The application of a Web-geographic information system for improving urban water cycle modelling

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ABSTRACT

Research in urban water management has experienced a transition from traditional model applications to modelling water cycles as an integrated part of urban areas. This includes the interlinking of models of many research areas (e.g. urban development, socio-economy, urban water management). The integration and simulation is realized in newly developed frameworks (e.g. DynaMind and OpenMI) and often assumes a high knowledge in programming. This work presents a Web based urban water management modelling platform which simplifies the setup and usage of complex integrated models. The platform is demonstrated with a small application example on a case study within the Alpine region. The used model is a DynaMind model benchmarking the impact of newly connected catchments on the flooding behaviour of an existing combined sewer system. As a result the workflow of the user within a Web browser is demonstrated and benchmark results are shown. The presented platform hides implementation specific aspects behind Web services based technologies such that the user can focus on his main aim, which is urban water management modelling and benchmarking. Moreover, this platform offers a centralized data management, automatic software updates and access to high performance computers accessible with desktop computers and mobile devices.

Key words | hydrodynamic sewer system simulations, online scenario simulation, urban water management modelling, Web processing services

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INTRODUCTION

In the last few years, research in urban water management has experienced a transition from traditional model applications to modelling water cycles as an integrated part of urban areas. The focus has been set on scenario based simulations for modelling alternative infrastructure systems (e.g. centralized vs. decentralized systems (Zhou *et al.* 2012; Sitzenfrei *et al.* 2013)), interactions with urban development (Willuweit & O'Sullivan 2013), transitions and socio-economic aspects (Bos *et al.* 2013; Ferguson *et al.* 2013). Mainly, population change and urban development, especially the connection of newly developed areas, put pressure on the urban water infrastructure (Semadeni-Davies *et al.* 2008; Mikovits *et al.* in press).

One of the projects dealing with these research questions is DAnCE for Water (Dynamic Adaptation for eNabling City Evolution for Water). The main aim of this project is research on adaptation of urban water infrastructures in response to a changing environment (Urich *et al.* 2013). Due to the high complexity of newly developed models and its interactions, a free available (licensed under the terms of the GNU general public licence) scientific workflow engine implemented in C++ called 'DynaMind' has been developed. It provides a platform for researchers and planners to combine urban water specific performance models, geographic information system (GIS) functionality, efficient data management and data visualization (Urich *et al.* 2012). The main strength of this framework is the ability to handle huge data sets in space and time. However setting up the framework is still a challenging task, especially for engineers who are not trained in programming. Going one step further, the next challenge is to provide end users (such as decision-makers, etc.) and

doi: 10.2166/wst.2014.327

model developers with an easy to use Web based service to apply and test their approaches and models.

For a comprehensive assessment of such complex and dynamic systems, conventional planning methods are successively replaced by dynamic models. Further, to increase their usability, these models are moved towards Web based applications (Dubois *et al.* 2013; Evangelidis *et al.* 2014). This enables a quick development of distributed, integrated, interoperating and complex models which need computer power beyond the capacity of standard desktop or laptop computers. Moving urban water management modelling towards Web service based technologies means also bringing high performance computing into the user's offices. Complex integrated urban water management modelling and simple user interactions can be brought together. User interaction, data storage, model setup and computational processing/model simulation does not happen necessarily on the same computing device. This allows a set up for customers, stakeholders and decision-makers to use complex models which are expected to interact with each other. Consequently the tool enables better evaluation of options leading to reduced costs and risks.

This paper presents the basic ideas and concepts of such a Web based urban water management modelling platform by using Web service based technologies. At the same time, this platform allows the cooperation of many user groups (e.g. model developer and decision-makers) within the same data set. A first approach of interlinking models and data handling by using Web service based technologies will be investigated and demonstrated with an application example applied on a case study within the Alpine region. As an example for a complex model, an existing DynaMind model (impact of new catchments on the flooding behaviour of a combined sewer system) is remotely executed via a Web browser or GIS software (e.g. ArcGis or QGis).

MATERIAL AND METHODS

Figure 1 shows the general concepts and ideas of the Web service based DynaMind platform. It consist of three main physical hardware components, which are: (1) client hardware (Figure 1 – lower left box), (2) a data server (Figure 1 – top left box), and (3) a Web processing service (WPS) server (Figure 1 – lower right box). The latter two may also be running on the same physical machine.

Data server

The data server (Figure 1 – top left box) is a GIS server which stores spatial referenced data. Many different

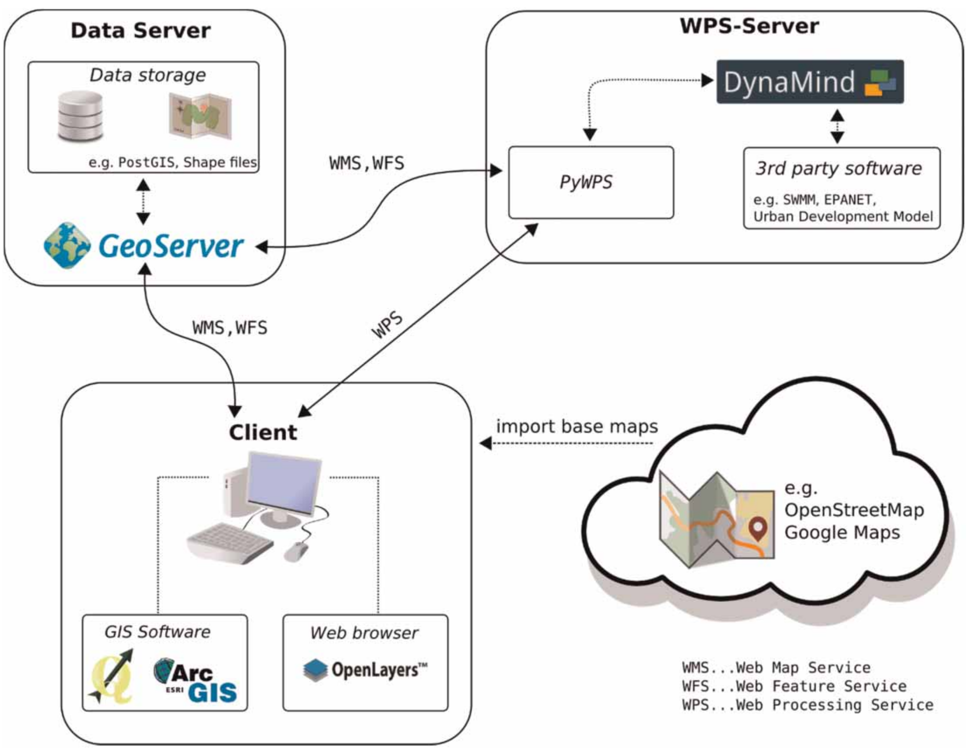

Figure 1 | General concept of the Web service based DynaMind platform.

techniques and storage formats are nowadays used e.g. PostGIS (data are stored in an object-relational database management system, such as PostgreSQL), Shapefiles (data are stored in a set of different files) or GeoTIFF files (an extension of the popular TIFF image format for storing georeferenced raster data). All these different storage formats can be seen as different data sources with the common goal to store spatial referenced vector and raster data. The development of all these formats happened over many years and also the development focus at each of them was slightly different. Consequently each format has its own access and modification routines. Hence, the development of applications which access many different data sources is time consuming. To overcome this problem, spatial data management environments were developed (e.g. GeoServer (Deoliveira 2008) or MapServer (Kropla 2005)) which are able to handle a huge set of different data sources and at the same time offering standardized protocols for accessing the stored raster and vector data. Such protocols are, e.g. Web map service (WMS) for raster data exchange and Web feature service (WFS) for vector data exchange. Data exchange between all three hardware components in the presented platform is realized with the standardized protocols developed by the Open Geospatial Consortium (Wenjue *et al.* 2004).

WPS server

The data stored at the data server and accessible with the standardized protocols can be modified by using WPS (Foerster & Stoter 2006). Which means the workflow for data manipulation can be defined by calling a single service or by cascading several services. The deployment of the services is realized with PyWPS (Schut & Whiteside 2007), which is a realization of the WPS 1.0.0 standard in the popular programming language Python. Data manipulation can now be implemented directly within this framework or by calling external programs. Under the scope of this work, data processing is realized by executing DynaMind models within PyWPS. Each model which is defined within the DynaMind framework can be seen as own WPS (Figure 1 – top right box).

Client

Due to the standardized exchange and manipulation of georeferenced data stored at the data server and manipulated at the WPS server respectively, the client can access the presented platform in two different ways: (1) by using a desktop GIS or (2) by using WPS, WMS, WFS capable frameworks (e.g. OpenLayers (Hazzard 2011)) within a Web browser. The latter technique is also known as Web-GIS where the client can be seen as data viewer and the major part of data manipulation is done at the WPS-server. This enables the usage of the whole platform for nearly any computing device that can run a Web browser.

Application example and proof of concept

The used application example in this work is a DynaMind model (Figure 3), which is callable via WPS using the PyWPS framework. The model simulates the impact of new catchments on the flooding behaviour of a combined sewer system by varying the catchment imperviousness of a new catchment and design storm events over the whole combined sewer system model. Therefore, the needed input is a polygon defining the new catchment area. This polygon/catchment can be manually drawn/specified by the user within a Web browser by using the OpenLayers framework and sent as argument within the WPS call to the DynaMind framework. Results of the model simulation are stored at the data server and can be accessed by the Web browser via the WFS.

Dynamind model

Figures 2 and 3 show the workflow of the used DynaMind model. The inputs are the user defined catchment area (e.g. new urban development area) represented as polygons and an existing or user defined combined sewer system model (e.g. stored at the WPS server or at a Web space which is accessible by the WPS server) which will be affected by the new catchments (Figure 3 – top white boxes).

In the first step of the model (Figure 3 – Step 1) the user defines a polygon (representing a new urban development area and therefore a new catchment – Figure 2(a)). This catchment is divided into several smaller polygons/subcatchments by normal distributing new inlet nodes within the polygon (Figure 2(b)) and creating a Voronoi diagram (Aurenhammer 1991) on the bases of these nodes (Figure 2(c)). Afterwards these new catchments are connected to the existing combined sewer system model (Figure 2(d)). Due to the splitting of the new urban development area into several subcatchments the runoff is distributed over several inlet nodes to the existing system. This prevents unrealistic flooding at single nodes due to a too coarse catchment representation. The result of these two steps is a new combined sewer system model which can further be

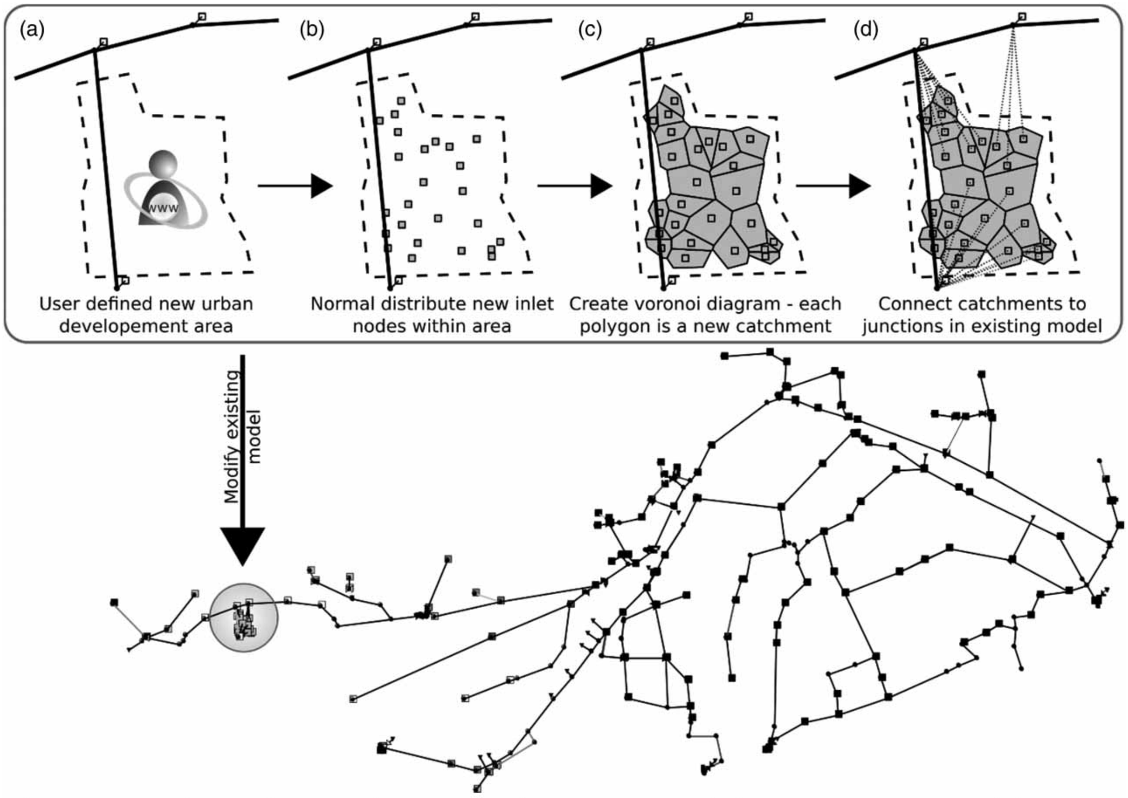

Figure 2 | Creating and connecting new catchments to an existing sewer system model.

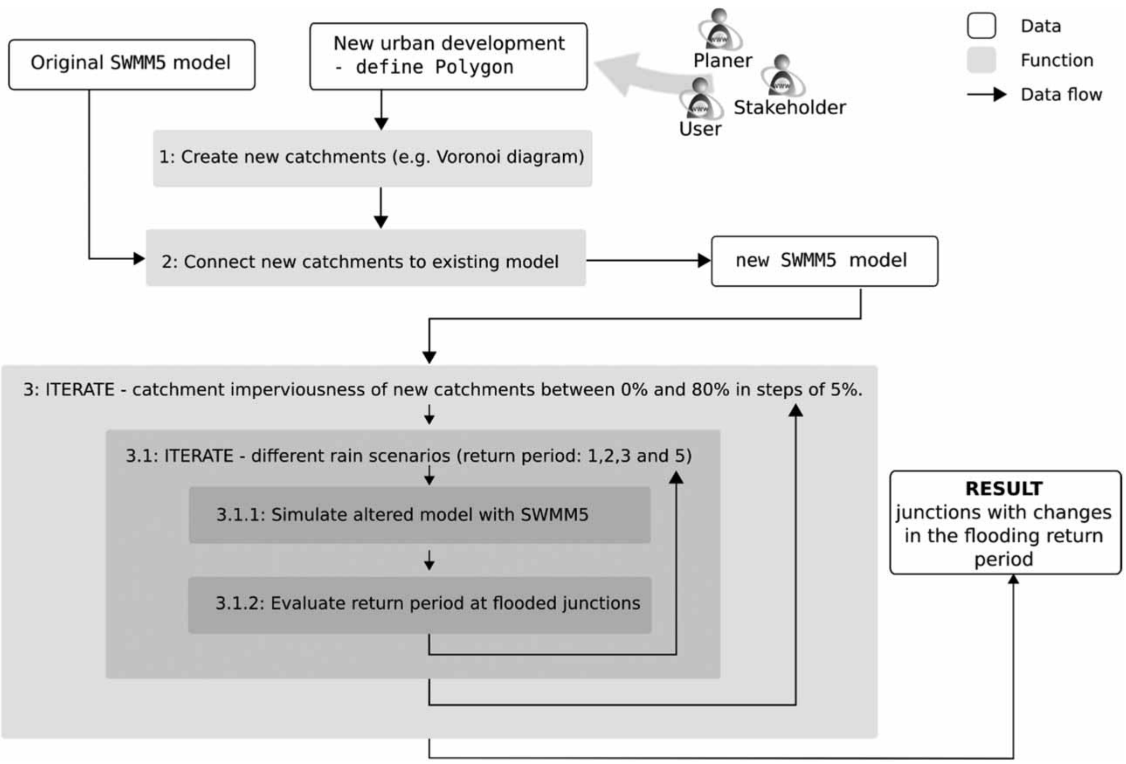

Figure 3 | DynaMind model of the application example.

analysed by varying model parameters and evaluating the results. For hydraulic performance assessment a parallelized version of the storm water management model (SWMM) software (Burger *et al.* 2014) is used. As benchmark procedure a one at a time parameter variation is used (Mair *et al.* 2012) in which the catchment imperviousness of the new catchments is varied between zero and 80 percent in steps of 5 percent (Figure 3 – Loop 3). As rainfall input and scenario variation, four different EULER II design storm events with a return period of one, two, three and five years are used (Kleidorfer *et al.* 2009) (Figure 3 – Loop 3.1). Each parameter variation defines a new combined sewer system model which will be simulated with all storm event scenarios. The simulation results are evaluated by investigating the flooding behaviour at each model junction (Figure 3 – Box 3.1.2).

First, all junctions where flooding occurs during the simulation period are extracted and afterwards the return period of the used design storm event within this simulation is mapped to that junction. If the catchment imperviousness for the new catchments is zero (First iteration of loop 3 – Figure 3), the resulting design storm events for the flooded nodes can be seen as initial value. All ongoing results are compared to these values and only stored if the return period for which flooding occurs decreases compared to the initial system. The result of the whole DynaMind simulation is a set of junctions showing a change in the flooding return period. Each junction has result parameters which are: old flooding return period, new flooding return period and the minimum catchment imperviousness of the new catchments which triggered the change in the flooding return period. This is a simple example to demonstrate the capabilities of the Web service based DynaMind platform. It can be used, e.g. by urban planners to assess the impact of a new development area on the sewer system performance. The advantage of this is that these user groups are not made responsible for data management, model building and maintenance. To get sound propositions about the system behavior a more detailed and accurate model (e.g. a coupled 1D/2D model for modelling conduit and surface flow, respectively) may be used in the future.

Case study

The whole platform is demonstrated on a small Alpine city with approximately 120,000 inhabitants. Storm water and sewage is discharged in a mainly gravity-driven and combined sewer system. The total catchment is 2,076 ha of which 774 ha are effective impervious area. For the whole case study a coarse combined sewer system model (SWMM5 model) is used. This model consists of 250 nodes 290 links and 182 subcatchments.

RESULTS

The developed platform is presented using a small case study in the Alpine region. Figure 4 shows a whole use case and workflow of the presented application example. The user/urban developer enters the presented platform via a Web browser (e.g. Firefox, Chrome or Internet Explorer) (Figure 4 – top screen shot). The platform includes an open street map as base map and therefore any investigation area can be presented on this platform. However, to benchmark an existing sewer system with new urban development areas the underlying sewer system model must exist. Currently, the platform supports one specific area which is the sewer system service area of the described case study, but it is easy to integrate new areas assuming all needed data are available. First, the user has to zoom to the area of interest (Figure 4(a)) where a change in land use is planned (e.g. new urban development area). As a next step (Figure 4(b)) a polygon can be drawn indicating this area. Now the benchmark can be started (Figure 4(c)). The data (user defined polygon) are sent to the WPS server and the DynaMind model starts. The subcatchments are automatically generated, connected to the existing combined sewer system model and simulated with the one at a time parameter variation method combined with all storm water event scenarios. Once all SWMM5 simulations are finished the results are sent back to the Web browser (client). The results in the demonstrated application example are geometric data of all conduits of the existing combined sewer system model, geometric data of the newly created catchments and a data set including all junctions where a change in the flooding behaviour occurred (Figure 4 – bottom screen shot). By moving the mouse pointer over a junction the results at this junction are shown in a message box. In this example the results show that the selected junction gets flooded when using a design storm event with a return period of three years (Figure 4 – result box – Old return period) during the simulation and no new catchments are connected to the system at the same time (catchment imperviousness is set to zero for all new catchments). This demonstrates the flooding behaviour of the initial system with no change in the input data. When connecting a new catchment (with fraction imperviousness 10%), the return period when flooding

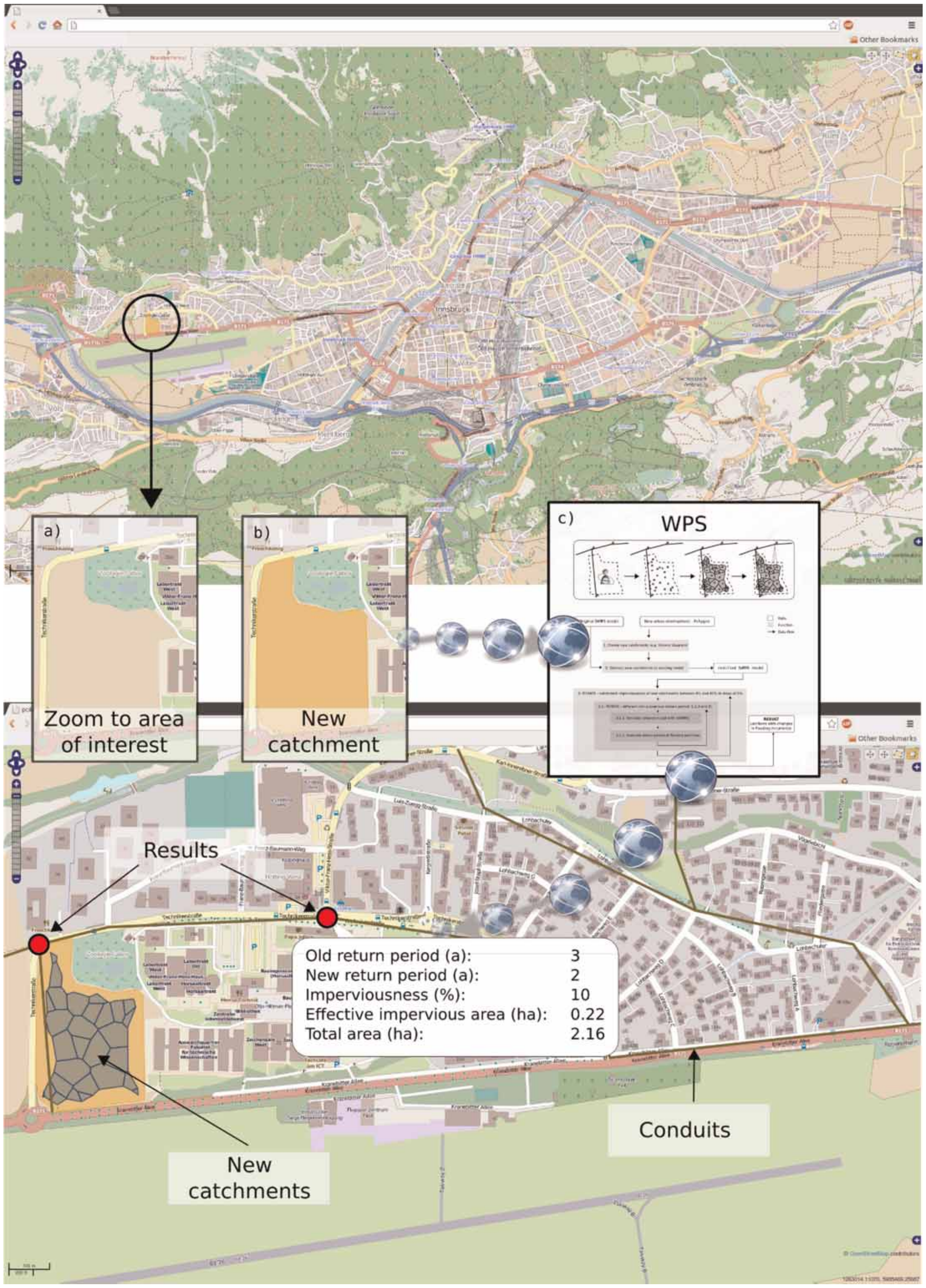

Figure 4 | Screen shots of the application example by executing a DynaMind model using WPS.

occurs changes from 3 to 2. This means that the development with a fraction imperviousness lower than 10% does not affect the flooding behaviour of the model. For higher values adaptation measures are required. In the same way, the impact of disconnection of impervious areas (e.g. when decentralized storm water management strategies are implemented) can be tested.

Figure 5 demonstrates a use-case for decentralized urban water management like water sensitive urban design (WSUD or low impact development (Bach *et al.* 2013a, b). Using the same platform stakeholders, urban planners or property owners can design, e.g. infiltration measures via the Web. Therefore, they can mark the surface, which generates runoff (e.g. roof area), and an area available for the

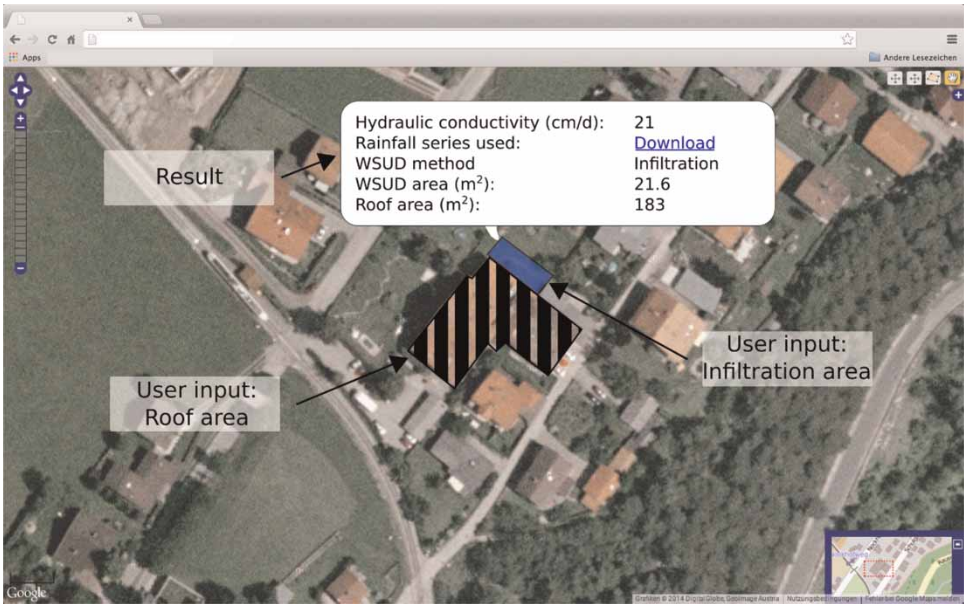

Figure 5 | Water sensitive urban design – Web based WSUD planning tool.

treatment facility (e.g. infiltration area) in their Web browser. In the background, the model identifies the nearest point for which rainfall data are available (stored on the data-server), evaluates soil characteristics (also available on the data-server) and designs the infiltration facility, e.g. the infiltration trench by determining minimum required storage volume.

DISCUSSION AND CONCLUSION

In this manuscript a prototype of a new Web based urban water management modelling platform is presented. Due to the high complexity of newly developed urban water management models and therefore the need of programming skills, this platform demonstrates an approach to simplifying the usage of these models by using Web GIS technologies. At the same time, implementation specific aspects are hidden and kept away from the user, so that they can focus on their main aim. The basic components of the platform are a client (e.g. Desktop GIS or Web browser), a data server and a Web processing service server (WPS server). Complex models (e.g. DynaMind models) are hidden behind the WPS server.

To demonstrate the platform, an application example was set up as proof of concept. The application includes a DynaMind model which represents a benchmark for the flooding behaviour of existing sewer systems when connecting new catchments to the systems. The application was demonstrated on a case study within the Alpine region, where a coarse combined sewer system model (SWMM5 model) exists. The user has to define a polygon (new catchment area/new urban development area) within a Web browser. Once the benchmark has finished, junctions with a change in the flooding return period are presented within the Web browser.

The current state of this platform is a prototype for demonstrating the idea and to prove the general concept of a Web based urban water management modelling platform. Currently, many limitations exist due to the fact that the platform is a prototype (e.g. user access control, simultaneous model simulations, calibration and validation of models) and therefore a huge amount of development and implementation work has to be done. However, we think the investigated concept does not change when implementing new features. For example access control for various users within different domains can be implemented within the GeoServer, simultaneous model simulations or long time simulations of complex models can be sourced out to well-known grid/cloud computing platforms such as Amazon cloud where the WPS server acts as a master node to guarantee the scalability of the whole platform for many users. However, one key question in integrated urban water management modelling (e.g. integrated model containing a sewer, water supply and socio-economic model) is: how can we calibrate and validate such complex models (Voinov & Shugart 2013; Bach *et al.* 2014)? Research on this topic is evolving in new directions, such as exploratory modeling and robust decision-making (e.g. Urich & Rauch (submitted)). The virtue of the presented platform is that these novel approaches are supported as well as traditional concepts.

Concluding, a Web based urban water management modelling platform can simplify the usage of complex models. This enables a group of users (e.g. stakeholders or decision-makers) with minor programming skills (needed for setting up and creating such models) to benefit from complex and interlinked model simulations.

ACKNOWLEDGEMENT

This work was funded by the *Austrian Science Fund* (FWF) in the project *DynaVIBe* P23250, by the Austrian Climate and Energy Fund as part of the Austrian Climate Research Program in the project *DynAlp* KR11AC0K00206 and by the Australian Government's 'Cooperative Research Centre for Water Sensitive Cities'. As part of this program, it will contribute to the development of an explorative computational strategic planning tool, DAnCE4Water (Dynamic Adaptation for eNabling City Evolution for Water). The authors gratefully acknowledge the financial support.

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First received 28 February 2014; accepted in revised form 8 July 2014. Available online 4 August 2014