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Dynamic adaptation of urban water infrastructure in response to a changing environment

L'adaptation dynamique de l'infrastructure de l'eau en milieu urbain, en réponse à un environnement changeant

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RÉSUMÉ

La durée de vie moyenne des réseaux d'assainissement étant de plusieurs siècles, ceux-ci doivent être planifiés et adaptés de façon prédictive. Il est important de ne pas traiter uniquement les problèmes actuels pour évaluer les conditions à venir. L'urbanisation, ainsi que le changement climatique, influencent les performances des systèmes d'assainissement en milieu urbain. Par conséquent, un cadre pour une étude intégrée du développement de la ville et du changement climatique sera développé. Dans un tel cadre, le développement de la ville et le changement climatique seront simulés pour fournir des projections jusqu'en 2030 et un pronostic jusqu'en 2050. Ainsi, en lieu et place de cycles coûteux de construction / reconstruction, une adaptation dynamique peut être appliquée à l'avenir afin de maintenir les performances de l'assainissement en milieu urbain à un niveau élevé. Les premiers résultats indiquent que la simulation et la projection des changements sociétaux (ex. consommation d'espace par personne) doivent être prises en considération, avec les changements dans la population et/ou le climat, étant donné que tous ces effets ont un impact sur la zone pavée assainie et par conséquent, sur le ruissellement maximum pénétrant dans le système d'assainissement à l'intérieur du bassin versant.

ABSTRACT

As the average live-span of sewer networks is several centuries, planning and adaptation has to be done in a predictive way. To not only address current problems it is crucial to assess future conditions. Urbanization, together with climate change, is influencing the performance of urban drainage systems. Therefore a framework for an integrated consideration of city development and climate change will be developed. Within this framework city development and climate change will be simulated to give projections until the year 2030, respectively a prognosis until 2050. Hence, instead of costly build - rebuild cycles, dynamic adaptation can be applied in the future in order keep urban drainage performance on a high level. First results give an indication that simulation and projection of societal changes (e.g. land consumption per person) have to be considered together with changes in population and / or climate as all those effects impact the drained paved area and consequently the peak runoff entering the sewer system within the catchment.

KEYWORDS

City development; Climate change; DynAlp, Sewer system; Urban flooding

1 INTRODUCTION

Urban drainage systems are an important part of city infrastructure and have drawn public attention due to some severe flooding of the urban environment. Pavement of surfaces, along with a possible climate change induced increase of rainfall intensities, is one of the key factors accountable for increased flooding in urban areas (Semadeni-Davies et al., 2008b; Booth and Jackson, 1997; Douglas et al., 2010). Previous studies have shown that ongoing urbanization puts more and more pressure on the existing drainage systems. Connecting new areas to existing sewer systems increases surface runoff and consequently runoff in pipes and/or discharge to receiving waters (Semadeni-Davies et al., 2008a; Kleidorfer et al., 2009a; Astaraie-Imani et al., 2012). Consequently higher runoffs have an impact on the performance of the sewer system in terms of higher risk of flooding and decrease of storm water treatment performance. Planners have to account for these changes in future sewer system maintenance and replacement works. (Grum et al., 2006; Ashley et al., 2005; Berggren, 2008).

As future conditions are uncertain, the assessment of the dynamic development of both cities and society are expected to be the keys for successful infrastructure management (Kenworthy, 2006). One possibility for adaptation is to disconnect paved urban areas from drainage systems and implementation of on-site stormwater infiltration facilities. Infiltration guidelines and new developments in urban drainage as found for example in CEN (2008) and UN - ESCAP (2011) might help to address current problems but might not fully compensate for a possibly increased runoff (Urich et al 2011). To respond to the changes continuous adaptation of the infrastructure is necessary by combining different technological solutions (e.g. on-site treatment, increase of pipe-sizes etc.). To reduce costs, adaptation of pipe networks should reasonably occur in line with the regular renewal/rehabilitation of aging infrastructure.

The project 'Dynamic Adaptation of Urban Water Infrastructure for a Sustainable City Development in an Alpine Environment (DynAlp)' focuses on city development and the potential impact of climate change on the adaptation and development of urban water infrastructure and addresses the aspect of pluvial flooding risk in detail.

This work focuses on the integration of urbanization, climate change and sewer network expansion in a strategic planning framework. To address these challenges the design and construction of urban water infrastructure has to be performed in a predictive way. Additionally upcoming challenges are highly uncertain and sustainable adaptation has to take into account different possible future conditions by implementing adaptive solutions.

The aim of this paper is to present a conceptual framework for an integrated consideration of potential climate change induced changes of the precipitation signal in the context of extreme events and city development within adaptive planning of urban water infrastructure by taking into account the dynamics of the systems. The framework is an integration of different technologies to evaluate different adaptation strategies and solutions under stress of climate and urban change.

2 METHODS

2.1 Conceptual framework and case study

The DynAlp framework consists of three dynamic urban environment modules, of which this work focuses on module 1:

- *M1 Climate Change & Urban Development:* The Module generates and provides the environmental data such as rain-series from the climate change model, GIS-data about land-use, population, impervious area from the urban development model (Sitzenfrei et al., 2010).
- *M2 Guideline & Infrastructure Adaptations:* Based on data from M1 and according to the guideline adoptions the existing infrastructure is algorithmically adapted to the changing environment (Urich et al., 2010).
- *M3 Simulation & Assessment:* In the Module M3 the performance of the adapted infrastructure is assessed by using integrated conceptual and/or hydrodynamic simulations.

The development cycle of the urban environment allows the evaluation of different adaptation strategies. Since module M1 and M2 are based on stochastic methods numerous case studies (i.e. possible realisations of future development) will be generated and statistically analysed to consider uncertainties.

This framework will be applied on the case study Innsbruck (Austria). Innsbruck is located in the valley of the river Inn at an elevation of 574m and with a population of about 120,000 inhabitants and a population density of 3100 inhabitants per square kilometer within the settlement area. Whereas population stagnates within city limits since about the 1970ies, growth did not stop in the neighboring municipalities along the valley next to Innsbruck with a plus of more than 250% within the last 100 years as can be seen on Figure 1. The three colored lines resemble:

1. the city of Innsbruck itself (red)
2. neighboring small towns/settlements which are within 15min driving range (green)
3. the population within 15-30 minutes driving distance (blue).

The dotted lines show the projections until the year 2050 (Statistics Austria, 2012; Austrian Conference on Spatial Planning, 2012). Although the project concentrates on the development of the city itself it is necessary to consider changes in the surroundings as well as they affect Innsbruck as the major settlement in the area. Additionally the gray line shows the rising number of single person households in the Austrian federal state of Tyrol. Figure 2 shows that the population from the 1950ies to the late 1970ies was growing steadily within the city limits but far above average in towns nearby (Hanika, 2010).

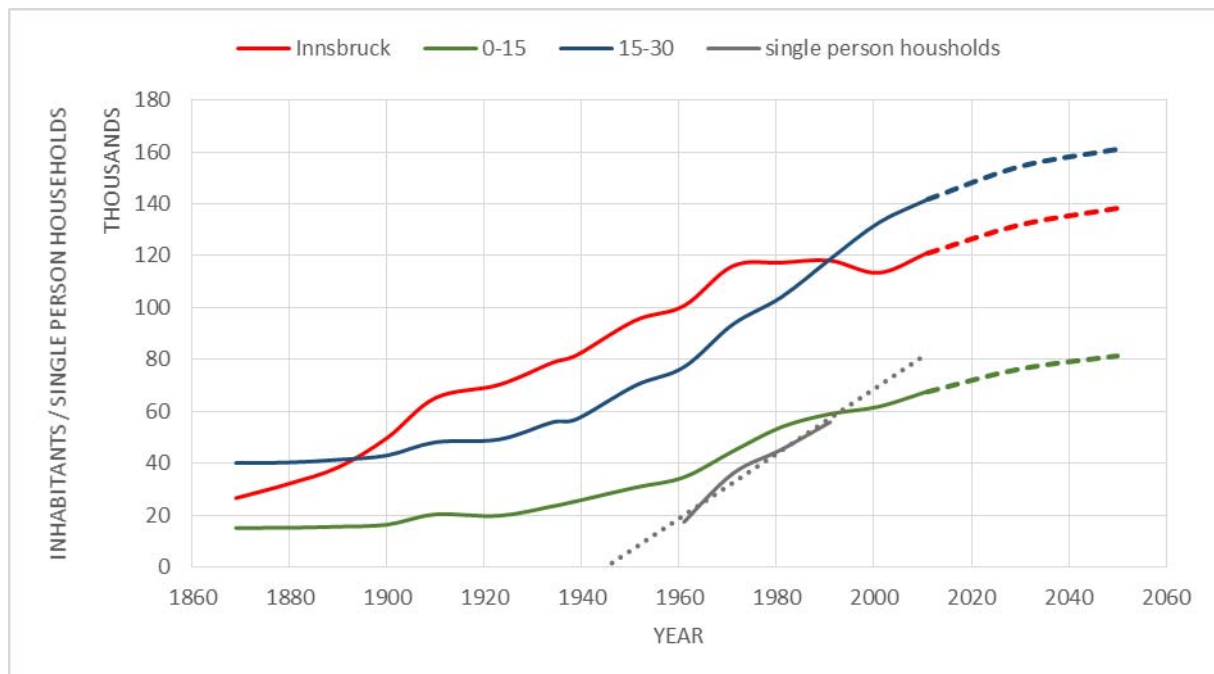


Figure 1: Changes in population in the city of Innsbruck and smaller cities and municipalities around Innsbruck; from 1869 to 2011 and single person household development

Most parts of the city are drained by a combined sewer system to a central waste water treatment plant. Also waste-water systems of communities around Innsbruck (additional 45.000 inhabitants) are connected to the network. Due to the extent of the sewer network and a large catchment area the system is prone to extreme weather events. In July 2010 the sewer system reached its limit when a storm with heavy rain and hail afflicted the city. This caused the drainage systems at junctions near the old town to collapse and water discharged out of the gullies (Welzenbach, 2010).

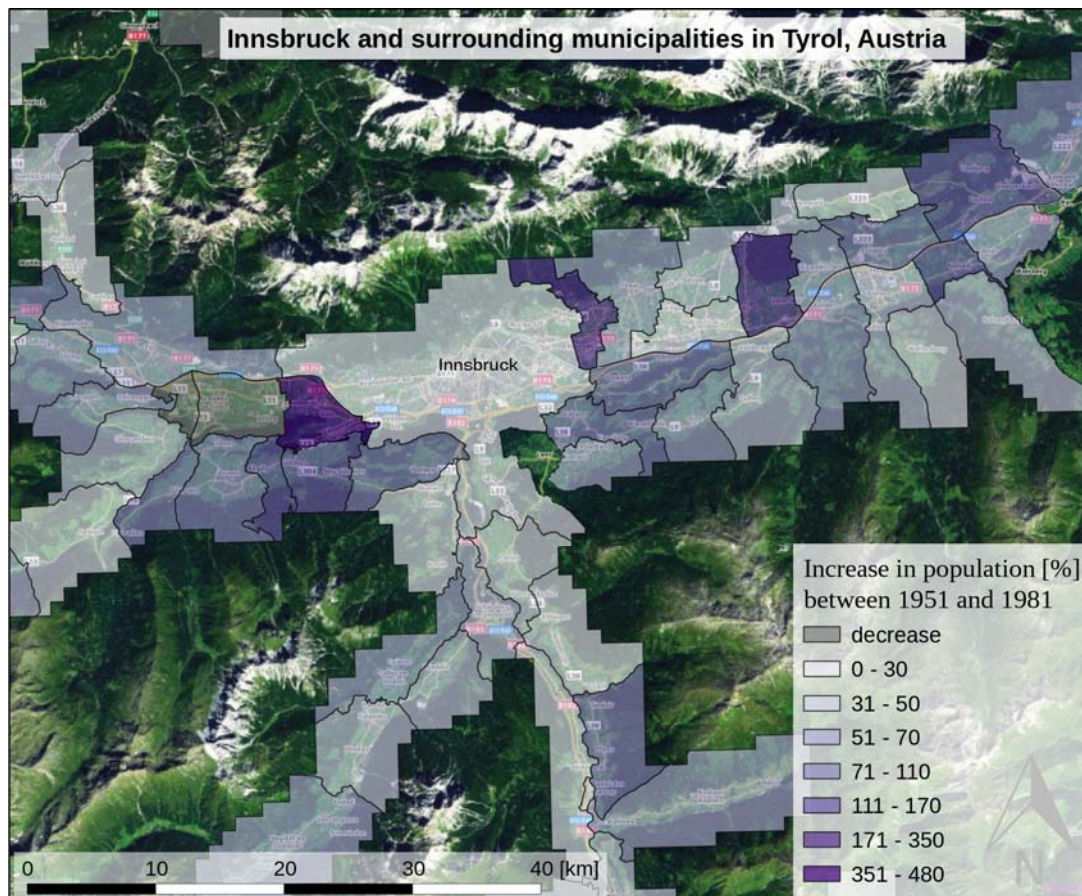


Figure 2: Increase in population in Tyrol between 1951 and 1981

2.2 Urbanization

Urban planning and development happens as a cyclic progress and has moved from a regulative approach towards an open approach with participation of the inhabitants, private companies and other stakeholders (Simpson & Chapman, 1999). Though: in reality focus while planning relies mainly on the given structure of parcels / buildings and on available and existing transportation network. Water infrastructure has to adapt to the newly given situations.

There are several urban development models available, however the choice was made for UrbanSim as it focuses on parcel based development and is free and open source software.

UrbanSim is an Open Platform for Urban Simulation (<http://urbansim.org>) which integrates numerous models to resemble an urban system on household level. Providing high quality input data and reasonable model coefficients is crucial to get viable results. Due to the extensive use (and need) of data (several GB even for a midsize city with 100k inhabitants) coupling of UrbanSim with a spatial enabled database management systems (eg. PostgreSQL with PostGIS) is recommended in order to handle the data and keep a desirable speed during simulation (Waddell, 2000; Waddell et al., 2003; Waddell and Borning, 2004). The models of the simulation include the transportation system, the labor market and real estate markets which are closely interacting and in a state of dynamic equilibrium. Maximum likelihood methods are used to estimate the parameters of the multinomial choice models (McFadden, 2001).

Currently a simplistic simulation for Innsbruck is developed to estimate city growth and dynamics on a parcel based level. Input data are the official urban development plan of the city of Innsbruck and population projections and prognoses from Statistics Austria. Placement of population and buildings as well as the calculation of impervious area are simulated into the future until 2050 to provide input data for the sewer system generation which feeds the hydrodynamic model and also the surface runoff model. (Sitzenfrei et al, 2010) Furthermore the existing road layout is used to place new water infrastructure, both centralized and decentralized according to the chosen scenario. As Mair et al. (2012) showed more than 80% of water infrastructure are situated below or beneath roads.

2.3 Climate Change

Climate Change, in addition to urbanization, states a challenge for city drainage due to changes in temperature, rainfall intensities, evaporation and snow-melt. (Kalnay and Cai, 2003; Mark et al., 2008; Frei et al., 2006). For the project DynAlp, climate projections from different regional climate models (RCMs) will be analyzed with a focus on extreme precipitation.

In RCMs cloud processes and precipitation are parameterized as the sub-grid scale processes cannot be resolved (Fowler et al., 2007b). This is known to be an important error source for model precipitation characteristics (Fowler et al., 2007a, Haerter et al., 2010). When regarding future extreme precipitation, the scale difference between climate model output and the necessary scales to adequately assess convective events is an obstacle for use in hydrological models. Statistical downscaling methods can be used to overcome this gap (Fowler et al., 2007a, Maraun et al., 2010). Bias correction methods can improve precipitation output of climate models but cannot replace an adequate representation of the physical processes (Haerter et al., 2010, Piani et al., 2009). Empirical statistical methods such as the analogue method, quantile mapping and local intensity downscaling have shown to be better capable of catching extremes compared to regression based downscaling approaches (Thermeßl et al., 2011).

Special challenges and difficulties result from an alpine environment with strong orographic effects (e.g. Schmidli et al., 2007). RCMs do not fully resolve the orographic structures. However, atmospheric processes such as convection and cloud formation are strongly affected by orography and spatial variability of temperature and precipitation is increased in alpine regions (Arnold et al., 2009, Thermeßl et al., 2011). As a result, uncertainties of future precipitation trends are usually high in alpine regions. Analysis of extreme precipitation trends in the European Alps using ensembles of RCMs has been done by Frei et al. (2006), Arnold et al. (2009) and Schmidli et al., 2007).

Results including uncertainty ranges give an estimate of the current knowledge, (including scenario uncertainties, accuracy of measurement data, parameterizations and feedbacks on regional and global scales). Uncertainty ranges can be compared to uncertainties in city development and in the occurrence of extreme events under present climate conditions. The uncertainty of extreme event occurrence is high also when neglecting climate change effects. If climate model trends are in the range of this uncertainty, possible statistical accumulations of extreme rainfall events in future decades have to be taken into account (e.g. DWD, 2005). If projected trends are beyond, this shows an increased need for flexible solutions in urban infrastructure.

An ensemble of new RCM runs with a grid size of 10kmx10km has recently been calculated for the Alps (Loibl et al., 2011). In the DynAlp project, this data should be used as basis for an empirical statistical downscaling procedure, similar to the procedure described by Jasper-Tönnies et al. (2012). First, a bias correction of model daily precipitation will be carried out, using grid-size data of precipitation measurements. Second, the bias-corrected daily sums will be used as predictor for a downscaling procedure, based on an analogue method. Historical analogues will be searched as matches for model days. Station data of the historical analogues from Innsbruck rain gauge stations will then be used to construct high resolution time series which can serve as input data for urban sewer simulations. An important task of the work package will be the evaluation of the applied bias correction and downscaling procedure regarding the effects on future trends and extreme precipitation events.

2.4 Performance Assessment

To estimate the consequences of urbanization and climate change it is necessary to generate a drainage network and to evaluate the system performance under changing conditions. To evaluate the impact of the above mentioned drivers to the urban drainage system the indicators are chosen from following categories:

- Pluvial flooding caused by capacity overload of different drainage technologies (indicators are based on e.g. sewer system performance, infiltration system performance)
- Pluvial flooding induced vulnerabilities and risks
- River water quality (pollution) caused by discharge to receiving water bodies

Performance assessment will be based on results of numerical computer models. The framework is linked to commonly used simulation models as SWMM for hydrodynamic simulation and CityDrain3 for integrated conceptual simulation (Burger et al., 2010; Rauch et al., 2002).

2.5 Dynamic Adaptation

Urbanization and Climate Change not only cause a change in the amount of water reaching urban drainage systems, but also a change in magnitude and a probable superposition of the water wave. Even if infiltration areas are created it is likely that saturation is reached more rapidly due to compacted soils. In storm runoff cases this might sever the situation. In contrast societal changes and changes in technology and regulations might result in a decreased water demand. (Booth and Jackson, 1997; Nuissl et al., 2009; Haase and Nuissl, 2007; Haase, 2009) This leads to a continuously adapted urban water infrastructure as boundary conditions change continuously. Dynamic adaptation in favor of build/rebuild-cycles of urban water infrastructure in densely populated areas plays a key role in a city to change from unsustainable forms of development to a sustainable one. This not only avoids unnecessary costly investments but also makes urban water systems adaptable as due to their long lifespan they are often unfit to address future challenges. (Urich et al., 2011; Ashley et al., 2005) Additionally the dynamics include the transition from centralized infrastructure to decentralized methods like infiltration of stormwater or cleansing waste water. (Bach et al., 2011).

The DynAlp project should assist decision makers to understand potential impacts of climate change, to identify important prospective points in system behaviour and to test different adaptation strategies to maintain or enhance current system performance in a changing environment. Those important points (see Figure 3) might be *failure points* – when the system fails to fulfil certain limits (e.g. required by technical guidelines) or *critical points* – when system performance starts to decrease rapidly with ongoing changes of the boundary conditions. A certain adaptation strategy can be chosen up to a *bifurcation point* – because later adaptation can no longer be achieved with the latter.

Figure 3 shows a schematic description of system performance over time for different (exemplary) adaptation strategies. To current state of knowledge it is expected that the development of an “adaptive adaptation”, which is continuously updated by increasing knowledge about climate change and urban development will lead to the most cost effective adaptation strategy.

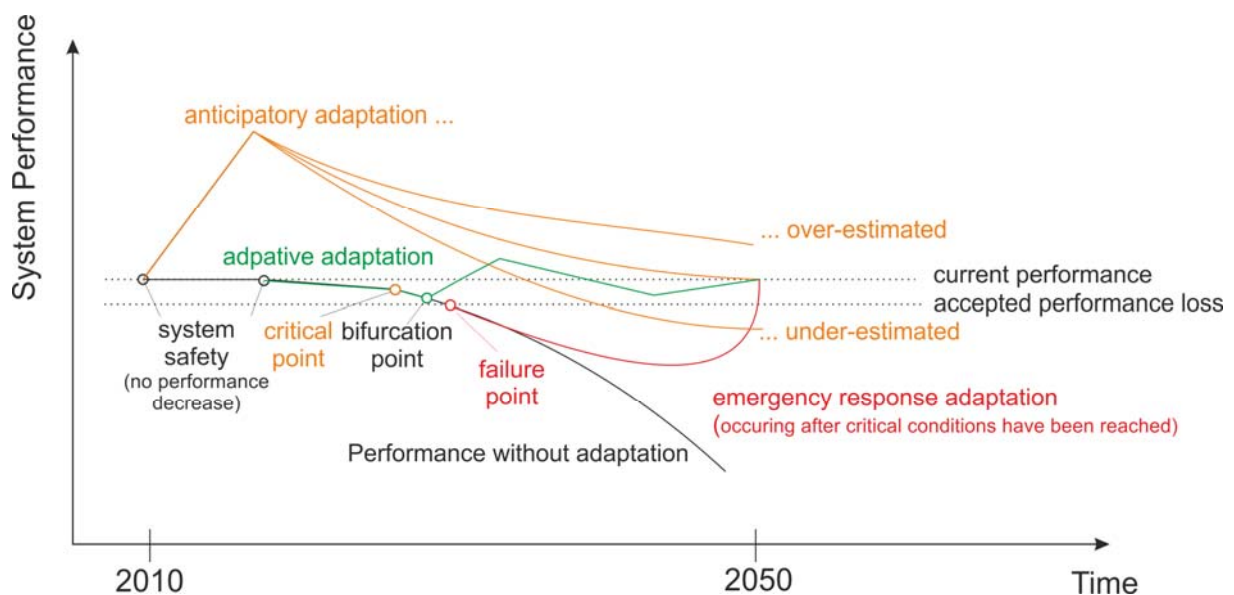


Figure 3: adaptive adaptation

3 RESULTS AND DISCUSSION

First results show that population data alone are not sufficient to describe the effects of city development on urban water infrastructure. Even if population within city limits remain stagnant, the land use per capita increases (increase of single person households) resulting in a change of flow characteristics in drainage systems. Thus, during extreme weather events the volume entering the combined sewer system will be larger than in previous situations. In the ongoing study areas with risk of pluvial flooding will be identified by means of hydrodynamic simulations.

Adaptation of urban water infrastructure to the increased demands can be achieved by fitting existing

systems, implementing new strategies or a combination of both.

Retrofitting existing systems would comprise measures such as increasing pipe diameters or storage volume. Alternatively, new strategies that could for example utilise separate sewer systems instead of combined systems could be implemented. Furthermore, existing systems and strategies can be combined with the alternative measures of stormwater infiltration, rainwater harvesting etc. (also referred to as WSUD - water sensitive urban design).

In order to evaluate adaptation strategies, the temporal aspect of their implementation is very important to answer the questions of when the implementation of a new technology should start and how fast the implementation should be expedited.

Figure 4 shows a hypothetical urban expansion on the premises of the Innsbruck airport which is situated only three kilometres west of the city centre (a currently unrealistic development scenario that is only used to test the framework). Generation of the street layout happens automatically according to population density. Connecting the new layout to the existing road network is manual work at the moment which will be replaced by an agent based or procedural approach in the near future. Although this scenario is not likely to happen in the near future it gives an insight on how urban development is carried out with the help of UrbanSim and other urban simulation software.

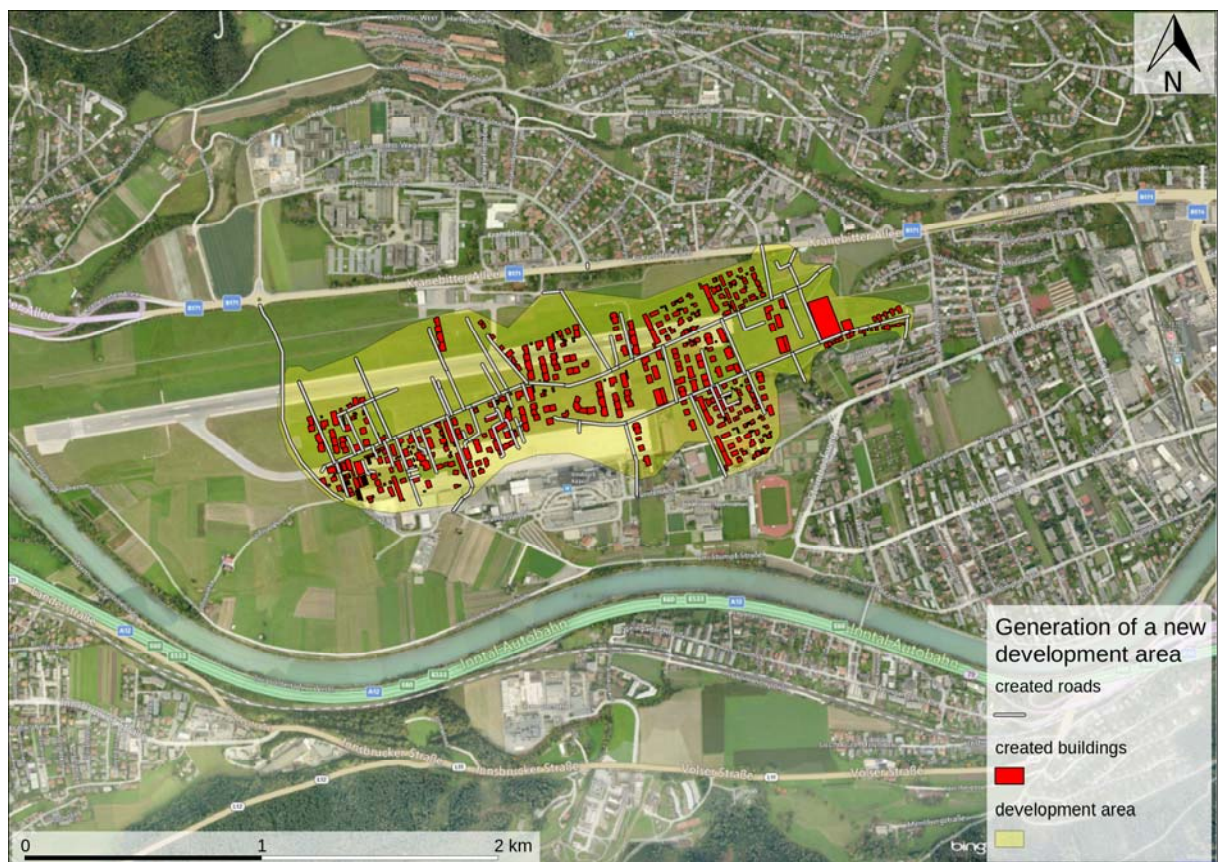


Figure 4: Possible city development on the area of the airport

4 SUMMARY AND OUTLOOK

This paper presents a framework for integrated planning of adaptation strategies in the DynAlp project. The novelty of this approach lies in an *integrated consideration of climate change and urban development* in a *dynamic temporal scale*. Adaptation strategies can be tested and evaluated in conjunction with changes of boundary conditions. All investigations will apply to Austrian (Alpine) conditions, characterised by cold winters and summers with intense rainfall. The impact of urban drainage systems on both society (e.g. impact of increased rainfall intensities on pluvial flooding) and environment will be addressed.

Main tasks of the project are:

- Assessment of climate change effects on heavy precipitation in the alpine environment, with focus on Innsbruck
- Assessment of city development scenarios
- Assessment of the impact of climate change effects on Austrian urban water infrastructure including the choice of appropriate performance indicators
- Development and application of appropriate vulnerability and risk analysis concepts
- Development, evaluation and comparison of adaptation strategies and technical guidelines for a changing environment
- Development of a modelling toolkit to integrate city development and climate change with its dynamics
- Visualization of model results (including uncertainty) for decision making

The aim is to produce a comprehensive climate change impact and adaptiveness assessment framework for urban infrastructure planning in alpine environments. This will account for the impact of city development and uncertainties at a temporally dynamic scale. The evaluation of adaptation strategies and its visualization for different target groups (e.g. the public, decision makers) can help to raise awareness and to build preventive adaptation measures.

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