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An integrated view of the urban water cycle: A shift in the paradigm?

Habilitationsschrift

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ABSTRACT

Decades ago, the idea of integrated urban drainage systems was introduced, characterizing the interactions between combined sewer systems, wastewater treatment and receiving water bodies. The increasing computer capabilities and digital availability of data and information currently show great potential to increase our knowledge of the environment and especially the “system city”. Furthermore, the temporal development of spatial data and its history can provide input for complex integrated models, which can assist in gaining insight into system coherence, and there are still new data sources to explore (e.g., social networks, among others). Therefore, this approach is a great opportunity but also a great responsibility for water engineers and others. This thesis contributes to an enhanced understanding of integrated urban water models at different levels, and it encompasses different aspects of the urban water cycle. This work focuses not on classical integrated models (e.g. integrated urban drainage models or integrated urban water models), but on broad range of actual integrated research tasks. The specific contributions of this thesis are subdivided into water distribution system analysis, urban drainage system analysis, urban development, urban water and energy, vulnerability and risk assessment and software and model development, combining different subtopics for integrated assessment. A subsequent critical discussion reflects on how modelling urban water management has become more comprehensive and holistic than ever. There is an outline to address how the integrated view of the urban water cycle is shifting to understand the urban water cycle as part of the city. For a successful and useful shift in the paradigm for assessing water-related issues in cities, another shift is required in documenting and archiving all data. A shift is required in modelling efforts and results to make the models and results comprehensible, reproducible and ultimately useful.

KURZFASSUNG

Bereits vor Jahrzehnten wurde die Idee einer integrierten Betrachtung der Stadtentwässerung entwickelt. Dabei wurden erstmals Interaktionen zwischen Mischwasserkanalisation, Abwasserreinigung sowie Wasserqualität im Vorfluter betrachtet und numerisch abgebildet. Zurzeit schafft die immer umfangreichere Verfügbarkeit von digitalen räumlich und zeitlich aufgelösten Daten aber auch noch weitgehend für solche Fragestellungen ungenutzte Datenquellen (z.B. Soziale Netzwerke), ein großes Potential das System Stadt besser zu verstehen. Nicht nur für Wasser- und Umweltingenieure bietet sich hier eine Vielzahl von Möglichkeiten aber auch Risiken. Diese Arbeit zielt auf eine weitere Verbesserung der integrierten Betrachtung des urbanen Wasserkreislaufes ab, wobei die klassische integrierte Betrachtung der Stadtentwässerung nicht im Vordergrund steht, jedoch eine Bandbreite von verschiedenen integrierten Anwendungen. Diese spezifischen Beiträge dieser Arbeit umfassen die Themen Analyse von Wasserversorgungs- und Entwässerungssystemen, Stadtentwicklung, Wasser und Energie, Vulnerabilität und Risikoabschätzungen sowie Software- und Modellentwicklungen im siedlungswasserwirtschaftlichen Kontext. Der eigentliche Fokus liegt jedoch auf der integrativen Betrachtung mehrere dieser unterschiedlichen Subthemen für gesamthafte Analysen. In einer kritischen Reflektion, werden aktuelle wissenschaftliche Bestrebungen adressiert und die Siedlungswasserwirtschaft im Wandel der Zeit diskutiert. Dabei wird der Ansatz der Betrachtung des Wasserkreislaufes als Teil des Stadtgefüges als Paradigmenwechsel aufgegriffen, bzw. die Notwendigkeit einer neuen Art der Modell- und Datendokumentation um verwertbare und nützliche wissenschaftliche Ergebnisse zur erzielen als notwendiger Schritt auch für den urbanen Wasserkreislauf identifiziert.

PREAMBLE

What is a habilitation thesis?

This thesis is a substantial part of a postdoctoral qualification. Although this type of thesis is usually only common in German-speaking countries and is used to receive the “venia docendi”, this thesis is written in English to allow international referees to evaluate the quality of the work (and most of the research work was also published in English). For international comparison, a habilitation corresponds approximately to finishing a tenure track position (associate professor). Although the habilitation supports the quality and extent of the conducted research, the qualifications with respect to teaching and dealing with administrative issues is documented in separate documents.

A total of 101 full papers have been authored and co-authored over my academic career. Of these 101, 50 full papers form the integral part of this cumulative thesis. The structure and aim of this thesis does not allow for a reference to each paper in terms of a specific chapter or subchapter because most of the work is comprehensive, and it involves different overarching topics. Therefore, all of the integral papers of this thesis are annexed at the end of this thesis but are referred to as specific publications in each chapter. These scientific publications originated from research conducted at the Unit of Environmental Engineering at the University of Innsbruck. This research was primarily integrated into third party-funded projects from regional, national and international funding. Over the course of that work, there were scientific publications that also originated from national and international cooperation with other scientific institutions, venture partners or over course of developing national guidelines. Another aspect to mention is that the papers that form an integral part of this thesis are also the results of supervised bachelor, master and co-supervised PhD theses and are therefore the results of the entire working group. The author has investigated in many different aspects of urban water management. In this context, the aim of this thesis is to provide, as much as possible, a sound picture of that work.

The phrase in the title of this thesis “a shift in the paradigm” describes a constitutional change in boundary conditions or in knowledge and is therefore always referred to and compared with the practice up to the present. This approach also means that the past practice is of great interest to understanding existing and future changes.

> *To note the importance of understanding historical decisions, part of this thesis was integrated into a research project dealing with the dynamics of the water infrastructure of Innsbruck (Sitzenfrei et al., 2014). The aim of that project was to explore the historical city and water network development since approximately 1900 to understand the impact of historical decisions on the current situation. Therefore, the different chapters of this thesis refer to that case study and that project report as indicated by this formatting.*

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List of Papers

A total of 101 full papers were authored and co-authored during my academic career until present (see page vi - xxi) with 39 as first/corresponding author. The following list of 50 full papers makes up the integral part of this thesis and is attached in the appendix. Out of these 50 annexed papers, 37 are peer-reviewed and 24 are published as first/corresponding author. These integral papers cover a broad range of research in urban water management and are published in very diverse international and widely recognized national media (* indicates Scopus listed media and a Web of Science impact factor for 2013 in brackets).

- Water Research* (Impact factor 2013: 5.323)
- Environmental Modelling and Software* (Impact factor 2013: 4.538)
- Renewable Energy* (Impact factor 2013: 3.361)
- Water Resources Management* (Impact factor 2013: 2.463)
- Water Resources Planning and Management* (Impact factor 2013: 1.760)
- Journal of Hydroinformatics* (Impact factor 2013: 1.336)
- Water Science and Technology* (Impact factor 2013: 1.212)
- Structure and Infrastructure Engineering* (Impact factor 2013: 0.954)
- Urban Water Journal* (Impact factor 2013: 0.905)
- Engineering Sustainability* (Impact factor 2013: 0.604)
- Procedia Engineering* (peer reviewed)
- gwf – Wasser/Abwasser* (peer reviewed)
- World Environmental and Water Resources Congress* (peer reviewed)
- Korrespondenz Abwasser (peer reviewed)
- Österreichische Wasser- und Abfallwirtschaft*
- Springer book chapter in Computational Engineering
- Water Asset Management International
- DVGW energie/wasser-praxis
- Wiener Mitteilungen
- Proceedings of Aqua Urbanica

PAPER I

Sitzenfrei, R.; von Leon, J; (2014): Long-time simulation of water distribution systems for the design of small hydro power systems. Renewable Energy. Volume 72, p182-187, (peer reviewed) Impact factor 3.361 (2013)

PAPER II

Sitzenfrei, R.; Rauch, W. (in press) Optimizing a small hydro power systems in a water distribution systems based on long time simulation and future scenarios. Journal of Water Resources Planning and Management, (peer reviewed) Impact factor: 1.760 (2013)

PAPER III

Sitzenfrei, R.; Berger, D.; Rauch, W.; (submitted): Design and optimization of small hydropower systems in water distribution networks under consideration of rehabilitation measures. In: Urban Water Journal (peer reviewed) Impact factor: 0.905 (2013)

PAPER IV

Sitzenfrei, R.; von Leon J..; Rauch, W. (2014): Design and optimization of small hydropower systems in water distribution networks based on 10years simulation with Epanet2. Procedia Engineering, 89C, p533-539 (peer reviewed)

PAPER V

Sitzenfrei, R.; Mair, M.; Rauch, W. (2014): Stability of traditional urban water systems – integrated assessment of transition options. Procedia Engineering, 89C, p727-733 (peer reviewed)

PAPER VI

Sitzenfrei, R.; Rauch, W. (2014): Integrated hydraulic modelling of water supply and urban drainage networks for assessment of decentralized options. Water Science and Technology. Vol. 70(11), p. 1817-1824 (peer reviewed) Impact factor 1.212 (2013)

PAPER VII

Sitzenfrei, R.; Rauch, W.; Rogers, B; Dawson, R.; Kleidorfer, M; (2014): Editorial: Modelling the urban water cycle as part of the city. Water Science and Technology. Vol. 70(11), p. 1717- 1720 (peer reviewed) Impact factor 1.212 (2013)

PAPER VIII

Burger, G.; Sitzenfrei, R.; Kleidorfer M.; Rauch, W. (in revision): The Quest for a new solver for EPANET2. In: Water Resources Planning and Management, (peer reviewed) Impact factor: 1.760 (2013)

PAPER IX

Mair, M; Rauch, W.; **Sitzenfrei, R.;** (submitted): Where to find water pipes and sewers? – on the correlation of infrastructure networks in the urban environment. Structure and Infrastructure Engineering. p 1 -11 (peer reviewed) Impact factor 0.954 (2013)

PAPER X

Tscheikner-Gratl, F.; **Sitzenfrei, R.;** Rauch, W.; Kleidorfer, M. (in press): Dealing with limited data in rehabilitation management of water supply networks. Structure and Infrastructure Engineering. p 1 -11 (peer reviewed) Impact factor 0.954 (2013)

PAPER XI

Tscheikner-Gratl, F.; **Sitzenfrei, R.;** Rauch, W.; Kleidorfer, M. (in revision): Integrated rehabilitation planning of urban infrastructure systems using a street section priority model. Urban Water Journal. p 1 -11 (peer reviewed) Impact factor 0.905 (2013)

PAPER XII

Sitzenfrei, R.; Mair, M.; Tscheikner-Gratl, F.; Hupfauf, B.; Rauch, W. (in press): What can we learn from historical water network transition? Proceedings of the World Environmental and Water Resources Congress 2015; Austin, Texas, United States, May 17-21, 2015 (peer reviewed)

PAPER XIII

Tscheikner-Gratl, F.; **Sitzenfrei, R.;** Stibernitz, C.; Rauch, W.; Kleidofer, M. (in press): Integrated rehabilitation management by prioritization of rehabilitation areas for small and medium sized municipalities. Proceedings of the World Environmental and Water Resources Congress 2015; Austin, Texas, United States, May 17-21, 2015. (peer reviewed)

PAPER XIV

Zischg, J.; Mair, M.; Rauch, W; **Sitzenfrei, R.;** (in press): Stochastic performance assessment and optimization strategies of the water supply network transition of Kiruna during city relocation. Proceedings of the World Environmental and Water Resources Congress 2015; Austin, Texas, United States, May 17-21, 2015. (peer reviewed)

PAPER XV

Rauch, W.; **Sitzenfrei, R** (2014): ÖWAV-Arbeitsbehelfs 43: „Leitfaden zur Anwendung der Thermalformel des ÖWAV Regelblattes 207“. In: ÖWAV Österreichische Wasser- und Abfallwirtschaft – Mischwasserbewirtschaftung, Ausgabe 9-10/2014

PAPER XVI

Mair, M.; Mikovits C.; Sengthaler, M.; Schöpf, M.; Kinzel, H; Urich, C.; Kleidorfer, M.; **Sitzenfrei, R.;** Rauch, W. (2014): The application of Web-GIS for improving urban water cycle modelling. Water Science and Technology. Vol. 70(11), p. 1838-1846 (peer reviewed) Impact factor 1.212 (2013)

PAPER XVII

Kleidorfer, M.; Tschiesche, U.; Tscheikner-Gratl, F.; **Sitzenfrei, R.;** Kretschmer, F.; Muschalla, D.; Ertl, T.; Rauch, W. (2014): Von den Daten zum Modell: Anforderungen an hydraulische Entwässerungsmodelle in kleineren und mittleren Gemeinden. In: Wiener Mitteilungen Band 231 Seiten J1 – J14

PAPER XVIII

Sitzenfrei, R.; Rauch, W. (2014): Investigating transitions of centralized water infrastructure to decentralized solutions – an integrated approach. Procedia Engineering, Volume 70. p1549-1557 (peer reviewed)

PAPER XIX

M. Mair, W. Rauch, **R. Sitzenfrei** (2014): Improving Incomplete Water Distribution System Data, Procedia Engineering, Volume 70. p1055-1062 (peer reviewed)

PAPER XX

Kleidorfer, M.; **Sitzenfrei, R.;** Rauch, W. (2014): Simplifying impact of urban development on sewer systems. Water Science and Technology. Vol. 70(11), p. 1808-1816 (peer reviewed) Impact factor 1.212 (2013)

PAPER XXI

Sitzenfrei, R.; Mair. M.; Diao K.; Rauch, W. (2014): Assessing model structure uncertainties in water distribution models. Proceedings of the World

Environmental and Water Resources Congress 2014; Portland, Oregon, United States, June 1-5, 2014. (peer reviewed)

PAPER XXII

Mair, M.; Rauch, W.; **Sitzenfrei, R.;** (2014): Spanning tree based algorithm for generating water distribution network sets by using street network data sets. Proceedings of the World Environmental and Water Resources Congress 2014; Portland, Oregon, United States, June 1-5, 2014. (peer reviewed)

PAPER XXIII

Tscheikner-Gratl, F., **Sitzenfrei, R.;** Rauch, W.; Hammerer, M.; Kleidorfer, M. (2014): Prioritization of rehabilitation areas – a case study. Procedia Engineering, 89C p811-816, (peer reviewed)

PAPER XXIV

Sitzenfrei, R.; von Leon, J. Rauch, W. (2014): Long time simulations and analysis of future scenarios for design and benefit costs analysis of small hydro power systems in water distribution systems. Proceedings of the World Environmental and Water Resources Congress 2014; Portland, Oregon, United States, June 1-5, 2014. (peer reviewed)

PAPER XXV

Sitzenfrei, R.; Rauch, W. (2014): Anwendungsgrenzen einfacher analytischer Lösungen zur Bestimmung von Temperaturanomalien im Grundwasser. In: gwf – Wasser/Abwasser. 03/2014. p330 – p339 (peer reviewed)

PAPER XXVI

Burger, G.; **Sitzenfrei, R.;** Kleidorfer M.; Rauch, W. (2014): Parallel Flow Routing in SWMM 5. In: Environmental Modelling & Software, Vol. 53. p. 27 - 34. (peer reviewed) Impact factor 4.538 (2013)

PAPER XXVII

Möderl, M.; **Sitzenfrei, R.;** Lammel, J.; Apperl, M.; Kleidorfer, M.; Rauch, W. (2014): Development of an Urban Drainage Safety Plan Concept based on Spatial Risk Assessment. Structure and Infrastructure Engineering. (peer reviewed) Impact factor 0.954 (2013)

PAPER XXVIII

Sitzenfrei, R.; von Leon, J; Jarosch, H; Rauch, W. (2014): Langzeitsimulation von Wasserversorgungsanlagen zur Auslegung von Trinkwasserkraftwerken. In: gwf – Wasser/Abwasser 10/2014, p1105-1110. (peer reviewed)

PAPER XXIX

Mair, M.; **Sitzenfrei, R.;** Kleidorfer, M..; Rauch, W. (2014): Performance improvement with parallel numerical model simulations in the field of urban water management. In Journal of Hydroinformatics Vol 16. No 2 pp 477 -486 (peer reviewed) Impact factor 1.336 (2013)

PAPER XXX

Sitzenfrei, R.; Möderl, M.; Rauch, W. (2013): Assessing the impact of transitions from centralized to decentralized water solutions on existing infrastructures - integrated city-scale analysis with VIBe. Water Research. Volume 47, Issue 20, Pages 7251 – 7263. (peer reviewed) Impact factor 5.323 (2013)

PAPER XXXI

Möderl, M.; **Sitzenfrei, R.**; Friedl, F.; Fuchs-Hanusch, D.; Kretschmer, F.; Ertl, T. Rauch, W. (2014): Analyse einer hydraulischen Zustandsbewertung von Mischwassersystemen. Korrespondenz Abwasser – 08/2014, p688 - 694 (peer reviewed)

PAPER XXXII

Bach P.M.; McCarthy, D.T.; Urich, C.; **Sitzenfrei, R.;** Kleidorfer, M.; Rauch, W.; Deletic, A.; (2013): A planning algorithm for decentralized water management opportunities. In Water Science and Technology. Vol. 68(8), p. 1857-1865 (peer reviewed) Impact factor 1.212 (2013)

PAPER XXXIII

Bach P.M.; Deletic, A.; Urich, C.; **Sitzenfrei, R.;** Kleidorfer, M.; Rauch, W.; McCarthy, D.T.; (2013): Modelling Interactions Between Lot-Scale Decentralised Water Infrastructure and Urban Form – a Case Study on Infiltration Systems. In Water Resources Management Vol 27 Issue 14. (peer reviewed) Impact factor 2.463 (2013)

PAPER XXXIV

Urich, C.; Bach P.M.; **Sitzenfrei, R.;** Kleidorfer, M.; McCarthy, D.T.; Deletic, A.; Rauch, W. (2013): Modelling Cities and Water Infrastructure Dynamics. In

Engineering Sustainability. Issue 166 Vol. 5, pages 301 – 308. (peer reviewed) Impact factor 0.604 (2013)

PAPER XXXV

Urich, C.; **Sitzenfrei, R.;** Kleidorfer, M.; Rauch, W. (2013): Klimawandel und Urbanisierung – wie soll die Wasserinfrastruktur angepasst werden. In: ÖWAV Österreichische Wasser- und Abfallwirtschaft. April 2013, Volume 65, Issue 3-4, pp 82-88

PAPER XXXVI

Sitzenfrei, R.; Urich, C.; Möderl, M.; Rauch, W. (2013): Assessing the efficiency of different CSO positions based on network graph characteristics. Water Science and Technology. Vol. 67(7), p. 1574-1580. (peer reviewed) Impact factor 1.212 (2013)

PAPER XXXVII

Sitzenfrei, R.; Möderl, M.; Rauch, W. (2013): Automatic Generation of Water Distribution Systems based on GIS-Data. In: Environmental Modelling & Software, Vol. 47. p. 138 -147. (peer reviewed) Impact factor 4.538 (2013)

PAPER XXXVIII

Kleidorfer, M.; Urich, C.; Leonhardt, G.; **Sitzenfrei, R.;** Rauch, W. (2012): Asset management and sustainability: planning for the unknown future. In: Water Asset Management International Volume 8 Issue 4, p. 3 - 7

PAPER XXXIX

Möderl, M.; **Sitzenfrei, R.**; Rauch, W. (2012): Sicherheits- und Notfallplanung bei Kontamination der Wasserversorgungsanlage. In: gwf – Wasser/Abwasser – Ausgabe 09 2012 (peer reviewed)

PAPER XL

Möderl, M.; **Sitzenfrei, R.;** Jarosch, H.; Rauch, W. (2012): Örtliche Sensitivitätsanalyse zur Identifikation von effizienten Standorten für Trinkwasserkraftwerke. In: ÖWAV Österreichische Wasser- und Abfallwirtschaft. Vol (64) 9-10

PAPER XLI

Sitzenfrei, R.; Möderl, M.; Fritsch, E.; Rauch, W. (2012): Schwachstellenanalyse bei Mischwasseranlagen für eine sichere Bewirtschaftung. In: ÖWAV

Österreichische Wasser- und Abfallwirtschaft - Mischwasserbewirtschaftung. Vol (64) 3-4

PAPER XLII

Mair, M.; **Sitzenfrei, R**.; Kleidorfer, M.; Möderl, M.; Rauch, W. (2012): GIS-based applications of sensitivity analysis for sewer models. In: Water Science and Technology. Vol. 65(7), p. 1215-1222. (peer reviewed) Impact factor 1.102 (2012)

PAPER XLIII

Sitzenfrei, R.; Mair, M.; Möderl, M.; Rauch, W. (2011): Cascade Vulnerability for Risk Analysis of Water Infrastructure. In: Water Science and Technology. Vol. 64(9), p 1885 – 1891. (peer reviewed) Impact factor 1.102 (2012)

PAPER XLIV

Sitzenfrei, R.; Mair, M.; Kinzel, H.; Möderl, M.; Rauch, W. (2011): Kaskadenvulnerabilität kritischer Wasserinfrastruktur. In: DVGW energie/wasser-praxis Spezial: LESAM 2011, S. 7 – 9

PAPER XLV

Kleidorfer, M.; Urich, C.; Leonhardt, G.; **Sitzenfrei, R.;** Rauch, W. (2011): Dynamik von Anpassungsstrategien der Wasserinfrastruktur. In: DVGW energie/wasser-praxis Spezial: LESAM 2011, S. 45 – 47.

PAPER XLVI

Sitzenfrei R., Kleidorfer, M., Meister, M., Burger, G., Urich, C., Mair, M., Rauch W. (2014): Scientific Computing in Urban Water Management. Kapitel von: „Computational Engineering“. 257 S., ISBN-13: 978-3319059327

PAPER XLVII

Sitzenfrei, R.; Kleidorfer, M.; Arming, G.; Rauch, W. (2014): Auswirkungen von alpinen urbanen Einzugsgebieten auf den Hochwasserschutz. Aqua Urbanica 2014; Innsbruck, Austria, 23 – 24 Oktober, 2014

PAPER XLVIII

Sitzenfrei, R.; Möderl, M.; Mair, M.; Rauch, W. (2012): Modeling Expansion of Water Distribution Systems for New Urban Development. Proceedings of the World Environmental and Water Resources Congress 2012; Albuquerque, New Mexico, United States, May 20-24, 2012.

PAPER XLIX

Sitzenfrei, R.; Möderl, M.; Hellbach, C; Fleischhacker, E.; Rauch, W. (2011): Geothermal Energy in a Central European Perspective – Challenges and Opportunities. Proceedings of the World Environmental and Water Resources Congress 2011; Palm Springs, California, United States, May 22-26, 2011.

PAPER L

Sitzenfrei, R.; Möderl, M.; Hellbach, C; Rauch, W. (2011): Application of a Stochastic Test Case Generation for Water Distribution Systems. Proceedings of the World Environmental and Water Resources Congress 2011; Palm Springs, California, United States, May 22-26, 2011.

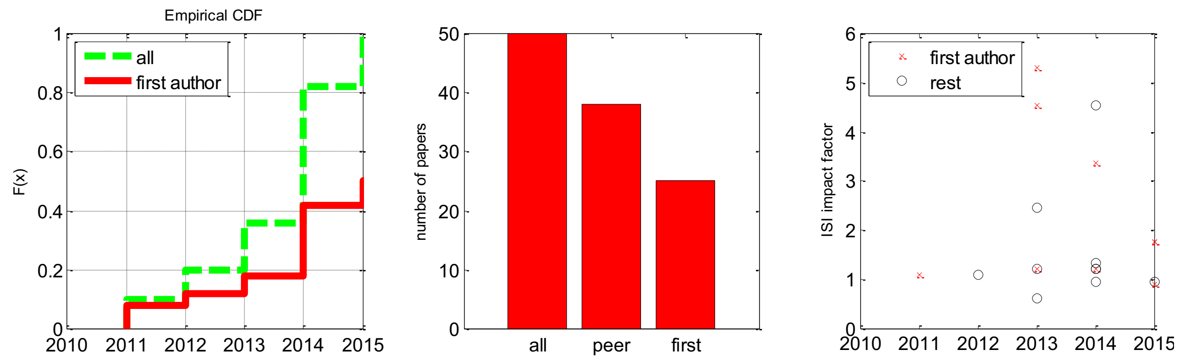

Figure 1: Evaluation of integral papers of this thesis regarding years and contributions

The publication performance (only the integral papers of this thesis) over time is characterized in Figure 1. In Figure 1 left, the temporal development of published papers and the published papers as first author are shown. Of the 50 total papers, 24 were first-authored with the peak in yearly publications occurring in 2014. Figure 1 middle shows the fraction of peer-reviewed papers in a context with all of the papers and the first-authored papers. In Figure 1, right, the impact factors of the published papers are shown over time. The sum of all of the impact points for the integral papers of this thesis is equal to 36.5.

Because the focus is on the integrated view of the urban water cycle and beyond, only a selection of the authored papers are the integral part of this cumulative thesis. The published works in excess thereof are also listed in the following work for the sake of integrity. The following publications were also derived over the course of this habilitation project or earlier (PhD project). These following papers are not integral parts of this thesis because they would also exceed the volume of the thesis. Therefore, these 51 authored and co-authored full paper publications are not included in the appendix, but they also provide valuable additional information for readers of this thesis and round out a picture of the author's work.

[1] Urich, C.; **Sitzenfrei, R.;** Bach, M; Kleidorfer, M.; Mair, M.; McCarthy, D.; Deletic, A.; Rauch, W. (2014): Modelling the Co-evolution of Cities and their Water Infrastructure. In proceedings of 13th International Conference on Urban Drainage, Sarawak, Malaysia, September 7 to 12, 2014.

[2] Mair, M.; Mikovits C.; Sengthaler, M.; Schöpf, M.; Kinzel, H; Urich, C.; Kleidorfer, M.; **Sitzenfrei, R.;** Rauch, W. (2014): Moving urban water management modelling towards web-service based technologies. In proceedings of 13th International Conference on Urban Drainage, Sarawak, Malaysia, September 7 to 12, 2014.

[3] Fuchs-Hanusch, D.; Möderl, M.; **Sitzenfrei, R.**; Friedl, F.; Muschalla D. (2014): Systematic estimation of discharge water due to transmission mains failure by the means of EPANET2. Proceedings of the Water Loss Conference 2014; Vienna, Austria, 30 March to 2 April, 2014.

[4] **Sitzenfrei, R.**; Mair, M. Rauch, W. (2014): Stability of traditional urban water systems – integrated assessment of transitions scenarios. 16th Conference on Water Distribution Analysis, WDSA 2014; Bari, Italy, July 15-17, 2014.

[5] **Sitzenfrei, R.**; von Leon, J. Rauch, W. (2014): Design and optimization of small hydropower systems in water distribution networks based on 10years simulation with Epanet2. 16th Conference on Water Distribution Analysis, WDSA 2014; Bari, Italy, July 15-17, 2014.

[6] Tscheikner-Gratl, F. **Sitzenfrei, R.**; Rauch, W.; Hammerer, M.; Kleidorfer, M. (2014): Prioritization of rehabilitation areas – a case study. 16th Conference on Water Distribution Analysis, WDSA 2014; Bari, Italy, July 15-17, 2014.

[7] Mair, M.; Rauch, W. **Sitzenfrei, R**. (2013): Improving incomplete water distribution system data. Computing and Control for Water Industry, 2013, Perugia, Italy 2-4 September 2013.

[8] **Sitzenfrei, R**.; Rauch, W. (2013): Investigating transitions of centralized water infrastructure to decentralized solutions – an integrated approach. Computing and Control for Water Industry, 2013, Perugia, Italy 2-4 September 2013.

[9] Burger, S. Urich, C. **Sitzenfrei, R**.; Rauch, W. (2013): Assessment of heating and cooling demand of buildings as part of a regional analysis of shallow geothermal potentials. In: Proceeding European Geothermal Congress 2013, Pisa, Italy 3-7 June 2013.

[10] Urich, C. **Sitzenfrei, R.;** Kleidorfer, M.; Rauch, W. (2013): City dynamics as driving force for urban water management. In: Proceeding 2nd International Conference on Water Research, 20-23 January, 2013, Singapore.

[11] **Sitzenfrei, R**.; Urich, C. Möderl, M.; Rauch, W. (2012): Assessing CSO efficiency of different CSO positions based on network graph characteristics. In: Conference Proceeding 9th International Conference on Urban Drainage Modelling, 3 – 7 September, 2012, Belgrade, Serbia.

[12] Bach, M. P.; Urich, C; McCarthy, D. T.; **Sitzenfrei, R.**; Kleidorfer, M.; Rauch, W.; Deletic, A. (2012): DAnCE4Water's BPM: Interactions between urban planning, climate and integrated urban water infrastructure. In: Conference Proceeding 9th International Conference on Urban Drainage Modelling, 3 – 7 September, 2012, Belgrade, Serbia.

[13] Urich, C. **Sitzenfrei, R.**; Kleidorfer, M.; Rauch, W. (2012): Development and Adaptation of Drainage Networks in DAnCE4Water. In: Conference Proceeding 9th International Conference on Urban Drainage Modelling, 3 – 7 September, 2012, Belgrade, Serbia.

[14] Diao, K.; Mair, M.; Möderl, M. Kleidorfer, M.; **Sitzenfrei, R**.; Urich, C.; Rauch, W. (2012): Automated Pipe-sizing of Storm Sewer or Combined Sewer Systems Based on Hydrodynamic Modelling. In: Conference Proceeding

9th International Conference on Urban Drainage Modelling, 3 – 7 September, 2012, Belgrade, Serbia.

[15] Rauch, W.; Bach, P.M.; Brown, B.; Deletic, A.; Ferguson, B.; de Haan, J. McCarthy, D.T.; Kleidorfer, M.; Tapper, N.; **Sitzenfrei, R.**; Urich, C. (2012): Modelling transition in urban drainage management. In: Conference Proceeding 9th International Conference on Urban Drainage Modelling, 3 – 7 September, 2012, Belgrade, Serbia.

[16] Urich, C.; **Sitzenfrei, R**.; Kleidorfer, M.; Rauch W. (2012): Anpassung von Entwässerungssystemen an Urbanisierung und Klimawandel. In: Conference Proceeding aquaurbanica 2012, 08. Mai 2012, München.

[17] Mair, M.; **Sitzenfrei, R.**; Urich, C.; Kleidorfer, M.; Möderl, M.; Rauch, W. (2012): Performance Improvement with parallel numerical model simulations in the field of urban water management. Proceedings of the 10th International Conference on Hydroinformatics; Hamburg, Germany, July 14-18, 2012.

[18] Möderl, M.; **Sitzenfrei, R.**; Jarosch, H. and Rauch, W. (2012) Identifying Hydropower Potential in Water Distribution Systems of Alpine Regions. Proceedings of the World Environmental and Water Resources Congress 2012; Albuquerque, New Mexico, United States, May 20-24, 2012.

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1 INTRODUCTION

Urban water management addresses all water-related issues in urban agglomerations. Because structures in urban water management have life expectancies of up to 100 years or more, urban water systems as implemented today are strongly influenced by historical decisions and implementations. In the same way, current decisions will have a long-term impact on that system. Therefore, it is also important to understand what happened in the past and what the influence of those actions are on today's system.

For the traditional systems as we know them today, the technical water supply was first introduced to bring high-quality drinking water into the city and also to distribute it throughout the city. The water is usually taken from springs, groundwater or surface water and brought to and distributed throughout the city via pipe networks. There were simultaneously recognized needs to improve the hygienic conditions of cities (Metcalf and Eddy, 1914) and also to take the large amount of used water and wastewater out of the cities.

> *In Innsbruck, an average water demand of 150 litres per capita and day was already assumed during the design of the water supply network in 1880s and it also had to be transported out of the city after usage. During the first construction period between 1888 and 1891, a water supply network for approximately 23,000 inhabitants was built.*

After experiments with different technologies, an urban drainage pipe network was favoured, which transported the rainfall runoff out of the cities, usually by directly discharging it into a receiving water body. In major industrialized cities, the implementation of these pipe networks mostly started in the 19th century, and the networks were continuously expanded following the urban expansions, and always in relation to new regulations and the implementation of emerging technologies. The introduction and implementation of these traditional pipe systems were very important steps for industrialization, societal health and security (e.g., for fire-fighting). The decisions of that time, such as the collection of wastewater and rainwater in one system (a combined system), decisively defines how the current and future systems operate.

The criteria for the hydraulic design of the combined sewer system in Innsbruck almost 120 years ago were almost comparable with those of today. The usual discharge of the combined wastewater into the receiving water during long-term rain events was released downstream, after the city, to ensure that there were no quality or odour issues in the city. Only during heavy rain events was diluted wastewater (design ratio 1:3) allowed to be discharged at multiple points, which are now called CSOs (combined sewer overflow). For the design criteria, 4 heavy rain events were observed with, relative to today, only modest devices and knowledge. With excellent engineering judgment (and to some extent a gut-level instinct), a design rain event was estimated that almost exactly corresponds to the design rain event for a 5 year return period found in modern guidelines.

Dealing with polluted wastewaters and preserving the qualities of receiving waters came into focus shortly after that time. Starting in the 19th century, wastewater treatment plants with different treatment steps had already been developed and implemented (Seeger, 1999).

In Innsbruck in the 1960s a mechanical treatment was implemented and enhanced during the 1970s with a biological treatment step. The aim of the already implemented combined system was to collect all of the wastewater under normal conditions (no heavy rain events) and discharge the combined wastewater into the receiving water after the city. Therefore, that approach was favoured for the waste water treatment plant and was installed without major adaptations of the implemented pipe network.

Population growth and ongoing technical progress in all areas of society in addition to economic wealth also triggered growing demand for potable water (e.g., dish washers, washing machines, etc.) in all industrialized countries and cities and hence also increased demand for the corresponding water treatment. Therefore, there was a need to tap additional water sources and also an awareness of water-saving measures. Some years later, an awareness of water efficiency and conservation was established within society (to some extent, the expected assumption of population growth did not take place), which in some places led to problems from an implemented overdesign in the systems.

During the 1980s, the Innsbruck wastewater treatment plant was designed for future with 400,000 expected population equivalents, and in 2012, approximately 270,000 population equivalents were used.

In addition to the water demand, the energy demand grew along with technical progress. To provide the energy for heating and cooling demands, heat pumps were increasingly installed in components of the urban water cycle. In the 1970s, shallow geothermal systems (closed loop systems and open loop systems for extracting and injecting groundwater) received a substantial boost.

The aquifer below Innsbruck is a fast-flowing Alpine aquifer that almost fills the entire valley floor at a thickness of approximately 50 m. The flow velocity of the groundwater is approximately 1 meter per day. Under the atmospheric buffer zone (roughly a depth of 5 metres), the unaffected temperature is approximately 12°C throughout the year. These hydraulic and thermal boundary conditions are ideal for use with open loop (but closed loops can also be installed) systems for the heating and cooling of buildings. Geothermal utilization and heat input from buildings, underground parking and sewers result in a measured groundwater temperature below the city of up to 17°C.

More recently, the heat recovery of wastewater at different levels was also enforced. The mathematical description of these processes in addition to the numerical methods and hardware needed to assess the systems were increasingly developed and found their way into everyday engineering practice.

There are currently countless facets to urban water management and only a subset can be addressed in the context of this thesis. The high life expectancy of these systems and their components illustrates that historical decisions and implementations have a great impact on today's management and operation strategies. Today's decisions will likewise have a great impact on the possible future solutions and transitions of urban water systems. Therefore, learning from historical decisions and coping with uncertain future conditions are the primary focuses of this thesis.

Although most of these systems have already been built in industrial countries, today's challenges are to shift to the cost-efficient operation, management and maintenance of these systems and to cope with emerging problems such as climate change, rapid or uncertain population changes, new technologies or newly discovered harmful substances and products. To enhance technical performance under critical conditions, there is also an increasing awareness of sustainability and more environmentally friendly solutions.

In the current water infrastructure of Innsbruck, there are still parts of the initial networks in place that still perform quite well. In approximately 4% of the current water supply network length, there are still pipes in place from the first construction period that took place in the 1890s, and there are even more for the sewer system.

For all of those challenges, a scenario-based analysis with numerical models will help to enhance the understanding of the system and identify coherences and critical pathways in these processes. Although these different facets and parts are traditionally assessed separately, there is a high chance of deepening our understanding and gaining insight with integrated numerical models by combining the subsystems into overall integrated models. The urban water cycle became a rather complex and manifold system over the decades and a lot of in-depth knowledge was found in different disciplines. This approach also resulted in very specialized experts in the different fields. Although engineers are taught to have at least an overview and technical insight of all aspects, in practice there is often a separation among the fields, and cross-linked thinking is often not possible or left behind.

The rise in digital technology use in recent decades has provided great potential, not only for urban water engineers, for combining manifold spatial and temporal information to produce considerable awareness of city scale processes. In addition to data and hardware improvements, tools and software improvements from different fields and the open source community have also made their contributions; the “system city” can be described more accurately than ever, and the potentials are yet not fully exploited. Years ago, attempts to develop integrated urban drainage models (e.g., Rauch, 1996) had already been made, but they focused solely on assessing the technical performance in a way that was more or less detached from the city. More recently, different attempts were undertaken to describe the entire urban water cycle in integrated urban water models as part of the city to understand the interactions of the different subsystems and fully exploit available data and modelling techniques (Bach *et al.*, 2014). However, engineering in that context has become more interdisciplinary and challenging than ever. Reliably combining techniques from computer science, urban planning, socio-economics, geography and biology with traditional environmental and civil engineering approaches is a critical endeavour. This thesis aims to contribute to some of these integrated research and technology gaps.

In addition to the first rough introduction to this thesis on the relevant parts of the urban water cycle, chapter 2 puts the research into a context with the latest related international findings to outline the integrity and contributions of this work. The context is the setup, referring to the papers in the appendix as an integral part of this thesis. Chapter 2 is further subdivided into classical stand-alone topics in urban water management (subchapter 2.1 - 2.6), and as a last subchapter (2.7), different approaches to benefit from linking the different separate topics to overall approaches are discussed, and the possibilities and advantages are outlined (chapter 3). A critical reflection of the developed and proposed approaches is also given in detail in chapter 3, before the outlook for future work is given (chapter 4).

Because this is cumulative thesis, the different integral papers should be inserted into the different chapters of the thesis. For a clear structure, all integral papers in this thesis and the personal contributions to the papers are shown in the appendix. All 50 full papers (Paper I - L) that make up the integral part of this thesis are included in the appendix.

2 THE CURRENT STATE OF RESEARCH AND CONTRIBUTIONS

As outlined before, urban water management is a very multi-layered discipline, and the urban water cycle has many more parts than are described in this thesis. It is not the aim of this work to explore all of the different facets but rather to put the author's research contributions into a context with other related excellent, international research work. The primary topics of this thesis encompasses the following:

- water distribution system analysis
- urban drainage system analysis
- urban development
- urban water and energy
- vulnerability and risk assessment
- software/ model development

Because this thesis is especially focused on integrated approaches, the last subchapter is about integrated approaches and assessments. Outstanding progress was achieved during the past decades in all of these topics by several different researchers and groups, but the aim of the following descriptions is to put the findings of this thesis in a context with other recent findings (primaly after 2010) to outline the integrity of the current scientific developments. For in-depth scientific contexts (beyond recent findings), the reader is referred to the individual introductions of the appended papers.

2.1 Water distribution system analysis

For the past several decades, the focus of water distribution systems analysis, among other topics, has been the optimization of different design aspects and the operation of water distribution networks (Sitzenfrei, 2010). For example, recent research has aimed to minimize costs, maximize reliability and resilience (e.g., Farmani *et al.*, 2006, Ostfeld *et al.*, 2014) and reduce greenhouse gas emissions (e.g., Wu *et al.*, 2010, Stokes *et al.*, 2014) or life cycle costs (Shahata and Zayed, 2013). In this context, and for long range planning, the maintenance and rehabilitation of water distribution systems (Ammar *et al.*, 2012; Shahata and Zayed, 2012; Beale *et al.*, 2013) and their optimization is still in focus as the water infrastructure ages and reaches its expected lifespan. Because the water infrastructure is a critical infrastructure (Möderl *et al.*, 2011a), the impact of its failures and stability play important roles in public health (Besner *et al.*, 2010). Recent research on water distribution analysis therefore also focuses on identifying critical components within that type of distribution networks (Perelman and Ostfeld, 2011; Dunn and Wilkinson, 2012; Soltanjalili *et al.*, 2011), also accounting for its cascading effects (Zio and Sansavini, 2011).

In that context, several groups have recently focused on different sources of uncertainties, among others the impact of pipe roughness (Seifollahi-Aghmiuni *et al.*, 2013) and reliable design under uncertainties (Chung *et al.*, 2009) on the model predictions, stochasticity of water demand (Blokker *et al.*, 2011), future water demand uncertainties (Neunteufel *et al.*, 2014) and flexible design (Basupi and Kapelan, 2013) or long-range planning (Kang and Lansey, 2014).

Initially, water consumption per capita per day of 150 litres was assumed in Innsbruck when designing the water distribution system. However, people were used to running wells and used their water as they had in former times. In 1895, water consumption was 350 and in 1927 there was a maximum amount of 500 litres per capita per day. Furthermore, consumers had to pay per outlet and not per volume consumed. Therefore, public awareness and consumer behaviour conflicted with the implemented system. Technical bottlenecks and high investment needs enforced a reduction in water consumption below 300 litres per capita and day in 1933.

After steadily increasing water demand again in the 1980s the water demand per capita and day rose up to 380 litres per capita and day, before it declined again to about to below 190 litres per capita per day in 2010 (domestic water demand is approximately 130 litres per capita per day). The additional capacity and the decline in water consumption provided additional capacity with respect to population growth and also increased the redundancy in the system.

These new approaches in water distribution analyses are usually tested on one or a few benchmark systems (before they are applied to real systems). On the one hand, this makes their findings comparable, but on the other hand, the results are usually very case-specific. Because of data availability and security reasons, models of water distribution systems are rarely published or available for research. For that reason Möderl *et al.*, (2007) established the idea of stochastically creating benchmark sets. Following that idea, automatic generators of benchmark networks were developed (Sitzenfrei *et al.*, 2010b; 2010a; 2010c; Trifunovic *et al.*, 2012; Muranho *et al.*, 2012; De Corte and Sörensen, 2013), and they increasingly find their way in the scientific community.

In addition to integrating developed approaches with other aspects and fields (see chapter 2.7), the specific contributions of this thesis on water distribution system analysis encompass the development and application of automatic network generators (PAPER VIII, PAPER XXI, PAPER XXX and PAPER L). The developed models have up to the present an island position because they also account for geographical information on cities such as land-use and population densities (PAPER XXXVII), and the dynamic expansion of the city over time can be considered (PAPER XII, PAPER XIV, PAPER XLVIII). This approach enables a comparison of multi-stage planning strategies and the testing of different layout strategies, with regards to cost and performance. In bringing network generators to the next level, system coherence with free available street network data were investigated (PAPER IX), and rules for that correlation were formulated (PAPER XXII) to create semi-virtual water distribution models out of freely available street network data. This strategy also brings the network generator technology into practice by showing the potential of stochastically adding and improving incomplete network data for the hydraulic modelling process (PAPER XIX).

Another major advance was also achieved by establishing a long-term simulation approach for the water distribution system (PAPER I). The statistical impact and uncertainties of highly variable daily demand patterns over a long simulation period (e.g., one decade) can thereby be quantified. The advantage of that type of statistical analysis of the modelling results are shown in PAPER II, PAPER III, PAPER IV, PAPER XXIV and PAPER XXVIII by estimating and assessing the impact of uncertain future demand and population scenarios on the technical performance and economic analysis. Furthermore, by using a long-term simulation approach, the design procedure for small hydropower systems (PAPER I, PAPER II, PAPER IV, PAPER XXVIII) was enhanced, allowing for a better assessment that type of system under highly variable water distribution system. In that context, the impact of uncertain future developments and options for decentralized measures were investigated. The impacts on the technical performance of the water distribution system were therefore quantified (PAPER XXIV). Furthermore, ways to improve limited data availability for rehabilitation management were investigated and enhanced (PAPER X).

Another important contribution of this thesis is the development of a system wide-risk assessment and vulnerability analysis approaches for water distribution systems (PAPER XXIX) by means of a GIS-based sensitivity analysis (Möderl *et al.*, 2011b). Additionally, the cascade vulnerability term for critical water infrastructure was introduced (PAPER XLIII, PAPER XLIV) and applied to water distribution models.

2.2 Urban drainage system analysis

The focus of the current research is related to the water distribution system analysis, and also on urban drainage modelling optimization procedures. In comparison with the water distribution system analysis, the computational efforts are much greater, and therefore, the optimization was not extensively applied for the last several decades. Nevertheless, layout optimization procedures (Afshar, 2010; Moeini and Afshar, 2012; Haghighi and Bakhshipour, 2012) and optimal design strategies (Cimorelli *et al.*, 2012; Dong *et al.*, 2012) in addition to the optimization of integrated models (Muschalla, 2008) have been developed and applied.

In recent years, extensive attention has been paid to coping with uncertain future developments such as climate change and its accompanying water-related problems (e.g., Hallegatte, 2009; Kleidorfer *et al.*, 2009; Mailhot and Duchesne, 2010; Mailhot and Duchesne, 2010) or urban development and population change (e.g., Doglioni *et al.*, 2009).

Having initially been built for 23,000 inhabitants, the water infrastructures of Innsbruck currently serve 130,000 inhabitants and there is also wastewater collection and treatment for the greater surroundings. For the inner city, which was sewered approximately 1900, the assumed future population of 80,000 was never reached, but the system provided additional hydraulic capacity to connect expansions. An optimized solution without overdesign would have been obstructive for the actual future developments.

The comprehensive investment costs for inflexible and only slowly adaptable centralized infrastructure (i.e., pipe networks) shifted the focus to a flexible and more easily adaptable, decentralized water infrastructure. In that context, sustainability in general in urban water management and beyond became the focus of more and more awareness (e.g., Brown and Farrelly, 2009) by integrating water management issues into the urban tissue, preserving natural water flows and using and reusing the different water stream more efficiently with decentralized water systems (e.g., Marlow *et al.*, 2013; Penn *et al.*, 2013a and 2013b). Different approaches and denotations have been used such as “water-sensitive urban design” (Brown *et al.*, 2009) or “low impact development” (e.g., Wang, 2013). To evaluate these approaches, sustainability assessment frameworks were also defined and developed (e.g., Ole *et al.*, 2012; Fratini *et al.*, 2012). Furthermore, selection procedures (Moore *et al.*, 2012) and the spatial optimization of decentralized options (Dong *et al.*, 2012) were developed and applied.

To implement of decentralized measures, the transition from traditional pipe-based urban water management to decentralized options is an important issue in industrialized areas where centralized systems are already in place (Urich *et al.*, 2011a; Fratini *et al.*, 2012; Rauch *et al.*, 2012). Problems may arise when the technical performance of the remaining pipe network (or during the transition) cannot be maintained, e.g., increased sewer deposits (Vongvisessomjai *et al.*, 2010, Ota and Perrusquia, 2013) because of declining dry weather flow.

In urban drainage modelling, the idea of “virtual case studies” as a playground for researchers to test these new approaches was successfully established. For that reason, different case study generators were also developed and applied in urban drainage modelling (e.g., Borsanyi *et al.*, 2008; Möderl *et al.*, 2009a; Sitzenfrei *et al.*, 2010c; Urich *et al.*, 2010a; Maurer *et al.*, 2010; Scheidegger *et al.*, 2011; Blumensaat *et al.*, 2012; Haghighi, 2013), and also by considering infrastructure development over time (Sitzenfrei *et al.*, 2010e; Urich *et al.*, 2011a and 2011b).

In addition to integrating the developed approaches with other aspects and fields (see chapter 2.7), the specific scientific contributions of this thesis to urban drainage system analysis encompass different aspects of the urban drainage modelling process such as defining data requirements for practitioners (PAPER XVII), sensitivity analysis (PAPER XLII), optimization (PAPER XXXVI) and designing drainage systems with regards to interactions with river catchments (PAPER XLVII). Furthermore, an identification of the weak points in the systems (PAPER XLI) for reliable and safe operation (PAPER XXVII) in the context of long-term planning and rehabilitation measures (PAPER XI, PAPER XIII, PAPER XXXI) were also addressed.

In the context of pipe network transitions, the implementations of decentralized measures were investigated to determine the degree of possible technology diffusion ensuring the technical performance of the traditional systems (PAPER V, PAPER VI, PAPER XXIII and PAPER XXX). Regarding uncertain future developments, general challenges were defined for future planning (PAPER XXXVIII) and possible future scenarios and urban drainage dynamics were explored (also with virtual case studies) in PAPER XX, PAPER XXXIV, PAPER XXXV and PAPER XLV. Furthermore, to enable an interdisciplinary future planning process (e.g., in stakeholder workshops), a web-based scenario analysis platform was developed (PAPER XVI).

2.3 Impacts of urban form and society

Urbanization and therefore the urban form have a strong influence on the local water balance (Barron *et al.*, 2013) and the urban water cycle in general. When the impervious area changes because of settlements, the entire watershed function is influenced (Aichele and Andresen, 2013), which can lead to increased runoff and therefore flooding (e.g., Suriya and Mudgal, 2012).

Furthermore, the temperature distribution in compact urban agglomerations is impacted (Qiao *et al.*, 2014; Feng *et al.*, 2014) and known as the urban heat island effect. In addition, the subsurface and groundwater temperatures are influence by the modifications of the natural state (Gunawardhana *et al.*, 2011 Gunawardhana and Kazama, 2012; Epting and Huggenberger, 2013). In groundwater these changes are primarily exhibited as increased temperatures, which also lead to the "geothermal heat island" effect and additional geothermal potential for energy utilization (Zhu *et al.*, 2010). Urich *et al.*, (2010b) investigated the impact of urban form on geothermal open loop systems in this context and identified a major influence from the building density on the possible utilization level.

The urban infrastructure and urban form, and therefore its development over time, are strongly linked. The urban development plans (i.e., master plans) mostly define requirements for water infrastructure development. Depending on the importance and awareness of water in the city, water infrastructure-related issues can/should be taken into account for urban development to some extent (Shandas and Hossein Parandvash, 2010) or at least for building regulations.

Different fields within urban water management have recently addressed the detailed connections between the urban form and centralized water infrastructure (e.g., Suriya and Mudgal, 2012; Farmani and Butler, 2013) and also in the context of the energy required for sufficient technical performance (e.g., Filion, 2008). As in decentralized water infrastructure, the impact of the urban form and the interactions were investigated (e.g., Spatari *et al.*, 2011; Bach *et al.*, 2013). As also described in the previous section, a combination of both centralized and decentralized water infrastructure is regarded as more flexible for facing upcoming challenges and more sustainable (preserving the natural water cycle). When implementing these measures, it has to be noted that a transition to these decentralized technologies has an impact on both centralized water infrastructures.

In the context of this transition, and also to understand the socio-technical transition, socio-economic drivers and barriers (Brown and Farrelly, 2009; Domènech and Saurí, 2010; Mankad and Tapsuwan, 2011, Ferguson *et al.*, 2013; Dobbie and Green, 2013; Sun and Hall, 2013) are of great interest in the current research.

> *Shortly after the decision to install a combined sewer system in Innsbruck, a mandatory sewer connection was enforced during the first construction period (1903 - 1907). After criticism regarding social concerns, for low-income residents, financial amenities were provided. Although private costs arose for connecting to the public sewer system, the centralized system had and still has major advantages, enabling, among other characteristics, comfort and ensured hygienic conditions for everybody, as guaranteed by a public utility. Soon, all of the sewered areas were connected to the combined sewer system.*
>
> *Another major transition in Innsbruck started in 2001, approximately 100 years after the first construction period. After gaining confidence in rain water infiltration technologies and the monetary advantage of not increasing the centralized system capacity, the administration enforces an infiltration obligation (except in areas where it is not possible because of soil conditions or available space). Without gaining public awareness, identifying social barriers etc., solely based on technically documented knowledge, a step-wise detachment of the impervious area was conducted by binding building regulations. Currently, approximately 1.5% of impervious area from private buildings is detached each year.*

When a city expands, the requirements for future developments, and therefore the impact of different urban expansion strategies for centralized water infrastructure, were addressed (e.g., Yazdani *et al.*, 2011; Chang *et al.*, 2012), which can also be seen as the driver and the potential for infrastructure rehabilitation (e.g., Dirksen *et al.*, 2012; Kleidorfer *et al.*, 2013).

> *Although there is a constant population increase in Innsbruck, there is hardly any urban expansion anymore. The primary strategy to cover the required living space is an agglomerated dense construction with high density building types and space saving construction methods. This densification is also enforced for areas that were already built (as also promoted by building subsidies).*

In addition to integrating the developed approaches with other aspects and fields (see chapter 2.7), the specific scientific contributions of this thesis on urban development are in urban drainage, water distribution and groundwater utilization. In PAPER XLIX, in addition to the central European geothermal potentials, the impact of dense urban form and the accompanying intense geothermal utilization of the groundwater energy budget are quantified.

In PAPER XXXVII, the strong correlation of the urban form with water infrastructure layouts is used to create possible water distribution layouts for given city layouts. This topic is further deepened in PAPER IX, by investigating network correlations with the street network based on statistics and graph theory. Sitzenfrei *et al.*, 2010e described the concept of coupling urban development models with infrastructure development to investigate scenarios and technical transitions over time. That approach was applied and enhanced in PAPER XXXIV and PAPER XXXV for the evolution of drainage networks and in PAPER XLVIII to investigate different expansion strategies for water distribution systems. In PAPER XVI, a web-GIS platform is presented that allows the very quick testing of network expansion strategies without many input data online for, e.g., interdisciplinary stakeholder workshops.

In PAPER XXXII, an approach to identify decentralized water management opportunities based on urban form was presented and in PAPER XXXIII, the interaction between the urban form and possible decentralized solutions was investigated. In PAPER V, PAPER VI and PAPER XVIII, water distribution and drainage models are coupled via the population and the urban form to investigate the impact of the increased implementation of decentralized water options on the existing centralized water infrastructure. In addition to very advanced research applications that might be applicable in the future and also in practice, there is a simple empirical correlation found between land use change and a change in the return period for the design of urban drainage systems in PAPER XX, which can easily be implemented in state-of-the-art design guidelines.

2.4 Urban water and energy

In the EU27, approximately 40 MWh per capita are consumed per year at present (Azhar Khan *et al.*, 2014). Within the urban water cycle, different processes consume a considerable amount of energy. Energy is consumed for exploitation, water preparation, transportation, heating, collecting, and water treatment. Approximately 80% of the primary energy demand in the (domestic) urban water cycle is required for water heating and the rest is for transportation and treatment (Elias-Maxil *et al.*, 2014). Just in the operational phase of the urban water infrastructure approximately 220–260 kWh per capita per year are consumed (Venkatesh and Brattebø, 2011), but these values can vary quite a lot (up to 700 kWh per capita and year or even more; Olsson, 2012) depending on, for example if the system is gravity-driven or not or if a desalination plant is implemented. For the centralized water infrastructure (without water heating), approximately 0.5–2% of the total energy amount per capita is consumed and for water heating approximately 5–10%. This rate puts energy savings-based optimization procedures in water transportation networks into perspective. Nevertheless, all different sectors can contribute to a sustainable energy strategy, at least to some extent, and energy should not be wasted. Furthermore, implementing single measures can have an impact on many people, and the amounts of saved or recovered energy add up and help to counter climate change.

In addition to reducing the amount of energy consumed, the consumed/available energy source and synergies must also be taken into account. For example, energy storage is of great interest for efficiently using wind energy. When combining the required pumping for water supply with wind energy and hydro power, even pump storage hydro power stations within a water supply network are feasible (e.g., Vieira and Ramos, 2009 Ramos *et al.*, 2011). In this context the CO_2 emissions are the driving factor. Recent research was therefore focused on minimizing greenhouse gas emissions in the potable water supply network (Wu *et al.*, 2010 and 2013; Stokes *et al.*, 2014). In addition, pressure management and loss reductions (Fontana *et al.*, 2012; Mutikanga *et al.*, 2013; Xu *et al.*, 2014) can help to decrease the required energy amount and the amount of energy lost, respectively.

Under regular conditions, the water supply in Innsbruck is and always was fully gravity driven. The required water is fed-in from elevated hillside springs. Under emergency conditions, the water can also be pumped from groundwater wells. Because of the excellent water quality, no drinking water treatment is usually required. For gravity-driven distribution, the available pressure is sufficient and exceeds regulatory requirements (the regular pressure is approximately 8-11bar).

However, the water industry can also contribute to some extent to energy production, but as long as the energy consumption per capita is that high, it can only contribute marginally to covering the required demand (Svardal and Kroiss, 2011). In the urban water cycle, there are different sources for extracting energy. In addition to chemical energy in the wastewater, thermal energy can also be recovered (van der Hoek, 2012). Heat can be recovered from the wastewater with heat exchangers that are decentralized and centralized at several locations throughout the system from the source (e.g. in the bathrooms), via the sewers and at the wastewater treatment plant (Meggers and Leibundgut, 2011). It is important to consider that the biological processes at the wastewater treatment plant are inhibited when the temperature is too low (Wanner *et al.*, 2005). Even industrial cooling with wastewater could be a feasible use, but for these applications, knowledge about the temperature distribution and the impact of thermal utilization is required. Therefore, Dürrenmatt and Wanner, (2014) presented a mathematical description of the effect of heat recovery in sewers. When installed in a combined sewer system, there is especially high variability in the flow rates and temperatures (Cipolla and Maglionico, 2014) throughout the year, which requires extensive numerical efforts (Abdel-Aal *et al.*, 2014).

Under specific conditions, thermal energy from drinking water can also be used. In the Netherlands, water intakes have temperatures of up to 25°C (van der Hoek, 2012) which can represent a quality problem for drinking water. In that case, a heat extraction with heat exchangers could benefit both the water quality and cover heating energy demand.

The water temperature of the primary water intake in Innsbruck is constantly approximately 5°C. Through its distribution via the supply network, the water is slightly warmed (to approximately 8°C) depending on the residence time in the network. By contrast, groundwater from the emergency wells has a temperature of approximately 12°C.

For hot water production, the water has to be heated up and depending on the initial temperature, a higher or lower primary energy demand is required. The 3°C higher temperature of the given potable water could save up to approximately 10% of the *warm water heating demand (approximately 100kWh per capita per year). To obtain warmed potable water, different water sources (if available) could be used or the water could be pre-used for cooling buildings etc. before consumption. However, this approach is commonly assumed to represent significant problems and risks in the safety and security of the water supply.*

Another possible contribution from the urban water cycle to energy production is to use excess pressure and excess water in the supply networks with turbines (Möderl *et al.*, 2012; McNabola *et al.*, 2013; Chen *et al.*, 2013). Even very small turbines (pico turbines below 5 kW) can be operated in an economic fashion in water supply networks (Williamson *et al.*, 2014). These systems are especially beneficial for Alpine regions with great height differences where pressure reducing valves usually have to be installed to reduce water losses and avoid harming the pipes, controls and instruments (Giugni *et al.*, 2013). Economically, reverse-running pumps can also be installed, which even further reduces the investment costs for such devices (Nautiyal *et al.*, 2010).

In relation to technical progress and increased water consumption over the decades, the energy demand in Innsbruck grew continuously as in every industrialized city. In addition to other different potentials for energy production, the implementation of hydro powers systems in the urban water cycle was also accelerated. In 1954, a hydropower system that employed the height difference between the tapping of the source and the tank with a performance of 6MW was installed in Innsbruck and is still in use, covering approximately 5% of the total electric energy demand of Innsbruck. The province of Tyrol currently has approximately 700,000 inhabitants and around 70 hydro power systems within water distribution systems installed. Approximately 50% of these systems have an installed capacity below 50kW.

Groundwater is also a possible source for covering the heating and cooling demand. The use of shallow geothermal potentials via open loop systems has become increasingly important in recent decades (Hähnlein *et al.*, 2013). Because the sun is a relevant source for shallow geothermal systems, the thermal regeneration of used groundwater is of great interest (Sitzenfrei *et al.*, 2010d). For that strategy, the thermally affected zone around ground water heat pumps (Lo Russo *et al.*, 2012) and the ecological impacts were intensively investigated (Brielmann *et al.*, 2011).

In addition to integrating the developed approaches with other aspects and fields (see chapter 2.7), the specific scientific contributions of this thesis are to present methods for identifying the potential (PAPER XL) and to perform cost benefit analyses of small hydropower systems in Alpine water supply networks (PAPER I to

PAPER IV). Furthermore, optimization potentials under the population uncertainties of such systems were investigated (PAPER II).

For geothermal utilization, the central European perspective of geothermal potential was critically reviewed (PAPER XLIX). Furthermore, for national implementation, research was conducted on the thermally affected zone around groundwater heat pumps (PAPER XV and PAPER XXV), which provided the basis for national guideline ÖWAV AB43 (ÖWAV-AB43, 2014) for calculating the vertical and horizontal extents of thermal plumes.

2.5 Vulnerability and risk assessment

The water infrastructure is regarded as critical infrastructure and it is crucial for social well-being and supporting economic growth (Dunn and Wilkinson, 2012). The most important task of the water infrastructure in this regard is a high level of reliable service. To assess these systems, there are different definitions of risk. A common definition of risk is the product of consequence and the likelihood or vulnerability and hazard (UN DHA, 1992). For that purpose, the hazard is a process that puts pressure on the system and the vulnerability is the level of response or sensitivity to that hazard. A major task for risk assessment is therefore to identify vulnerable components to help design water networks that are also more robust during critical events (Pinto *et al.*, 2010).

Critical events for water infrastructures can be manifold, such as construction sites, manuring, accidents, power outages, terrorism and sabotage, mechanical fatigue, frost, avalanches and debris flows, storms, rock falls, earthquakes and many more. These different events can harm different components of the infrastructure. Therefore, the exposure of the different components for vulnerability assessment is important. Möderl *et al.*, (2011a) developed exposure matrices for different components of water infrastructure based on expert knowledge and a literature review as the basis for a systematic risk assessment. For example, a landslide or an earthquake can harm all components, and an avalanche will not affect underground structures such as pipes and junctions.

Extensive research was conducted to identify vulnerabilities and to perform a quantitative risk assessment of water distribution systems (e.g., Pinto *et al.*, 2010; Dunn and Wilkinson, 2012; Yazdani and Jeffrey, 2012) and urban drainage systems (e.g., Möderl *et al.*, 2009b; Goulding *et al.*, 2012). Möderl *et al.*, (2011b) developed a

GIS-based sensitivity analysis for vulnerability assessment based on the systematic hydraulic modelling of failure events. Recently, this research has been especially focused on failure cascades and multicomponent failure scenarios (Soltanjalili *et al.*, 2011; Zio and Sansavini, 2011; Gheisi and Naser, 2014).

In addition to integrating the developed approaches with other aspects and fields (see chapter 2.7), the specific scientific contributions on vulnerability and the risk assessment of this thesis are intended to develop an approach for minimizing the effects of contamination events in water distribution systems (PAPER XXXIX). Furthermore, this work contributes to the vulnerability assessment of urban drainage systems (PAPER XLI) and GIS-based sensitivity analyses of sewers in general (PAPER XLII). In PAPER XXVII the concept of an “Urban Drainage Safety Plan” is developed and first introduced.

In PAPER XLIII and PAPER XLIV, the term “Cascade Vulnerability” is first introduced to urban drainage and water distribution models by considering simultaneous critical conditions for risk assessment. Systematic vulnerability assessments in water networks based on systematic hydraulic modelling is a computationally intensive and therefore time-consuming task. To improve the simulation time for these tasks, the speed-up behaviour of different parallelization strategies were systematically tested to identify the best strategies for different tasks (PAPER XXIX).

The concept of systematic vulnerability analysis based on a GIS-based sensitivity analysis was further developed in PAPER VI to investigate zone- and region-wise demographic changes systematically in both water infrastructures.

2.6 Software and model development

Model development in environmental modelling requires both a scientific understanding of the phenomena and software development skills (David *et al.*, 2013). Extensive research has recently been conducted on the temporal-spatial analysis of environmental systems (e.g., Dong *et al.*, 2012; Aichele and Andresen, 2013; Nino-Ruiz *et al.*, 2013; Bastin *et al.*, 2013). The “digital age” has contributed its part, and massive amounts of data and different models are now available (Sitzenfrei and Rauch, 2011). In addition to developing software and models, scientists have also attempted to aggregate different types of models, developing open source frameworks for model aggregation and cross language in addition to flexible scientific workflow engines (David *et al.*, 2013). Modelling interactions between social and natural systems is also of great interest (e.g. Carneiro *et al.*, 2013).

The scientific modelling procedure has generally changed over the years. Decades ago, it was important to develop and code your own models, and more recently comfortable graphical user interfaces were developed, and now there is hardly any need for programming skills (Bakker, 2014).

The state-of the-art research tools are built for the rather complex tasks of assimilating and processing massive amounts of data. Furthermore, modern computer power enables new approaches, focusing on automatization and systematic analysis. Therefore, there is a comeback in programming in the form of scripting (Bakker, 2014). Although there is a comeback of programming, there are already attempts to simplify the procedure again, by operating complex frameworks and engines via graphical user interfaces.

In addition, to employ modern architecture of computers (e.g., multi-core processors, graphical processing units and cloud computing), model development and adaption are important (e.g., Dong *et al.*, 2013; Bryan, 2013). Nevertheless, the aim of the research in this context still remains as building theories and models of complex simulations or to support theories and hypotheses based on modelling (Wainwright and Mulligan, 2013).

In addition to integrating the developed approaches with other aspects and fields (see chapter 2.7), the specific scientific contributions of this thesis are about the parallelization strategies of parallel model simulation software in urban water management (PAPER XXIX) and simulation software parallelization itself (PAPER VIII, PAPER XXVI).

Several new models were developed, tested and applied (*WDS Designer*, PAPER XXXVII; *VIBe* PAPER XXX and PAPER XXXVI; *Achilles* PAPER XXXIX, PAPER XLI, PAPER XLII, PAPER XLIII and PAPER XLIV; *DynaVIBe* PAPER XIX, PAPER XXII), and a modelling framework was also developed and applied (PAPER XXXII, PAPER XXXIII, PAPER XXXIV, PAPER XXXV).

For water distribution modelling, a long-term simulation over decades was developed and successfully applied (PAPER I, PAPER II). Additionally, different types of models were coupled to perform an integrated analysis. In PAPER V and

PAPER XVIII, a water distribution model was spatially coupled to an urban drainage model via the population. In PAPER XXXIV and PAPER XXXV, an urban drainage model and a water distribution model were coupled to an urban development model. To bring interactive stakeholder and decision-maker involvement/support to the next level and allowing them to interact easily with complex models, a web GIS system was developed and introduced (PAPER XVI).

A major contribution of this thesis is also about building theories based on complex numerical model simulations. In PAPER XXX, which is based on systematically investigating numerous different case studies, a simple model was developed to predict shear stress under different conditions. In PAPER XX, a simple regression was found for the impact of land use change on drainage performance. This findings allows for future conditions to be accounted for in the design and also to predict the response of hydraulic performance to changes. These simple theories were also put into practice and into national guidelines. To assess the extent of thermal plumes from open loop geothermal utilization, PAPER XXV presents the process that was investigated based on systematically evaluating numerous scenarios. In that work, the limitations of the existing semi-analytical models were quantified, and an empirical model for the vertical extent was extracted and implemented in the state-of-the art assessment tool (PAPER X, ÖWAV-AB43, 2014).

2.7 Integrated approaches and assessment

Decades ago, the idea of integrated urban drainage systems was introduced for characterizing the interactions between combined sewer systems, wastewater treatment and receiving water bodies. These findings also recently found their way into engineering practice and the legislations of many countries (Muschalla *et al.*, 2009). In the literature, these interactions were extensively investigated (e.g., Fu *et al.*, 2009; Candela *et al.*, 2012), enhanced and the system performance was optimized (e.g. Muschalla, 2008). In a critical review on integrated urban water modelling, Bach *et al.*, (2014) argue that the intrinsic complexity of our environment must be considered instead of simplifying the problems. Therefore, different classifications of the integration level of integrated urban water system modelling were defined in that work. The highest level of integration, which was performed while keeping the water centric focus in that context, was defined as integrating different urban water streams (i.e., integrating the water supply and urban drainage) with models from other fields such as climate, economy, ecology, energy, demographics, etc.

In the recent literature, many different issues were in the focus of integrated models, e.g., a source to tap water cycle modelling (Rozos and Makropoulos, 2013), the impact of land use changes on wastewater infrastructure (Doglioni *et al.*, 2009), the reduction of sewer corrosion through integrated urban water management (Pikaar *et al.*, 2014) and many more. In each of these approaches the integrated view enabled a new insight into the interactions of different sub-processes. PAPER VII is the editorial in a special issue on “Modelling the urban water cycle as part of the city” in Water Science and Technology, and it compiles the current knowledge on modelling urban water management in interactions with urban development in the context of socioeconomic effects.

In this thesis, many types of integrating models were developed and applied (but not in a classical, integrated urban drainage modelling context that included receiving water and waste water treatment). The different aspects encompass the different fields/disciplines mentioned before (according to the prior subchapter prior) as follows:

(1) water distribution system analysis
(2) urban drainage system analysis
(3) urban development
(4) urban water and energy
(5) vulnerability and risk assessment
(6) software and model development

A detailed textual illustration of each contribution would be confusing and unclear. For a systematic illustration of the different integrated views, each integral paper of this thesis was classified according to the covered topics. For each topic (1)–(6) was assigned to quantify the level of coverage for that topic. A 1 indicates that the topic is fully integrated in that analysis and a 0 is not regarded (with three interim steps, namely 0.75, 0.5 and 0.25). To quantify the level of interdisciplinarity (in this context, the coverage of the six disciplines mentioned above), the sum of the assignments on the different topics is calculated (the interdisciplinarity in Table 1, Appendix B).

Most papers cover software and model development (for a sum of 37.25), water distribution analysis (30.75) and urban drainage analysis (28.75). In Figure 2, the evaluation of Table 1 is visualized. Figure 2 left, shows a histogram of the defined interdisciplinarity. Most papers contain 3 different disciplines, and the highest number is achieved for PAPER XLVI, which is a review work that gives an overview of the research area of the entire group. Almost 40% of the integral papers achieve an interdisciplinarity of 3 or more. The highest number of technical papers is 4.5 (PAPER XV and PAPER XXX). In this context, PAPER XXX also has the highest Impact factor (Figure 2, right).

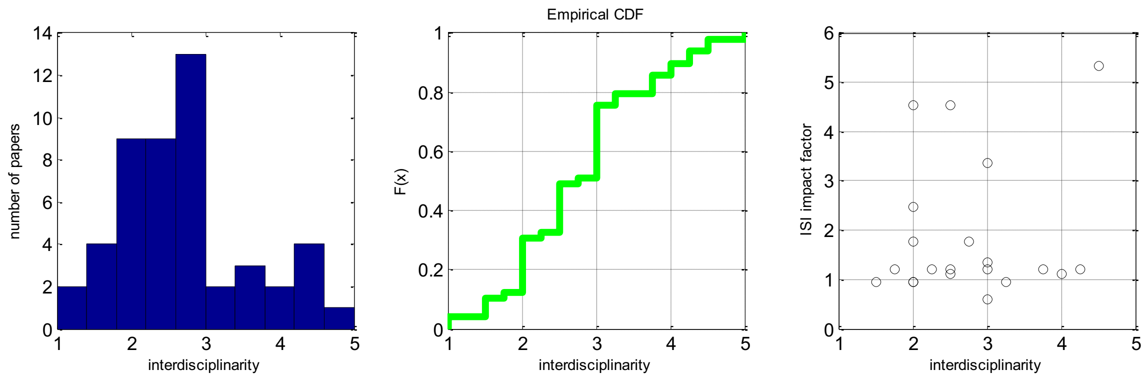

Figure 2: An evaluation of the integral papers in this thesis with respect to years and interdisciplinarity

Notably, more details on the developed approach presented in PAPER XXX are outlined here. PAPER XXX presents the impact of transitions from centralized to decentralized water solutions on existing Alpine water infrastructures and also the impact of centralized growth scenarios. The general idea of that work is shown in Figure 3. Based on the determined characteristics of Alpine case studies, the VIBe approach (Sitzenfrei, 2010) is used to obtain case-non-specific results for the investigated coherence. For that approach, the virtual test cases on an integrated city scale are automatically generated in a great number, which is intended to provide comprehensive case study data for statistical evaluations. Furthermore, the city scale test cases contain all of the required geospatial information (GIS data) for water-centric evaluations (land use, topography, population densities, water demand, dry weather flow production, impervious area, etc.) and also hydraulic models for combined sewer systems and water distribution systems. With all that available information, the hydraulic models for the water infrastructure are coupled via the population data. With that coupled model, integrated analyses are performed to determine under which changes (e.g., the level of decentralized water infrastructure that is implemented or the population growth and land use change) the central water infrastructure technically performs to a sufficient extent. To quantify that findings, an overall integrated performance indicator was defined, combining normalized performance indicators to present the technical efficiency of the drainage systems (combined sewer overflow, flooding and shear stress) and the water supply systems (pressure and water age). Because these analyses are performed on the basis of numerous case studies, the results are expressed in value ranges and probabilities (Figure 3).

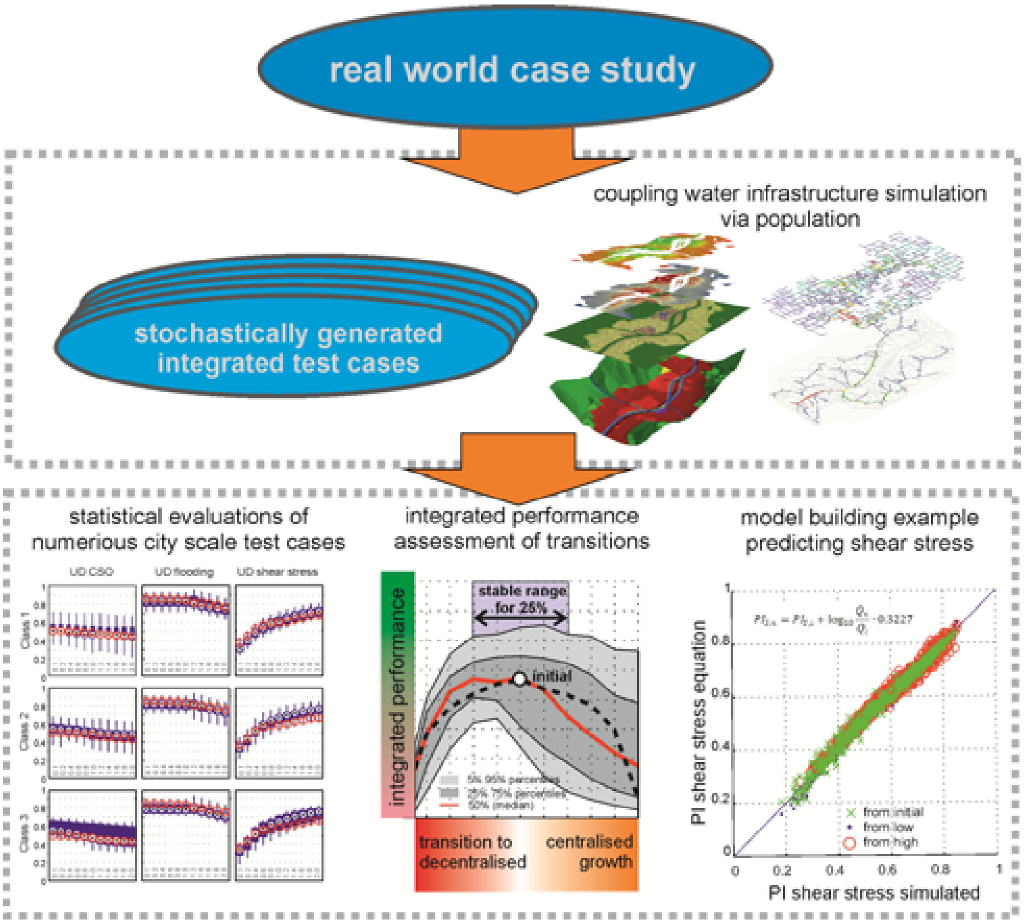

Figure 3: An extended graphical abstract for PAPER XXX (Sitzenfrei *et al.*, 2013)

The systematic evaluation of Alpine case studies revealed, that smaller case studies (below 100,000 inhabitants) are more affected by the implementation of decentralized water infrastructure but also by centralized growth in comparison with bigger systems. The large systems can compensate for more of the relative changes because of their larger redundancies.

In addition, a simple model was developed to predict the shear stress performance of the entire system easily under changing conditions. In that paper, the topics (1) water distribution system analysis, (2) urban drainage system analysis, (3) urban development and (6) software and model development were fully covered (for a value of 1), and (5) risk analysis, was partly covered (with a value of 0.5).

Because this is a cumulative thesis, the different integral papers should be inserted at this position in the thesis. However, for a clear structure, all integral papers in this thesis and the personal contributions to the papers are shown in the appendix.

3 POSSIBILITIES FOR INTEGRATED MODELS AND CRITICAL REFLECTION

The increasing digital availability of spatial data bears great promise for a better understanding of our environment and especially the "system city". Furthermore, the temporal development of data and its history are available, and there are still new data sources to explore (e.g., social networks, etc.). Thus, this is a great opportunity but also a great responsibility.

The water infrastructures and the entire urban water cycle are rather complex systems. Therefore, there is great opportunity for water engineers to understand the urban water cycle as part of the city, as a piece of the big picture, and to deepen the understanding of coherence. Because of the complexity of the urban water system, researchers believe that an integrated view can give additional insight into behaviours and interactions not only coupling sub-models to overall models, but also by combining the data streams and model interactions of the sub-systems.

Before every modelling or model coupling process, extensive work is required to decide what to describe, to define the modelling aim (targeted results), and to determine what model structure is required (Möderl, 2009). This process has to be performed by also accounting for the efforts needed to gather data, and the availability and quality of data. Therefore, choosing the right models and approaches for the intended use before the modelling work itself is of great importance and is often left behind (*we developed a great model, so what can we now assess with it?*).

As classified in Bach *et al.*, (2014), there are different types of model couplings and levels of integrated approaches. Models are often coupled to investigate the effects of changing a parameter in one model on the results of another coupled model without focusing on interactions or feedback loops. There is an increasing number of published and available environmental (Alexandrov *et al.*, 2010) and water-related, models which intensifies the risk of combining them to produce inappropriate and useless models. Voinov and Shugart, (2013) state that it is not trivial to synthesize larger models from pieces, the whole is greater than the sum of the parts. In this context, the term “integronster” was defined as “useless and ugly models” and was a result of these failed model coupling processes.

Furthermore, the increasing complexity of the models and the comprehensive amount of processed data make it difficult to ensure the quality of the developed and published studies. In this context, the modellers role in integrative research became more important than ever (Kragt *et al.*, 2013). Models are powerful as long as users are careful about how the results are used (Wainwright and Mulligan, 2013). For urban water systems Bach *et al.*, (2014) suggested an universal approach for developing integrated models. An important issue in this regard is to use the required amount and level of detail in the data (“fit for purpose data scale”). For example when coupling a complex and costly urban population model with a hydraulic model to predict future flooding characteristics, modelling detailed future roof areas of buildings is of no great use. This is especially true when the model for a combined sewer system is based on catchments sizes within the limits in hectares, and yet the implied uncertainties exceed that impact anyway. Therefore, it is important to be aware of the required complexity of the given models. In this context Grand, (2003) states the following:

“Something is complex if it contains a great deal of information that is high utility, while something that contains a lot of useless or meaningless information is simply complicated.”

Therefore, the complexity of a system is the amount of information used to describe it sufficiently, and an optimal model contains sufficient complexity to describe the process and not more (Wainwright and Mulligan, 2013). Nevertheless experiments are crucial for fundamental research, but the overall aim is still to find simplicity in complexity (Wainwright and Mulligan, 2013) and for that, an appropriate level of abstraction is still crucial.

Another issue when producing “complicated models” is that they produce a large amount of useless information, shifting the complexity to interpreting the results rather than defining the modelling aim in advance and making the right abstraction of the system before the modelling task. Interpreting the data from “complicated models” implies the risk of results that cannot be verified and it is hard to determine if the results are just a product of inappropriate analysis algorithms or poorly chosen models. Furthermore, the results might be too complex for a critical reflection and are irreproducible because the entire modelling endeavour is hard to document (Bakker, 2014).

In this context researchers, but especially scientific journals will require mandatory supporting material for systematic documentation, enabling the reproduction of results (Bakker, 2014). Otherwise, the uncontrolled application of more and more complex/complicated models will prevail, flooding scientific journals with incomprehensible modelling results. However, it is not only the documentation of results that is important. The great number of available models could trap investigators into relying only on existing models, without fully understanding the theory and limitations within. It is even more complex when coupling different models from different disciplines with different assumptions, complexities, and capabilities. The risk and also the possibilities will further increase in the future, and the profound scientific attention of experienced researchers to modelling tasks is more important than ever.

Traditional engineering judgement is also more important than ever to produce simple models with sufficient complexity and to apply “fit for purpose models”. Simplifying the problem and making assumptions requires a researcher concentrate intensively on the problem, which also leads to an indepth understanding of the problem. To that end, describing the aim of the analysis first and the desired results are the most important steps. Building a theory prior to the modelling process and testing and validating that theory through the modelling procedure (also with coupled and integrated models) is the preferable order for a good modelling practice.

4 CONCLUSIONS AND OUTLOOK

This thesis contributed to an enhanced understanding of integrated urban water models on different levels and encompassed different aspects of the urban water cycle. However, the aim was not to introduce the most complex/complicated models but to address different specific questions about the urban water cycle with appropriate models. This thesis therefore focuses not on the classical integrated models (e.g. integrated urban drainage models or integrated urban water models), but it covers a broad range of actual research tasks. The specific contributions of this thesis were subdivided into water distribution system analysis, urban drainage system analysis, urban development, urban water and energy, vulnerability and risk assessment and software and model development. Furthermore, the different fields were combined and integrated for assessment. For specific modelling aims and to support the hypotheses of different works, it is helpful to refer to the different integral papers of this thesis in the appendix.

Over the last decade, there has been an overwhelming gathering of spatiotemporal and all types of digital data. In addition, computer capabilities are constantly growing enabling a holistic view of our environment (Laniak *et al.*, 2013). Therefore, there is also great opportunity for water engineers to understand the urban water cycle as part of the city, as a piece in the big picture, and to deepen the understanding of coherences. However, there is also an increasing risk of producing complicated and less than useful models. More interdisciplinary work and models also increase the risk of misunderstanding. Furthermore, the increasing complexity of the models and the comprehensive amount of processed data make it difficult to ensure the quality of the developed and published studies. In this context, the modeller's role in integrative research has become more important than ever. The preferred order of performing complex, integrated modelling efforts should still start with building a theory first, and then supporting the theory with numerical experiments. For that approach, a combination of fundamental research practices with traditional engineering approaches is important. It is still necessary to make things as simple as possible to obtain sufficiently complex and uncomplicated models. In this context, researchers, but especially scientific journals, will require mandatory supporting material for the systematic documentation of the entire modelling endeavour, enabling a reproduction of results (Bakker, 2014). Another major future issue will be to bring current fundamental research endeavours into engineering practice and to support actual engineering tasks.

Summarizing the interdisciplinary advance in urban water management is more extensive than ever and still growing. There is a shift from an integrated view of the urban water cycle to the water cycle as part of the city. Therefore, there is also a paradigm shift in assessing the urban water cycle. The real shift and new paradigm is expected to relate to the documentation and archiving of all of the modelling efforts and results to make the results comprehensible, reproducible and useful.

5 ACKNOWLEDGEMENTS

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Yazdani A. and Jeffrey P. (2012). Applying Network Theory to Quantify the Redundancy and Structural Robustness of Water Distribution Systems. *Journal of Water Resources Planning & Management*, **138** (2), 153-161.

Yazdani A., Otoo R. A. and Jeffrey P. (2011). Resilience enhancing expansion strategies for water distribution systems: A network theory approach. *Environmental Modelling & Software*, **26** (12), 1574-1582.

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Zio E. and Sansavini G. (2011). Component Criticality in Failure Cascade Processes of Network Systems. *Risk Analysis*, **31** (8), 1196-1210.

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

1/2011 - 12/2014

Post-doctoral researcher, Unit of Environmental Engineering, University of Innsbruck

01/2010 - 03/2010

Visiting Researcher, Civil Engineering Department, Monash University, Melbourne, Austrialia

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

A.3 Other activities

since 2014:

Associate Editor, Water Science and Technology

2013/2014:

Guest Editor, Water Science and Technology, Special Issue

Reviewer panel:

Water Science & Technology; Water Science & Technology: Water Supply; Biosystems Engineering, Water Research, Environmental Modelling & Software, Risk Analysis

A.4 Honours

(1) 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.

(2) Innovation Award of the economic chamber of trade of the province of tyrol, 2011 in the category "service innovation", Ingenieurbüro Passer & Partner Ziviltechniker GmbH, Innsbruck for participation at the research project "Achilles Approach for vulnerability analysis"

(3) CCWI2013, Early Career Award, 2013 for paper and presentation of: "Investigating transitions of centralized water infrastructure to decentralized solutions – an integrated approach. At Computing and Control for Water Industry (CCWI2013), 2013, Perugia, Italy 2-4 September 2013.

(4) IVB-Innovation Award (Innsbrucker Verkehrsbetriebe) 2013, for the work „Assessing the impact of transitions from centralized to decentralized water solutions on existing infrastructures - integrated city-scale analysis with VIBe".

(5) Trevithick Fund - price for the best paper published by the journal last year (2014): Urich, Christian; M. Bach, Peter; Sitzenfrei, Robert; Kleidorfer, Manfred; T. McCarthy, David; Deletic, Ana; Rauch, Wolfgang. for the work: "Modelling cities and water infrastructure dynamics" in Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 166, issue 5, 2013, pages 301-308

A.5 Conference Talks

(1) Stability of traditional urban water systems – integrated assessment of transitions scenarios. 16^{th} Conference on Water Distribution Analysis, WDSA 2014; Bari, Italy, July 15-17, 2014.

(2) Design and optimization of small hydropower systems in water distribution networks based on 10years simulation with Epanet2. 16^{th} Conference on Water Distribution Analysis, WDSA 2014; Bari, Italy, July 15-17, 2014.

(3) Long time simulations and analysis of future scenarios for design and benefit costs analysis of small hydro power systems in water distribution systems. World Environmental and Water Resources Congress 2014 (EWRI2014); Portland, Oregon, United States, June 1-5, 2014.

(4) Assessing model structure uncertainties in water distribution models. World Environmental and Water Resources Congress 2014 (EWRI2014); Portland, Oregon, United States, June 1-5, 2014.

(5) Investigating transitions of centralized water infrastructure to decentralized solutions – an integrated approach. In: Proceedia Engineering. Computing and Control for Water Industry, 2013, Perugia, Italy 2-4 September 2013.

(6) Assessing the efficiency of different CSO positions based on network graph characteristics. 9th International Conference on Urban Drainage Modelling (9UDM), Belgrad, Serbia, 03.09.2012 - 07.09.2012.

(7) Modeling Expansion of Water Distribution Systems for New Urban Development. World Environmental and Water Resources Congress 2012; Albuquerque, New Mexico, United States, May 20, 2012.

(8) Identifying Hydropower Potential in Water Distribution Systems of Alpine Regions. World Environmental and Water Resources Congress 2012; Albuquerque, New Mexico, United States, May 20, 2012.

(9) Nutzung oberflächennaher Geothermie – Vereinfachte Berechnungsmethoden und regionale Potentiale. Geologisches Fachgespräch, KIT Institut für Angewandte Geowissenschaften, Karlsruhe, 15.12.2011

(10) Assessment of Cascade Vulnerabilty for Water Networks. 4th IWA Leading-Edge conference on Strategic Asset Management of water and wastewater infrastructures. Mühlheim, Germany, September 27, 2011.

(11) From water networks to a „Digitial City" – a shift of Paradigm in Assessment of Urban Water Systems. 12th International Conference on Urban Drainage, Porto Allegre, Brazil, September 16, 2011.

(12) Application of a Stochastic Test Case Generation for Water Supply Systems. World Environmental and Water Resources Congress 2011; Palm Springs, California, United States, May 26, 2011.

(13) Geothermal Energy in a Central European Perspecitve – Challenges and Opportunities. World Environmental and Water Resources Congress 2011; Palm Springs, California, United States, May 23, 2011.

(14) Systematische Gefahren- und Schwachstellenanalyse mit dem Achilles-Ansatz. Mike Urban Anwendertreffen, Wien, 27.04.2011

(15) PowerVIBe – Energy and Technology Strategies Benchmarking. "Strategische Entscheidungsgrundlagen für die österreichische Klima-, Energie und Technologiepolitik", Science Brunch, Wien, 27.10.2010

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

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

(18) 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

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

(20) 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.

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

Appendix B. PAPERS

Table 1: classification of different papers (with conditional colour formatting)

	topic						
	1	2	3	4	5	6	sum
PAPER I	1	0	0	1	0	1	3
PAPER II	1	0	0	1	0	0.75	2.75
PAPER III	1	0	0	1	0	0.75	2.75
PAPER IV	1	0	0	1	0	1	3
PAPER V	1	1	1	0	0.5	1	4.5
PAPER VI	1	1	0.75	0	0.5	1	4.25
PAPER VII	0.75	0.75	0.75	0	0.75	0.75	3.75
PAPER VIII	1	0	0	0	0	1	2
PAPER IX	1	1	0	0	0	0	2
PAPER X	1	0	0	0	0	0.5	1.5
PAPER XI	1	1	0.75	0	0	0.5	3.25
PAPER XII	1	0	1	0	0	1	3
PAPER XIII	1	1	0	0	0	1	3
PAPER XIV	1	0	1	0	0.75	1	3.75
PAPER XV	0	0	0	1	0.5	1	2.5
PAPER XVI	0	1	0.25	0	0	1	2.25
PAPER XVII	0	1	0	0	0	0	1
PAPER XVIII	1	1	0.75	0	0.5	1	4.25
PAPER XIX	1	1	0	0	0	0	2
PAPER XX	0	1	1	0	0	1	3
PAPER XXI	1	0	0	0		1	2
PAPER XXII	1	0	1	0	0.75	1	3.75
PAPER XXIII	1	0	0	0	0	0.5	1.5
PAPER XXIV	1	0		1		1	3
PAPER XXV	0	0	0	1	0.5	1	2.5
PAPER XXVI	0	1	0	0	0	1	2
PAPER XXVII	0	1	0	0	1	0	2
PAPER XXVIII	1	0	0	1	0	1	3
PAPER XXIX	1	1	0	0	0.5	0.5	3
PAPER XXX	1	1	1	0	0.5	1	4.5
PAPER XXXI	0	1	0	0	0.5	0.5	2
PAPER XXXII	0	1	0.5	0	0	1	2.5
PAPER XXXIII	0	1	1	0	0	0	2
PAPER XXXIV	0	1	1	0	0	1	3
PAPER XXXV	0	1	1	0	0	1	3
PAPER XXXVI	0	1	0	0	0	0.75	1.75
PAPER XXXVII	1	0	0.5	0	0	1	2.5
PAPER XXXVIII	0	1	1	0	0	0.5	2.5
PAPER XXXIX	1	0	0	0	1	1	3
PAPER XL	1	0	0	1	0	1	3

	topic						
	1	2	3	4	5	6	sum
PAPER XLI	0	1	0	0	1	0.5	2.5
PAPER XLII	0	1	0	0	0.75	0.75	2.5
PAPER XLIII	1	1	0.25	0	1	0.75	4
PAPER XLIV	1	1	0.25	0	1	0.75	4
PAPER XLV	0	1	1	0	0	0.5	2.5
PAPER XLVI	1	1	1	0	1	1	5
PAPER XLVII	0	1	0	0	0	0	1
PAPER XLVIII	1	0	1	0	0.25	1	3.25
PAPER XLIX	0	0	0	1	0.5	0	1.5
PAPER L	1	0	0	0	0	1	2
SUM	30.75	28.75	17.75	10	13.75	37.25	2.77 (average)

The following table quantifies the contributions to each integral paper of this thesis. For that the following classification was defined:

(1) first or corresponding author

(2) contributing author

(3) senior author

Table 2: contributions of different papers

PAPER	authors	year/ status	title	contri- bution
I	**Sitzenfrei, R.;** von Leon, J;	2014	Long-time simulation of water distribution systems for the design of small hydro power systems	1
II	**Sitzenfrei, R.;** Rauch, W.	in press	Optimizing a small hydro power systems in a water distribution systems based on long time simulation and future scenarios	1
III	**Sitzenfrei, R.;** Berger, D.; Rauch, W	submitted	Design and optimization of small hydropower systems in water distribution networks under consideration of rehabilitation measures	1

PAPER	authors	year/ status	title	contri- bution
IV	**Sitzenfrei, R.;** von Leon J..; Rauch, W.	2014	Design and optimization of small hydropower systems in water distribution networks based on 10years simulation with Epanet2	1
V	**Sitzenfrei, R.;** Mair, M.; Rauch, W.	2014	Stability of traditional urban water systems – integrated assessment of transition options	1
VI	**Sitzenfrei, R.;** Rauch, W.	2014	Integrated hydraulic modelling of water supply and urban drainage networks for assessment of decentralized options	1
VII	**Sitzenfrei,** R.; Rauch, W.; Rogers, B; Dawson, R.; Kleidorfer, M;	2014	Editorial: Modelling the urban water cycle as part of the city	1
VIII	Burger, G.; **Sitzenfrei, R.;** Kleidorfer M.; Rauch, W.	in revision	The Quest for a new solver for EPANET2	2
IX	Mair, M; Rauch, W.; **Sitzenfrei, R.;**	submitted	Where to find water pipes and sewers? – on the correlation of infrastructure networks in the urban environment	3
X	Tscheikner-Gratl, F.; **Sitzenfrei, R.;** Rauch, W.; Kleidorfer, M.	in press	Dealing with limited data in rehabilitation management of water supply networks	2
XI	Tscheikner-Gratl, F.; **Sitzenfrei, R.;** Rauch, W.; Kleidorfer, M.	in revision	Integrated rehabilitation planning of urban infrastructure systems using a street section priority model	2
XII	**Sitzenfrei, R.;** Mair, M.; Tscheikner-Gratl, F.; Hupfauf, B.; Rauch, W.	in press	What can we learn from historical water network transition?	1
XIII	Tscheikner-Gratl, F.; **Sitzenfrei, R.;** Stibernitz, C.; Rauch, W.; Kleidofer, M.	in press	Integrated rehabilitation management by prioritization of rehabilitation areas for small and medium sized municipalities	2
XIV	Zischg, J.; Mair, M.; Rauch, W; **Sitzenfrei, R.;**	in press	Stochastic performance assessment and optimization strategies of the water supply network transition of Kiruna during city relocation	3
XV	Rauch, W.; **Sitzenfrei, R**	2014	ÖWAV-Arbeitsbehelfs 43: „Leitfaden zur Anwendung der Thermalformel des ÖWAV Regelblattes 207	2
XVI	Mair, M.; Mikovits C.; Sengthaler, M.; Schöpf, M.; Kinzel, H; Urich, C.; Kleidorfer, M.; **Sitzenfrei, R.;** Rauch, W.	2014	The application of Web-GIS for improving urban water cycle modelling	3

PAPER	authors	year/ status	title	contri-bution
XVII	Kleidorfer, M.; Tschiesche, U.; Tscheikner-Gratl, F.; **Sitzenfrei, R.;** Kretschmer, F.; Muschalla, D.; Ertl, T.; Rauch, W.	2014	Von den Daten zum Modell: Anforderungen an hydraulische Entwässerungsmodelle in kleineren und mittleren Gemeinden	2
XVIII	**Sitzenfrei, R.;** Rauch, W.	2014	Investigating transitions of centralized water infrastructure to decentralized solutions – an integrated approach	1
XIX	M. Mair, W. Rauch, **R. Sitzenfrei**	2014	Improving Incomplete Water Distribution System Data	3
XX	Kleidorfer, M.; **Sitzenfrei, R.;** Rauch, W.	2014	Simplifying impact of urban development on sewer systems	2
XXI	**Sitzenfrei, R.;** Mair. M.; Diao K.; Rauch, W.	2014	Assessing model structure uncertainties in water distribution models	1
XXII	Mair, M.; Rauch, W; **Sitzenfrei, R.;**	2014	Spanning tree based algorithm for generating water distribution network sets by using street network data sets	3
XXIII	Tscheikner-Gratl, F.; **Sitzenfrei, R.;** Rauch, W.; Hammerer, M.; Kleidorfer, M.	2014	Prioritization of rehabilitation areas – a case study	2
XXIV	**Sitzenfrei, R.;** von Leon, J.; Rauch, W.	2014	Long time simulations and analysis of future scenarios for design and benefit costs analysis of small hydro power systems in water distribution systems	1
XXV	**Sitzenfrei, R.;** Rauch, W.	2014	Anwendungsgrenzen einfacher analytischer Lösungen zur Bestimmung von Temperaturanomalien im Grundwasser	1
XXVI	Burger, G.; **Sitzenfrei, R.;** Kleidorfer M.; Rauch, W.	2014	Parallel Flow Routing in SWMM 5	2
XXVII	Möderl, M.; **Sitzenfrei, R.;** Lammel, J.; Apperl, M.; Kleidorfer, M.; Rauch, W.	2014	Development of an Urban Drainage Safety Plan Concept based on Spatial Risk Assessment	2
XXVIII	**Sitzenfrei, R.;** von Leon, J; Jarosch, H.; Rauch, W.	2014	Langzeitsimulation von Wasserversorgungsanalagen zur Auslegung von Trinkwasserkraftwerken	1
XXIX	Mair, M.; **Sitzenfrei, R.;** Kleidorfer, M..; Rauch, W.	2014	Performance improvement with parallel numerical model simulations in the field of urban water management	2

PAPER	authors	year/ status	title	contri- bution
XXX	**Sitzenfrei, R.;** Möderl, M.; Rauch, W.	2013	Assessing the impact of transitions from centralized to decentralized water solutions on existing infrastructures - integrated city-scale analysis with VIBe	1
XXXI	Möderl, M.; **Sitzenfrei, R.;** Friedl, F.; Fuchs-Hanusch, D.; Kretschmer, F.; Ertl, T. Rauch, W.	2014	Analyse einer hydraulischen Zustandsbewertung von Mischwassersystemen.	2
XXXII	Bach P.M.; McCarthy, D.T.; Urich, C.; **Sitzenfrei, R.;** Kleidorfer, M.; Rauch, W.; Deletic, A.;	2013	A planning algorithm for decentralized water management opportunities	2
XXXIII	Bach P.M.; Deletic, A.; Urich, C.; **Sitzenfrei, R.;** Kleidorfer, M.; Rauch, W.; McCarthy, D.T.;	2013	Modelling Interactions Between Lot-Scale Decentralised Water Infrastructure and Urban Form – a Case Study on Infiltration Systems	2
XXXIV	Urich, C.; Bach P.M.; **Sitzenfrei, R.;** Kleidorfer, M.; McCarthy, D.T.; Deletic, A.; Rauch, W	2013	Modelling Cities and Water Infrastructure Dynamics	2
XXXV	Urich, C.; **Sitzenfrei, R.;** Kleidorfer, M.; Rauch, W	2013	Klimawandel und Urbanisierung – wie soll die Wasserinfrastruktur angepasst werden	2
XXXVI	**Sitzenfrei, R.;** Urich, C.; Möderl, M.; Rauch, W.	2013	Assessing the efficiency of different CSO positions based on network graph characteristics	1
XXXVII	**Sitzenfrei, R.;** Möderl, M.; Rauch, W.	2013	Automatic Generation of Water Distribution Systems based on GIS-Data	1
XXXVIII	Kleidorfer, M.; Urich, C.; Leonhardt, G.; **Sitzenfrei, R.;** Rauch, W.	2013	Asset management and sustainability: planning for the unknown future	2
XXXIX	Möderl, M.; **Sitzenfrei, R.;** Rauch, W.	2012	Sicherheits- und Notfallplanung bei Kontamination der Wasserversorgungsanlage	2
XL	Möderl, M.; **Sitzenfrei, R.;** Jarosch, H.; Rauch, W.	2012	Örtliche Sensitivitätsanalyse zur Identifikation von effizienten Standorten für Trinkwasserkraftwerke.	2
XLI	**Sitzenfrei, R.;** Möderl, M.; Fritsch, E.; Rauch, W.	2012	Schwachstellenanalyse bei Mischwasseranlagen für eine sichere Bewirtschaftung	1
XLII	Mair, M.; **Sitzenfrei, R.;** Kleidorfer, M.; Möderl, M.; Rauch, W.	2012	GIS-based applications of sensitivity analysis for sewer models	2

PAPER	authors	year/ status	title	contri-bution
XLIII	**Sitzenfrei, R.;** Mair, M.; Möderl, M.; Rauch, W.	2011	Cascade Vulnerability for Risk Analysis of Water Infrastructure	1
XLIV	**Sitzenfrei, R.;** Mair, M.; Kinzel, H.; Möderl, M.; Rauch, W.	2011	Kaskadenvulnerabilität kritischer Wasserinfrastruktur.	1
XLV	Kleidorfer, M.; Urich, C.; Leonhardt, G.; **Sitzenfrei, R.;** Rauch, W.	2011	Dynamik von Anpassungsstrategien der Wasserinfrastruktur	2
XLVI	**Sitzenfrei R.,** Kleidorfer, M., Meister, M., Burger, G., Urich, C., Mair, M., Rauch W.	2014	Scientific Computing in Urban Water Management	1
XLVII	**Sitzenfrei, R.;** Kleidorfer, M.; Arming, G.; Rauch, W.	2014	Auswirkungen von alpinen urbanen Einzugsgebieten auf den Hochwasserschutz	1
XLVIII	**Sitzenfrei, R.;** Möderl, M.; Mair, M.; Rauch, W.	2012	Modeling Expansion of Water Distribution Systems for New Urban Development	1
XLIX	**Sitzenfrei, R.;** Möderl, M.; Hellbach, C; Fleischhacker, E.; Rauch, W.	2011	Geothermal Energy in a Central European Perspective – Challenges and Opportunities.	1
L	**Sitzenfrei, R.;** Möderl, M.; Hellbach, C; Rauch, W.	2011	Application of a Stochastic Test Case Generation for Water Distribution Systems	1

Note that due to copyright issues, the papers cannot be published in the online version of this thesis. Nevertheless, via the provided online links to the papers (by clicking on the publication title), the integral papers of this thesis can be accessed.

PAPER I

Long-time simulation of water distribution systems for the design of small hydro power systems

Sitzenfrei Robert and Judith von Leon

published in:
Renewable Energy, 72 (2014) p182 - 187

Impact factor 2013: 3.361

PAPER II

Optimizing a small hydro power systems in a water distribution systems based on long time simulation and future scenarios

Sitzenfrei Robert and Wolfgang Rauch

submitted to:
Journal of Water Resources Planning and Management (in press)

Impact factor 2013: 1.760

PAPER III

Design and optimization of small hydropower systems in water distribution networks under consideration of rehabilitation measures

Sitzenfrei Robert, Berger Damian and Wolfgang Rauch

submitted to:
Urban Water Journal

Impact factor 2013: 0.905

PAPER IV

Design and optimization of small hydropower systems in water distribution networks based on 10years simulation with Epanet2

Robert Sitzenfrei, Judith von Leon and Wolfgang Rauch

published in:
Procedia Engineering (2014), 89C, p533-539

peer reviewed

PAPER V

Stability of traditional urban water systems – integrated assessment of transition options

Robert Sitzenfrei, Michael Mair and Wolfgang Rauch

published in:
Procedia Engineering (2014), 89C, p727-733

peer reviewed

PAPER VI

Integrated hydraulic modelling of water supply and urban drainage networks for assessment of decentralized options

Robert Sitzenfrei and Wolfgang Rauch

published in:
Water Science and Technology (2014), Vol70(11), p1817-1824

Impact factor 2013: 1.212

PAPER VII

Editorial: Modelling the urban water cycle as part of the city

Robert Sitzenfrei, Wolfgang Rauch, Briony Rogers, Richard Dawson, Manfred Kleidorfer

published in:
Water Science and Technology (2014), Vol70(11), p1717-1720

Impact factor 2013: 1.212

PAPER VIII

The Quest for a new solver for EPANET2

Gregor Burger, **Sitzenfrei Robert** Manfred Kleidorfer and Wolfgang Rauch

submitted to:
Journal of Water Resources Planning and Management (in revision)

Impact factor 2013: 1.760

PAPER IX

Where to find water pipes and sewers? On the correlation of infrastructure networks in the urban environment

Michael Mair, Wolfgang Rauch and **Sitzenfrei Robert**

submitted to:
Structure and Infrastructure Engineering

Impact factor 2013: 0.954

PAPER X

Dealing with limited data in rehabilitation management of water supply networks

Franz Tscheikner-Gratl, **Robert Sitzenfrei**, Wolfgang Rauch and Manfred Kleidorfer

submitted to:
Structure and Infrastructure Engineering (in press)

Impact factor 2013: 0.954

PAPER XI

Integrated rehabilitation planning of urban infrastructure systems using a street section priority model

Franz Tscheikner-Gratl, **Sitzenfrei Robert**, Wolfgang Rauch and Manfred Kleidorfer

submitted to:
Urban Water Journal

Impact factor 2013: 0.905

PAPER XII

What can we learn from historical water network transition?

Sitzenfrei Robert, Michael Mair, Franz Tscheikner-Gratl, Bernhard Hupfauf and Wolfgang Rauch

submitted to:
Proceedings of the World Environmental and Water Resources Congress 2015 (in press)

peer reviewed

PAPER XIII

Integrated rehabilitation management by prioritization of rehabilitation areas for small and medium sized municipalities

Franz Tscheikner-Gratl, **Sitzenfrei Robert**, Christina Stibernitz, Wolfgang Rauch and Manfred Kleidorfer

submitted to:
Proceedings of the World Environmental and Water Resources Congress 2015 (in press)

peer reviewed

PAPER XIV

Stochastic performance assessment and optimization strategies of the water supply network transition of Kiruna during city relocation

Jonatan Zischg, Michael Mair, Wolfgang Rauch and **Sitzenfrei Robert**

submitted to:
Proceedings of the World Environmental and Water Resources Congress 2015 (in press)

peer reviewed

PAPER XV

ÖWAV-Arbeitsbehelfs 43: Leitfaden zur Anwendung der Thermalformel des ÖWAV Regelblattes 207

Wolfgang Rauch and **Robert Sitzenfrei**

published in:
ÖWAV Österreichische Wasser- und Abfallwirtschaft (2014)

PAPER XVI

The application of Web-GIS for improving urban water cycle modelling

Michael Mair, Christian Mikovits, Markus Sengthaler, Martin Schöpf, Heiko Kinzel, Christian Urich, Manfred Kleidorfer, **Robert Sitzenfrei** and Wolfgang Rauch

published in:
Water Science and Technology (2014), Vol70(11), p1838-1846

Impact factor 2013: 1.212

Paper XVII

Von den Daten zum Modell: Anforderungen an hydraulische Entwässerungsmodelle in kleineren und mittleren Gemeinden

Manfred Kleidorfer, Ulrich Tschiesche, Franz Tscheikner-Gratl, **Robert Sitzenfrei**, Florian Kretschmer, Dirk Muschalla, Thomas Ertl and Wolfgang Rauch

published in:
Wiener Mitteilungen, Band 231 (2014)

PAPER XVIII

Investigating transitions of centralized water infrastructure to decentralized solutions – an integrated approach

Robert Sitzenfrei and Wolfgang Rauch

published in:
Procedia Engineering (2014), 70, p1549-1557

peer reviewed

PAPER XIX

Improving Incomplete Water Distribution System Data

Michael Mair, Wolfgang Rauch and **Robert Sitzenfrei**

published in:
Procedia Engineering (2014), 70, p1055-1062

peer reviewed

PAPER XX

Simplifying impact of urban development on sewer systems

Manfred Kleidorfer, **Robert Sitzenfrei** and Wolfgang Rauch

published in:
Water Science and Technology (2014), Vol70(11), p1808-1816

Impact factor 2013: 1.212

PAPER XXI

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Michael Möderl, **Sitzenfrei Robert**, Franz Friedl, Daniela Fuchs-Hanusch, Florian Kretchmer, Thomas Ertl and Wolfgang Rauch

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