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A multi-layer cellular automata approach for algorithmic generation of virtual case studies: VIBe

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ABSTRACT

Analyses of case studies are used to evaluate new or existing technologies, measures or strategies with regard to their impact on the overall process. However, data availability is limited and hence, new technologies, measures or strategies can only be tested on a limited number of case studies. Owing to the specific boundary conditions and system properties of each single case study, results can hardly be generalized or transferred to other boundary conditions. virtual infrastructure benchmarking (VIBe) is a software tool which algorithmically generates virtual case studies (VCSs) for urban water systems. System descriptions needed for evaluation are extracted from VIBe whose parameters are based on real world case studies and literature. As a result VIBe writes Input files for water simulation software as EPANET and EPA SWMM. With such input files numerous simulations can be performed and the results can be benchmarked and analysed stochastically at a city scale. In this work the approach of VIBe is applied with parameters according to a section of the Inn valley and therewith 1,000 VCSs are generated and evaluated. A comparison of the VCSs with data of real world case studies shows that the real world case studies fit within the parameter ranges of the VCSs. Consequently, VIBe tackles the problem of limited availability of case study data.

Key words | case study generator, stochastic analysis, urban drainage systems, virtual case study, virtual infrastructure benchmarking (VIBe)

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INTRODUCTION

Evaluation of system performance by means of case studies is a well known instrument for research tasks. Besides problem recognition and identification of correlations in systems, detailed analysis of case studies allows building of new models and testing of hypothesis. Furthermore, conclusions about different measures can be obtained by evaluating the data derived from these case studies. Owing to the fact that data collection is a cost and time consuming process, data availability is limited. Hence, new technologies, strategies or measures can only be tested on a limited number of real world case studies. Because of the specific boundary conditions and system properties of each single case study, it is problematic to generalize and transfer the results to other systems. Therefore the application of virtual case studies to test measures, approaches or models is a well suited and known technique. Hypothetical/virtual catchments and drainage systems designed accordingly to national guidelines were used e.g. to:

- determine operational potential of combined sewer systems (Schutze *et al.* 2002);
- point out the importance of treatment plant performance during rain to acute water pollution (Rauch & Harremoes 1996);
- compare combined sewer systems with separate sewer systems regarding cost effectiveness (De Toffol *et al.* 2007);
- test different stormwater management strategies (Welker *et al.* 1999).

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The generation of virtual networks is subject of several software tools. An “Artificial Network Generator” (ANGel) for city-scale analysis was presented in Ghosh *et al.* (2006). Therein artificial sewer networks were generated for city-scale analyses based on the dendritic and space-filling Tokunaga fractal tree. Möderl *et al.* (2007) developed the modular design system (MDS) as a graph theory based methodology to generate a multitude of virtual water distribution systems (WDS) in order to evaluate their performance. The “Case Study Generator” (CSG) algorithm presented in Möderl *et al.* (2009) is capable to create an unlimited number of dendritic virtual sewer systems based on a Galton Watson branching process adapted for urban drainage systems. Therein catchments of randomized size are connected subsequently to the sewer tree layout generated firstly. The algorithm regards at the catchment level runoff effective area, varying population densities and therefore a variation of dry weather flow. To obtain more realistic data for catchments and population, D’Artista & Hellweger (2007) described the potential of simulation games like SimCity combined with operational urban models for urban hydrology.

In this paper the software virtual infrastructure benchmarking (VIBe) is presented which algorithmically generates virtual case studies for water related systems. The scientific novelty of VIBe is that the software tool firstly generates an entire virtual urban environment (in contrast to ANGel, MDS and CSG) including a digital elevation model, natural water bodies, urban structures like streets and housing, land use as well as population density maps. Based on this information (remotely comparable to information available in computer games like SimCity) the water infrastructure is generated in the virtual system meeting the requirements of the urban structure and the design guidelines. Owing to the algorithmic generation, an unlimited number of virtual case studies for water systems can be stochastically analysed at city scale and interactions of urban structure and infrastructure systems can be investigated.

METHODS

The software VIBe is based on a multi-layer cellular automata approach to generate all data necessary to build models of urban drainage systems. In this approach the major target is to enhance the stochastic approaches for urban water management (e.g. as presented in MDS, CSG) with multi cellular automata approach to generate a virtual urban structure close to reality. Therefore, firstly the principles of cellular automata adapted for this issue are discussed. In the second part of the methodology the architecture of VIBe is outlined with a focus on the generation process of the urban structure and infrastructure. Finally, the background and characteristics for an alpine valley as investigation area are shown.

Cellular automata

Cellular automata are dynamic grid based computer models and therefore spatial distributed. The cells of the grid can be of diverse shape (e.g. hexagonal). To simplify matters they are mostly constricted to quadratic cells. Each cell i ($i = 1 \ldots N$) is defined by its position in the cellular automata grid and can capture different states from a predefined range of values. By transition of the cell states for discrete time steps the development of the system is dynamic over time. This transition is controlled by free settable transition rules/functions f which have to be applied to each cell. Depending on the states of its local neighbour cells Ω_i^t and its own state D_i^t at time step t the cell’s state D_i^{t+1} for the next time step $t+1$ can be evaluated with $D_i^{t+1} = f(D_i^t, \Omega_i^t)$ (Batty 2005). For a multi-layer cellular automata with L layers ($j = 1 \ldots L$) the states D_{ij}^t of different data layers j are linked via the corresponding transition rules f_j with the states of the local neighbour cells Ω_{ij}^t to calculate the state D_{ij}^{t+1} at the next time step $t+1$.

$$
\begin{aligned}
D_{i,1}^{t+1} &= f_1\left(D_{i,1}^t, D_{i,2}^t, \ldots D_{i,L}^t, \Omega_{i,1}^t, \Omega_{i,2}^t, \ldots, \Omega_{i,L}^t\right) \quad \forall\ i = 1 \ldots N \\
D_{i,2}^{t+1} &= f_2\left(D_{i,1}^t, D_{i,2}^t, \ldots D_{i,L}^t, \Omega_{i,1}^t, \Omega_{i,2}^t, \ldots, \Omega_{i,L}^t\right) \quad \forall\ i = 1 \ldots N \\
&\vdots \\
D_{i,L}^{t+1} &= f_L\left(D_{i,1}^t, D_{i,2}^t, \ldots D_{i,L}^t, \Omega_{i,1}^t, \Omega_{i,2}^t, \ldots, \Omega_{i,L}^t\right) \quad \forall\ i = 1 \ldots N
\end{aligned}
$$

Controlling processes of urban structure are modelled with cellular automata approach. In Reaney (2008) an approach for hydrology modelling is shown to picture the temporal and spatial dynamic of flow during a storm event. The potential use of dynamic land use/cover change models

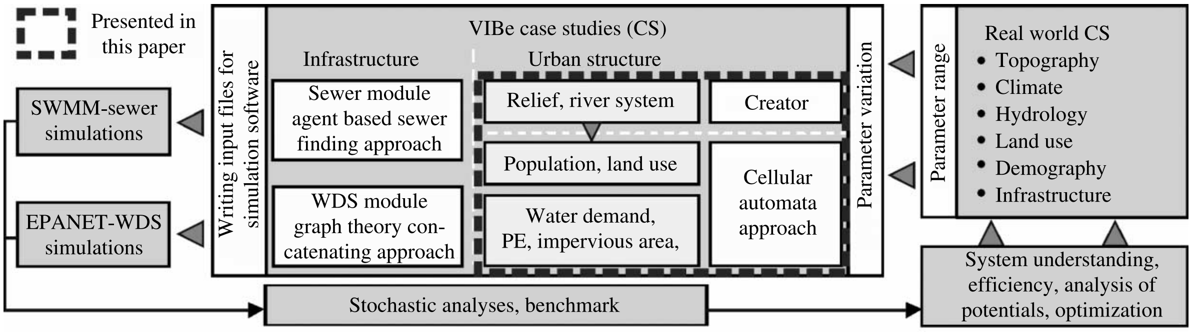

Figure 1 | Architecture of VIBe.

that focus on human environment interactions is described in Parker *et al.* (2003). A land use change model using elementary probabilistic methods to simulate urban change was further proposed by Almeida *et al.* (2003). Various models, approaches and applications are developed and presented for urban development and growth (e.g. Stevens *et al.* 2007) including socio economic aspects (e.g. Yan Liu & Phinn 2003). These approaches of urban and population development from geographic and architectural research field are combined with stochastic engineering approaches for infrastructure design and development. Therewith the generated virtual infrastructure systems draw closer to real world systems compared with the stochastic approaches discussed before (MDS, CSG).

Architecture of VIBe

The modular software architecture of VIBe ensures an adaption of the approach for benchmarking of different infrastructure systems, like urban drainage systems, water distribution systems, power supply systems or district heating systems. Exemplarily, the generation process of urban structure as basis for investigations of water infrastructure is described.

From real world case studies (CS) and from literature, ranges of parameters (e.g. percentage of land use classes, population densities, population equivalents, relief properties et cetera) can be evaluated (Figure 1). With a variation of these parameters within the extracted ranges, numerous VIBe case studies of urban structure are generated in the urban structure module. For each urban structure data set the sewer module and water distribution system module (WDS module) generate infrastructures with different system properties (for the sewer module these system properties are presented in Urich *et al.* (2009) and for the WDS module presented in a future paper).

As a result the urban structure module writes raster data files for geographic information systems (GIS) and the infrastructure modules write input files for simulation software as EPANET (Rossman 2000) for water supply networks and SWMM (Rossman 2004) for sewer simulations. The infrastructure systems and the results of the infrastructure simulations can be benchmarked and analysed stochastically to improve the system understanding, efficiency and determine potentials of real world systems.

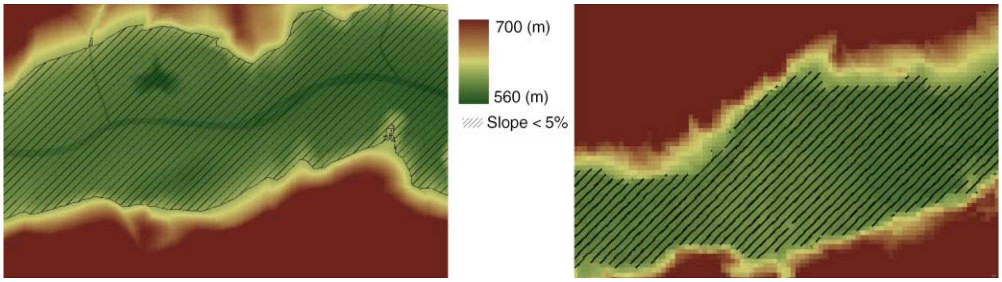

Figure 2 | DEM for an alpine area; left side "Virtual", 8,000 × 5,000 m^2 quadratic grid, 20 m cell size; right side, "Innsbruck", 8,000 × 5,000 m^2 quadratic grid, 125 m cell size. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

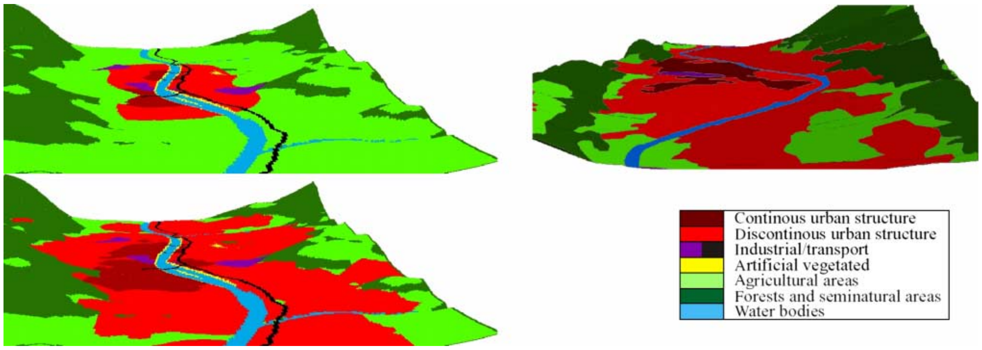

Figure 3 | Land use of alpine case studies "Initial virtual" (upper left side), "final state - virtual" (lower left side), "Innsbruck" (right side). Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

Urban structure in VIBe

The urban structure module so far handles 40 grid based data layers (e.g. elevation map, land use, population, et cetera) with quadratic cells. The cell size of the grid is an input parameter. For the highest resolution a cell size of 20×20 m is intended. The generation process in the urban structure module consists of three main parts which generate the virtual case study (VCS) within the specified parameter ranges. In the first part the topography including a river system is generated. In the second part the land use and the distribution of the population are added taking into account the relief and river system. In the third part data for water demand, population equivalents (PE) and impervious area are generated based on relief, river system, land use and population.

Relief and river system

According to predefined boundary conditions for the topography (alpine areas, foreland or lowland) the river system is generated as a set of cubic spline curves (Rabelo *et al.* 2007). E.g. for alpine areas the width of the valley floor in which the river can meander is defined as area with minor slope (less than 5% slope for Innsbruck, see section real world case studies and Figure 2 hachured area). In a next step a digital elevation model (DEM) is created on basis of the river system and/or on basis of the input parameters (Figure 2 left side). The properties of the DEM (e.g. mean elevation, mean slope, maximal elevation) are input parameters for the urban structure module.

Land use and population

The present development process of VIBe with regard to the land use and population change does not coincide with real world processes. Only the final state after the development process is comparable to real world data. In the first step the city centres are randomly sited within the valley. Depending on slope, altitude, distance from city centres with cellular automata approach an initial land use (Figure 3 upper left side) with different land use classes is generated according to a model of urban structure (Heineberg 2001). In VIBe currently seven land use classes are implemented (Table 1). Because VIBe is designed for analysis of urban agglomerations, a higher level of details is taken into account for artificial surfaces (Table 1, CORINE (CEC 1994) nomenclature).

The initial population is generated based on the initial land use (Figure 3 upper left side) and the population densities of the land use classes as input parameters. The transition function $f_{\text{Population}}$ calculates the states of the cells $i = 1 \ldots N$ concerning the population for the next

Table 1 | Land cover classes in VIBe according to CEC (1994)

Land cover description	Used abbreviation
Continuous urban fabric	CUF
Discontinuous urban fabric	DCUF
Industrial, commercial and transport units	INF
Artificial vegetated areas	AV
Agricultural areas	AGRI
Forests and semi-natural areas	WOOD
Water bodies	W

time step $D^{t+1}_{i,\text{Population}}$. The transition function $f_{\text{Population}}$ uses actual states of population $D^{t}_{i,\text{Population}}$, land use $D^{t}_{i,\text{Landuse}}$, transport access $D^{t}_{i,\text{TransportAccess}}$ (see Figure 3 black colour) and the neighbouring population values $\Omega^{t}_{i,\text{Population}}$. In total P time steps are calculated with the transition function $f_{\text{Population}}$. Every qth time step the redesigned land use is recalculated with the transition function f_{Landuse}. The number of population growth steps P and the number of land use growth steps P/q are input parameters and used to adapt the land use by the land use model according to the population growth of the last q growth steps.

In detail with $f_{\text{Population}}$ the mean value mV_5 of the quantitative largest 5 elements of the set $\{D^{t}_{i,\text{Population}}, \Omega^{t}_{i,\text{Population}}\}$ is calculated. The value mV_5 is multiplied with a stochastic growth factor g_1, which is determined by the current land use state in each cell $D^{t}_{i,\text{Landuse}}$. The ranges $(g_{1,\text{low}}, g_{1,\text{high}})$ of the equal distributed growth factors are input parameters and can be adapted to calibrate the growth process. The product $mV_5 \cdot g_1$ is multiplied with a transport access factor g_2 which represents the distance to the main transport road. The state of the next time step $D^{t+1}_{i,\text{Population}}$ is calculated with

Because the development from the initial state to the final state does not represent a real world process, the regarded population growth factors are not comparable with real world growth factors. However, the cellular automata steps are parameters which characterise the degree of urbanisation in the VCSs. The ranges for population densities of the final state are also calibration parameters to obtain the final state of the VCSs (Figure 3 lower left side). The final states of the generated land use and population densities are comparable with real world data (for land use see Figure 3 right side).

Water demand, population equivalents (PE) and dry weather flow (DWF)

The water demand and the PE are calculated on basis of the generated population densities and the land use. For industrial land use the range of the PE and water demand can be specified separately. The spatial distributed DWF is calculated within commonly applied ranges for domestic, parasite and industrial dry weather flow–in this paper according to the Austrian guideline ÖWAV-RB 11 (2009).

$$D^{t+1}_{i,\text{Population}} = f_{\text{Population}}\left(D^{t}_{i,\text{Population}}, D^{t}_{i,\text{Landuse}}, D^{t}_{i,\text{TransportAccess}}, \Omega^{t}_{i,\text{Population}}\right) \quad \forall\ i = 1 \ldots N$$

$$D^{t+1}_{i,\text{Population}} = f_{\text{Population}} = mV_5 \cdot g_1 \cdot g_2 \quad \text{with}\, g_{1,\text{low}} \le g_1, g_2 \le g_{1,\text{high}}$$

For the land use change model maximum population densities for CUF and DCUF are defined as input parameters ($f_{\text{CUF}} > f_{\text{DCUF}}$). These values are limit values for the redesign process with regard to land use. If in a qth development step in a land use class the corresponding limit value for population density is exceeded land use will be redesigned. The maximum population densities factors f_{CUF} and f_{DCUF} are used for calibration.

Impervious area

The spatial distribution of the impervious area coefficient for the virtual case study is assessed by combining following two approaches. For agricultural areas and for discontinuous urban fabric with population densities (pD) below 67.6 (population/($\text{m}^2 \times 10^4$)) the percentage of impervious area ψ is assessed with the following linear regression (Chabaeva *et al.* 2004).

$$D^{t+1}_{i,\text{Landuse}} = f_{\text{Landuse}}\left(D^{t}_{i,\text{Population}}, D^{t}_{i,\text{Landuse}}, \Omega^{t}_{i,\text{Landuse}}\right) \qquad \forall i = 1 \ldots N$$

$$D^{t+1}_{i,\text{Landuse}} = \begin{cases} \text{if}(D^{t}_{i,\text{Landuse}} = \text{AGRI}) \wedge (D^{t}_{i,\text{Population}} > f_{\text{DCUF}}) & \text{then(DCUF)} \quad \text{else}(D^{t}_{i,\text{Landuse}}) \\ \text{if}(D^{t}_{i,\text{Landuse}} = \text{DCUF}) \wedge (D^{t}_{i,\text{Population}} > f_{\text{CUF}}) \wedge (\Omega^{t}_{i,\text{Landuse=CUF}} > 4) & \text{then(CUF)} \quad \text{else}(D^{t}_{i,\text{Landuse}}) \end{cases}$$

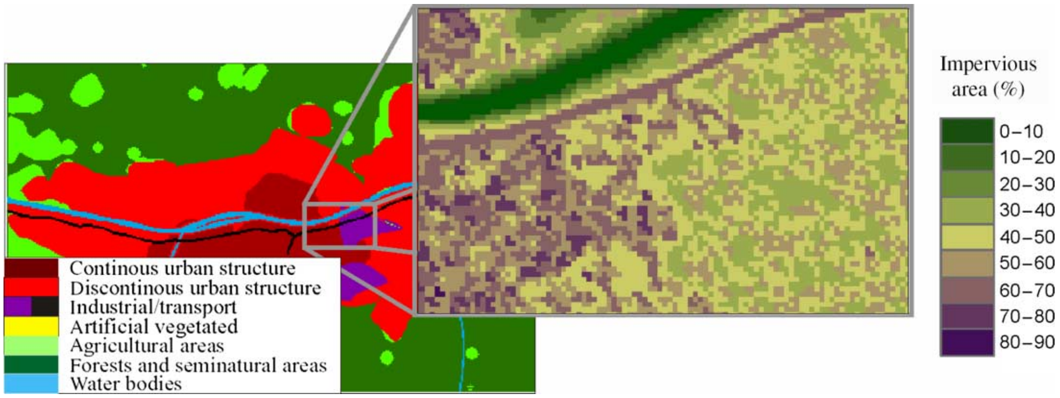

Figure 4 | Left side: land use, right side: clustered impervious area, 20 m cell size. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

$$\psi = 0.492 \cdot \mathrm{pD} + 16.732$$

$$\text{for } \psi < 50(\%),\ \mathrm{pD} \text{ in } (\text{population}/(\mathrm{m}^2 \times 10^4))$$

Additionally a cell based stochastic variation of the impervious area is superposed. The remaining impervious area is determined by input parameters and the ranges of their variation for the land use classes of Table 1. To cluster the randomized data at a local scale for impervious area a cellular automaton data clustering model (Batty 2005) adapted for this issue is applied (Figure 4).

Infrastructure in VIBe

With the infrastructure modules of VIBe combined sewer systems and water distribution system are designed meeting the requirements of the urban structure. Both virtual infrastructures are designed according to the state of the art design rules. The sewer module of VIBe generates combined sewer systems with an agent based approach for sewer placement presented in Urich *et al.* (2009). The water distribution module generates water distribution systems with a graph theory based concatenating approach following the principles of the modular design system approach of Möderl *et al.* (2007).

Real world case studies

As investigation area the river Inn valley in Austria was selected (Figure 5). The length of this section of the U-shaped valley approximately measures 70 km, whereas the width of the valley floor ranges from 1 to 3 km. Within this area numerous urban agglomerations are sited, which were investigated in this study.

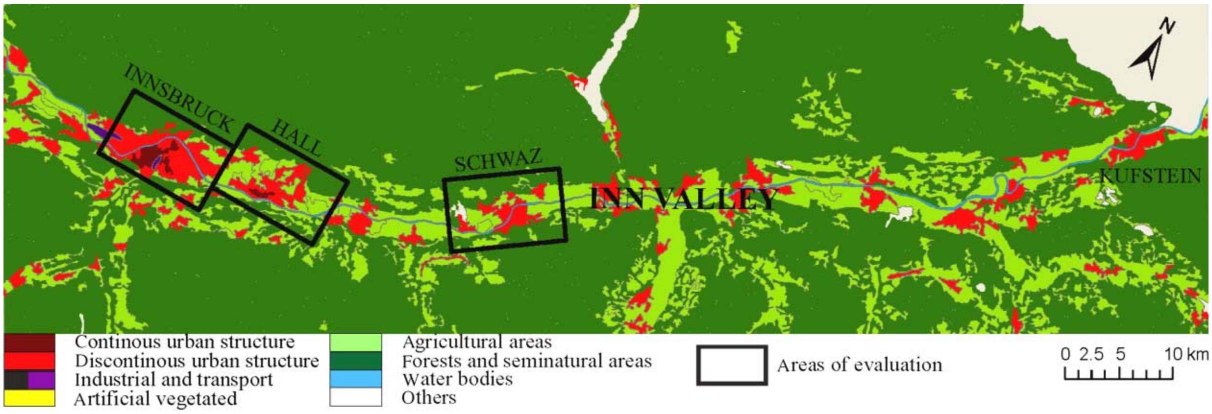

Figure 5 | CORINE land use of the Inn valley, simplified to land use classes in VIBe. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

Table 2 | Percentages of land cover classes, simplified to land use classes in VIBe

Land cover description	Innsbruck (%)	Hall (%)	Schwaz (%)
Continuous urban fabric (CUF)	7.9	1.6	0.0
Discontinuous urban fabric (DCUF)	41.3	22.6	16.2
Industrial and commercial and transport units (INF)	1.6	6.6	1.7
Artificial vegetated areas (AV)	–	–	–
Agricultural areas (AGRI)	14.8	32.5	32.1
Forests and semi-natural areas (WOOD)	32.1	34.6	48.0
Water bodies (W)	2.3	2.2	2.1

In Figure 5 the evaluated areas of the cities Innsbruck, Hall and Schwaz with an extent of 8,000 × 5,000 m are marked with black rectangles. Within these areas the percentage of land use classes and population are determined (Table 2). With ranges for width and slope of valley floor, maximal height of hill side, river's mean width and slope as well as the percentages of land use classes of Innsbruck and Schwaz the generation process of alpine urban structure in VIBe is calibrated. By reason that the generation is a stochastic process, 100 case studies were generated for each calibration state. With theses calibration sets the mean values were used for calibration. With randomised variation of the calibration parameters numerous data sets were generated. Although the data of Hall is located from nearby region of the data of Schwaz (concerning population), the land use characteristics of both regions (especially CUF and WOOD) are significantly different. The data of Hall is therefore used in a way for validation of the generation process.

RESULTS AND DISCUSSION

Totally, 1,000 virtual case studies (VCSs) for urban structures in an alpine region were generated with parameter ranges evaluated from the two cities Innsbruck and Schwaz in the Inn valley. Each VCS has an extent of 8,000 × 5,000 m with 20 m raster resolution. In Figure 6 left side the box plots of land use classes according to Table 2 for 1,000 VCSs are shown. In each box the median is marked with a red line and the edges of the boxes are the 25th and 75th percentiles. In the box plots the results of the real world data are plotted with black markers. Therefore, Figure 6 left side shows the fitting of the calibration data (Innsbruck, Schwaz) and validation data (Hall) in the ranges of the VCSs. Figure 6 right side shows the range of population and the urban area (sum of population in CUF, DCUF, INF, AV) of the VCSs in square kilometres (sqkm or $(m^2) \times 10^6$) with gray markers. The percentages of land use classes for the cities Innsbruck and Schwaz (black markers), which were used for calibration of the land use, fit into these the ranges and alike the case study data of Hall which was used for a validation.

In Figure 7 left side the box plots of DWFs for CUF, DCUF and AG are shown. In Figure 7 right side the

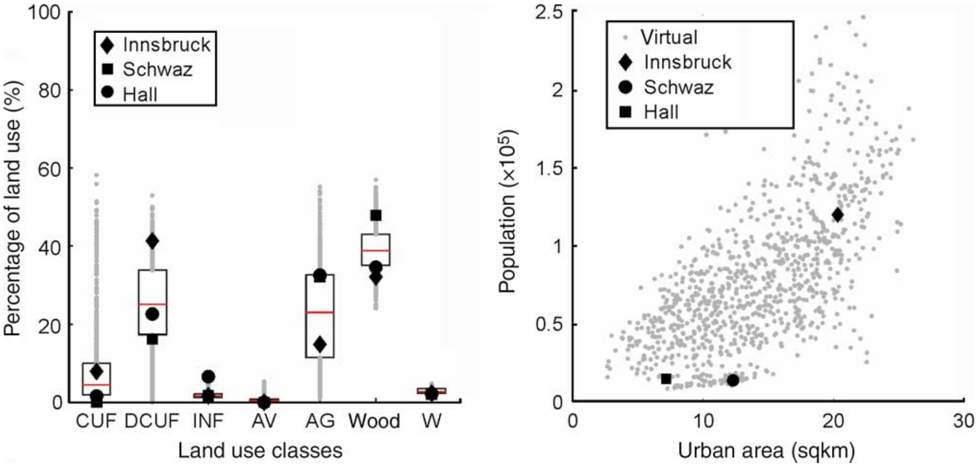

Figure 6 | Box plots of land use (left side), urban area and population (right side).

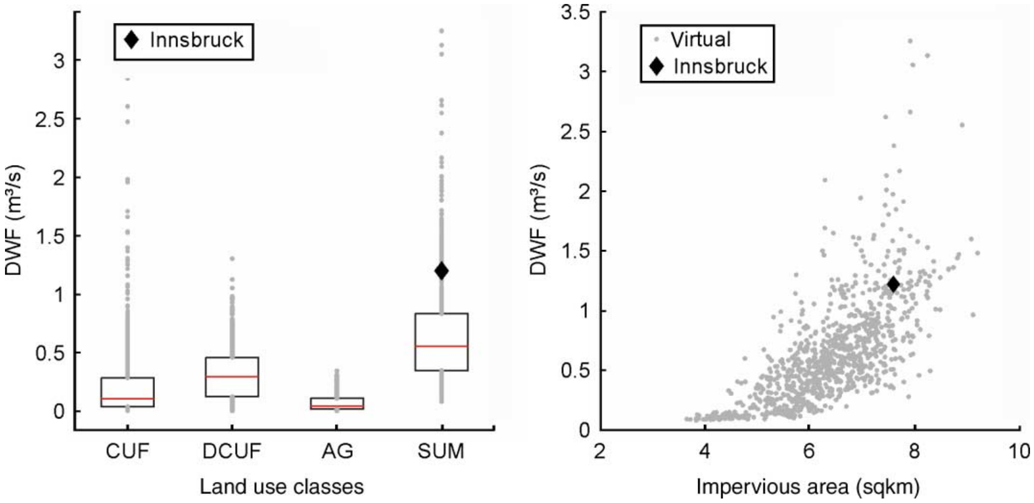

Figure 7 | Box plots of DWF in land use classes (left side), impervious area and DWF (right side).

impervious area (sqkm) and the DWF (m^3/s) of the VCSs are shown. Data for DWF and impervious area in land use classes for the regarded real world case studies is not available. Only the sum of DWF and impervious area of Innsbruck are obtainable whereas these values fit in the range of the VCSs.

The approach presented was applied to alpine case studies which are located in an alpine valley. Owing to the U-shape valley the generated case study is characterised by elongate settlement. Especially with regard to generated VCSs for other topographic boundary conditions, the topography generation and initial land use approach used, have to be adapted respectively modified for this task (e.g. the strategy for placement of city centres has to be modified in order to represent a more general settlement characteristic).

CONCLUSIONS AND OUTLOOK

Concluding, this paper presents how an application of VIBe tackles the problem of limited availability of real world case study data by generating numerous virtual case studies. It is shown that theses virtual case studies are comparable with real world data. It is revealed that VIBe provides a methodology to test new or existing technologies, strategies and measures on numerous case studies with different properties to obtain case unspecific results. Further, detailed data of VCSs is provided that allows analysing virtual water systems at a city scale. Therein the urban structure models, e.g. population model, are linked with the infrastructure construction model which allows investigating impacts of population on water infrastructure. An application of the approach is shown for a section of the Inn valley with calibration data of the two cities Innsbruck and Schwaz and parameter ranges from literature. It was shown that properties (percentage of land use, population, DWF, impervious area) of the real world cities fit to the ranges of 1,000 VCSs generated. The VCSs of urban structure are the input for infrastructure construction models for combined sewer systems (Urich *et al.* 2009) and water distribution systems (presented in a future paper). Therewith different development states of cities and urban agglomerations in an alpine valley and their water infrastructure can be benchmarked and investigated systematically. With the current development state of VIBe the setup of data sets for different types of topographies (e.g. foreland and lowland) will be pursued. With this data sets water infrastructures will be generated, stochastically analysed and benchmarked.

Numerous assumptions and simplifications were made for the generation process included in VIBe. Important investigations have to be done in order to determine parameters sensitivities and dependencies of parameters. This issue will be pursued in further work. In further developments of VIBe the generated VCSs will include spatial distributed data for pollutants concentrations, build up and wash off rates. The layout of the sewer network and water distribution network as well as the water demand and amount of waste water will be linked with an integrated model. The implemented population model will be enhanced with different social classes to investigate socio economic aspects on the infrastructure. Furthermore, additional data layers (e.g. aquifers) and infrastructure modules (e.g. energy supply, geothermal utilisation) will be implemented.

Owing to VCSs generated with VIBe are limited to one certain state of time, efforts are spent in the development of an enhanced approach which provides development of a VCS over time. Additional, the application of this enhanced approach to real world case studies is planned. Therewith, the temporal development of the infrastructure as well as the impact of defined requirements of urban structure on the infrastructure can be investigated with VCSs as well with real world case studies.

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