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Dynamics in urban development, population growth and their influences on urban water infrastructure

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Abstract

For a comprehensive adaptation of urban water infrastructure to constantly changing and evolving systems a detailed simulation of the dynamics in city development is crucial. Several scenarios are developed within model boundaries to take a consequences of growth into account. For simulating the parceling of available areas and placement of buildings and population a programming toolbox (http://dynamind-toolbox.org) developed at the University of Innsbruck is used. Within this toolbox it is easy to set up a dynamic, cyclic process of automated city growth. Further the software enables for a later generation and adaptation of urban drainage systems and performance analysis. First results show that population data alone are not sufficient to describe the effects of city development on urban water infrastructure. For a comparison of the simulated urban development scenarios SWMM simulations are performed to show differences in runoff and flooding according to the developed areas. Results show that an increase of effective impervious area results in a twice as high increase in total flooding volume if no adaptation or extension of the sewer system takes place. The only slight increase in flooding junctions confirms the necessity for a thorough planning and adaptation of the drainage system.

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Keywords: urban development; water infrastructure; land-use change; adaptation; pressure

1. Introduction

Population growth and urban development, especially the sealing of surfaces and land use change, put pressure on urban water infrastructure as some severe flooding events in the recent past have shown. Particularly connecting

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newly developed areas to the existing drainage structures puts areas at risk which have not been endangered by flooding before (Ashley et al., 2005). For a comprehensive adaptation of urban water infrastructure to constantly changing and evolving systems a detailed simulation of the dynamics in city development is crucial. Conventional planning and management practices undergo a shift towards integrative approaches which are coupled to city development but also take social changes into account (De Haan et al., 2011). The development of several scenarios within the model boundaries defined by estimated population growth and existing spatial conditions is necessary to take all urban development possibilities into account.

Previous studies have shown that ongoing urbanization puts more and more pressure on existing drainage systems. The provision of drainage services for newly developed areas increases surface runoff and consequently runoff peaks in pipes. Higher runoffs lead to a higher risk of flooding and decrease the performance of storm water treatment as well (Astaraie-Imani et al., 2012; Semadeni-Davies et al., 2008). Additionally to potential flooding problems urbanization might also result in higher peaks and frequencies of storm water discharge contaminated with pollutants from different surfaces. Especially road and roof runoffs are rich in heavy metals which are not degradable by the environment. A close relation of water quality and city growth has been shown before (Roesner, 1999). This problem might intensify due to increased rainfall intensities and longer dry periods as a consequence of climate change which potentially also leads to a possible violation of regulations in the future (Kleidorfer and Rauch, 2011).

According to the World Urbanization Prospects (United Nations, 2012) most population growth will be absorbed by urban areas on a global perspective which leads to increasing proportions of the population living in cities. Nevertheless there is a significant diversity in the urbanization levels, especially in Europe where the majority of urban population will remain in cities with fewer than 500,000 inhabitants. Furthermore European cities already experienced a rapid urbanization wave within the past century. Along with that a fast built-up of urban infrastructure including sewer systems happened. Nowadays these systems are already in need for repair or will be in a possible critical condition within the next years or decades (Tscheikner-Gratl et al., 2013). Additionally ongoing urban sprawl leads to a higher proportion of population living in areas with a relatively high risk for natural disasters where flooding is considered as the '*most frequent and greatest hazard'* (United Nations, 2012). These facts point out the need for a thorough analysis of city development with a scope on urban drainage.

This work presents a computer framework to automatically generate scenarios using as few as possible input data to simulate city growth. In contrast to other systems using complex transportation or socio-economic models, e.g. UrbanSim (Waddell et al., 2008) which need a huge amount of input data and/or massive computational power, we applied a simplistic approach. Even if data is available it takes weeks or months to obtain the data and get the simulation to run. This enables for a fast setup of the simulation and a quick reconfiguration and adaption of boundary conditions to even model unanticipated situations like population stagnation or decline. The automatic development of designated areas for Innsbruck, Austria, is shown using a programming toolbox (http://dynamind-toolbox.org) developed at the University of Innsbruck for parceling the available area and the placement of buildings and population. Finally the impact of urban growth scenarios on surface runoff and waste water generation is shown.

Summarizing: This work focuses on a simplistic urban development model specifically designed to fulfil the needs of decision makers and planners with a focus on urban infrastructure, exemplary for urban drainage.

Nomenclature

CSO	combined sewer overflows
KML	keyhole mark-up language
EIA	effective impervious area
DWF	dry weather flow

2. Material and Methods

2.1. Study Area: Innsbruck

Innsbruck is located in the federal state of Tyrol which is part of western Austria. The city is located in the Inn Valley at an elevation of 574 meters above sea level. The area of the whole municipality is 104.84 km2, permanent settlement is only possible on 32.3% of the total area. Population by March 2013 counts 124,656 inhabitants plus another estimated 30,000 secondary-residence or non-registered residents. Fig. 1 shows the development and prognosis of inhabitants of the city of Innsbruck and surrounding municipalities divided into a driving time of below 15 minutes and from 15 to 30 minutes from the city center. Also included is the data on the increase of single person households for the federal state of Tyrol (Statistics Austria, 2012).

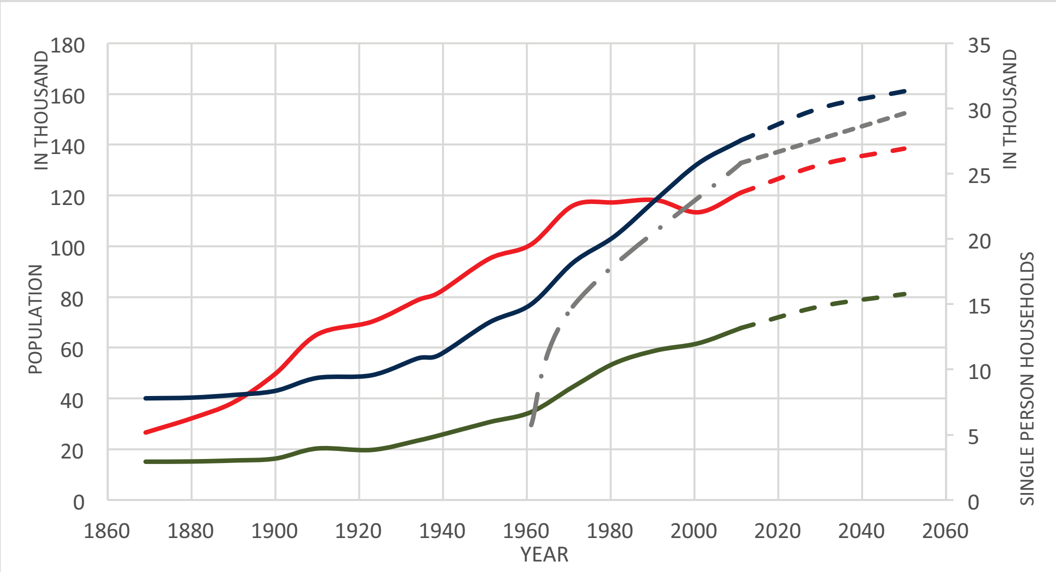

Fig. 1. Development and Projection of the population in and around Innsbruck including the trend towards single person households

2.2. Input Data

Apart from the inhabitants data mentioned above the official development plan of Innsbruck (Stadt Innsbruck, 2002) ranging from the year 2000 to 2020 was transformed into a GIS vector format along with mandatory fields with few mandatory fields:

- TYPE: residential, commercial, industry, public or mixed
- DENSITY: density classes 1, 2 and 3
- MAXIMUM_HEIGHT: defines the maximum number of stories of buildings
- TIMEFRAME: current, near or far future
- EIA_c: current effective impervious area

The TYPE and DENSITY are defined by the governmental development plan. While ‘public’ is designated to be used for educational (school, university, museum) or administrative purposes, ‘mixed’ defines a zone of buildings with intermixed housing and commercial functions. Density classes 1-3 resemble the denseness of floor area (the sum of floor space divided by parcel area) where class 1 stands for values below 0.8, 2 for 0.8-1.5 and 3 more than a value of 1.5. From the density class a calculation of the approximate maximum height of buildings would be possible. Nevertheless it was chosen to be defined by hand according to neighboring areas to get more accurate results. The TIMEFRAME sets the parcels earliest built year, while EIA_c defines the effective impervious area which is fundamentally defined by the impermeable fraction of an area.

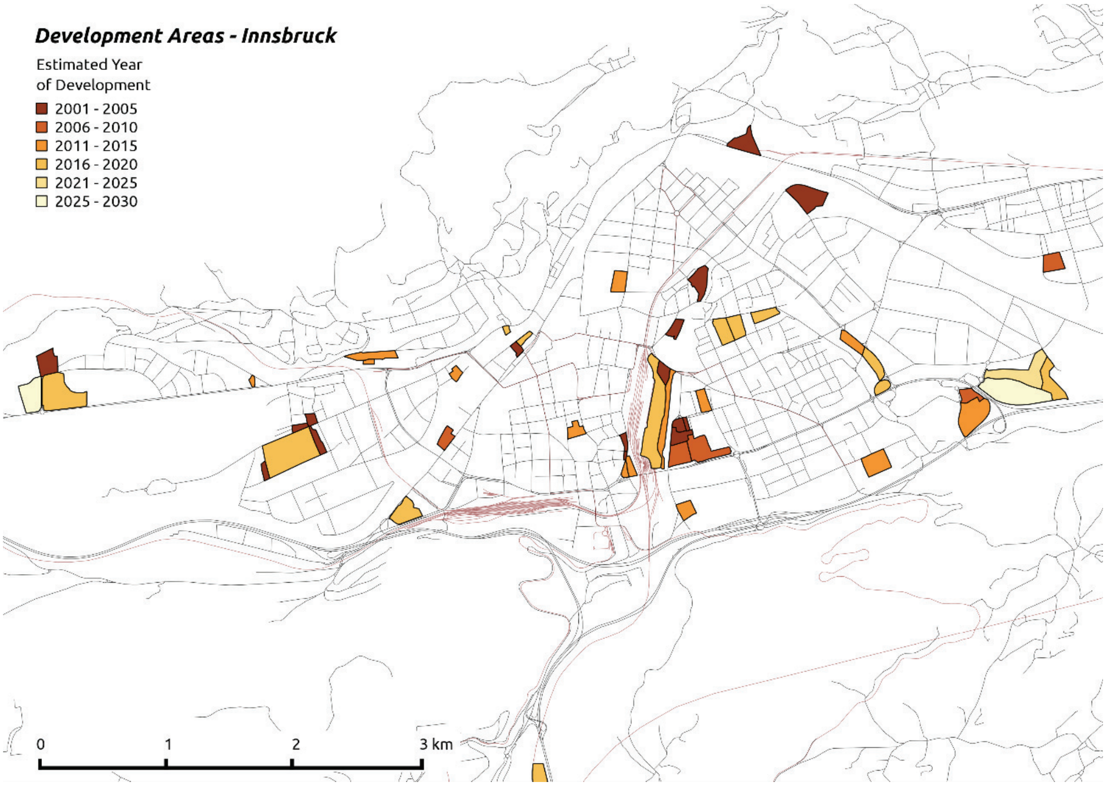

Fig. 2. Development areas of the city of Innsbruck according to the development plan of the government, the main street layout in black, the train system in red

2.3. Simulation

The Simulation Framework *DynaMind* (Urich et al., 2012), a scientific workflow engine with focus on dynamics, is used to read the input data and simulate parceling of areas, generation of households, distribution of population and calculation of drainage relevant parameters like dry weather flow and the peak runoff coefficient. Fig.3 shows the dynamic development cycle of the system. Dynamic evolution of the city connotes that no matter which development year is set for an area that parceling and generation of buildings (housing, commercial or industry) only happens if population data values are high enough. Depending on the conditions after a cycle the simulation dynamically evolves from this state further in time. In the simulation even a retrofitting of existing buildings and moreover a recalculation of the attributes can be achieved.

Within this investigation one cycle resembles 5 years in reality starting from the year 2000.The simulation includes 5 steps (until 2030) with population dynamics based on predictions. This cycle was performed with 3 different boundary conditions which resemble slow, average and fast, or disproportionately high, evolution of the city. The boundary conditions are controlled by adjusting the population data and leveling the density controls of the parceling and the buildings module of the simulation cycle. Furthermore 3 different scenarios have been calculated for this work.

- Scenario A can be seen as a base scenario according to population projections and a decent economic development, which means that commercial and industrial usage are developed at the same level as residential within each time step. Parameters for the EIA remain at the level preset in the input data from the urban development plan.
- Scenario B projects less population increase and also less increase in economy. This translates to 3% less population and therefor also less sealing of residential areas. Commercial and industrial are developed at the same rate as the residential category.
- Scenario C takes parameters for residential development from scenario A, but economic development from scenario B. This gives a normal population growth but less growth in economy.

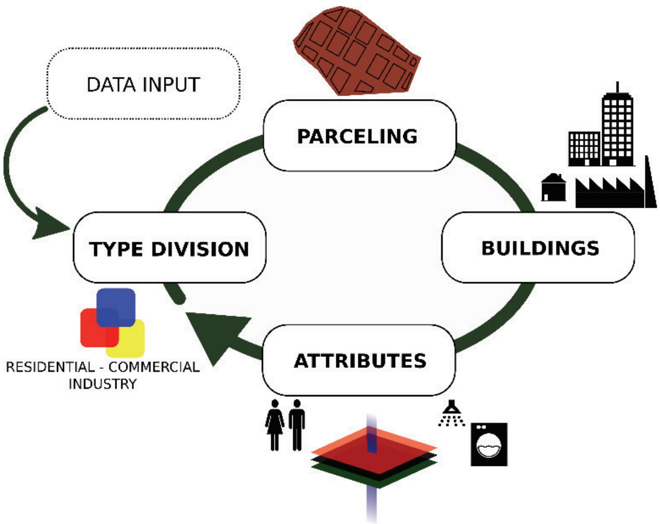

Fig.3. Dynamic Simulation Cycle

2.4. Output Data

The simulation generates 2 different types of output for each cycle. The first output is a file which defines buildings created by the simulation in the commonly used KML format (Open Geospatial Consortium Inc., 2008). Secondly updated ESRI Shapefiles containing all input data and additional information on the EIA for each cycle. For each building and parcel a DWF and the EIA was calculated on basis of Austrian regulations (Österreichischer Wasser- und Abfallwirtschaftsverband, 2009) and statistical data on water demand per person (Statistics Austria, 2012). Dry weather flow is defined to be 4 l/s for 1000 inhabitants for residential areas. Industrial areas are calculated on hectare basis with an amount between 0.2 and 1 l/s. As DWF is not used within this work a fixed amount of 0.5 l/s is set at the moment. EIA basically is defined by the total area connected to the sewer system and the fraction of imperviousness plus a certain amount of losses at the area. The fraction of imperviousness depends on the density class including a slight correction downwards to account for the losses.

As mentioned the dry weather flow is calculated from water consumption in liters per day and person while buildings size and consequently the impervious area is calculated from the number of persons on a parcel. For this simulations a fixed value of 40m2 per person, which resembles the current figure for living space per person in Austria, is used. This data enables for an ample analysis of changes in potential storm water runoff in a changing urban environment. Infiltration is directly incorporated into the EIA by simply using a smaller fraction of impervious area.

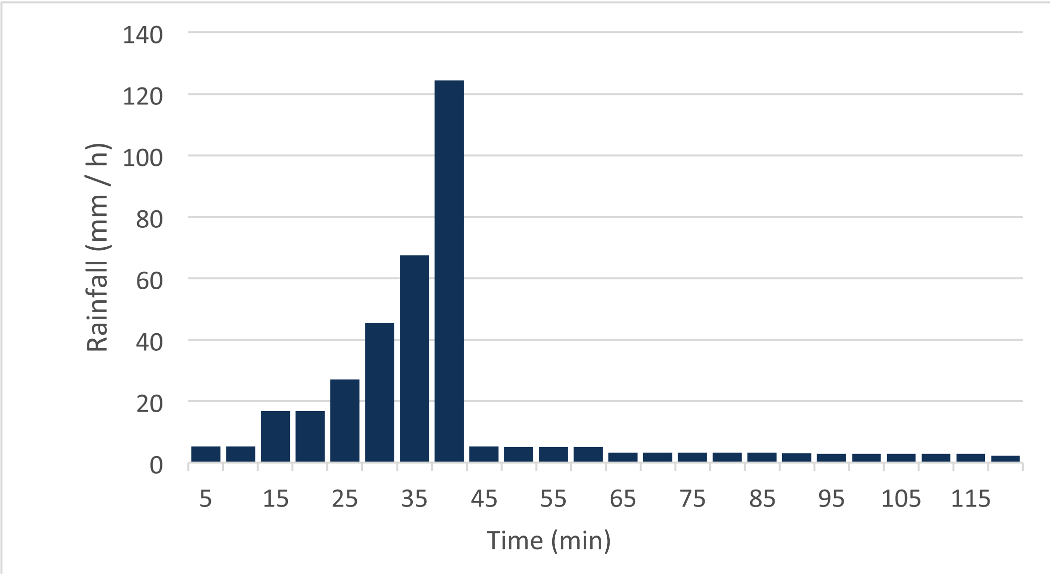

Fig 4. Design Storm Rainfall Euler II, 10yr, 5min steps; used in SWMM to test the effect of chaning EIP on the sewer network

Additionally, to verify the model and as a proof of concept runoff and flooding calculations with the well-known free and open source software SWMM (storm water management software) (Rossman, 2013) developed by US EPA are performed to show differing results according to the sealing of additional areas. For better performance in computing also a parallel computing version of SWMM is used (Burger and Rauch, 2012). Therefore commonly used design storm events of type Euler II are used (description available from Manfred Kleidorfer et al., 2009). Fig 4 shows the 120 minutes Euler II design storm event with a return period of 10yrs, which is used as an input for the hydro-dynamic model. The combined sewer system used for simulation consists of 5358 nodes, 4528 sub-catchments, 5695 links and 53 outfalls. For each scenario and year sub-catchments affected by a change are adapted in size and imperviousness.

3. Results and Discussion

3.1. Urban Development

Exemplary for all scenarios Fig. 5 shows that urban development and consequently a change in EIA for scenario A is happening in many parts of the city between 2000 and 2010, although only at a small or medium scale. Due to regulations of the city of Innsbruck enforcing infiltration methods applied on newly established buildings whenever groundwater levels allow it. Even though this regulation is in force EIA of most areas increases simply due to the fact as there was no sealing at all before (e.g. undeveloped agricultural areas). From 2010 to 2020 larger parts of the city get developed leading to an increase in EIA, except for the former freight train station where the EIA is expected to lower during the re-development of the area. Until 2030 steady construction occurs although large scale areas in the city are not available anymore.

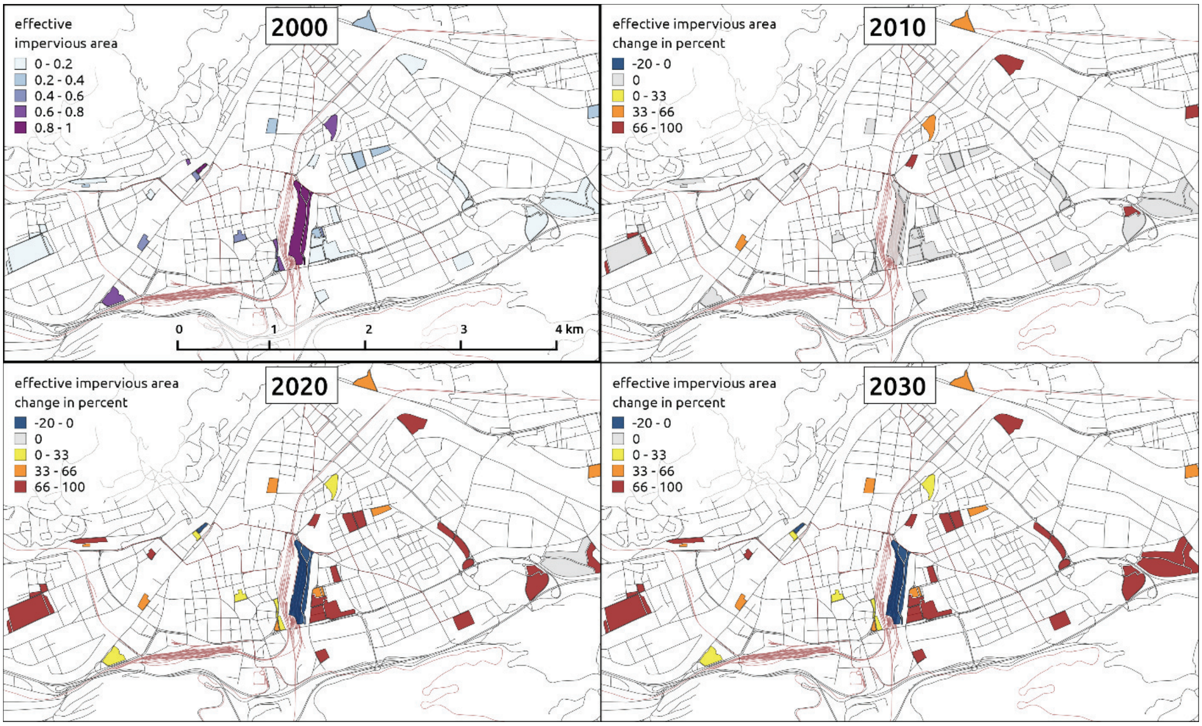

Fig. 5. Development of the EIA for scenario A in steps of 10 years

3.2. SWMM Simulation

Fig. 6 displays time series plot of the flooding events for each scenario if no adaptation and extension of the existing sewer system happens plotted as the difference to values of the base year (2000). As expected scenario A shows the highest peaks and total gains for both surface runoff and flooding. Values peak up to 9000 l/s respectively 7000l/s surplus within the whole system. Therefor almost 80% of the additional runoff counts up for the surplus in flooding volume showing that the sewer system already has reached its total capacity (which is not surprising for a rainfall event with return period 10 yrs.). Nevertheless also scenarios B and C cause only slightly less surplus in runoff and flooding. Table 1 shows insights in the total amounts of EIA of the city and the amount of total flooding volume calculated. The number of flooded nodes does not change significantly throughout the scenarios with only an additional 1-2%.

For a comprehensive analysis on the spatial distribution of flooding events Fig. 7 displays the flooding volume for single nodes with size and color defining the severity at a specific point. Small points in green signal no problem whilst red and big nodes indicate problems. Scenarios B and C show no increase in flooding nodes but an increase in volume. In contrast scenario A seems to intensify problems at many points, especially at the neuralgic point at the train station visualized by the second red dot above the white area in the middle of the figure.

As results show changes for every scenario adaptation of the urban drainage system is necessary to decrease damage through flooding from the sewer system due to newly connected areas. Even though extension and rehabilitation happens at various places these projections can be used to identify critical points in the system. Some areas show a decrease of EIA during the retrofitting process, though flooding increases as parts of these areas have not been connected to the sewer system in the base year.

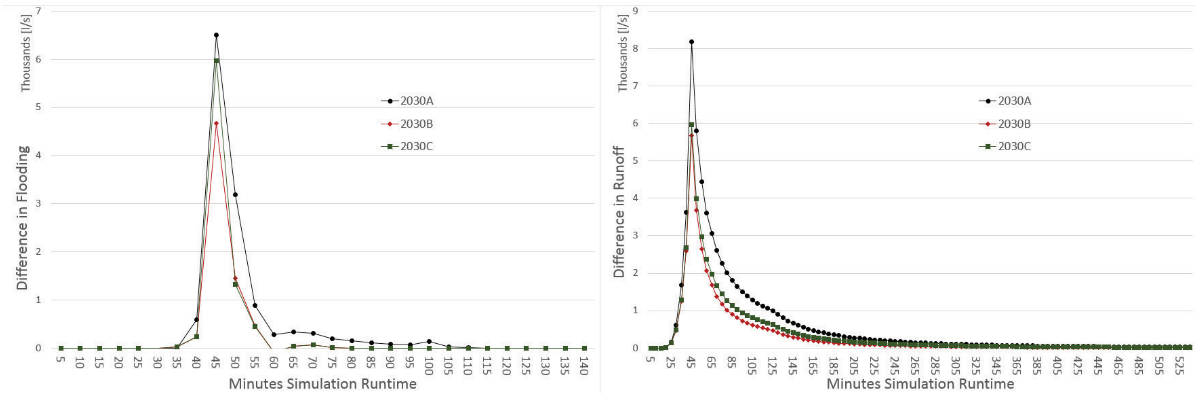

Fig. 6. Differences in runoff volume and flooding volume compared the year 2000 for all scenarios

4. Conclusions and Outlook

This study proves that the consideration of the dynamic development of urbanization is useful for a thorough analysis of the existing sewer system to identify possible flooding nodes in the system before actually flooding happens. First results displayed already show the potential of this tool for urban developers or civil engineers by only considering storm water runoff. The inclusion of DWF and pollution load from different surfaces would trigger even more insight.

Next steps are a more comprehensive and fine grained urban development model both on a spatial and temporal scale. This enables for a more realistic simulation of city growth including consideration of single buildings for DWF and possibly methods of reducing the EIA through infiltration of rainwater at the parcel including consideration of pollutants from street or roof surfaces.

The results enable not only a comparison which and how areas change in terms of drainage as the EIA and the DWF are automatically calculated. Also a comparison of results between different scenarios is easily possible by only adjusting boundary conditions. As input needs are low this method could be used by planers without the necessities of buying and preparing large amounts of data. Moreover this toolbox could be easily adapted for the usage in other parts of the world were data is simply not available. Furthermore this framework allows for testing consequences of new types of urban design on drainage (Rebekah Brown et al., 2008; C. Urich et al., 2011)

The ongoing work will be necessary for an integrated approach to analyze pollution load due to a decrease in CSO performance. Furthermore comprehensive performance analysis are necessary to display tipping points in the sewer system as it is shown in by Kleidorfer et al. (2013).

Table 1. EIA for the year 2000 and all scenarios in 2030 including the corresponding total flooding volume

Year and scenario	EIA [rel. to 2000]	Flooding [rel. to 2000]
2000	-	-
2030 A	+9.4%	+17.2%
2030 B	+5.1%	+9.2%
2030 C	+6.2%	+10.8%

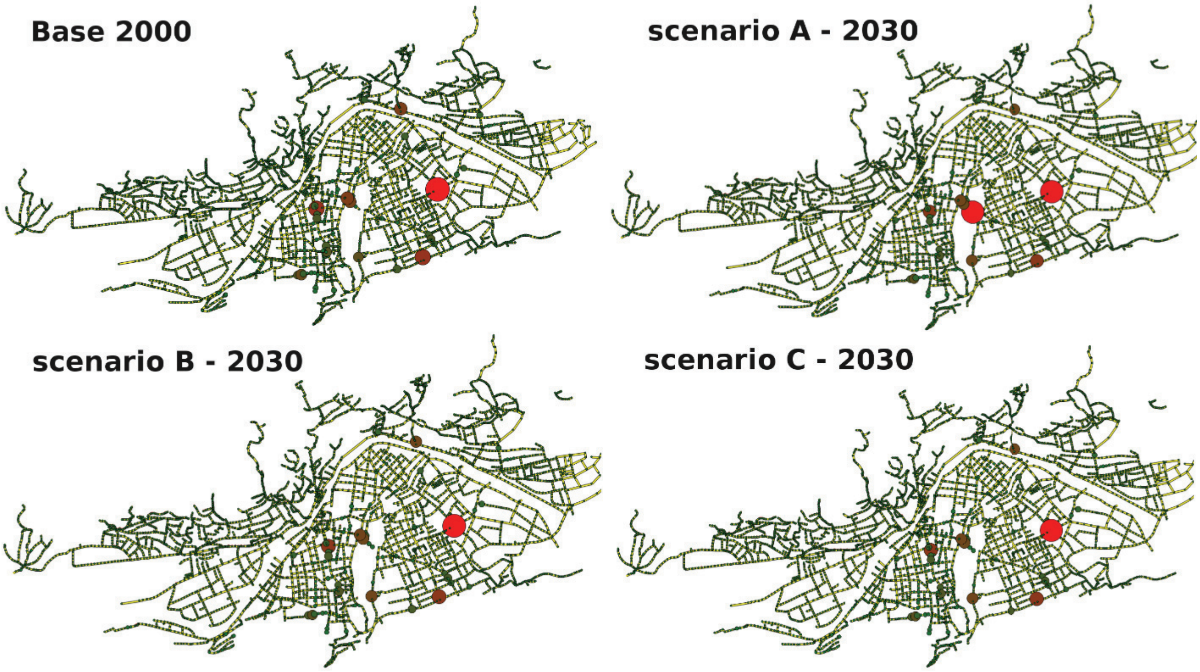

Fig. 7. Spatial development of flooding nodes for displayed for the base year and all scenarios in 2030 (output generated with PCSWMM 2013)

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