

Dynamics of cities and water infrastructure in the DAnCE4Water model

C. Urich^{1*}, P. M. Bach², C. Hellbach¹, R. Sitzenfrei¹, M. Kleidorfer¹, D. T. McCarthy²,
A. Deletic² and W. Rauch¹

¹ *Unit of Environmental Engineering, University of Innsbruck, Technikerstr. 13, Innsbruck
6020, Austria*

² *Centre for Water Sensitive Cities, Civil Engineering Department, Monash University,
Clayton VIC 3800, Australia*

**Corresponding author email: christian.urich@uibk.ac.at*

ABSTRACT

Urban water systems are under increasing pressure due to the impact of climate, population growth and urbanisation. Conventional water infrastructure is frequently classified as highly unsuited to address future challenges. In order to make our urban water systems more resilient to these challenges, the development of new water management strategies is vital. During the last 20 years, many new decentralised technologies have emerged. Their mix with existing centralised technologies in particular creates complex interactions within the urban water system. To deepen our understanding of these interactions at a city scale and to identify possible transition strategies to a resilient city, the development of the DAnCE4Water model within the project “PREPARED enabling change” as a potential strategic planning tool is thus proposed. This paper focuses on the development of the urban environment and the city and water system within the DAnCE4Water model. This module facilitates the evolution of the urban environment and water system (comprising central- and decentralised technologies) in time and space. The dynamics of the model is shown for alpine cities. Numerous cities are stochastically generated by means of the Virtual Infrastructure Benchmarking (VIBe) approach and evolved over time. Different scenarios for the development of the urban environment and water system are statistically evaluated.

KEYWORDS

DanCE4Water, VIBe, UrbanSim, Urban Dynamics, WSUD

INTRODUCTION

Urban water systems are under increasing pressure due to the impact of climate and urban change. Conventional water infrastructures, especially the networks with their long lifespan, are frequently classified as highly unsuited to address future challenges (Ashley et al., 2005). In order to make our urban water systems more sustainable and adaptable to future challenges, the development of new water management strategies is vital. During the last 20 years, many new decentralised technologies in stormwater harvesting and management have emerged. These technologies – known as low impact development (LID) in the United States or water sensitive urban design (WSUD) in Australia – integrate stormwater management into urban design. Additionally, a lot of new technologies for water saving and reuse have been developed. As highlighted by Wong and Brown, (2009) not only a technical overhaul of conventional urban water systems is required but also an overhaul of the existing social-

political environment is necessary to enable sustainable and water sensitive decision-making and behaviour. The European FP7 project “PREPARED enabling change” aims to deliver a decision support model that exploits the opportunities for such innovative adaptation technologies and solutions.

On a small scale, numerous projects have been successfully realised, but the transition from a conventional (centralised) urban water system to an adaptable and sustainable system at a city scale is still unknown. The mix of existing central- and novel decentralised technologies, in particular, creates complex interactions within the urban water system. To deepen our understanding of such interactions at a city scale and to identify possible transition strategies, new analysis tools are required. The development of the DAnCE4Water (Dynamic Adaptation for eNabling City Evolution for Water) model as a strategic planning tool for urban planners, government, watershed managers, and local councils has thus been proposed. The model is based on the concept of Virtual Infrastructure Benchmarking (VIBe) (Sitzenfrei et al., 2010a and Sitzenfrei et al., 2010b) that enables the evaluation of different technologies and strategies within a dynamic urban environment (both in space and time) by means of a stochastic modelling approach. Within the model three major modules are linked under consideration of complex interactions to simulate an entire urban water system. The modules are (I) the urban development module (UDM) to evolve the urban environment (II) the biophysical module (BPM) to generate the urban water infrastructure and assess the performance (Bach et al., 2011) and (III) a societal transition module (STM) to assess the societal system (De Haan et al., 2011) and its future development.

This paper focuses on the design of the dynamics and interaction within the urban development module and the biophysical module of DAnCE4Water. The dynamics of the module are illustrated using virtual case studies based on the dataset of Innsbruck (Austria). This includes the development of the urban environment and of the drainage system. As an example of a possible adaptation strategy, the potential of on-site stormwater infiltration for combined sewer systems in new or redeveloped residential areas with discontinuous urban fabric is tested. In contrast to similar previous studies (e.g. Kleidorfer et al., 2009), the new approach proposed in this paper considers the temporal dynamics of adaptation strategies. Hence, it is possible to investigate which renewal rates are required to compensate for different climate change scenarios and to also assess the transition process.

MATERIALS & METHODS

DAnCE4Water Model

DAnCE4Water is designed as a software tool that enables a wide variety of stakeholders to explore possible future scenarios and consequences of policies and action strategies. Therefore, what-if scenarios for the urban water system can be investigated in a dynamically evolving environment, which considers the interactions between urban water infrastructure, urban environment and the societal system in space and time. Users can identify sustainable and reliable adaptation strategies for the urban water system.

As explained in the introduction, DAnCE4Water has three modules (Figure 1) which can be run independently of one another. Each module provides interfaces to react on external drivers like climate change or urban development and to interact with the urban water system. For example, the UDM provides an interface, where the societal needs (calculated from the

societal transitions module) are linked with its household location choice model. This enables a reflection of an increased environmental awareness in the urban development, i.e. it is more likely that households move into residential areas beside a healthy water way.

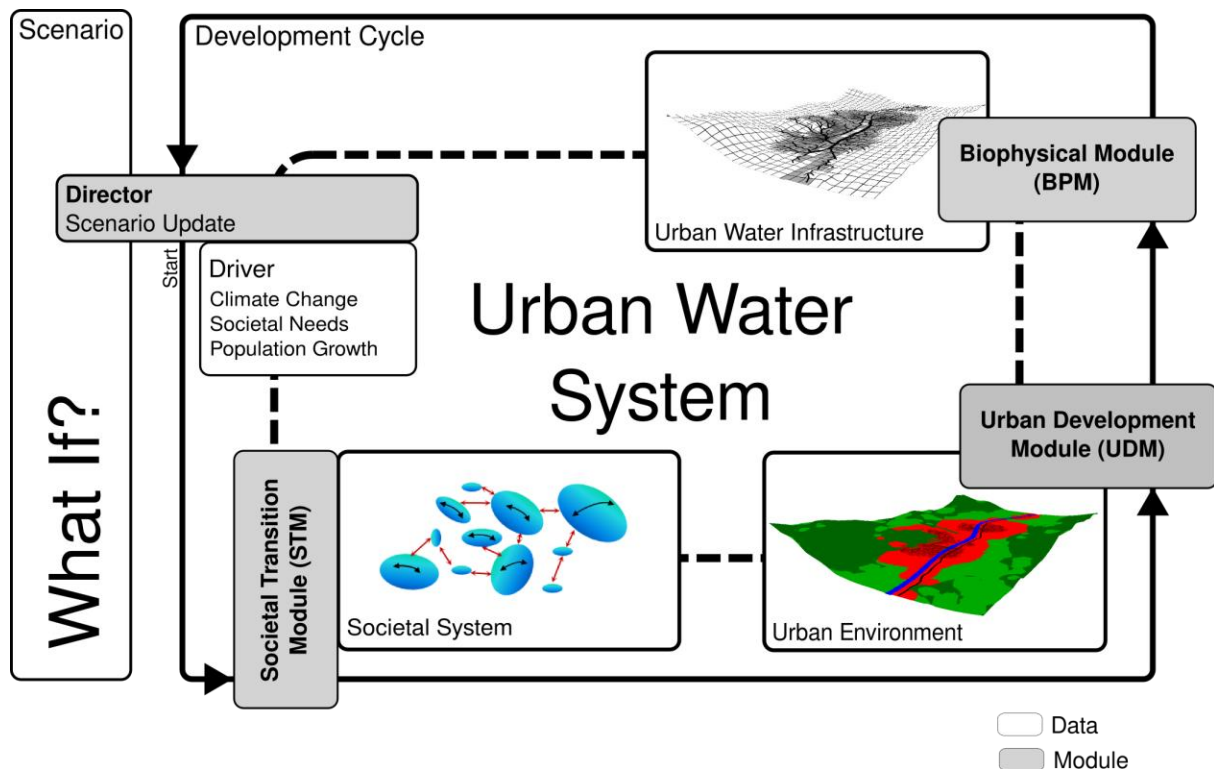


Figure 1. Overview of the DAnCE4Water Model

The external drivers (climate and demographic change, etc.) as well as the hypotheses that are tested (e.g. adaptation strategies) are defined in the scenarios. These are the input for the *Director* that orchestrates the simulation and evolves the urban water system into the future using an annual time step.

This paper focuses on the integration of the UDM and BPM in DAnCE4Water and presents the current state of the model development. The interdependencies of the modules are demonstrated using a simple scenario.

Urban Development Module (UDM)

The UDM spatially translates the population projections and the master plan for the urban development (e.g. growth corridors) in time steps of one year. The well-known and widely applied UrbanSim package (Waddell et al., 2008) is integrated in the DAnCE4Water model and enables a detailed projection of the urban environment including, not only future land use and population, but also number of households, housing types etc. UrbanSim is a software tool that is designed to reflect the interdependencies in dynamic urban systems, focusing on the real estate market and the transportation system. The model reflects the key decision makers – households, businesses and developers - and choices impacting urban development (The UrbanSim Project, 2011).

Currently, a simple UrbanSim Model has been integrated in DAnCE4Water. It is derived from the Eugene-Springfield model delivered with UrbanSim. The model is based on a grid representation (200m x 200m) of the urban environment. Based on future projections of

households, the model evolves the urban environment by means of sub-models for household transition and the household location choice.

To set up the UrbanSim model, a detailed description of the urban environment is required. This includes information on households (e.g., size, number of children, income), buildings and jobs. Based on available land-use and population maps as input, the missing data (e.g. household size, income) are stochastically sampled from distributions extracted from real world case studies.

Biophysical Module (BPM)

The Biophysical Module has 2 separate sub-modules: City and Water System Generator and Performance Assessment module. It provides the representation of the urban water infrastructure and its performance. This module uses a coarse grid-based representation (termed *building blocks*) of the urban environment. Based on characteristics in each block (Bach et al., 2011), the corresponding detailed water infrastructure can be identified and placed. The infrastructure within the blocks is then connected with the central network infrastructure. Performance of the infrastructure is also assessed within the BPM.

City and Water System Generator. At present state, urban catchments including on-site stormwater systems for residential buildings and combined sewer system facilities (combined sewer overflows and sewage pipes) are included in the City and Water System Generator. Based on a given population and land use maps the percentage of impervious area (split up in streets, roof, and other areas) can be calculated. As an example, for a decentralised solution the stormwater runoff from connected roofs in areas of discontinuous urban fabric can be infiltrated on the lot by using on-site stormwater infiltration systems. To connect newly populated blocks (output of the UDM) to the existing infrastructure the agent based approach for generating the combined sewer system presented in Urich et al., (2010) has been enhanced.

Performance Assessment. The performance of the generated combined sewer system is assessed using the SWMM software tool (Rossman, 2004). Therefore SWMM input files are generated. They also include decentralized storm water technologies. After simulation, the results of the hydrodynamic simulation are stored in a block database.

For this study, two hydraulic performance indicators were evaluated. A detailed description of these hydraulic parameters can be found in Möderl, 2009).

PI1 assesses the combined sewer overflow (CSO) efficiency and is calculated as the percentage of surface runoff (V_R) (without infiltration water) treated in the wastewater treatment plant (WWTP) (V_{WWTP})

$$PI1 = \frac{V_{WWTP}}{V_R} (-) [0 | 1]$$

PI4 is a performance indicator for surface flooding. It is calculated as unity minus the volume of the ponded water (V_P) over V_R

$$PI4 = 1 - \frac{V_P}{V_R} (-) [0 | 1]$$

Scenarios

To show the dynamics of UDM and the BPM, VIBe cities are generated with the characteristics of the alpine city of Innsbruck (Sitzenfrei et al., 2010a) and subsequently evolved 20 years into the future. For the urban development, the population and demographic projections for Innsbruck are used (ÖROK-Prognosen, 2010). As a climate change adaptation strategy, the impact of implementing on-site stormwater infiltration systems is evaluated. Therefore, for newly built or redeveloped buildings in areas with discontinuous urban fabric, an infiltration system for roof water is installed on the lot. The aim is to determine which renewal rates are required to compensate the effects of climate change and urban development. In the evaluation of system performance, a decrease of 5% in the described performance indicators is tolerated in the period 2010 to 2030.

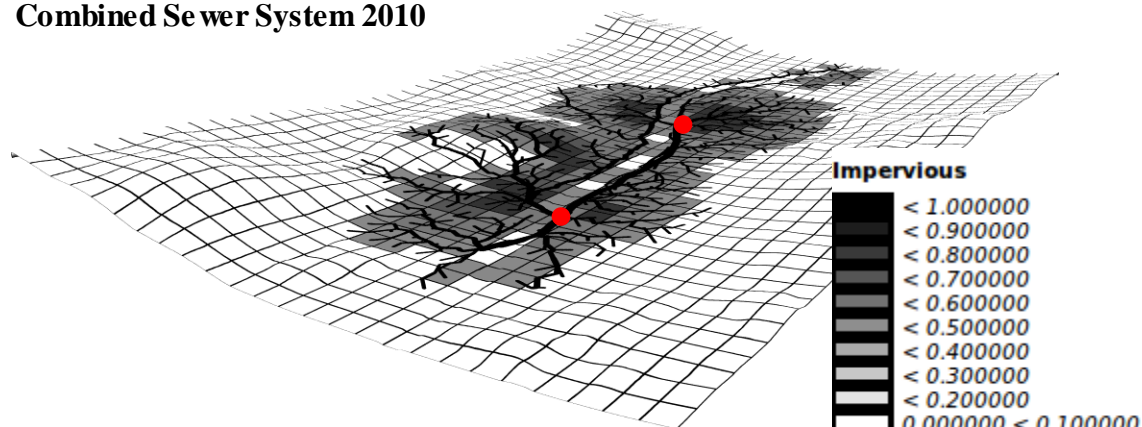
As a climate change scenario, a shift in rainfall intensities is considered. Depending on duration, return period and anticipated technical lifetime of sewer systems, Arnbjerg-Nielsen, (2008) suggests an intensity increase by 10 – 50%. In that range, four climate change scenarios are investigated. Therefore, a linear function of time is used to model the increase in rainfall intensities from 2010 to 2030. Three end points were chosen for this linear approximation: 100% (i.e. rainfall intensities do not change with time), 110%, 130% and 150% (i.e. the rainfall intensity in 2030 was 50% higher than that in 2010). Of course the integration of more sophisticated climate change projections is possible when such data is available. In our case a design storm “Euler Type II” (described in De Toffol, (2006)) for an alpine region, with a duration of two hours and a return period of 5 years is used. Building stock renewal rates of 0%, 1%, 3% and 5% are investigated.

As each renewal rate is combined with each climate change scenario, a total of 16 scenarios were investigated. For each scenario, 100 VIBe cities were created and evolved 20 years into the future, resulting in 1600 simulations in total. The results are statistically evaluated.

RESULTS

Results of a single simulation are shown in Figure 2. Impervious area and the combined sewer system dynamics in the years 2010 and 2020 when assuming a renewal rate of the building stock of 3% and an increase in the rainfall intensity of 50% are also shown. It can be seen how newly populated *building blocks* are automatically connected to the existing sewer network. A decrease in imperviousness due to on-site stormwater infiltration systems can also be seen. Flooded nodes are marked in the urban environment.

Combined Sewer System 2010



Combined Sewer System 2020

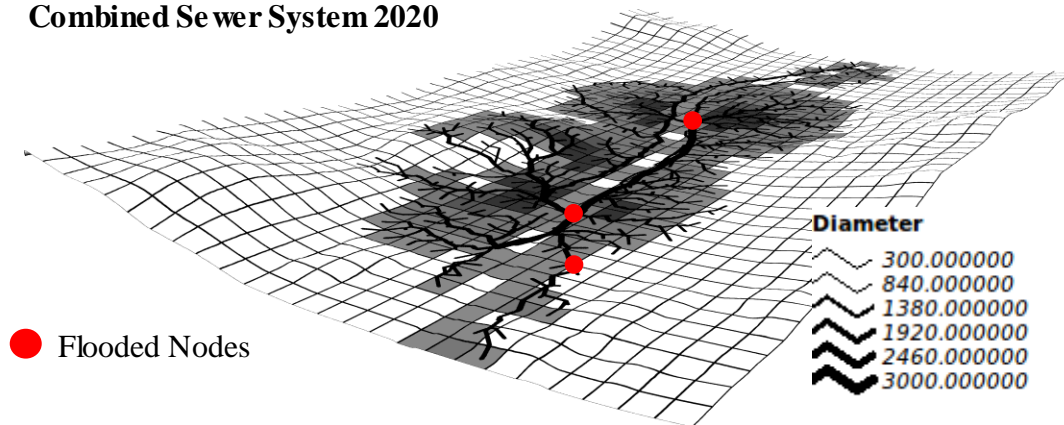


Figure 2. Combined sewer system 2010 and 2020 with impervious area and flooded nodes. Diameters are in mm and imperviousness values are in proportion of catchment area.

In Figure 3, the evolution of the urban population (pop) and the impervious area (imp) as well as the impervious area connected to the sewer network (drained imp) is shown. On the right, the development of PI1 and PI4 is shown. It can be seen that a renewal rate of 3% cannot sufficiently compensate the increase in rainfall intensity.

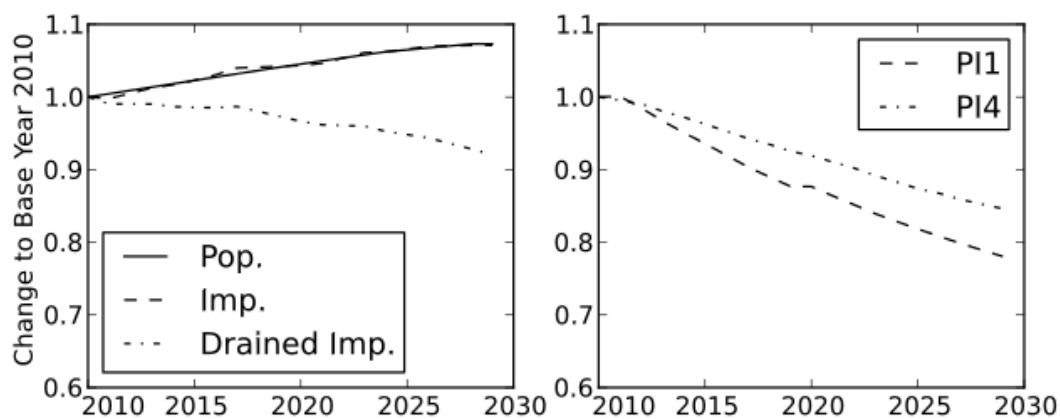


Figure 3 Storyline Base-Scenario (2010 – 2030)

For the statistical analysis in Figure 4, the performance indicators in the year 2030 are evaluated and compared. In this figure, results for climate change factors (CF) 1.0, 1.1, 1.3, 1.5 (increase of the rainfall intensity) are shown. The increase in performance due to the implementation of on-site stormwater infiltration systems is more significant for PI1 than for PI4. For PI1, a 10% increase is observed for a renewal rate of 5%, whereas for PI4 only a 5% increase is observed.

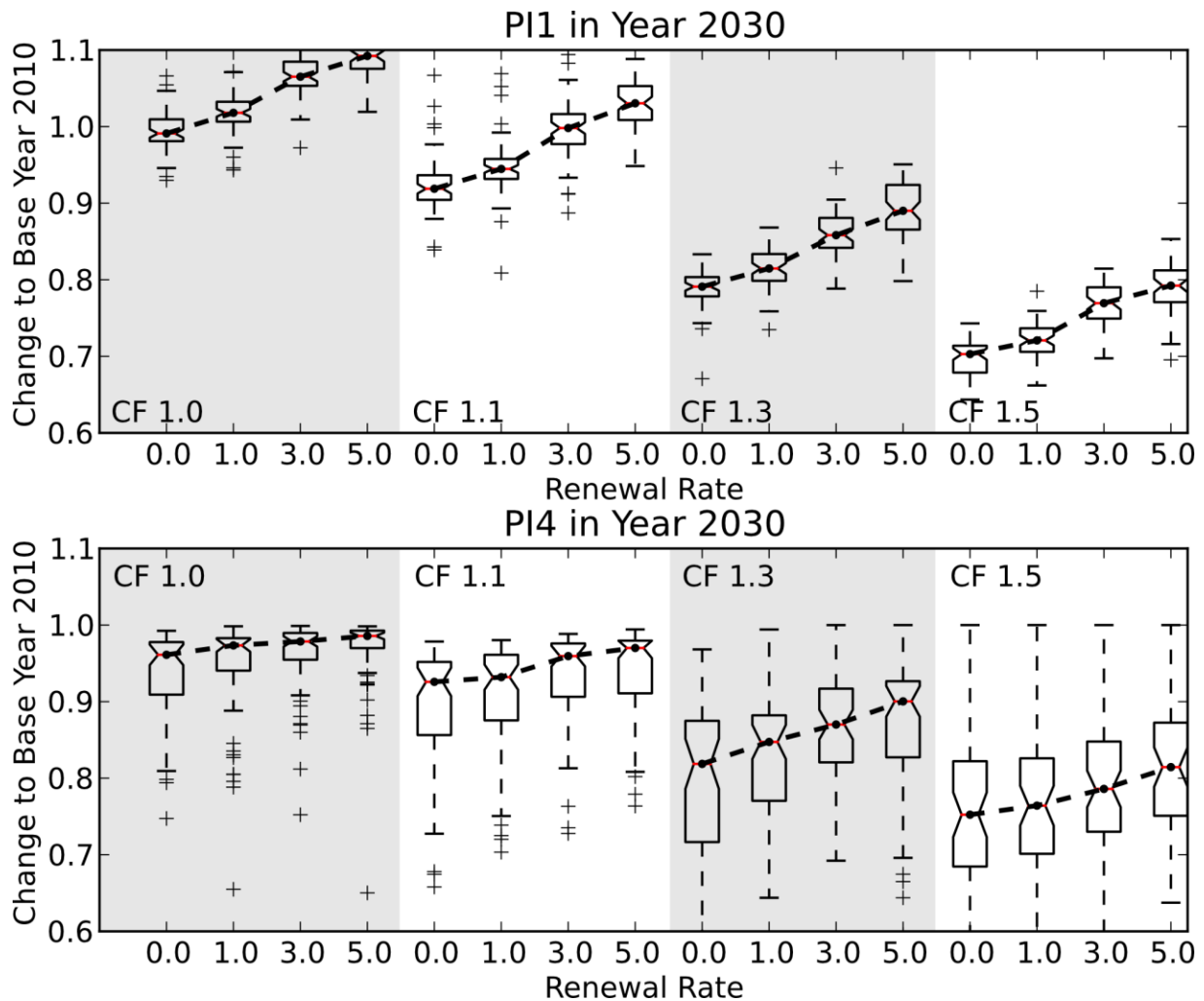


Figure 4. Change of performance indicator PI1 and P14 in 2030 compared to the base year 2010. The box plots show the median, 25% and 75% percentile, the bars show the 1.5 interquartile range and the notches show the 95% confidence interval of the median. The dotted line connects the median values of the simulations. The change in the performance when compared to the base year 2010 (y-axis) for various renewal rates (x-axis) is shown.

CONCLUSION & OUTLOOK

To enable transition to a more sustainable and resilient urban water system, new strategic planning tools that consider the complex interaction of the urban water infrastructure with the urban environment and the societal system are required and has prompted the development of DAnCE4Water. In this paper, the integration of the UDM and the BPM that represents the urban water infrastructure in a conceptual way is shown. To demonstrate the applicability of this model, an adaption strategy is tested, in which new or redeveloped buildings are required to install on-site infiltration systems. It is investigated which renewal rate would be required to compensate the effects of different climate change scenarios and urban development. A total of 1600 virtual cities have been evolved into the future and statistically evaluated. In the presented test cases it is shown that climate change and land use change cannot be compensated for by infiltration trenches. Hence additional measures have to be developed.

DAnCE4Water model is an important strategic tool that enables a wide variety of stakeholders to explore possible futures and consequences of policies and strategic action of

the urban water system under consideration of the interactions between urban water infrastructure, urban environment and the societal system.

In further work the societal transition module presented in De Haan et al., (2011) is integrated in DanCE4Water. The BPM presented in Bach et al., (2011) is enhanced to represent the whole urban water system including water supply systems, natural water bodies, separate and stormwater drainage systems as well as alternative decentralised solutions. The model will be validated for real world scenarios and different adaptation scenarios will be tested.

ACKNOWLEDGEMENTS

This research is part of a project that is funded by the EU Framework Programme 7 PREPARED: Enabling Change. This research is also partly funded by the Australian Government's Department of Industry Innovation, Science and Research.

REFERENCES

- Ambjerg-Nielsen (2008): Quantification of climate change impacts on extreme precipitation used for design of sewer systems. In: *Proceedings of the 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 2008*.
- Ashley, R.M.; Balmforth, D.J.; Saul, A.J. and Blanksby, J.D. (2005): Flooding in the future - predicting climate change, risks and responses in urban areas. In: *Water Science and Technology*, Vol. 52(5), p. 265-273.
- Bach, P.M.; Urich, C.; D.T., M.; Sitzenfrei, R.; Kleidorfer, M.; Rauch, W. and Deletic, A. (2011): Characterising a city for integrated performance assessment of water infrastructure in the DANCE4Water model. In: *Proceedings of the 12nd International Conference on Urban Drainage, Porto Alegre/Brazil, 10-15 September 2011*.
- De Haan, J.; Ferguson, B.; Brown, R. and Deletic, A. (2011): A Workbench for Societal Transitions in Water Sensitive Cities. In: *Proceedings of the 12th International Conference on Urban Drainage, Porto Alegre/Brazil, 11-16 September 2011*.
- De Toffol, S. (2006): *Sewer system performance assessment - an indicator based methodology*. University of Innsbruck, Unit of Environmental Engineering, Dissertation.
- Kleidorfer, M.; Moderl, M.; Sitzenfrei, R.; Urich, C. and 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. (2009): *Modelltechnische Analyse von Netzwerksystemen der Siedlungswasserwirtschaft*. Universität Innsbruck, Dissertation.
- ÖROK-Prognosen (2010): *Kleinräumige Bevölkerungsprognose für Österreich 2010-2030 mit Ausblick bis 2050 („ÖROK-Prognosen“)*. STATISTIK AUSTRIA.
- Rossman, L.A. (2004): *Storm water management model - User's manual Version 5.0*. National Risk Management Research Laboratory - U.S. Environmental Protection Agency.
- Sitzenfrei, R.; Fach, S.; Kinzel, H. and Rauch, W. (2010a): 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.; Fach, S.; Kleidorfer, M.; Urich, C. and W., R. (2010b): Dynamic Virtual Infrastructure Benchmarking - DynaVIBe. In: *Water Science and Technology: Water Supply*, Vol. 19(4), p. 600-609.
- The UrbanSim Project (2011): *The Open Platform for Urban Simulation and UrbanSim Version 4: Users Guide and Reference Manual*.
- Urich, C.; Sitzenfrei, R.; Möderl, M. and Rauch, W. (2010): An agent based approach for generating virtual sewer systems. In: *Water Science and Technology*, Vol. 62(5), p. 1090-1097.
- Waddell, P.; Wang, L. and Liu, X. (2008): *UrbanSim: An Evolving Planning Support System for Evolving Communities*. MA: Lincoln Institute for Land Policy, Cambridge.
- Wong, T.H.F. and Brown, R.R. (2009): The water sensitive city: principles for practice. In: *Water Science and Technology*, Vol. 60(3), p. 673-682.