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A Visual-Scenario-Based Environmental Analysis Approach to the Model-Based Management of Water Extremes in Urban Regions

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Abstract

Due to the present climate crisis, the increasing frequency of the water extreme events around urban regions in river basins may result in drastic losses. One of the most effective preventive measures is a prior analysis of the eventual effects to comprehend the future risks of such water extremes. As well as analysis of historical impacts, the model-based management of water extremes have also a crucial role. Therefore, we present a 3-dimensional visual-scenario-based environmental analysis framework by utilising a Virtual Geographic Environment for the visualisation and the exploration of model-based management of hydrological events in urban regions. Within the study, we focused on the City of Dresden in eastern Germany located in the basin of the Elbe River. We integrated a large set of historical observation data and the results of numerical simulations to explore the consequences of modelled heavy precipitation events within different scenarios. Utilising a framework developed in Unity, the resulting visualisation of different scenarios dealing with water extremes simulated with coupled numerical models constitute the overall focus of this particular study. The resulting application is intended as a collaboration platform in terms of the knowledge transfer among domain scientists, stakeholders and the interested public.

CCS Concepts

• ***Computing methodologies*** → *Virtual reality;* • ***Information systems*** → *Geographic information systems;*

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1. Introduction

During the last two decades, the climate crisis has become more and more apparent in everyday life. An increasing number of short and long term water extreme events [FK15, BFC*20, HCH*20] threatens lives in urban regions more frequently than in previous years [AG14, BAB*18]. Besides the economic damage these events are causing, they also have a much deeper long-term socioeconomic impact within the population living around the disaster zones [TPR94, BBNLGLM14]. Throughout Europe the number of flood events has increased tremendously during the past 150 years as well as the number of people affected and the total economic loss has increased significantly [PSMNJ18]. One of the most recent flooding events, the Ahr Valley disaster in July 2021, has caused at least 184 deaths. As such, it is by far the deadliest flooding event in the past 60 years in Germany. It is also roughly estimated that the damage costs to Germany amount to more than €30 billion Euro. In contrast, floods of the Elbe River are occurring reasonably often. Nevertheless, severe flooding events of the Elbe river are also causing a lot of damage in cities such as Dresden, due to the fact that the city is located within the rift valley of the Dresden basin [SKE*15]. The floods in 2002 and 2013, with levels of 940 cm and 877 cm respectively, were two of the three record-breaking water levels of the entire measurement history of the Elbe river in Dresden [TKK*16], resulting in fatalities and the evacuation of tens of thousands of people [US05, KDU*14]. On the other hand, the prolonged drought seasons and increased water shortages within the last a few decades around the rivers of the region may create even higher risks for the inhabitants [BRZ20]. Although the short-term consequences are less observable, the frequency increase of low water periods may potentially result in shortages of the fresh water supply. The observation and analysis of the water cycle and the estimation of future risks in terms of preventing possible upcoming disasters has become more crucial nowadays for the entire region.

The prospective future risk analysis and possible disaster estimation in urban regions due to water extremes requires a collaborative involvement of broad working groups with a similar focus. The historical observation data examination of the region and models for the simulation of water extremes are highly relevant research top-

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ics for domain scientists. We present a set of such studies, including observation data-set collection, analysis of the relationship between data-sets, creating numerical simulations based on such data, and the development of a model-based coupled approach. In addition, we are going to focus on the visualisation of the various environmental compartments in the scope of this article. The goal of the study is to provide a scenario-based 3D visual environmental application that enables domain scientists to explore the relevant data for this region and reach out to stakeholders and interested public groups with their developed model results, predicting the risk of future causalities and damages as well as precautions to prevent such disasters. Therefore, driven by the aforementioned target within this particular study, we present a concept for urban water management focusing on hydraulic interaction in the subsurface. A number of hydronumerical models based on a digital urban model have been created with open data and free software as well as coupled using unified interfaces correspondingly.

Section 2 briefly discusses previous studies about the current techniques for the visualisation of environmental data collections and simulations making use of Virtual Geographic Environments and Environmental Information Systems in terms of urban areas and hydrological extremes. Preparation, processing and integration phases of the data-sets used throughout the study are detailed and presented in Section 3. Numerical simulations and constructed models based on different water extreme scenarios and their results as well as their integration to the visualisation application is discussed in Section 4. The resulting application and visual composition of both observation data and the simulation results based on a predefined storyline is elaborated in Section 5. Section 6 gives the conclusions of the overall study and briefly discusses future work.

2. Related Work

The popularity of the scenario-based 3D applications in environmental management is growing due to the visual impact of representing the results of the studies, in particular in urban regions. Traditionally, the prevalent way of presenting environmental science studies is making use of the Geographic Information System (GIS) [PG19, KAR13]. Although GIS are very powerful tools for representing geographically referenced spatial observation data and visualising the results of experiments, their 2D-based visual techniques and the lack of immersive storytelling and capabilities to present the results of numerical simulations is a drawback compared to 3D visualisation software to analyse and present environmental studies. Virtual Geographic Environments (VGEs) [Ell94,Bat97] have become a new generation of geographic analysis tools by integrating the 3D visualisation features into the GIS application capabilities [Bat08, Yin10]. By including numerical models and components to visualise homogeneous data in 3D environments, Lin et al. presented a number of studies which are basically 3D extension of the GIS applications [LCL*13].

For this particular study, rather than just the integration of heterogeneous environmental data, it is more significant to create a platform for data presentation, demonstration of simulation results of the environmental model and the portrayal of the effects of extreme events. This leads to two main challenges: the construction of a VGE for the visualisation of urban regions in terms of urban effect analysis, and the establishment of a system for the representation of simulation results alongside measured data integration within the same geographic context. Numerical models and simulations considering the water behaviours [KBB*12, KSA13] and visualisation methods of water-related extreme events [LYZ*15, GFW17, RCB*18] within VGEs are also two different sets of relevant studies throughout the historical development of the 3D urban effect analysis approach. Zhu et al. is offering different modelling paradigms of 3D city models into a VGE [ZHZD09]. In a 2013 study, Huang et al. present a visualisation approach for complex geologic environments based on VGEs [HCC*13]. An urban modelling and simulation platform covering the model integration and multi-type visualisations in a VGE with collaborative analysis on pollution profiles use case has been proposed by Lin et al. [LXC*22]. On the other hand, Rink et al. proposed an environmental information system that allows exploration of multiple heterogeneous data-sets in Urban regions, supporting the animation of observation data or simulation results to display changes in the environment [RcS*22]. Wang et al. applied a similar visualisation approach to demonstrate a flood event in an urban region in terms of water extreme for the assessment of flood risk management in sponge cities [WHM*19]. In another 2022 study, Rink et al. propose a framework for the 3D exploration of heterogeneous environmental data for visual scenario analysis of Hydro-Meteorological Extremes [RcH*22]. There are also two scenario-based approaches of Cornel et al. in the similar domain. A 2015 study [CKS*15] aimed to create a flood hazard management tool to visualise the object-centered vulnerability among a pre-simulated flooding event scenario pool. In another study in 2020 the authors focused on a scenario-based decision support system utilising a game engine to establish a real-time simulation tool for a storm water management system [CBKW20]. Both studies are embedded in the geographic context of a predefined region of interest and have the characteristics of a VGE even that precise term is not explicitly used.

The application proposed in this study includes an environmental analysis platform around a virtual geographic environment that presents a concept for urban water management through the integration of hydronumerical models, providing a visual storyline of the impacts of different water extreme scenarios in the examined urban area, so that domain scientists can visualise and evaluate the results of developed management models.

3. Data Preprocessing & Integration

Dresden, the capital city of Free State of Saxony with the population of more than 560,000 inhabitants, is the second-largest city located in the Elbe basin after Hamburg in terms of population. The topographic characteristic of the city of Dresden is different from other cities in the same basin as it is located within a narrow valley in a relatively mountainous terrain. Dresden is one of the cities having the largest flood risk in the Elbe Catchment [Sch05] since the Elbe river starts to overflow its increased volumetric mass around this region due to the heavy precipitation occurring upstream and in its regional catchment.

Figure 1: ***Left:*** *Aerial view of the Laubegast, a district of Dresden, Germany, during the 2013 flood event [Pet13].* ***Centre:*** *a model of the same region from a similar viewpoint in our Virtual Geographic Environment using high-resolution aerial imagery as texture.* ***Right:*** *The same model with landuse data texture applied.*

3.1. Topographic Frame of Reference

The first step of building a visualisation platform for the collaboration between researchers and the regional stakeholders in terms of environmental exploration and analysis is that the unique topographic characteristic of the study region should be properly visualised in 3D employing a VGE. A VGE, by extending a geographic information context, enables the visualisation of georeferenced environmental data and numerical simulations interactively in a 3D application in an immersive way. Therefore, the geographic 3D representation of the topographic frame of reference is to be generated from the digital elevation model (DEM) of the region of interest. This task is straightforward as the required data can be geographically referenced via transformations using GIS software; in this particular study, we are using the UTM zone 33N projection (EPSG:25833) for all data-sets with the help of the QGIS. [QGI09] A vector data-set representing the boundary of the City of Dresden covering 328.8 km^2 has been obtained from the open access geographic environmental data libraries of the state of Saxony [Lan22]. After tessellating the georeferenced boundary, a digital elevation model of the City of Dresden has been used to create a triangulated 3D digital surface data. We employed DGM1 data, a 1 m resolution digital elevation model of the region of interest [Lan15] to add elevation information to the tessellated flat surface using the OpenGeoSys Data Explorer [RBK14] and thus received a highly detailed surface mesh consisting of over 1.2 million triangles with a 30 m resolution representing the topographic region. The raster aerial imagery of a rectangular area covering the area of the city in 25 m resolution having an image size of 8192 × 8192 pixels has been obtained from Google Earth (©2023 GeoBasis-DE/BKG (©2009), Google), has also been projected into EPSG:25833 coordinate reference system using QGIS. Then, this georeferenced raster image was used as a high-resolution texture to the previously generated surface mesh by specifying its texture coordinate properties.

3.2. Urban Infrastructures

A meaningful representation of the urban region is the main focus of this study, focusing on both risk analysis and visualisation of the urban interest locations and landmarks for easy recognition. With more than 560,000 residents, incorporation of the overly populated dense housing data into the pre-constructed VGE is challenging. We are incorporating CityGML [Con12] open access model data of the City of Dresden [Lan05]. The data-set is subdivided into $2\,km \times 2\,km$ blocks and is available in two levels of detail. The Level-of-Detail 2 (LoD2) data-set integrated in the VGE is consisting of a total of 11 predefined separate building constructions whose structural entities are properly semantically identified.

A script-base data importer [Jae18] has been employed to create triangulated polygons from corresponding defined locations of each infrastructure element in the CityGML data-set file for import into the VGE. Predefined semantic entities have been then used in the VGE to create different materials so that wall, roof and ground sections of the building could easily be visualised in different colours to be divergently perceived. In total, 26 blocks of most populated and salient areas of urban infrastructure data of Dresden have been integrated into the VGE, consisting of over 2.3 million triangles. (see Fig. 1, centre) We have made some adjustments to the VGE urban data importer such that the number of polygons have been merged within their respective $2\,km \times 2\,km$ blocks instead of creating individual building objects, as hundreds of thousands of virtual objects would cause a dramatic runtime performance drop. Keeping semantic entities to construct sub-meshes of a defined block region still allowed to visualise structural sections of buildings with distinctive materials.

3.3. Landuse Data

Besides the aforementioned topographic data, hydrologic and hydraulic models require various additional input data sources such as soil infiltration, evapotranspiration or surface roughness. Whereas some may be directly available for our study area, many data attributes need to be derived from other map data. Therefore, publicly available landuse (B-DLM) and biotype (BTNLK) data [Lan14, Sä05] was processed. The Basis-DLM consisting of multiple categories of buildings, water bodies, urban infrastructures and simplified vegetation was extended with detailed vegetation from the BTNLK and afterwards clipped, merged and dissolved with the street-, pathway- and general transport infrastructure. In the next step we further aggregated multiple redundant landuse classes, leading to 15 distinct types. For visualisation purposes, a QGIS QML file was created to map the landuse classes to a relatable color scheme. Finally the landuse vector data was rasterised using the provided color scheme and stored as GeoTIFF for later texturing purposes (see Fig. 1, right).

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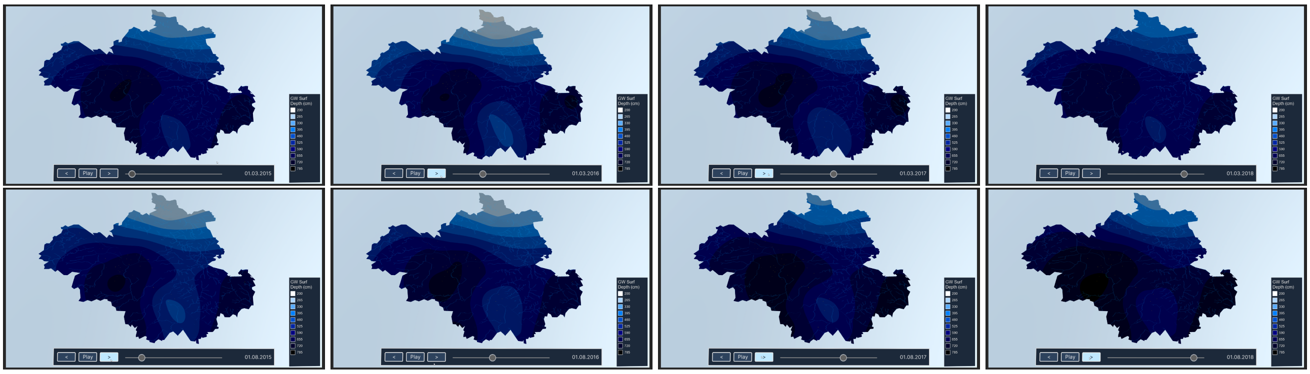

Figure 2: *Yearly change of the depth of groundwater head of Dresden. Every March (top row) and every August (bottom row) from 2015 to 2018.*

3.4. Groundwater Data

Field researches indicate that fluctuations of the present groundwater levels and the groundwater flow as well as the saturation of the geological layers have also a crucial impact on the surface hydrological anomalies and consecutive flood events. [MRCDB18, MNM*21, NFMCPPM19] Therefore, acquisition of reliable historic groundwater level observation data and the integration of this data into the VGE for the analysis of groundwater/surface water relationship is substantial. The groundwater level measurement data of the Free State of Saxony [Sä15] itself is stored within a large database that consists of station-attributes such as locations of groundwater observation stations and the depth of observation wells along with some periodic measurement attributes like elevation of the groundwater head above the sea level and the depth of the groundwater head beneath the surface. The database provides the daily groundwater measurements of all the observation sites until 2019, with varying measurement frequencies.

The representation of this complex data in 3-dimensional space in a VGE requires considerable processing of the data. The first step was the reduction of the data to the regional context. Thus, we have created a shape file out of this database, converting a list of all the historic measurements in a CSV-file into georeferenced location markers to display within QGIS. Then, we have cropped this data regionally around a rectangular bounding box somewhat larger than the topographic frame of the city of Dresden to create a database of groundwater measurement of the region. We have applied a query based database filter to gather all the monthly measurements between 2015 and 2018 to analyse the seasonal fluctuations within this four-year time frame. This specific time frame has been chosen both because data was available for a large number of stations in regular intervals and because more recent data has a larger relevance for predictions into the future. Due to the slow changes to water levels, the data has been further reduced to consistent monthly measurements across all observation sites over the selected four-year frame. This resulted in a data-set to demonstrate the monthly fluctuations of groundwater levels in 48 time-steps. To construct a spatial 3D animation of that data, we first have sliced the filtered data regarding their measurement dates and created 48 sets of groundwater measurement data of all the stations around Dresden. Then we spatially interpolated using the kriging method [OW90, WW03, Wil21] to create 2D raster data of interpolated groundwater levels for every time-step. These extracted raster data of groundwater levels beneath the surface have then been used to map 3D surfaces out of the interpolated raster files. That way, we procured 48 surfaces of the groundwater location throughout Dresden for the 48 monthly points in time. Discussions with hydrologists revealed that besides the groundwater head, the depth attribute of the groundwater level beneath the surface was of particular interest to them. Therefore we used this data for texturing the resulting surface with a depth based colour map which allows the inference of two different attributes at the same time from the same data representation(see Fig. 2).

4. Modelling & Simulations

In addition to the integration of environmental data into the VGE, the visualisation of numerical simulation results for water management scenarios is essential. Particularly, how heavy precipitation events and the surface topography will affect efficient storm water management is one key attribute that needed to be evaluated. Besides being one of the severely affected districts in previous floods, Lockwitzbach district in southeastern Dresden is a well-suited study region for water management. This area consists of hilly and valley-shaped topographic formations as well as natural streams and headwaters of Elbe, alongside well-connected storm water systems. The topographic virtual surface of the Lockwitzbach area is also generated by the same aforementioned surface generation method at 20m resolution and integrated into the VGE. In regard to urban water extremes, we focused on heavy precipitation events and investigated a number of related hydraulic processes, in particular surface-, sewage-, and groundwater flow.

4.1. Surface Runoff Model

The initial stage of the coupled hydraulic simulations is a surface runoff model driven by heavy precipitation events. Since a high-performance computational core was required for running large-scale 2D hydro-numerical models, we chose to use the BASEMENT software tools [VPV*21], as they offer a fast, CUDA-based solver and provide easy to automate model interfaces. A computational triangle mesh was created using BASEmesh, utilising the DEM with 1-metre resolution and breaklines derived from our landuse data. The mesh consists of ca. 3 mio cells, ranging from $3\,m^2$ to $50\,m^2$, for a total of roughly $35\,km^2$. Several preprocessing steps are automatically performed on the base model, refining it with additional per-cell data such as surface roughness (manning) and precipitation-runoff transformations taking infiltration and transpiration into account. The created surface runoff model uses Euler II [DWA06] design storms as a boundary condition for precipitation input, which were generated using the LARS-WG stochastic weather generator [SBLW02]. The design storm projections were conducted for two future periods: near future 2041-2060 and far-future 2081-2100. Using the random Bartlett Lewis model [RICI88], the disaggregation of global circulation models (GCMs) precipitation data into a finer resolution (5 min data) was performed according to the approach proposed by Kossieris et al. [KMOK18]. After running a heavy precipitation simulation, results include water depth, flow velocity and specific discharge per computational cell for an adjustable time step (default: five minutes) as shown in Fig. 3.

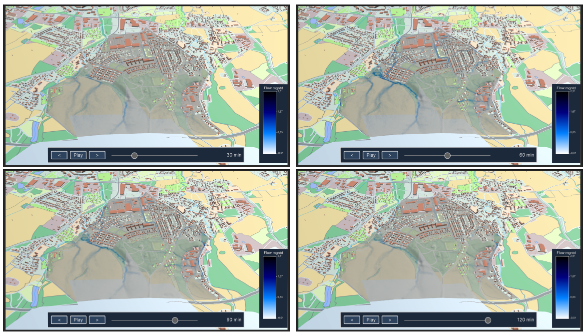

Figure 3: *Simulation of 120 minutes of surface runoff during a heavy precipitation in the modeled area. Time-steps are 30 minutes apart from left to right.*

4.2. Sewer System Runoff Model

A hydrodynamic sewer system model is developed for the United States Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM) [Ros15]. The software can model rainfall-runoff processes and introduction of runoff into sewer systems, as well as the hydraulics of the sewer system and other components of wastewater and storm-water infrastructure. The drainage management company Stadtentwässerung Dresden provided the data for the sewer system network and infrastructure. Using this data in combination with land use data, a DEM, and hydrological data derived from the DEM, a SWMM model has been developed with the tool GistoSWMM5 [WNT*17]. Moreover, the model is coupled to a groundwater (GW) model and a surface flow model. Using Python [VRD09], and the package swmm-api [Pic22], the model will be updated at every time step of the simulation as in Fig. 4.

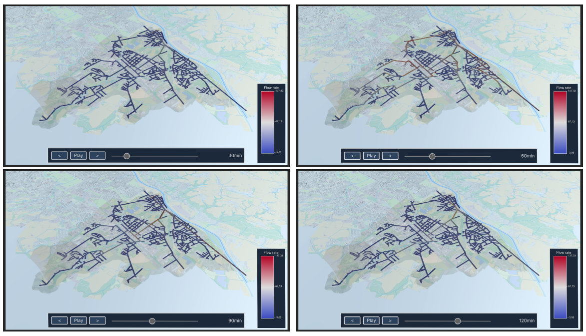

Figure 4: *Simulation of 120 minutes of sewage runoff during a heavy precipitation in the larger modeled area in Lockwitzbach. Time-steps are 30 minutes apart from left to right.*

4.3. Groundwater Model

For groundwater flow demonstration in the Lockwitzbach area we used a simplified quasi steady-state model by using the open-source multi-physics, finite-elements software OpenGeoSys (OGS) [KBB*12, BFK*19]. The simulation domain is represented as a 2D model of the catchment discretised with 66,721 grid points for numerical accuracy. The groundwater is driven by boundary conditions in the West and the river Elbe in the East which are based on measured data (see Fig. 2). Additionally, a part of the sewer network is included into the model in order to mimic infiltration/exfiltration scenarios depending on groundwater level fluctuations. All boundaries are assigned by time-dependent Dirichlet type conditions based on measured historical data [Sä15]. Technically, all boundary conditions have been assigned via OGS's Python-functionality which allows for setting specific value of the groundwater levels for all related nodes at outer and inner boundaries for each time step. The simulation time is almost four years (47.5 months) with half-monthly time step size resulting in total of 95 time steps. The numerical simulation shows the temporal evolution of the groundwater surface and Darcy velocity distribution in the Lockwitzbach catchment during the simulated time period of almost 4 years (see Fig. 5). As mentioned above, the groundwater model is highly simplified and intended for demonstration purposes to visualise potential differences between observed and simulated groundwater regimes, e.g. for efficient model optimisation and uncertainty analysis.

4.4. Staggered Coupled Models and Simulation

Each of the three models is able to be run standalone. To further improve the quality of the results, it was chosen to couple the spatiotemporally varying models using a staggered approach. Therefore, we implemented a Python framework to discretise the three input simulations, automatically generate new models and run the simulations in parallel. The frameworks consists of a preprocessing and coupling stage, primary model-generation and simulation loop and finally a preprocessing stage. At the beginning of each loop iteration, results from the previous iteration are processed and exchanged with the other simulations as boundary conditions. To achieve better performance, e.g. for mapping structural elements from one model to another, we use acceleration data structures such as KD-trees. Overall coupled processes include: inflow from the surface into manholes and gullys, outflow from sewage system to the surface, surface to groundwater infiltration, infiltration of groundwater into the sewage system and exfiltration from the groundwater depending on the groundwater level.

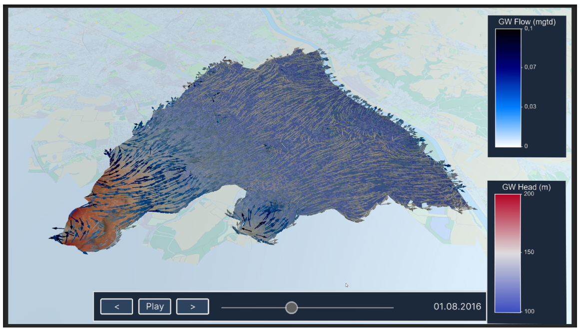

Figure 5: *Simulation of groundwater levels and flow velocities influenced by precipitations in the long term. The infiltration and the exfiltration by the sewage system is also taken into account.*

5. Visualisation

Establishment of a proper visual-scenario-based VGE for the analysis of the environmental impact analysis with different compartments is an extensive collaborative work. Usage of a GIS application for this purpose is insufficient due to lack of immersion and 3D perception. Therefore, we are utilising a 3D graphics engine as well as a game engine for building a VGE for the environmental impact analysis. Besides their 3D mesh data integration capabilities, creating a visual storyline out of a predefined scenario defining the demonstration of salient data-sets and simulation results is straightforward. In this regard, a framework to build a VGE for the visual demonstration of environmental data using the Unity Game Engine [Uni20] has been proposed for previous case studies [RNZ*20, RcH*22, RcS*22]. The framework proposes a wide range of toolkits to import a variety of environmental data-sets from various sources and representation of these data-sets, to define visual characteristics and visibility properties of imported data-sets, to create a storyline by some presentation-specific features and to interact with the properties and runtime parameters of the data.

The aforementioned framework has been extended to construct a proper VGE representing urban infrastructures. The urban infrastructure data blocks provided from the Free State of Saxony [Lan05] have been gathered to cover the region of interest around the City of Dresden. Then, this CityGML data has been transferred to Unity as 3D polygons by the utilisation of a CityGML import module for Unity [Jae18]. This module is able to process the CityGML file and it is capable of generating georeferenced polygons from all defined attributes in the file and grouping them according to the building they belong to. However, importing a combined infrastructure data of such a large region has caused some performance issues while running the VGE. Therefore, the module has been extended to create a single merged mesh out of the imported block of region from the urban data. The semantic entities that define the structural fragments of a building have been formed together to create a sub-mesh so that they could be used to assign a separate material which allows to visually identify the building's sections with different colours. The framework has been enhanced and diversified to meet the requirements of both visualisation of urban infrastructure and hydrological data-sets in terms of user interface builders and viewpoint management systems as well as data-set visualisation shaders. To integrate both static and time-varying 3D data-sets with varying spatial and temporal resolutions, the capacity of the data import and integration module of the presented framework [RNZ*20, RcH*22, RcS*22] has been upgraded to support a variety of previously unsupported data-types such as high-resolution 3D urban models. In addition, the surface and line-mesh renderers have been improved to accurately visualise the water-body accumulation and sewage runoff simulations. There have also been some improvements in the storyline configuration manager, the viewpoint interpolator and the visual settings manager of data presentation layer along with some enhancements of time-series data animation interfaces, lighting settings and vertex shader procedures for accurate data representation during the runtime of the pre-configured storyline.

The overall pipeline starts with georeferencing the data into the predefined coordinate reference system. The coordinate reference system of this particular study is UTM zone 32 (EPSG:25833) and all the data-sets are accommodated by being reprojected to this reference system in QGIS application. Afterwards, they are converted into 3-dimensional data with the application of a significant attribute, mostly the elevation of the data in OGS Data Explorer. The mentioned 3-dimensional data can either be a surface mesh or a 3D representation of vector data such as point clouds and line-strips. While line-strip data type is used for representation of the rivers and streams, the measurement stations are defined as point clouds in the study. The topographic frame is designated by a surface mesh constituted by mapping the DEM data representing the actual elevation onto the 2D boundary vector of the region. Interpolated historical groundwater observation data and the modelled groundwater flow simulation are also defined as 3D surfaces. However, the height attribute of these data-sets is utilised to represent the actual and estimated elevation of the groundwater head instead of the DEM of the surface. All of the georeferenced datasets are exported into glTF-format [BCKP17], a popular open-source 3D model format with also offers the integration of texture, so that the Unity framework can import and properly transform all the data-sets which are to be integrated into the VGE.

The visual composition of the VGE is determined by the storyline which represents an intuitive way of presenting the integrated static data and dynamic simulation results in terms of environmental impact analysis. A storyline requires the definition of a sequence of points of interest and a suitable presentation of datasets and simulation results at each of these points. In addition to setting and adjusting the visual data properties of all datasets visible at that point, a 'viewpoint configuration' function controls the visual and focal transition between regions of interest. The visual properties and settings of the data in the VGE scene are namely the type of visual representation of the vector or raster data, the opacity and the apparency in the scene at a determined time period, the ability of controlling the elevation and vertical position for a comprehensible output analysis as well as the timeline control ot the time-series simulation results. Furthermore, the viewpoint configuration function includes building descriptions and positioning of virtual cameras rendering the particular region of interest, the definition of the transition track of the virtual cameras coherent with the narration of the story and the alteration of the visual properties of the focused data-sets according to the active viewpoint's field of view. Therefore, visual data characteristics and visibility properties as well as the transition during scenario-specific viewpoints focusing on data-sets or phenomena of particular interest have been adjusted beforehand. Redefinition of these predefined properties is optionally possible during runtime via user interface interactions modules of the framework. Thus a perpetual scenario flow has been enabled to demonstrate all the coupled data-sets.

6. Conclusion & Future Work

Within the scope of this particular study, we propose a visual-scenario-based environmental analysis method utilising a VGE for the model-based management of water extremes in urban regions based on a case study for the City of Dresden. A broad extension and refinement to our existing Unity framework in terms of spatial data import and geographic transformations as well as environmental visualisation and interactive exploration has been successfully implemented to visualise observation data and numerical models above and below the topological virtual surface in a unified context. Some distinctive features of the proposed application include the interactive exploration of the virtual urban region, the integration of numerical models and environmental simulation scenarios for the visualisation and analysis of the environmental impact, the integration of multiple environmental compartments within a geographic context and the control of the synchronised animation of multiple 3D time-series data-sets with varying spatial and temporal resolution. We have presented a methodical approach and tools to generate, couple, and visualise hydrological and hydrodynamical models based on a digital urban model to improve communication and increase risk awareness. Digital urban models are the perfect basis for collaboration between stakeholders from the domains of water management and distribution. We have thus created a platform for the collaboration between researchers, stakeholders and interested public groups for the assessment and prevention of future risks.

Coupling models verifyably increases the modelling quality, but requiresfurther development and calibration for a validated application. As this particular study covers observation data and numerical models of water extremes around the City of Dresden, a number of improvements will be implemented in the future regarding the integrated data and simulation coupling. Numerical models simulating extreme events currently depend on generated precipitation data. The observed historic precipitation events and realistic approximations of the future events will result in a better understanding about the potential threats that the region will face. The staggered coupling approach allows for the integration of further processes in the future to also include simulation results for water quality, reactive transport, or evapotranspiraton. The groundwater recharge simulation will also be improved by taking into consideration the water saturation of the soil layers, extending the current 2D model into 3D. This information is not publicly available, but will be provided in the near future. This will extend this study in terms of more practical multi-compartment coupling. Due to the generalised implementation of the framework, similar VGEs can be created for different regions of interest without much effort as methods for data conversion, visualisation and presentation are now available. Given reliable observation data, the analysis of the potential water extreme threats for other urban areas will be straightforward using these methods.

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SACHSEN

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