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Importance of scenario analysis in urban development for urban water infrastructure planning and management

Christian Mikovits*, Wolfgang Rauch[1], Manfred Kleidorfer[1]

University of Innsbruck, Unit of Environmental Engineering, Austria

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ABSTRACT

Sealing of surfaces and land use change induced by population change puts pressure on urban water networks. Changes in paved areas can also increase the risk of pluvial flooding at places that have not been endangered before. For an anticipatory planning and adaptation of the existing water infrastructure to a dynamic and evolving system like a growing or shrinking city, a comprehensive urban development scenario analysis is essential. This work presents an urban development model designed especially for simplistic simulation of multiple predefined population and spatial scenarios and allowing for an integration with successive urban water network models.

Results show that an analysis of different development scenarios can help to increase a city's resilience to unexpected changes. Hence it is crucial to simulate a variety of scenarios to cover as many future outcomes of city development as possible for a systematic and rigorous inquiry for problematic situations in the future.

1. Introduction

All over the world population growth within the next decades will be absorbed mostly by cities (United Nations, 2011) resulting in an increasing share of population living in urban areas. Within the 20th century, cities in Europe and North America have already faced a rapid urbanization wave, which included a rapid built up of urban infrastructure including water supply and wastewater networks. These systems are now, 100 years old, in need for rehabilitation to avoid serious incidents within the next years and decades (Tscheikner-Gratl, Mikovits, Rauch, & Kleidorfer, 2014). Some cities are also confronted with deindustrialization and economic decline, which result in mismatched supply of infrastructure, combined with a reduced tax base for maintenance. Especially in cases of a mosaic decline and residential demolition of a city, the supply of water and the functioning of the wastewater system is at risk (Müller, Ignatieva, Nilon, Werner, & Zipperer, 2013; Shuster, Dadio, Drohan, Losco, & Shaffer, 2014). This situation puts increasing pressure on existing infrastructure, particularly subsurface networks as for e.g. urban drainage or water supply systems. To find practical solutions for adaptation and expansion of stressed water systems an integrated and interdisciplinary approach for analysis is beneficial (Brown, Keath, & Wong, 2009; Urich et al., 2013). Integrated analysis of urban development and water systems can also be seen in Makropoulos & Butler, 2010, Astaraie-Imani, Kapelan, Fu, & Butler, 2012 and also Mitchell, 2005 where urbanization is considered as one of the main drivers of flooding from urban drainage networks. Previous studies have proven that urban changes can put pressure on existing drainage systems resulting in higher risk of pluvial flooding and a concurrent increase of storm water discharges contaminated with different pollutants (Kleidorfer et al., 2014; Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008). With respect to urbanization road and roof runoff containing heavy metal pollutants are a problem as they are non-degradable (Roesner, 1999). In particular, combined sewer overflows (CSOs) play a role as significant sources of pollution for the environment and have to be considered (Lau, Butler, & Schütze, 2002; The Council of the European Communities, 1991).

Hence, the need for integrated modelling of urban development and urban drainage has been determined, but the integration of the models is still ongoing work. Temporal and spatial scales between these two models vary on both temporal and spatial scales. Where urban change (growth and decline) is a complex process driven by environmental conditions, geography, society, politics, economy, urban drainage models are based on physical rules (Saint-Venant equations). Nevertheless, cities are not disordered systems, but follow orders and patterns (Batty, 2008) and even during rapid growth the number of buildings does not change by more than 1% or 2% per year (Simmonds, Waddell, & Wegener, 2013). Modelling city development and land use

* Corresponding author at: Technikerstraße 13a, 6020 Innsbruck, Austria.
E-mail addresses: christian.mikovits@uibk.ac.at (C. Mikovits), wolfgang.rauch@uibk.ac.at (W. Rauch), manfred.kleidorfer@uibk.ac.at (M. Kleidorfer).
[1] Co-author.

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change is still a challenging task as data requirements are intense and running a variety of scenarios requires a complicated setup. Ever since the 1950s model efforts to study the interaction of transport and spatial development in urban areas have been made with accessibility as the main driver location choice (Hansen, 1959) eventually resulting in a feedback loop (Lowry, 1964). Recent models are not using only transport modelling as the only driver for land use change and population distribution, but incorporate economic and social sub-models as well as the consideration of policy changes (Felsenstein, Axhausen, & Waddell, 2010; Waddell, Wang, & Liu, 2008; Wegener, 2011). Up to now, the urban modelling projects in development are mostly used for scientific purposes or transportation modelling and land use modelling in metropolitan areas for a best possible planning of future city expansion in concordance with (future) environmental regulations (Batty, 2013; Joshi, Guhathakurta, Konjevod, Crittenden, & Li, 2006; Löchl, Bürgle, & Axhausen, 2007). After almost 5 decades of development and research the use of urban development models is still a difficult and complex task, mostly due to data availability but also the need for improved methodology (Herold, Goldstein, & Clarke, 2003).

Several urban development simulation frameworks exist, such as Urbansim/Synthicity (Waddell, 2002) or Simulacra (Batty et al., 2013) but often do not allow for easy integration of successive models or are simply too costly to be run by small communities or infrastructure planning offices. Usually the models are not a single monolithic model but represent frameworks incorporating a variety of models including transport (people and goods), employment, location choice (housing), land use and population forecasts. This also implies that data needs of the models are high and pose a major effort, even though there is a trend towards models which can be run with less data (Simmonds et al., 2013). At the same time, the level of detail of results from such models is usually not required or of little benefit in the context of urban water management. This includes results on exact household size predictions, job movement predictions or simulation on real estate prices. Others may be simplistic and give the possibility for succeeding models, but do not offer the automatic generation of a street layout in newly developed areas. Urban water supply or drainage systems are not specifically mentioned in Wegener, 2004, but they are considered to have a response time equal to housing construction, a large response duration and to be hardly reversible, as they are mostly bound to street layouts which do not change over centuries (Mair, Rauch, & Sitzenfrei, 2017).

As conditions in the future are uncertain, the assessment of changes within urban areas is a necessity. For urban drainage systems, this involves, especially, the connection and disconnection of impervious areas to and from the drainage networks. The installation and analysis of drainage systems including the installation of new technologies mainly focuses on newly developed areas (Mitchell, 2005) leaving out possible problems or weaknesses occurring in already connected areas but also innovative solutions. Hence, for this work, an urban development model is developed, which is comprehensive in terms of city simulation on a spatial and temporal scale, but, at the same time, requires only limited input data. The model can be considered to be a random utility model and shares many ideas with the SIMULACRA model (Batty et al., 2013). As an application example, this paper shows the generation of urban development results, derived from user-defined scenarios. The urban development model is linked to a hydrodynamic sewer model (Storm Water Management Model - SWMM) (Burger, Sitzenfrei, Kleidorfer, & Rauch, 2014; Gironás, Roesner, Rossman, & Davis, 2010) i.e. input parameters of the sewer model are automatically adapted, the network layout itself is not changed during the simulations.

This work presents a newly developed simplistic multi-scenario urban development model with an emphasis on low data requirements and a focus on scenario analysis, easy setup and high performance under the overall objective of easy integration of urban water models. Hence, this work contributes essentially to solutions for early detection and management of potential future problems in urban areas. The intention of this model is not to compete with existing models used by urban and transport planners, especially on the level of accuracy and comprehensiveness. It is intended to provide a simplistic model for planners from a different area of expertise and not a single result, but a bandwidth of stochastic results to allow for testing for various future possibilities.

2. Methods

2.1. Software architecture

The *DynAlp-urbandevel* dynamic urban development model uses the *DynaMind* Framework (Urich, Burger, Mair, & Rauch, 2012) as a basis to run the dynamic modelling. *DynaMind* is a freely available (GPL license) scientific workflow engine implemented in C + +. It provides a platform for researchers and planers to combine urban water centric models with GIS (Geographic Information System) functionality including visualization. For performance reasons the urban development modules are also written in C + + instead of using Python (which would also be possible).

2.2. Input data structure

As indicated, the model is designed to run with minimal data needs. Table 1 gives an overview about the GIS type needed, the layers used and the mandatory and optional attributes. Mandatory and optional layers are shown, as well as which attributes of each layer are mandatory or optional. Data is inserted into the model as GIS-data. Files (e.g. Shapefiles) or a spatial database (e.g. PostGIS) can be used as an input. CITY represents the city centre with expected population and corresponding year as comma separated values as mandatory attributes. The GRAVITY layer defines attraction points within the city, where the weight attribute specifies the ‘gravitational force’ of the point used for ranking of areas during the simulation. SUPERBLOCK represents parishes of a city, which are used as spatial input. Empty SUPERBLOCKS optionally contain a designated development year, type (**res**idential, **com**mercial or **ind**ustrial) and maximum height of buildings in metres. For already developed SUPERBLOCKS the type is mandatory. A CITYBLOCK represents subdivisions of a SUPERBLOCK and is used to create a street layout within the SUPERBLOCK. The BUILDING layer

Table 1
Input data needs for the *DynAlp-urbandevel* model.

	Layer name	Shape type	Attributes				
			Development year	Area type	Population	Height	Weight
Mandatory	CITY	Point			M		
	GRAVITY	Point					M
	SUPERBLOCK	Polygon	O	O/M		O/M	
Optional	CITYBLOCK	Polygon					
	BUILDING	Polygon		O/M	M	M/M	

M stands for mandatory, O means optional attributes.