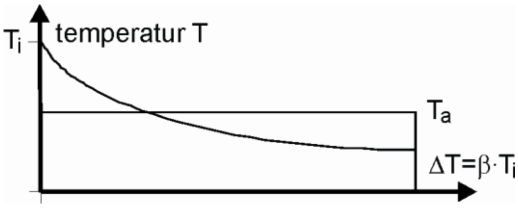


Figure 56: Determining the averaged temperature difference

For T_i=3K and ΔT=1K the averaged temperature difference is T_a=1.8K. The thermal regeneration rate with the different models for a settlement area of 1,000m times 1,000m is shown in Table 2.

Table 2: Thermal regeneration rates for different heat transfer models for 1km²

Model Description	Regeneration Rate (kW) Ta=1.8
Fluid model	360
Bilinear model (temperature gradient to half of the aquifer, in this study 12.5m)	160
Combination of fluid and bilinear model (temperature gradient to half of the filter pipe, in this study 5m)	240

The convective heat transfer (due to water transport with natural flow velocity) can be calculated with the filtration velocity and the aquifer cross section area (continuity equation). For a hydraulic conductivity of 0.005(m/s) a ground water flow of 0.125(m³/s) can be determined. Also the potential utilisation P(W) for variable tolerable temperature differences can be calculated with the groundwater flow Q(m³/s) the temperature difference T_a and the specific heat capacity of water c = 4.2e06 (J/m³K)

$$P = Q \cdot T_a \cdot c$$

The potential of the convective transport with an average temperature difference of T_a=1.8K can be calculated with 945(kW). Exemplarily, for three housing densities (Table 3) with different building standards the different theoretical potentials were determined and the supply rates were compared with the technical potential in Paper VII (see 8.4.1).

8.4 Results and Discussion

The results of the systematic investigations in detail can be looked up in Paper VII. In this chapter, a few striking examples of the results are shown. Exemplarily, the resulting temperature anomalies of a section of a scenario are shown in Figure 57.

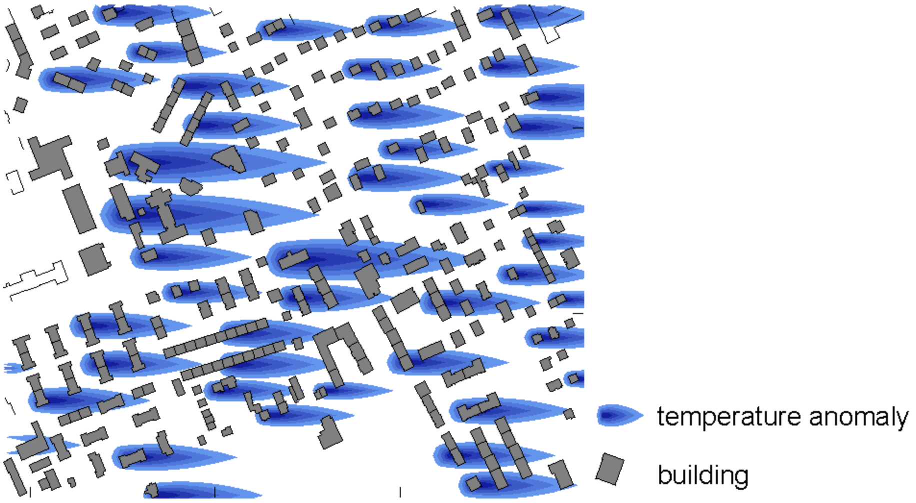


Figure 57: Visualisation of a scenario to determine the technical potential

Special attention is drawn to the critical reflection and discussion of the proposed methodology at the end of this chapter.

8.4.1 Geothermal Potentials

Different geothermal potential respectively different impacts on the geothermal potential are investigated. On the one hand there is the theoretical potential which is based on energy balance, and on the other hand, there is the technical potential and the impact of the building standards, housing densities and the grouping factor.

Theoretical Potential

In addition to Paper VII, different theoretical potential were determined and a sensitivity analysis of the parameters, the used models and assumptions was made. In Table 3, the supply rates for five different scenarios are shown.

The listed supply rates in Table 3 compare the technical potential with the theoretical one. A value over 100% in Table 3 indicates that the technical potential exceeds the determined theoretical one. Values over 100% therefore, reveal that the approach (solar regeneration model) is inappropriate to be compared with the approach for technical potential.

It is also revealed that the solar regeneration model has a significant impact on the resulting supply rates. For example for the passive house standard the theoretical potential obtained with the fluid model and the one with the bilinear model differs with a factor of 2.25 (288/128).

Table 3: Different utilisation scenarios with supply rates compared to theoretical potential (technical potential/theoretical potential)

Description	Passive house standard (%)	New building standard (%)	Old building standard (%)
Scenario 1: solar regeneration with fluid model	128	112	136
Scenario 2: solar regeneration bilinear model	288	252	306
Scenario 3: solar regeneration bilinear model with adaption	192	168	204
Scenario 4: Scenario 1 + convective transport	35	31	44
Scenario 5: Scenario 2 + convective transport	42	36	37

The potential due to convective flow for the investigated region is not regarded in the study to determine the technical potential. Taking into account the convective transport (scenario 4 and 5) to determine the theoretical potential and compare it with the technical is therefore not appropriate. Anyhow, to quantify the impact these two scenarios (4 and 5) are listed in Table 3.

With the fluid model (scenario 1) the best agreements of the theoretical potential with the technical can be achieved (differences between +12% for new building standard and +36% for old building standard). But the theoretical potential should exceed the technical one. Therefore, with the results in Table 3 it is revealed that the method to determine the technical potential includes discrepancies. This difference can be traced back to following reasons:

- In the 3-dimensional calculations, the thermal plume is determined with a tolerable temperature difference of 1K. In the investigated system, the energy which is introduces with a temperature differences below 1K is therefore neglected. This means that also in the approach to determine the technical potential, this amount of energy is neglected. A consideration of that amount of energy would therefore decrease the technical potential.
- The model for the solar regeneration in the theoretical potential does not correspond with the model in the 3-dimensional numerical simulations (database of thermal plumes) (detailed model in contrast to models described in 8.3.3) and therefore, there is an underestimated thermal regeneration

Investigations concerning these points will be next development steps. Anyhow, the proposed approach is a first step for the evaluation of technical usable regional geothermal potential.

Impact of Building Standard and Housing Density

The supply rates (ration of heat provided with geothermal energy to total heat demand) for different building standards were determined. The described values of percentages are median values of the 100 samples (see 8.3.2). For old building standards the supply rates range (significant impacted by the hydraulic conductivity) from 22% to 4%. For passive house standard up to 69% of the required heat can be supplied with geothermal energy.

The different housing densities also have significant impact on the supply rate. E.g. for new building standards and for a hydraulic conductivity of 0.005 (m/s) the supply rate of the different housing densities varies from 31% to 9%.

It was determined that a reduction of the heating demand cannot directly be transferred to supply rate. Hence, a reduction of the heating demands for single-family houses with old building standard (75W/m²) to passive house standard (15/m²) with energy reduction factor of 1/5, leads to an increase of supply rate of a factor of 3 (8.2% to 25.3%). This clearly indicates the impact of the technical aspect on assessment of geothermal potentials.

In addition, the sum of well flow for the scenarios was analysed. The sum of well flows in systems with passive house standard is significantly lower (maximum 0.19 m^3/s) than for old building standards (maximum 0.37 m^3/s). This effect occurs because the passive house systems are small geothermal systems with little well flow and therefore with short filter pipes (incomplete wells, see also Sitzenfrei, 2007). Therefore, only a part of the entire aquifer is used. In contrast, for systems with old building standards, almost the entire aquifer is utilised (complete wells).

To compare the determined well flows based on the energy balance with the well flows based on the scenario analysis, the well flows have to be averaged. The theoretical well flow (usable groundwater due to solar regeneration and regional tolerable temperature difference) is based on yearly water consumption. For heating purposes, the operation time of the systems is in temperate climate and good building standard approximately 2,000 hours. To compare the peak well flows in winter with the theoretical flow of the energy balance, the peak flow has to be yearly averaged (multiplied with factor 2,000/8,760).

Impact of Grouping Factor

The simulation results for different grouping factors showed that centralised systems which supply entire building blocks in general, provide a better supply rate. This is the same effect as for different building standards (bigger systems with complete wells perform better than small systems with incomplete wells).

8.4.2 Critical Reflection of the Proposed Method

For the assessment of the geothermal potential several assumptions were made and various effects were neglected. Usually, the surface layer is dry and hence, like a thermal insulation. A constant layer of 5m leads in many cases to an underestimation of the heat transfer due to solar radiation. Also the fluctuation of the groundwater level over the year impacts solar regeneration. In particular in summer, there are higher groundwater levels and therefore the solar regeneration is even enhanced. These effects which could increase the technical geothermal potential are neglected in the proposed method.

In the estimation of the theoretical performance the convective transport was neglected (inflow to and outflow from control volume) (Paper VII). A regional thermal impact of geothermal utilisation up to 3K usually does not impact water quality, vegetation or fauna (Rauch and Stegner, 2004). Taking into account the convective transport and allowing a tolerable temperature difference at a regional basis up to 3K, would result in a significant higher geothermal potential. The theoretical geothermal potential determined in this thesis raises several questions, concerning which model to use and model consistence. It is proposed for further studies to intensively investigate model uncertainties and optional use an integrated model for all evaluations, hence, a complex 3-dimensional model with all systems in one calculation model to reproduce system interactions and coherences. For investigations of geothermal potentials at a regional basis, it is recommended that for a tolerable temperature difference 0.5K or even 0.25K is used.

For different building standards the performance of geothermal systems is variable. For old building standard the geothermal systems are not efficient (ÖWAV-RB 207, 2009). The investigation should be made considering energy demands and efficiency of the systems (Coefficient of Performance, detailed discussion can be found e.g. Li et al., 2008). With strategic regulatory approval of geothermal systems for good building standards could also increase geothermal potential.

Another neglected aspect is that especially office buildings and shopping centres utilise groundwater for cooling, even in winter. Therefore, the injection of warm water is not considered in this study. A consideration of this effect would result in a better energy-balance and a higher geothermal potential.

In the water and energy balance, the impact of surface water infiltration (colder water in winter, better regeneration in spring) is also neglected. But considering all these effects would require a complex numerical model and a comprehensive amount of measurement data for calibration. Without measurements and detailed numerical simulations it is not possible to determine if these effects increase or decrease the geothermal potential.

8.5 Outlook

The application of a complex numerical model requires a lot of computation power. For scenario based analysis of detailed technical geothermal potential, computer power is a limiting factor. Also the data requirements to calibrate the system and the efforts to develop such a model are still very intensive. Therefore, a database with numerous assumptions and neglecting several effects is a first stepping stone in such regional assessments of geothermal potentials. Further progress in computational power and new measurement methods could enable a more realistic consideration of all the neglected effects.

Various effects which were neglected in this study could result in a higher geothermal potential. In further analysis, these effects should be considered. Especially the injection of warm water due to cooling of office buildings and shopping centres are considered to improve the geothermal potential significantly.

To provide more holistic results, further development of the models should be based on the entire energy balance and therefore, also consider coefficients of performance of the heat pumps.

9 DYNAMIC VIRTUAL INFRASTRUCTURE BENCHMARKING – DYNAVIBE

The VIBe approach, as presented in the chapters 4 to 8, allows investigating stationary systems only. Hence, generated systems represent one certain point in time. This is a clear shortcoming, because the dynamics of the systems are both, influential to the performance assessment and also influenced in itself by the measures investigated. The tool DynaVIBe (Dynamic Virtual Infrastructure Benchmarking) aims to solve these shortcomings. Since the virtual case studies generated with VIBe represent a certain state of time, the objective of DynaVIBe is to extend VIBe with dynamic development algorithms (consideration of time). In the development algorithms - which represent real world processes - the virtual infrastructure as well as the city development is included. Therefore, the temporal development of the infrastructure based on the development of the city can be simulated and data is provided for case study analysis. These development algorithms take into account e.g. change processes in urban structure and infrastructure initiated by population growth or decrease. Furthermore, aspects like change of the amount of impervious areas connected to the sewer system due to the influence of new legal standards can be simulated dynamically.

The aim, conception and potential applications of DynaVIBe is described in Sitzenfrei et al. (2010b) which is an integral part of this thesis (Paper IX). In this chapter, the motivation and aim is specified in more detail. Further, special focus of this chapter is on required enhancements of the approaches implemented in VIBe and to discuss DynaVIBe in context with existing approaches.

9.1 Motivation and Aim

Three major aims of DynaVIBe can be defined. The first major aim is to provide numerous virtual case studies including temporal development (chapter 9.1.1). Due to the temporal development represents real world case studies, the DynaVIBe approach can also be applied to real world case studies for stochastic analysis of development scenarios (chapter 9.1.2). This is the second major aim of DynaVIBe. The third aim arises from the implementation of a complex population model in the approach. Therefore, the impact of socio-economic processes on technical infrastructure and vice versa can be modelled and investigated, compared to VIBe, in a more accurate way (chapter 9.1.3).

9.1.1 Virtual Case Studies with Temporal Development

DynaVIBe provides the feasibility to test the dynamics of new technologies, strategies or measures in a virtual environment with a close relation to real world. Compared with the time and effort required for collection of real world data, the proposed methodology has significant advantages. Analysis can be performed at an earlier point of development (of e.g. a new technology) and hence, the potential impact of measures can be determined sooner and with less effort. This provides a more cost effective and goal-oriented way of analysis. Basic questions of environmental engineering, such as - which urban drainage system is more reasonable (combined or separate systems) or what is the impact of a new technology on the entire system - can be investigated. Unlike evaluations based on only few real world case studies, analysis with DynaVIBe can be performed with varying boundary conditions taking into account temporal development. Further, questions of e.g. uncertainties in urban water models can be faced (see also Paper IX).

As simulations in DynaVIBe are dynamic over time, interactions of urban structure and infrastructure can also be investigated in a virtual environment. E.g. in the field of urban drainage, the decrease of the amount of connected catchment area (caused by regulating authority pursuing a decentralised rain water infiltration strategy) can be assessed and optimised. This evaluation can contain varying urban infrastructure, topography, class of population et cetera. The class of population contains socio-economic aspects as income level and the willingness to implement new regulatory guidelines. Therefore, the spatio-temporal process of implementation (technology diffusion process) can be analysed as well. The obtained results are expected to be comprehensive and can help decision makers to control such processes in real world cities, respectively, can outline complex effects.

9.1.2 Stochastic Scenario Analysis of Real World Case Studies

In Figure 58 exemplarily, scenario analysis of a virtual combined sewer system is shown. Starting from current state (e.g. 2010) different scenarios (e.g. 2020, scenario A, B, or 2030 et cetera) can be stochastically generated for investigations.

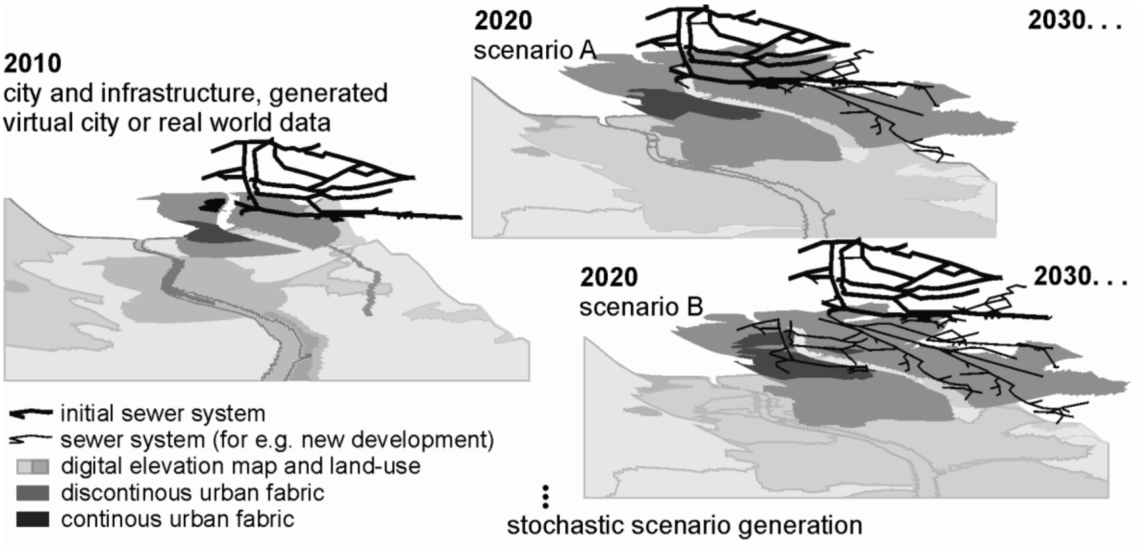


Figure 58: Stochastic scenario analysis with DynaVIBe

Thus, the DynaVIBe approach can also be applied to real world case studies (the generated current state is substituted with a real world case study) in order to stochastically investigate e.g. development scenarios or climate change adaption strategies. Therefore, scenario-based analysis of real world case studies, taking into account pressure from population (socio-economic impact), technical aspects (detailed infrastructure) and time dependent evaluation can be performed (socio-technical software tool, see also 9.1.3).

9.1.3 Socio Technical Software Tool

Modelling the water cycle taking in to account socio-economic processes is a challenging task. Especially, investigations based on agent based modelling techniques have the potential to manage such spatial-distributed and dynamic systems (Moglia et al., 2010). Investigations on the impact of climate change have to be done on a large temporal scale. To estimate e.g. the impact of climate change on our environment requires therefore, the inclusion of the temporal change of demography and infrastructure in the investigations. E.g. Barth et al. (2004) investigated these aspects on the Upper Danube Catchment with a multi-actor simulation framework denoted DANUBIA including agent-based approaches. To assess the impact on the entire water cycle, scenario analyses were performed with this modelling framework. For e.g. water supply, the model was used to evaluate water supply strategies on a catchment level (Barthel et al., 2008).

Parker et al. (2002) described the need for integrated assessment and modelling of environmental processes. Interdisciplinary is described to be the key to address environmental problems of the 21th century which has to be further improved (Pahl-Wostl, 2007). Therefore, the aim of DynaVIBe is to combine existing approach from engineering (stochastic analysis of infrastructure scenarios) and geographical research (development scenarios of cities, conceptual urban water cycle).

The approach described above (DANUBIA), basically analyses the water cycle on catchment levels. The aim of DynaVIBe is to provide a tool for investigating these issues from an engineering standpoint and therefore, a more technical point of view. This means that detailed infrastructure systems (network systems), designed according to the state-of-the-art design rules as well as city and population development are implemented in the approach and can also be regarded in the analysis process. Therefore, a socio-technical software tool taking into account detailed infrastructure is provided. This is considered to be the third aim of DynaVIBe.

9.2 Enhancement of VIBe to DynaVIBe

In this chapter it is described, how the conception of VIBe has to be enhanced in order to achieve the proposed aims and goals of DynaVIBe. The first task is the implementation of an Urban Simulation model in order to model real world change processes of the urban structure (9.2.1). A second enhancement is that module assumptions, made for the application of VIBe on alpine case studies, have to be reconsidered in order to ensure applicability to other topographic boundary conditions. Therefore, these assumptions are described (chapter 9.2.2) and it discussed how these issues can be enhanced (chapter 9.2.3). Finally, it is discussed how the conception/framework of VIBe has to be adapted (chapter 9.2.4) in order to cope with all the proposed modelling tasks (temporal development and modelling framework).

9.2.1 Implementation of an Urban Simulation Model

To describe a system like a city in geographical information system (GIS) the grid based representation with cells is widely applied. To model phenomena related to raster-based data imply the use of grid based models like Cellular Automata or agent-based models (see also 6.2). With these approaches complex temporal processes in urban systems can be modelled (Batty et al., 1999; see also Paper IV and Paper IX) by means of simple, flexible models (Santé et al., 2010). Especially in earth science and geography, spatio-temporal models which simulate change over time, are widely applied (Karssenberg et al., 2010).

Different urban simulation models are available, to some extent even open source. Waddell (2002) presented the open source urban simulation model UrbanSim. This management tool for urban growth can model dynamics annually taking into account, inter alia, demographic and economic transition, household and employment mobility, real estate development and land price spatially distributed (CUSPA, 2009). Clarke et al. (1997) described a cellular automaton urban growth model which uses multiple data sources (topography, land-use, road networks). The model was denoted SLEUTH. The abbreviation SLEUTH stands for a Cellular Automaton based model which takes into account six input layers: slope, land cover, exclusion, urbanisation, transportation and hill shade. The SLEUTH model was applied in various studies (e.g. Jantz et al., 2004; Chen et al., 2006; Rafiee et al., 2009; Wu et al., 2009b; Xi et al., 2009; Jantz et al., 2010). Anyhow, calibrating such cellular automata models for land-use change and urbanisation with real data is a challenging task (Maria de Almeida et al., 2003).

Coupling urban simulation models with other models got more applicable due to increasing knowledge on those systems and available computer power.

Arthur-Hartranft et al. (2003) demonstrated coupling the SLEUTH model with an satellite-based microclimate and hydrologic analysis to determine the impact of urban growth on water resources (temporal change of run-off coefficients driven by land-use change).

Polebitski and Palmer (2010) coupled a water demand model and an urban simulation model (UrbanSim, Waddell, 2002; CUSPA, 2009), in order to forecast detail spatially distributed water demand. The approach was applied to the Puget Sound Region of the United States with a population of over 4.2M and a +10% change in population from 2000 to 2008. From 2000 to 2040 a population increase of 1.7M is expected for that region. With this study it was revealed that an increased housing density in the investigated region reduced peak summer demands due to decreased yard spaces.

Also decreasing population and adaption strategies are a challenging research task. In Haase et al. (2010) agent-based modelling techniques were used to model residential mobility in shrinking cities. Tillman et al. (1999) applied an agent-based approach to model actors in water supply systems to reveal dynamics and their interactions. Based on game theory Madani (2010) illustrated how the parties and their behaviour can be modelled and how they individually and interactively cause problems in water resources management. van Oel et al. (2010) demonstrated how multi-agent simulations can be used to model distribution of water availability spatio-temporally.

In Shafiee and Zechman (2010) a modelling framework was presented to simulate contamination events in water distribution systems. Therein, agent based modelling was used to simulate consumers, their water consumption and consumer interactions. If such a consumer is exposed to a contamination, it changes its consumption behaviour and communicates with other consumers and decision-makers. Therefore, a spatial distributed water distribution network was coupled with an agent based modelling approach. The entire modelling framework was applied to the virtual city Mesopolis (Johnston and Brumbelow, 2008).

The examples described above showed different applications of coupling urban simulation models with other models, in order to investigate dynamics with more integrated approaches. Further, it was shown that open source urban simulation models are available. The description of DynaVIBe in this PhD project is conceptual and can also be seen as outlook to VIBe. Therefore, it is recommended for the further project development, to make a detailed literature review on existing urban simulation software. Potentially, instead of developing a new simulation model, an existing one can be adapted and implemented in the DynaVIBe approach.

9.2.2 Module Assumptions in VIBe

Numerous assumptions and simplifications were made in the generation processes implemented in VIBe. All modules focus on the generation of virtual case studies in an alpine region which are characterised by an elongated settlement in a U-shaped valley. However, the urban structure module as well as the infrastructure modules can be adapted for other boundary conditions. The sewer module does yet not include pumps and different cross-section shapes for the conduits. The design of the sewer network thus bears potential of improvement (e.g. implementation of these neglected elements or design of the combined sewer overflow structures).

The generated water distribution systems have diverse characteristics and properties, but there are assumptions and simplifications in the presented approaches. The generated water distribution systems represent alpine case studies in which the water distribution is only gravity driven and the hydraulic analyses were made under regular conditions. Further, demand patterns are not regarded. Therefore, elements like tanks and pumps are presently not considered in the approach. The assumption was made that the entire generated water distribution system has one pressure zone and therefore, no regulating valves are required.

Another important issue which is neglected in the infrastructure modules of VIBe is the consideration of different climatic conditions. Therefore, a weather and climate generator is considered to be important taking into account also climate change (e.g. changed water demand, different rain characteristics, et cetera).

9.2.3 Module Enhancements

To ensure that DynaVIBe can also be applied to a broad range of boundary conditions (amongst others e.g. for lowland or different climatic conditions) some technical aspects of the modules have to be improved.

Urban Structure Module

The urban structure module has to be tested under different boundary conditions or has to be enhanced to cope with other topographic boundary conditions, respectively. In addition, the urban structure module has to generate all required data for a more complex urban simulation model. Therefore, the data complexity (level of detail) has to be enhanced/ adapted.

Infrastructure Modules

Also for the sewer and the water distribution system module, more generic topographical boundary conditions have to be considered. Especially pumps have to be added to both infrastructure modules. Future work on the water distribution module (as intended in DynaVIBe) includes the implementation of pumps and regulating valves to the water distribution modules to apply this approach not only to alpine case studies but also to e.g. lowland. Further, demand patterns enable the consideration of filling and emptying of tanks. In addition, the water distribution system module will be enhanced dealing with “normal accidents” in the design process by means of stochastic models (e.g.: two pipes with diameter 200 mm are “accidently” connected with a pipe with diameter 125 mm).

For the sewer system an enhanced sewer design including improved design of the combined sewer overflow structures will be implemented. The sewer module has to be modified in order to generate also separate sewer systems.

In the sewer module of VIBe the sub-optimal design of the system is already implemented.

Furthermore, for an integrated investigation of water systems at a city scale, a coupled generation of the sewer system and the water distribution system is intended. Therefore, the pipes for the water distribution systems as well as the pipes for urban drainage are at the same horizontal position, following e.g. public thoroughfares. As DynaVIBe provides also a population model, an integrated model for the urban water cycle can be set-up in order to simulate e.g. the impact of water saving campaigns on the water consumption and the spatial impact on both, water distribution system and urban drainage system.

9.2.4 Enhancement of Conception

DynaVIBe represents a method to test new technologies, strategies or measures. On the one hand, this approach allows generating virtual case studies with different boundary conditions (topographic characteristics). On the other hand, a tool to analyse development scenarios of real world data sets is provided. The virtual case studies are generated algorithmically, spatially distributed and with the data complexity and level of details required.

A virtual case study in DynaVIBe is generated in two steps: the first step is to generate an initial city (alike to VIBe but with a higher level of detail; see 9.2.3) and in a second step, the development over time of the generated virtual city is simulated (by means of development algorithms or an extern Urban Simulation model). If data of a real world city is available, the first step - in which a virtual city is generated - can be substituted with the real world data.

By algorithmically applying the second step, DynaVIBe simulates a multitude of different development scenarios of a real virtual/world city, containing urban structure and infrastructure. This allows investigating the time dependence of processes and measures, as well as the influence of measures (or boundary conditions) on the development of the system itself.

This amount of generated data is therefore significantly higher than in VIBe. Therefore, this requires a new and strategic data management.

With increasing number of coupled models in the simulation framework, the data interfaces become more important (e.g. time consuming data transfer). Also to successfully couple different models and integrate the model results for feedback, special software frameworks are required. Karssenberg et al. (2010) presented a software framework which includes generic 2D and 3D operations combined in a Python script for data assimilation and time iterations. Claeys et al. (2006) introduced a framework for executing complex virtual experiments based on Grid Computing (a Master machine executes sub-experiments on Slave machines). Another integrated modelling framework for simulation of actor response at a regional scale to global change in the water domain is presented in Barthel et al. (2008).

Concluding, to enhance the conception of VIBe a modelling framework has to be adapted or developed, in order to successfully couple all models described above and to manage/ analyse the amount of generated data.

9.3 DynaVIBe in Context

In this chapter DynaVIBe is set in context with the stochastic engineering approaches: Case Study Generator (CSG), Modular Design System (MDS) and Virtual Infrastructure Benchmarking (VIBe). This is done regarding how the urban structure generation and infrastructure generation is implemented in the approaches and how well the generated systems resemble reality (complexities of the generation models). Therefore, the focus of Figure 59 is to highlight the data generation process and the data flow (i.e. which model is based on which data) and to indicate their intended complexity (left: simplified/abstract, right: real world). In the following subsections the columns of Figure 59 are discussed.

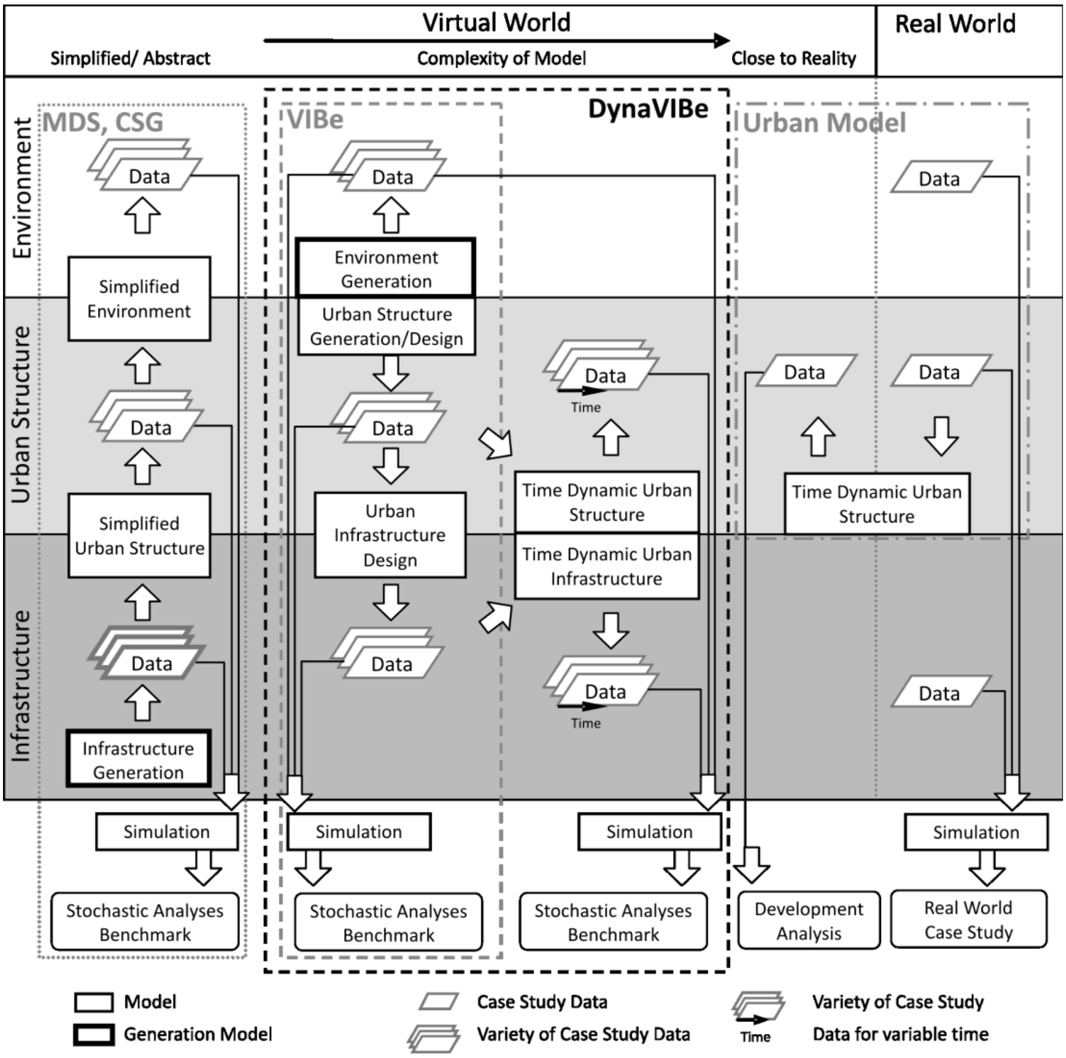


Figure 59: DynaVIBe in context with MDS, CSG, VIBe, Urban Models and Real World

Data flow in the Case Study Generator, Modular Design System

The basis for the stochastic analyses with the Modular Design System (MDS; chapter 2.3.2) and the Case Study Generator (CSG; chapter 2.2.2) are models which generate water infrastructure. Based on the data for virtual infrastructure (network data), the urban structure and the environment are derived in a simplified manner (Figure 59: left column, infrastructure generation module at the bottom, data flow from bottom up, see also 2.2.2 and 2.3.2).

Data flow in Virtual Infrastructure Benchmarking

In VIBe (see chapter 4) a model which generates a virtual environment is the starting point of the process (Figure 59, second column on the left side, environment generation module at the top, data flow from top down). The virtual topography data contains attributes like a digital surface model and the location of rivers. This topography data is basis for a model which generates an initial urban structure. However, the initial urban structure contains the position of city centres, the waste water treatment plant, et cetera. Based on the topography, the positions of the city centres, of the waste water treatment plant, of an initial main sewer and of the initial major roads are generated. As a final step of the initial generation process an initial land use is defined determined by all data generated before. With this initial data as input an urban model generates respectively designs a complex urban structure which is more close to real world than the abstract urban data generated in the MDS or the CSG. The generated urban structure is the input of an infrastructure design model which constructs infrastructures on the state of the art meeting the requirements of the urban structure.

Data flow Dynamic Virtual Infrastructure Benchmarking

In DynaVIBe the dynamics of urban simulation tools are combined with the approach of VIBe. Therefore, a dynamic model of urban structure simulates the development of the virtual urban structure. VIBe is a part of DynaVIBe, therefore for the initial state the data flow (generation model) is the same as for VIBe. Furthermore, a model for a dynamic development of the infrastructure (taking into account urban structure and infrastructure of the preceding time step as input) is implemented. This model provides data of urban structure and infrastructure over time for stochastic analyses and benchmarking processes (Figure 59, two middle columns).

Urban Models

In urban models, real world processes are attempted to be pictured. These urban models use real world data of urban structure and environment as input for simulations (Figure 59, right column). The output of such a simulation is a development scenario of an urban structure (hence, this can be considered as virtual) which represents the investigated urban structure at a future time step. With this virtual urban structure close to reality, the urban structure in the real world can be assessed with regard to development scenarios. Basically, the urban models are comparable with DynaVIBe but without water infrastructure and applied solely for real data.

Summary data flow and complexity

The stochastic analyses and benchmarking processes of all approaches in the virtual world provide an improved comprehension of the processes and coherence in the real world. In Table 4 the properties and characteristics of data in all approaches investigated are compared.

Table 4: Description of the data in MDS, CSG, VIBe and DynaVIBe

Data	MDS	CSG	VIBe	DynaVIBe
Environment	Möderl et al. (2007) based on composed WDS: constant elevation for all junctions constant elevation for all reservoirs	Möderl et al. (2009a) DTM based on sewer system generated to secure drainage	Sitzenfrei et al. (submitted) Topography generated with common properties, data with DTM and rivers as basis for further investigations	Sitzenfrei et al. (2010b) Topography generated with common properties, data with DTM and rivers as basis for further investigations
Urban Structure	population density stochastically varied and based on WDS, => hence evaluated demand per junction	population density stochastically varied and based on junctions of sewer system, => dry weather flow sizes of sub-catchments are stochastically varied	entire virtual city for one point of time, distribution of population, industry, etc close to reality	entire virtual city with data for period of time, distribution of population, industry, et cetera close to reality
Infrastructure	WDS composed with different modules, designed simplified	Sewer system generated based on Galton Watson branching process, simplified conduit design	Infrastructure designed accordingly to the state of the art based on environment and urban structure	Infrastructure designed accordingly to the state of the art based on environment and urban structure, development of infrastructure based on dynamic urban structure

MDS	Modular Design System	DynaVIBe	Dynamic Virtual Infrastructure Benchmarking
CSG	Case Study Generator	DTM	Digital Terrain Model
VIBe	Virtual Infrastructure Benchmarking	WDS	Water Distribution System

9.4 DAnCE

Adapting cities in order to cope with impacts of climate change is a demanding challenge (Birkmann et al., 2010). Alike, rapidly growing population confront society with serious challenges for water resources management (Vorosmarty et al., 2000).

The aim of traditional urban water management is to remove waste and storm water from the urbanised areas with technical measures. But often these technical measures (extend or improve the construction in order to e.g. reduce combined sewer overflow volume) are not appropriate for today’s problems (Krebs and Larsen, 1997). A change in available water resources due to climate change and increasing urbanisation require more holistic and more sustainable water management approaches (Brown and Farrelly, 2009). E.g. an auspicious non-conventional approach is to treat the waste water and storm water as a possible water source to substitute imported water (Mitchell et al., 2001). For that purpose, to estimate the technical effects of a total urban water cycle simulation models are required (Mitchell and Diaper, 2006).

Although social issues like political leadership, institutional reform and social change significantly impact the success of these technical solutions (Brown et al., 2006), administrative regime is mainly driven by technical solutions to solve these water management issues. E.g. the use of rainwater and gray water as a water source goes along with societal barriers (Brown and Davies, 2007). Therefore, special emphasis has to be spent on these issues and interdisciplinary socio-technical research programs are required. Further, for a sustainable urban and regional planning, water sensitive regional planning strategies have to be developed and evaluated (Carmon and Shamir, 2010). The software tool DAnCE for Water (Dynamic Adaption for eNabling City Evolution for Water) addressed these issues.

9.4.1 Aim of DAnCE

In course of the European Framework 7 project PREPARED, a scenario-based software tool to determine strategies for water resources due to climate change, taking into account socio-economical drivers is developed. The software tool, denoted DAnCE, is designed in order to model the technical issues as well as the socio-economical issues. Further, it is intended to model the interactions of these issues in course of adapting cities to more sustainable urban water systems. Wong (2006) defined the key principles of water sensitive urban design which can be looked-up in that paper and are in this thesis referred to as WSUD.

9.4.2 Modelling Conception of DAnCE

Basically, the software encompasses three main modules: a City and Water System Generator; a transition module including socio technical transition and a performance assessment module. With the City and Water System Generator entire case study description is set-up. Based on socio technical transition and a feedback from the performance assessment module, a transition trough time of the entire city is simulated. In the following chapters, conceptual aspects of the city and water generator module are discussed as these issues are mainly related to the work in this PhD project. A further description of performance assessment and the transition modules can be obtained in the report: Monash University and IUT (2010).

The City and Water System Generator module has the aim to provide a detailed digital description of the analysed case study for both, city and water system, respectively. Starting from a certain state in time (initial state) the description of the entire case study is provided for several time steps (dynamics). The development through time is impacted by limiting and driving factors (e.g.: vision/master-plan and their spatial translation, climate or diffusion of alternative water technologies). By varying these limiting and driving factors, data for detailed scenario analysis are provided for the performance assessment module.

The digital description of the investigated case study is based on GIS data. The water infrastructure (traditional and WSUD) is represented in a conceptual way by means of blocks with diverse properties which are arranged on the landscape. As output the City and Water System Generator Module provides discrete data sets for the performance assessment module and further, a feedback loop to the transition model is intended.

Initial State

The initial state represents the actual or also a past state in time of the investigated case study. At a first step, the City and Water System Generator module generates a digital description of the case study based on GIS input data. The GIS input data contains information about:

- terrain, climate and hydrology
- landscape features, land uses and intended further development
- population densities, demographic data, data about trade and industry
- main infrastructures (e.g. waste water treatment plant, major transport network, major water infrastructure)
- water technologies used

All data are used to set up the initial digital description at a high resolution. If the available data does not meet the required level of detail, the data sets are complemented on the basis of stochastic approaches (e.g. as described in the VIBe methodology). On the basis of the detailed description for the initial state, water related evaluations can be made (e.g.: potential of rainwater harvesting due to climate, rainfall, water demand and land use). The results of these evaluations are also represented by GIS-data. The digital description of the case is the input data for the water infrastructure generation process by means of blocks.

The approach of representing the water system of a city via blocks has several advantages. A major issue is the size of the selected case study, Melbourne. To handle such a demand of GIS and network data in the required resolution, the limiting factor is computer power and therefore, computation time. With conceptualised modelling by means of blocks a higher level of detail can be provided. Also, a more realistic modelling of retro-fitting of different scales of water management is feasible. Further, the adaption due to social transition can be modelled by substituting a block with a more adapted one.

To represent different states of technology diffusion, a set of diverse blocks is to be designed and investigated. The properties of each designed and evaluated block are administrated in a block database. The arrangement of a block on the landscape out of this database is determined by the requirements. These requirements are defined by the GIS data and socio-technical inputs that can be assumed or are fed back from the transition model. In such a block the water cycle is modelled on the basis of a conceptional description. The conceptional description contains the interactions of traditional systems (e.g. water supply, combined or separate sewer) but also interactions with water sensitive technologies (e.g. alternative supply sources, flood mitigation, pollution control and water efficiency). Therefore, the entire water infrastructure is divided into a block-wise conceptional description, whereas there are interactions of close-by blocks.

Dynamics

The City and Water System Generator module generates a data set of the urban landscape based on input data (GIS related data) by means of stochastics. The GIS-data are rasterised to a basic block grid on which different blocks are arranged and substituted.

To model the dynamics of the case study description, blocks are substituted for other blocks that suit the social and infrastructure norms and are compatible with the current state. The time dynamic diffusion process of technology (e.g. rainwater harvesting) can therefore, be modelled by substitution of a block at the current time step with a block at future times steps that contains more rainwater harvesting. This approach allows realistic transition from the current state (retro- fitting), but it is feasible to represent social transition in agreement with compatibility with the current state and limiting factors (e.g. climate, migration, population growth, et cetera).

More detailed exemplarily simulation of DAnCE

The approach of conceptually describing the water infrastructure of a city works on a basic block grid. The basic block grid of a city can be determined by evaluating real world data for city blocks (see Figure 60: digital description of case study). A database of blocks with diverse properties (e.g. for different land uses, different level of WSUD, different demand levels, et cetera) are designed and pre-evaluated. This database provides blocks to arrange a conceptual description of the entire water system. The digital description of the case study, and the preferences derived from the transition model, are the basis for the selection of suitable blocks from the database for the initial state e.g. t=2010 (see Figure 8: example block with e.g. 80% WSUD and 20% traditional water infrastructure, residential land use, high water demand). The blocks can be of different physical sizes, but are multiples of the basic block grid (e.g. 1x1, 3x1). Because all blocks are pre- designed and evaluated the performance is ensured and this also provides an estimation of the compatibility with other blocks. Since the arrangement of blocks is done sequentially, neighbouring blocks can be selected to ensure not only compatibility between adjacent blocks, but also to provide the best overall net benefit. For example, an industrial block with a high water demand may prefer to be located next to a residential block which produces an excess of water.

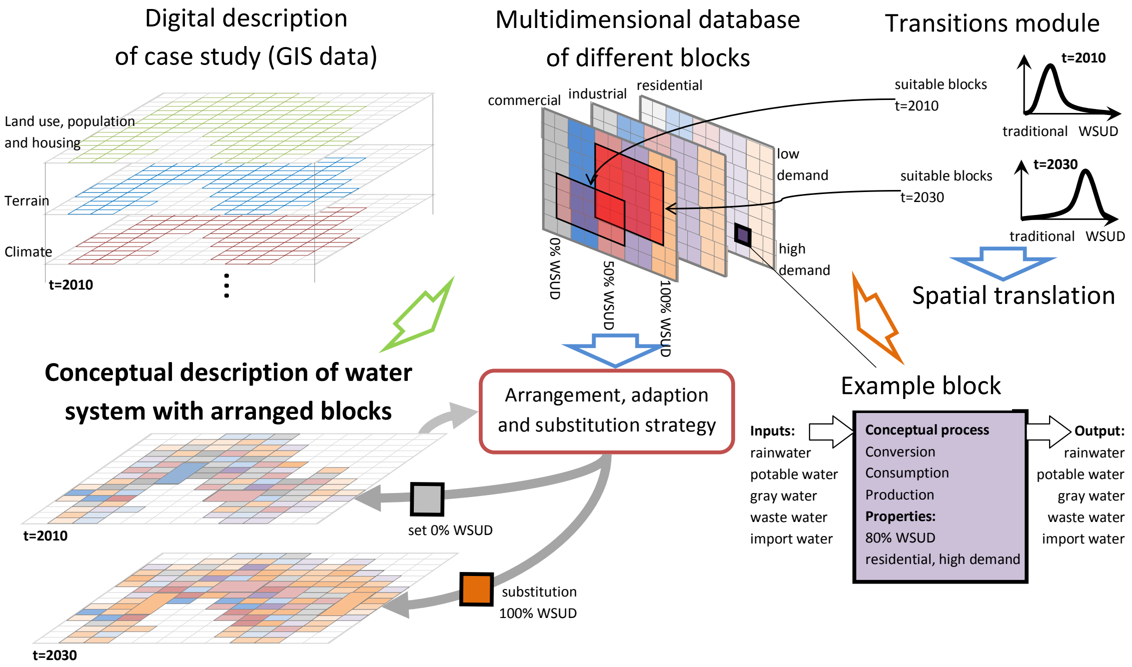


Figure 60: Conceptual description of water systems, database and example block

First, the initial conceptual description of the water system is set up for the actual state (see Figure 60, conceptual description of the water system for t=2010). Then, the transitions module and the spatial translator determine the adaption strategy for the conceptual description (see Figure 60, conceptual description of the water system, substitution of a block at t=2010 and 0%WSUD with a block at t=2030 with 100% WSUD, for example). The result of the adaptation strategy is a spatially referenced description of the case study through time. By varying the boundary conditions and by means of stochastics this approach can also provide the feasibility of identifying major spatial referenced drivers for the transition to a water sensitive city.

9.4.3 Expected Results

The modelling concept DAnCE 4 Water combines both, social and technical aspects of city and water infrastructure development. Therefore, traditionally separated disciplines are consolidated to an integrated approach. This approach is intended to be used as planning tool by policy makers and water managers in order to understand effectiveness of climate change adaption strategies in the context of technical and socio- economical drivers. As a specific case study the city Melbourne (case study overviews are available in Urrutiaguer et al., 2010 or Brown et al., 2010) is used and stochastically investigated based on possible future scenarios. The specific expected results of the Melbourne case are to investigate climate change adaption scenarios regarding effectiveness and sustainability.

9.4.4 DAnCE in Context with DynaVIBe

DynaVIBe is an “infrastructure-based” software tool which generates the water distribution system and the drainage system at a high level of detail. Anyhow, in the DynaVIBe approach there are the traditional technical water infrastructure (water supply and urban drainage) implemented.

In contrast, the DAnCE modelling concept encompasses an integrated conceptual block based description of the urban water cycle enabling systematic investigations of water sensitive urban design strategies at a city scale. Therefore, the water infrastructure is implemented at a – compared to DynaVIBe – lower level of technical detail.

While DynaVIBe is primarily developed for the stochastic generation of entire virtual cities, the DAnCE framework is primarily developed to investigate development scenarios of specific real world case studies. Anyhow, the modelling concepts of DynaVIBe (stochastic scenario analysis, time evolvement, et cetera) are also used for the DAnCE approach.

9.5 Outlook

Compared to VIBe, DynaVIBe provides data of virtual case studies which better resemble real world data. This is achieved by implementing additional complexity to the infrastructure (crucial elements like pumps are regarded) and urban structure (demographic composition of the population). In addition, DynaVIBe represents a tool for analysis of socioeconomic aspects on water systems on basis of stochastic generated virtual case studies. Since the module-based conception of the software DynaVIBe is highly adaptable, it can be extended for every infrastructure system in urban systems like energy supply systems, railway systems or public transport systems. Thus, effects of the change of system boundaries on infrastructure systems, like climate change scenarios, can be investigated.

The software DynaVIBe generates virtual urban structures and infrastructures and writes input files, to represent the investigated system for several simulation software products. These interfaces can be extended respectively translated to additional software input files. This offers the opportunity for software engineers to test new software with virtual data. Similarly, new developed calculation approaches and models can be tested with an amount of detailed data.

It is expected that with this modelling concept, a valuable contribution to interdisciplinarily model technical and socioeconomic aspects in order to face upcoming problems

10 SUMMARY, CONCLUSIONS AND OUTLOOK

In course of this PhD project a cumulative PhD thesis was authored. The thesis contains 9 papers as integral part which are attached in the appendix. Traditionally, cumulative PhD theses outline a framework which includes all included papers. In addition, in this PhD thesis in-deep information additional to the papers is provided for the reader.

One of the key approaches developed in this PhD project is the VIBe approach. The chapters in this thesis were arranged, in order to provide the reader a guideline through the developed approaches with increasing complexity, resulting in the VIBe approach and its different modules as main part. The last chapter in this thesis (chapter 9), can be considered as a detail outlook of the proposed methodology respectively as elaborated concept for a follow-up project.

Although, at the end of each chapter of this PhD thesis, a specific summary, conclusion and outlook are given, in this final chapter, an overall view is provided.

10.1 Summary

In chapter 1 an introduction to case study research was given. Starting with case study research in general and from a philosophy of science point of view, the importance of case study research in urban water management is discussed. Therein, special emphasis was given to point out the fact that case study data in urban water management is limited. Therefore, new studies, approaches or software can only be tested on a limited number of available case studies.

In chapter 2, it was shown, that the application of synthetic case studies, respectively benchmark systems, is common practice in urban water management. Investigations were discussed in which synthetic case studies were used to outline effects or test different approaches. Further, it was shown that there have already been efforts to investigate different synthetic case studies (with varying parameters according to literature) in order to obtain general and comprehensive conclusions. A special focus of this literature review was to show how and with which complexity the synthetic cases studies were constructed, and which advantages were attained in the investigation by using the synthetic case studies.

In addition, in chapter 2 approaches for the algorithmic generation of simplified case studies by means of stochastics were discussed. This encompassed approaches for water distribution systems and urban drainage systems. The aim of this discussion was to highlight the benefits of the proposed approaches, but also to point out the critical assumptions, neglected issues and simplified considerations in these approaches. In chapter 2.4, the systematic generation of conceptual water distribution systems is discussed in detail. This issue is also addressed in Paper I.

Enhancing the methodology proposed in Paper I, resulted in the WDS Designer which is a tool for generation of water distribution systems based on given GIS-data. Compared to the approaches in literature discussed before, with this approach case studies for water distribution system analysis can be algorithmically generated, taking into account user-defined input parameters and given GIS-data. Further, this approach is operated by a graphical user interface, which was also developed in course of this PhD project. The WDS Designer is presented in Paper II. As an example application of networks generated with the WDS Designer, the number of network sources depending on different mesh degrees (number of loops) was determined. This study was presented in Paper III.

In literature, available tools for the algorithmic creation of case studies generate virtual cases studies driven by the infrastructure layout or are without hydraulic performance evaluation. All discussion in these chapters and papers outlined the requirement for an integrated tool for the algorithmic generation of urban water systems for case study analysis. Therefore, the tool Virtual Infrastructure Benchmarking (VIBe) was developed. The modelling principles of VIBe were explained in chapter 4, Paper IV and Paper VIII.

In chapter 5, the urban structure module of VIBe is discussed. This issue is also addressed in Paper IV, but additional information on the generation process is provided in that chapter. The urban structures, generated with the urban structure module of VIBe, are the input for the infrastructure modules which generate water infrastructures. The module for the generation of combined sewer systems is presented in Paper VI and discussed in-depth in chapter 6. The module for the generation of water distribution systems is presented Paper V and discussed in chapter 7.

As a third infrastructure module, the geothermal energy module of VIBe was presented in Paper VII. The aim of this study was to determine the potential of geothermal heat utilisation with heat pumps. Therefore, the thermal regeneration of geothermal utilised shallow aquifers is required. To obtain generic conclusions of the impact of the building structure on the geothermal potential, urban areas of 1,000m times 1,000m with different building structures were systematically investigated. In addition, the obtained results were compared with simplified approaches for determination of regional potential. This study is discussed in chapter 8. But special focus of chapter 8 was on the critical reflection of the assumptions and simplification made in Paper VII.

Chapter 9 and Paper IX can be seen as detailed outlook for the project VIBe. Therein, discussions are provided which address the simplifications in the urban structure module and infrastructure modules, and how it is intended to enhance these issues. The main enhancement of a follow-up project denoted DynaVIBe (Dynamic Virtual Infrastructure Benchmarking) is to improve the conception of VIBe with algorithms for temporal development for both, urban structure and infrastructure. DynaVIBe focuses on the algorithmic generation of virtual case studies with detailed infrastructure networks. Another approach deals with the stochastic analyses of development scenarios of real world systems by means of conceptual description of the urban water cycle (DAnCE for Water, Dynamic Adaption for eNabling City Evolution for Water). The modelling concepts of DAnCE were also outlined in Chapter 9 with a special focus on the urban structure and infrastructure generation process.

10.2 Conclusions

The aim of this PhD project was to tackle the problem of limited data availability for research task. This was done by developing tools for stochastic generation of urban water system for case study analysis. The focus of these studies was therefore, on the generation of network data (sewer network and water distribution networks) for performance evaluation by means of an integrated approach. The different stages of development of this integrated approach are documented in the papers annexed to this thesis.

The idea of an integrated generation approach is to construct infrastructure based on before generated urban structure. This aim was fulfilled and it was shown that the generated case studies (urban structure an infrastructure) resemble reality. Further, it was shown with practical examples that there is a benefit for research studies to test hypothesis or models on numerous case studies and that generic conclusions can be made by means of these systematic investigations. Overall it can be concluded that the algorithmic generation of case studies for urban water systems can be valuable approach to obtain generic, comprehensive and more generalised results.

In addition, the infrastructure modules in VIBe can also be applied to real world data, in order to e.g. complement unknown data or for conceptual design of new infrastructures. Therefore, with the developed infrastructure modules also rough cost estimations and performance evaluations of new systems can be made.

10.3 Outlook

In all approaches discussed respectively applied in course of this PhD project, several simplifications and assumption were made and issues were neglected. Therefore, further research has to be done to investigate the impact of these respectively to enhance to tools. Also, investigations concerning parameter dependencies in these approaches have to be done.

It is intended to further develop the WDS Designer to a user-friendly tool without the restrictions discussed in this thesis. As a detailed outlook of VIBe, the description of DynaVIBe (chapter 9) can be seen. Chapter 9 outlines an enhancement of the conception of VIBe (denoted DynaVIBe) in order to provide case studies with temporal development. Further, potential applications of DynaVIBe are conceptually designed. DynaVIBe is a follow-up project of VIBe and the project proposal is currently under review.

Another important step in the further development of the VIBe approach is to integrate the modelling tools into an integrated modelling framework in order to provide are user-friendly operation of the modules and administrates the amount of generated data. To shorten simulation time of the generation and evaluation process, distributed simulations (simulation clusters) have to be integrated in this framework. These are important issues in order to provide this methodology to a broad field in research and also in practice.

Besides these enhancements of conception and modelling capability, the next important steps encompass the application of all these approaches. This enables to face unanswered questions in urban water management or respectively, to assess already investigated problems based on multiple case studies and therefore, obtain not case-specific results.

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Sitzenfrei, R.; Möderl, M.; Rauch, W. (in press): Graph-Based Approach for Generating Virtual Water Distribution Systems in the Software VIBe. In: *Water Science and Technology: Water Supply*.

Sitzenfrei, R.; Möderl, M.; Urich, C.; Rauch, W. (2009a): Assessment of thermal regeneration for improved groundwater management. In: *Proceedings of the Water & Energy*, Copenhagen, Denmark, 29.-31. October 2009.

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Zaher, U.; Grau, P.; Benedetti, L.; Ayesa, E.; Vanrolleghem, P.A. (2007): Transformers for interfacing anaerobic digestion models to pre- and post-treatment processes in a plant-wide modelling context. In: *Environmental Modelling & Software*, Vol. 22(1), p. 40-58.

Zecchin, A.C.; Simpson, A.R.; Maier, H.R.; Leonard, M.; Roberts, A.J.; Berrisford, M.J. (2006): Application of two ant colony optimisation algorithms to water distribution system optimisation. In: *Mathematical and Computer Modelling*, Vol. 44(5-6), p. 451-468.

Zhou, S.L.; McMahon, T.A.; Walton, A.; Lewis, J. (2002): Forecasting operational demand for an urban water supply zone. In: *Journal of Hydrology*, Vol. 259(1-4), p. 189-202.

Appendix A. CURRICULUM VITAE

A.1 Education and Qualification

12/2010

Degree Dr. techn (PhD), Thesis: Stochastic Generation of Urban Water Systems for Case Study Analysis, University of Innsbruck

02/2010 – 03/2010

Research visit Institute for Sustainable Water Resources, Department of Civil Engineering, Monash University, Melbourne, Australia

11/2007 - 12/2010

Doctoral programme: Engineering Sciences, Area of dissertation: Civil Engineering, University of Innsbruck

10/2007

Degree Diplom-Ingenieur (MSc), Thesis: Simplified numerical model to describe anthropogenic temperature anomalies in ground-water flow (in German, available at: http://www.uibk.ac.at/umwelttechnik)

10/2000 - 10/2007

Diploma programme: Civil Engineering, University of Innsbruck

A.2 Work Experience

11/2007 - 12/2010

PhD Candidate, Unit of Environmental Engineering, University of Innsbruck

08/2007 - 10/2007

Project Staff, Unit of Environmental Engineering, University of Innsbruck

03/2007 - 07/2007

Schaur ZT GmbH - Structural Engineering, Thaur

07/2005 - 09/2006

Wasser Tirol – Wasserdienstleistungs-GmbH Consulting Engineers, Innsbruck

11/2004 - 07/2005

Tutor at the Unit of Hydraulic Engineering, University of Innsbruck

A.3 Honours

UDM (International Conference on Urban Drainage Modelling) Young Researcher Paper Award, 2009 for the paper and presentation of “A multi-layer cellular automata approach for algorithmic generation of virtual urban water systems – VIBe” at the 8th International Conference on Urban Drainage Modelling, Tokyo (Japan) 7-11 Sep.

A.4 Attended Conferences, Congresses and Seminars

IWA World Water Congress and Exhibition, 19-24 September 2010, Montréal, Canada

1st IWA Austrian Young Water Professionals Conference, 09.06.2010 - 11.06.2010, Wien

World Environmental and Water Resources Congress 2010 - Challenges of Change, Providence, Rhode Island, 16.05.2010 - 20.05.2010, Providence, Rhode Island, United States of America

10. Internationales Anwenderforum Oberflächennahe Geothermie und Grundlagentag, 19. April – 21.April 2010,Linz

International Water & Energy Conference, 29 – 31 October 2009, Copenhagen Denmark

8th International Conference on Urban Drainage Modelling (8UDM), 7 – 12 September 2009, Tokyo, Japan

ÖWAV Seminar: Wärmepumpen - Thermische Nutzung des Grundwassers und des Untergrunds - Heizen und Kühlen, Vorstellung des ÖWAV-Regelblattes 207-2, 23 April 2009, Linz

ÖWAV Seminar: Simulationen in der Abwasserableitung und –Behandlung, ÖWAV-Regelblatt 11, 21 Jänner 2009, Innsbruck

11th International Conference on Urban Drainage (11ICUD), 31 August – 5 September 2008 Edinburgh, Scotland

Kanalmanagement– Betrieb und Mischwasser, 27 März 2008, Wien

ÖWAV Seminar: Bemessung von Mischwasserentlastungen, ÖWAV-Regelblatt 19/neu. 7 November 2007, Innsbruck

A.5 Lecture

Dynamic Virtual Infrastructure Benchmarking – DynaVIBe. At: IWA World Water Congress and Exhibition, Montréal, Canaga, 23 Sep. 2010

Thermal Regeneration of Aquifers for a Sustainable Resources Management. At: 1st IWA Austrian Young Water Professionals Conference, Wien 10 June 2010

WDS Designer: A Tool for Algorithmic Generation of Water Distribution System based on GIS Data. At: World Environmental and Water Resources Congress 2010 – Challenges of Change, Providence, Rhode Island, 17 Mai 2010

Erforderliche Abstände für die thermische Grundwassernutzung – Nachschlagewerk als Bemessungsbehelf. 10. Internationales Anwenderforum Oberflächennahe Geothermie und Grundlagentag, Linz, 20 April 2010

VIBe – Virtual Infrastructure Benchmarking. Monash University, Melbourne 04 March, 2010

A multi-layer cellular automata approach for algorithmic generation of virtual urban water systems – VIBe. At: 8th International Conference on Urban Drainage Modelling, Tokyo (Japan) 11 Sep. 2009.

2. ÖWAV Kurs "Anwendung von ÖWAV-Regelblatt 19 (neu) Richtlinien zur Bemessung von Mischwasserentlastungen in der Praxis" : Einführung in die Softwarewerkzeuge KAREN und NIEDA; Schulung zu NIEDA und KAREN. Österreichischer Wasser- und Abfallwirtschaftsverband (ÖWAV), Wien, 28.09.2009 - 29.09.2009.

ÖWAV Kurs "Anwendung von ÖWAV-Regelblatt 19 (neu) Richtlinien zur Bemessung von Mischwasserentlastungen in der Praxis" : Einführung in die Softwarewerkzeuge KAREN und NIEDA. Österreichischer Wasser- und Abfallwirtschaftsverband (ÖWAV), Wien, 26.11.2008 - 27.11.2008.

Auswirkung von Vereinfachungen bei der Bestimmung von Mischwasserentlastungen - quo vadis, Poleni? Kanalmanagement 2008 - Betrieb und Mischwasser, Wien, 27.03.2008.

Workshop zur Umsetzung des Regelblattes 19/neu in der Praxis anhand der Software KAREN. Leopold-Franzens-Universität Innsbruck - Institut für Infrastruktur, Arbeitsbereich Umwelttechnik, Innsbruck, 08.11.2007.

Appendix B. LIST OF PUBLICATIONS

B.1 Articles in Journals

Sitzenfrei, R. Urich, C.; Möderl, M.; Kinzel, H.; Rauch, W (in preparation): Stochastic Generation of Urban Water Systems with VIBe for Case Study Analysis. will be submitted to: Environmental Modelling & Software.

Möderl, M.; **Sitzenfrei, R**.; Fetz, T.; Fleischhacker, E.; Rauch, W. (2011): Systematic generation of virtual networks for water supply. In: Water Resources Research.

Sitzenfrei, R.; Möderl, M.; Rauch, W. (submitted-b): WDS Designer -Generator of Water Distribution Systems using GIS Data. In: Environmental Modelling & Software.

Sitzenfrei, R.; Fach, S.; Kleidorfer, M.; Urich, C.; Rauch W. (2010): Dynamic Virtual Infrastructure Benchmarking - DynaVIBe. In: Water Science and Technology: Water Supply. Vol. 10 (4), p. 600 – 609.

Sitzenfrei, R.; Fach, S.; Kinzel, H.; Rauch, W. (2010): A multi-layer cellular automata approach for algorithmic generation of virtual case studies - VIBe. In: Water Science and Technology, Vol. 61(1), p. 37 - 45.

Sitzenfrei, R.; Möderl, M.; Rauch, W. (2010): Graph-Based Approach for Generating Virtual Water Distribution Systems in the Software VIBe. In: Water Science and Technology: Water Supply, Vol 10(6), p. 923 -932.

Urich, C.; **Sitzenfrei, R**.; Möderl, M.; Rauch, W. (2010): An agent based approach for generating virtual sewer systems. In: Water Science and Technology. Vol. 62 (5), p. 1090 - 1097

Urich, C.; **Sitzenfrei, R**.; Möderl, M.; Rauch W. (2010) (in german): Einfluss der Siedlungsstruktur auf das thermische Nutzungspotential von oberflächennahen Aquiferen (Impact of the settlement structure on the geothermal potential of shallow aquifers). In: ÖWAV Fachheft: Geothermie

Kleidorfer, M.; Moderl, M.; **Sitzenfrei, R**.; Urich, C.; Rauch, W. (2009): A case independent approach on the impact of climate change effects on combined sewer system performance. In: Water Science and Technology, Vol. 60(6), p. 1555-1564.

Möderl, M.; Kleidorfer, M.; **Sitzenfrei, R.**; Rauch, W. (2009): Identifying weak points of urban drainage systems by means of VulNetUD. In: Water Science and Technology, Vol. 60(10), p. 2507-2513.

Fach, S.; **Sitzenfrei, R**.; Rauch, W. (2009): Determining the spill flow discharge of combined sewer overflows using rating curves based on computational fluid dynamics instead of the standard weir equation. In: Water Science and Technology, Vol. 60(12), p. 3035-3043.

Sitzenfrei, R.; Fach, S.; Rauch, W. (2008): Auswirkungen von Vereinfachungen bei der Bestimmung von Mischwasserentlastungsmengen- quo vadis, Poleni. In: Wiener Mitteilungen 2008, Vol. 209 (in German).

B.2 Articles in Conference Proceedings

Sitzenfrei, R.; Möderl, M.; Rauch, W. (2010): WDS-Designer – A tool for algorithmic generation of water distribution systems based on GIS-data In: Proceedings of the World Environmental and Water Resources Congress 2010: Challenges of Change; Rhode Island, United States, May 16-20, 2010.

Möderl, M.; **Sitzenfrei, R.**; Rauch, W. (2010): Empirical Equation for Spacing of Ground Water Heat Pump Systems. In: Proceedings of the World Environmental and Water Resources Congress 2010: Challenges of Change; Providence, Rhode Island, United States, May 16-20, 2010.

Möderl, M.; **Sitzenfrei, R.**; Rauch, W. (2010): How many network sources are enough? In: Proceedings of the World Environmental and Water Resources Congress 2010: Challenges of Change; Rhode Island, United States, May 16-20, 2010.

Sitzenfrei, R.; Möderl, M.; Urich, C.; Rauch, W. (2010) (in german): Erforderliche Abstände für die thermische Grundwassernutzung - Nachschlagewerk als Bemessungsbehelf. In: Proceedings of the 10. Internationales Anwenderforum, Oberflächennahe Geothermie, Erdgekoppelte Wärmepumpen und unterirdische thermische Energiespeicher, Regensburg, Deutschland, 19.-21. April.2010

Sitzenfrei, R.; Möderl, M.; Urich, C.; Rauch, W. (2010): Thermal regeneration of aquifers for sustainable resource management. In: Proceedings of the 1st IWA Austrian National Young Water Professionals Conference, Vienna, Austria, 9-11. June 2010.

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Urich, C.; **Sitzenfrei, R.;** Rauch, W. (2010): Stochastic Design of Urban Areas for Benchmarking Energy Strategies. In: Proceedings of the AAG (Association of American Geographers) 2010 Annual Meeting, Washington, United States, 14. – 18 April 2010

Möderl, M.; Urich, C.; **Sitzenfrei, R.**; Rauch, W. (2009): Spacing of Wells for Ground Water Heat Pumps. In: Proceedings of the Water & Energy, Copenhagen, Denmark, 29.-31. October 2009.

Sitzenfrei, R.; Möderl, M.; Urich, C.; Rauch, W. (2009): Assessment of thermal regeneration for improved groundwater management. In: Proceedings of the Water & Energy, Copenhagen, Denmark, 29.-31. October 2009.

Urich, C.; **Sitzenfrei, R**.; Möderl, M.; Rauch, W. (2009): Assessment of the technical usable shallow geothermal potential of an aquifer. In: Proceedings of the Water & Energy, Copenhagen, Denmark, 29.-31. October 2009.

Rauch, W.; Möderl, M.; **Sitzenfrei, R.**; Kinzel, H. (2009) (in german): Berechnung der Ausbreitung von Temperaturanomalien im Grundwasser als Planungsinstrument für Wärmepumpen, Stand der Wissenschaft. In: Proceedings of the WÄRMEPUMPEN – Thermische Nutzung des Grundwassers und des Untergrunds – Heizen und Kühlen, Linz, Österreich, 23.April, 2009.

Rauch, W.; Möderl, M.; **Sitzenfrei, R.**; Kinzel, H. (2009) (in german): Berechnung der Ausbreitung von Temperaturanomalien im Grundwasser als Planungsinstrument für Wärmepumpenanlagen. In: Proceedings of the 9. Internationales Anwenderforum Oberflächennahe Geothermie, Kloster Banz, Bad Staffelstein, 27.-29. April 2009.

Fach, S.; **Sitzenfrei, R.**; Rauch, W. (2008): Assessing the relationship between water level and combined sewer overflow with computational fluid dynamics. In: Proceedings of the 11th International Conference on Urban Drainage, Edinburgh, Scotland, 31. October - 5. September 2008.

B.3 Articles in non-scientific Journals

Sitzenfrei, R. (2008): Alles im Fluss unter der Stadt: Jedes System hat eine Geschichte. In: Der Standard - Beilage "Forschung Spezial" vom 05.11.2008.

B.4 Project Reports

Kinzel, H.; **Sitzenfrei, R.** und Rauch, W. (2007): GIS basierte Ermittlung und Darstellung regionaler thermischer Grundwassernutzungen in alpinen Aquiferen. Final Report, Institut für Infrastruktur, Universität Innsbruck

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Appendix C. PAPERS

Due to copyright issues, the papers cannot be published in the online version of this thesis.