A Virtual Geographic Environment for Multi-Compartment Water and Solute Dynamics in Large Catchments

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Abstract

We propose a visualisation framework for data exploration, analysis and presentation of complex hydrological studies in large catchments. This furthers a deeper understanding of the interrelations between the included datasets, allows for discussions among researchers from different disciplines and is the basis for illustrating complex phenomena to stakeholders or the interested public. Based on the 162,000 km^2 catchment of Poyang Lake, the largest freshwater lake in China, we developed a Virtual Geographic Environment that combines a wide range of 2D and 3D observation data sets with simulation results from both an OpenGeoSys groundwater model and a COAST2D hydrodynamic model visualising water and solute dynamics within and across hydrologic reservoirs. The system aims for a realistic presentation of the investigation area and implements approaches of scientific visualisation to il-

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lustrate interesting aspects of multi-variate data in intuitive ways. It employs easy-to-learn interaction techniques for navigation, animation, and access to linked data sets from external sources, such as time series data or websites, to function as an environmental information system for any region of interest.
Keywords: Environmental Information System, Virtual Reality, OpenGeoSys, Water Resources Management, Poyang Lake

1. Motivation

For complex environmental studies, there is a considerable number of data sets required for setting up models and providing sufficient context for reliable predictions and recommendations. However, usually not all datasets can be visualised in a unified context. Researchers need to view a certain subset in geographic information systems (GIS), view time series data from observation sites online or using a dedicated plotting software and one or more modelling frameworks to view their modelling data and simulation results. Any cross-connections between these subsets have to be made mentally or manually. Such a workflow is not only prone to result in mistakes, it also complicates presenting results to stakeholders or the public in an intuitive way. In addition, considering the complex hydrological cycle and its numerous parameters and subprocesses as one typical area of application, state-of-the art monitoring and modelling activities as well as sophisticated visualisation and data integration systems are required together to facilitate system understanding and water resources management. Particularly on the scale of entire catchments, which is appropriate for integrated management of water resources (Jaspers, 2003), the large amount of available output datasets from

models and remote sensing products are challenging for the development of efficient and informative visualization approaches. We propose integrating *all* datasets relevant for the analysis of a given region of interest into one unified framework that serves as an Environmental Information System (EIS) for data exploration, interdisciplinary research, and knowledge transfer. We presented a first prototype for such a framework in Rink et al. (2018). For the work presented here, we use this EIS for a hydrological multi-compartment study of the Poyang Lake Basin in China. Its large size of about 162,000 km^2 and the complex hydrological processes within the highly dynamic lake-river-wetland system influenced by numerous drivers in the catchment, are making it an ideal study site for developing an integrated Environmental Information System for large basins.

Considering that about 94 % of Jiangxi Province is located within Poyang Lake Basin, an improved holistic representation of the overall hydrological system and its interconnected compartments is beneficial for both the pursuit of sustainable water resources management and for the economic construction and development at the provincial level. The current management system of Poyang Lake is based on the Jiangxi Poyang Lake Wetland Protection Ordinance issued by the Provincial People's Congress. The resulting system consists of a large number of authorities working independently from each other which weakens the power of both management and law enforcement (Fan and Hu, 2018). As a response to this situation, China is fully establishing a "river chief mechanism," which assigns each part of a surface waterbody to an appointed official in order to improve the comprehensive management and public supervision of each basin. Consequently, integrat-

ing the relevant mechanisms and dynamics in the Poyang Lake Basin into a single visualisation framework has advantages with respect to evaluating future hydraulic constructions, forecasting future water quality, delineating protection zones, and mitigating environmental issues.

There have been previous initiatives to integrate data from different sources into a holistic visualisation platform for Poyang Lake Basin. Zhao (2018) set up a prototype system for analysing ecosystem simulation results obtained with the high accuracy surface modelling method HASM (Yue, 2011; Yue et al., 2015). The platform allows for the spatial-temporal analysis of raster files in the thematic areas climate change, forest carbon storage and population distribution. Gu et al. (2017) proposed a *watershed ecological virtual simulation and decision support platform* that combines GIS data with a 2D WATLAC hydrological model into a Virtual Geographical Environment to be presented on large displays. Chen et al. (2015) integrated GIS database management systems, results from a numerical soil model and a 3D Visualisation framework into a Virtual Hydrologic Environment (VHE) for Meijiang subcatchment. Zhu (2011) developed a 2D GIS environment to display hydrological data from WebGIS services and a POSTGIS database with the aim to validate the results of a two-dimensional hydrodynamic water and pollutant transport model for Poyang Lake. Similar approaches of using 2D GIS based visualization schemes for wetland data visualisation at Poyang Lake have been utilized by Zhong (2008), Xiang and Zhou (2009) and Zhao (2012) with the latter adding spatial relationship operations and their graphic representations into the developed framework. Focussing on flood inundation, Chen et al. (2012) set-up a 3D GIS system for the Poy-

ang wetlands embedding 3D structures and hydrodynamic simulation results as well as geographic objects from a object-relational database. Yan et al. (2018) developed a basic 3D environmental information system for Poyang Lake Basin. A large number of data sets, based on observation and simulation, have been included in this case study. Examples include temperature, precipitation, or ecosystem quality as well as water dynamics. However, from an implementation point-of-view the technical contribution is limited, as all data sets are imported as raster files and texture-mapped onto a 3D-model of a digital elevation model for the region.

The environmental information system (EIS) proposed here aims at creating suitable representations for all included data sets, such that the nature or certain aspects of the data are intuitively recognisable by users. Examples include the integration of precipitation data as point clouds or the simulated changes to the groundwater head as an actual triangulated plane within the 3D finite element model. This has the added advantage of being able to potentially display more data or simply remove colour as an indicator for a parameter in favour of alternative means of visualisation. In addition, we have extended the functionality of our EIS considerably and chose this case study to demonstrate both its portability to arbitrary regions of interest as well as the scalability for large volumes of data.

After a short introduction to Virtual Geographic Environments in section 2, section 3 gives an overview of the Poyang Lake Basin, including the multiple compartments included in this study. It presents details about specific data sets, modelling and simulation approaches, as well as necessary modifications during pre- and postprocessing. Section 4 gives an overview of

the Environmental Information System for the catchment. It shows workflows, lists extensions to the previously presented prototype and gives examples for data integration and visualisation based on specific data sets.

2. Virtual Geographic Environments

The holistic representation of all available data sets for a given region of interest is currently beyond the capabilities of established geographical information systems (GIS) such as ArcGIS or QGIS (Cox et al., 2013; Tian et al., 2016). Such frameworks have been originally designed for displaying vector- and raster-data sets. Though approaches for displaying data in 3D exist, the software is usually lacking both interfaces and methods for advanced visualisation of complex three- or four-dimensional data. Examples include the representation of climate- or subsurface models, the colour-coded display of vector data to represent locally varying parameters or measurements, or the handling of time-variant data in general. On the other hand, all-purpose visualisation software such as ParaView (Ahrens et al., 2005) or VisIt (Childs et al., 2012) includes state-of-the-art visualisation techniques but lacks interfaces to domain-specific software such as GIS or modelling frameworks. To close this gap, we have developed the OpenGeoSys DataExplorer (Rink et al., 2013, 2014) in recent years. This software serves as a graphical user interface to the open-source modelling software OpenGeoSys (Kolditz et al., 2012a) and implements interfaces to various GIS data formats, a wide range of free and commercial modelling frameworks (for instance, FEFLOW (Diersch, 2014), PETREL (Schlumberger, 2018), SWMM (Rossman, 2014), OpenFOAM (Weller and Tabor, 1998)) as well as all-purpose formats such as

NetCDF (Rew and Davis, 1990) and VTK (Schroeder et al., 2006). The Data Explorer allows for the 3D visualisation of data via the open-source library VTK (Visualization ToolKit). The Data Explorer has been designed for the preprocessing and evaluation for numerical THM/C models, its functionality is insufficient for complex collaborative research projects, where the handling of large numbers of data sets can become confusing for unexperienced users and the implemented visualisation algorithms can be insufficient for collections of complex, possibly multi-variate or multi-modal data sets. Therefore, we recently started developing virtual geographic environments (VGE) specifically for the purpose of integrating large collections of heterogenous data sets for the visualisation of complex environmental processes and interrelation of parameters of interest to researchers from a wide range of domains within the environmental sciences.

Based on the definition by Ellis (1994), the term "virtual environment" refers to an immersive, interactive experience inside a synthetic space. In recent years, the term has been adapted for computer-mediated communication in various domains, with "virtual learning environments" probably being the most often cited application in the media. Virtual geographic environments have been first proposed as an extension of GIS into 3D and VR (Batty, 2008; Yin, 2010). Later the concept has been extended to include data from numerical models and simulation results as well as web-based data and collaborative approaches for data interaction (Lu, 2011; Lin et al., 2013b; Kolditz et al., 2019).

However, our definition of a Virtual Geographic Environment slightly differs from the previously proposed framework: Lin et al. (2013a) and Lin

et al. (2013b) subdivide a VGE into four components: data environment, modelling and simulation environment, interactive environment, and collaborative environment. In contrast, a diagram of our framework is depicted in Fig. 1. The data life cycle starts with data added to some kind of data storage (e.g. a database or file storage). This data is preprocessed to remove artifacts, calculate derived parameter sets or project it into another coordinate system. That modified version of the data is either stored or forwarded into the VGE, depending on the complexity of the selected algorithms and the use of the processed data for other users or subsequent stages of the workflow. Not integrating the data processing component within the VGE is debatable, as it includes pre- and postprocessing algorithms for general data modification (e.g. for the removal of artefacts), specific algorithms for the modelling and simulation (e.g. for the assessment of mesh element quality for the finite element method), specific algorithms for a subsequent visualisation (e.g. data reduction methods for high-dimensional multivariate data), as well as algorithms required for both modelling and visualisation (e.g. the projection of data into a unified coordinate system). Both, data storage and preprocessing are what is called "data environment" in Lin et al. (2013a). If modelling- or simulation data is part of the VGE, the (preprocessed) data serves as input for a suitable simulation software and results are written back to the data storage. This simulation software might be OpenGeoSys, but as mentioned before, interfaces for files from a multitude of other software products have been implemented as well. While this modelling/simulation-component corresponds to the "modelling environment", it is explicitly not part of the VGE but simulation results are instead accessed via an interface

just like any other dataset. The VGE is agnostic to the origin of any dataset. As long as there is an interface to read the data it does not matter if it is research or observation data from scientific partners, state departments, companies, or data openly available on the net. Moreover, the data storage-, preprocessing-, and modelling components would work just as well without a VGE accessing the data afterwards.

Instead, our interpretation of a VGE consists only of a visualisation- and a presentation component, roughly corresponding to what Lin et al. (2013a) call "interactive environment" and "collaborative environment". The visualisation component is used to create tesselated 3D objects out of environmental data sets in the form of suitable metaphors or expressions (such as glyphs, streamlines, or surfaces). The presentation component includes everything required for the user experience in virtual reality, starting from the choice of shaders for 3D object and the lighting of the scene, but also animations, predefined viewpoints, picking objects to access additional information, or switching objects or parameter sets live during a presentation.

It is worth pointing out that the workflow described above is not definitive. As the immersive user experience is impaired if frame rates drop below 20 to 30 frames per second, it is common for complex and computationally expensive forms of visualisation to store pre-rendered representations of datasets on a file server or database to guarantee fast rendering at all times, thus creating a direct connection of the VGE to the data storage. Also, the VGE might access the simulation component directly if *in-situ* visualisation (Bauer et al., 2016) is part of the study. However, this requires that the simulation software includes interfaces specifically designed for *in-situ* visualisation.

We have previously implemented the above concept for a VGE for the catchment of Chao Lake in the Anhui Province of China (Rink et al., 2018) using the OpenGeoSys Data Explorer for preprocessing data sets and employing Unity (Unity Technologies, 2018), a cross-plattform game engine, for implementation. Since both pre-processing algorithms as well as the necessary extensions of Unity have been deliberately designed to be re-usable for future case studies, we were able to apply and extend the existing framework to build an application for the catchment of Poyang Lake presented here.

3. Case Study Poyang Lake Basin

3.1. Catchment Characteristics

Poyang Lake, the largest freshwater lake in China by maximum annual extension, is located in the southeastern part of China (Fig. 2a). Annual precipitation rates in the Poyang Lake basin show a distinct wet and a dry season with a short transition period in between. Although precipitation rates are highest in June (Fig. 2b), tropical cyclones regularly cause thunderstorms and heavy rainfall in the basin in late summer. The distribution of rainfall in its catchment controls runoff generation in the five large river systems (Ganjiang, Xinjiang, Xiushui, Raohe and Fuhe River) entering Poyang Lake with an basin-averaged runoff coefficient of about 0.6 (Huang et al., 2008). In addition, ungauged river systems may contribute between 12% (Li et al., 2019) and 15.6% (Du et al., 2018) of total water inflow to the lake. Poyang Lake drains into the Yangtze River at a rate of about 150 bn. m^3 per year which takes about 15.5% of the rivers total runoff (Zhao et al., 2011).

Seasonal water level variations of the lake also depend on the discharge

characteristics of Yangtze River and can reach more than $10\,m$ at Hukou and Xingzi station between dry and wet season. At maximum extention, the water surface of the lake expands up to 3 800 km^2 filled by a water volume of 32 bn. m^3. In addition, the fairly late yearly high water levels in Yangtze River (Fig. 2b) periodically cause a water blockage at the outflow of Poyang Lake which contributes to high water levels in the lake system (Ye et al., 2011; Yao et al., 2018). In contrast, the lake shrinks to little more than a river during the dry winter months. The corresponding change in inundation area (Hui et al., 2008) forms a unique system of water areas, wetlands and mudflats. For more details on the hydrology of the system, the interested reader is referred to the relevant publications, e.g. Li et al. (2014) and Guo et al. (2008).

According to the Chinese Environmental Quality Standards for Surface Water (GB3838-2002), Poyang Lake has an overall water quality that is better than most other large Chinese Lakes, such as Tai Lake or Chao Lake (Fig. 9). However, water quality is continuously deteriorating as the lake and the wetland system face several pollution pressures such as an continuous inflow of nutrients and fertiliser residuals from its extensively cultivated shorelines (Duan et al., 2016; Soldatova et al., 2018) as well as acidity and heavy metals from mining areas (He et al., 1998) and industrial sites (Xu and Wang, 2016). Additionally, the hydrological system is increasingly disturbed by hydraulic construction measures. The opening of the Three-Gorges-Dam (TGD) is considered one reason for generally decreasing water levels in Poyang Lake during the last decade (Li et al., 2017). Furthermore, prevalent sand mining activities increase water turbidity, restrict phytoplankton growth and

have contributed to an annual water level decrease of 1.2 to 2 m at the outflow of Poyang Lake during dry season (Lai et al., 2014; Yao et al., 2018).

Apart from its large size, the ecosystem of Poyang Lake is of international importance due its wide range of wetland habitats that support rich biodiversity (Huang et al., 2016; Sheng et al., 2016). For instance, many migratory birds coming from Siberia, Mongolia, Japan, Korea, Northeast and Northwest China rely on these diverse habitats for overwintering, giving the ecological importance of Poyang Lake an supranational component (Yang et al., 2016).

3.2. Preprocessing of Input Datasets

As motivated in section 2, we are able to integrate a large variety of data formats into the Virtual Geographic Environment by using the OpenGeoSys Data Explorer as a preprocessing tool and exporting the data representations subsequently into Unity. For the hydrological study presented in this paper, we focussed on integrating data available on the internet. Possible sources included both websites providing monitoring data and publications providing data sets.

Bibliographic studies showed that a total of about 9,600 Chinese and 1,300 English articles touching the topic "Poyang Lake" were published in scientific journals between 1983 to 2017 (Zhou, 2018). This includes a considerable number of publications in the field of Hydrology and Earth Sciences. However, many of the published datasets lack precise information on time and location of data acquisition or have an insufficient resolution. Both are necessary requirements for a meaningful representation within an environmental information system. In addition, accessibility of official environmental data-

sets provided by local or provincial authorities in the Poyang Lake Basin is limited. Therefore, open data from remote sensing sources as well as data produced by physically based models of parts of the hydrological system was used to fill data gaps in the visualisation of spatio-temporal dynamics in the Poyang Lake Basin. Consequently, a mix of data sets from open databases, articles, remote sensing information and official data have been integrated into the EIS. An overview of integrated data sets is given in table 1.

3.2.1. Surface Mapping

The catchment boundary of Poyang Lake Basin was obtained by applying a GIS catchment analysis on the digital elevation model (DEM) dataset provided by the HydroSHEDS project (Lehner et al., 2008). This dataset is based on data from the Shuttle Radar Topography Mission (SRTM), which has been processed for hydrological purposes. HydroSHEDs DEM defines the elevation of the lake's water level as constant. We modified the derived DEM for Poyang Lake Basin for pixels actually covered by water from the lake and replaced those values with available bathymetry data. Comparing the elevation in the non-flooded wetland areas provided by both the HydroSHEDS and the bathymetry dataset, the average difference of elevation values was not more than $2\,m$, i.e. less than the vertical height accuracy of the SRTM sensors (`https://www2.jpl.nasa.gov/srtm/statistics.html`). Due to the large size of the Poyang Lake Basin and the requirement for a detailed reconstruction of comparatively small areas within the catchment (such as subcatchments of tributaries or the lake region itself), the resulting surface mesh is very large when considering typically used data in Unity. The complete surface of the catchment consists of 1.8×10^6 nodes and 3.75×10^6 triangles

Table 1: Characteristics of primary data sources used within this study. Abbreviations are explained in the running text.

Data type	**Data source**	**Type**	**Spatial Resolution**	**Temporal Resolution**
Precipitation	GPM	Grid	0.1°	0.5 h
DEM	HydroSHEDS SRTM	Grid	3”	—
Terrain Texture	Google Earth	Grid	76.44 m (Basin) 19.11 m (Core)	—
River Network	OSM	Vector	—	—
Poyang Lake Hydrodynamics	(Du et al., 2018)	Grid	100 m	48 h
Poyang Lake Hydrochemistry	(Du et al., 2018)	Grid	100 m	48 h
Poyang Groundwater	(Nixdorf, 2018)	Grid	0.5–10 km	seasonal
Gan River Hydrochemistry	(Li et al., 2018)	Vector + Attributes	—	—
Le’an River Hydrochemistry	(Jian, 2018)	Vector + Attributes	—	seasonal
Surface Water Level	Jiangxi Water Authority	Vector + Attributes	—	—

with an average edge length of $500\,m$. This surface mesh has then been partitioned into smaller meshes to allow for performance optimisation such as view-frustum culling. Technical details on suitable visualisation techniques for large geoscientific data in Unity have been presented by Rink et al. (2017). In addition to the regular surface representation, a number of refined meshes

have been created for certain areas of interest. Most data acquisition, simulation and visualisation efforts focus on the Poyang Core Region, which is defined as the area of a dozen counties around Poyang Lake with a total area of about $19,833\,km^2$ (Tang et al., 2016). Poyang Lake is located in this core region as well as Nanchang, the largest city in the catchment with a population of about 3 million. Subsequently, the core region is in the focus of this case study. The surface mesh for the core region consists of roughly 10^6 triangles (0.5×10^5 nodes) with an average edge length of $250\,m$. A second, much smaller region of interest is the Dexing copper and gold mining area located about $100\,km$ east of Poyang Lake, which is represented by a surface representation using just 20,000 triangles. Textures for these meshes have been acquired from Google Earth in varying resolutions. For the Dexing Mining area, we made use of Google's "Historical view"-functionality to create a texture-series and show the expansion of the mines from 2009 to 2018.

3.2.2. Meteorological and Hydrological Datasets

For the visualisation of precipitation, two heavy rainfall events were selected from the precipitation datasets of the GPM satellite mission (Hou et al., 2014). The first event covers the heavy rainfall caused by Typhoon Soudelor in Southern China between 06 and 11 August 2015. A total of 287 global datasets in HDF5 format represent the time interval at a 30 minute temporal resolution. These datasets were automatically downloaded, clipped to the investigation area and converted into ASCII grids in the EPSG:16050 coordinate reference system using Python. A similar processing scheme was applied for 527 precipitation grids in the time interval between the 20 and 30

June 2017, which represent the heavy rainfall causing the 2017 China floods in June 2017. In addition, the location of all river gauging stations, reservoir gauging stations and weather stations maintained by the Jiangxi Water Resources Department as well as the related hydrographs were included in the EIS. The stream network of five main tributaries of Poyang Lake was obtained from OpenStreetMaps (OSM) and classified into three orders each. All observation sites and river geometries have been mapped onto the triangulated three-dimensional surface generated from the DEM using a linear interpolation algorithm proposed in Rink et al. (2014). In addition, the results of a two-dimensional hydrodynamic lake model (Du et al., 2018) were integrated into the EIS to visualise inundation changes as well as water and matter transport in Poyang Lake (see Fig. 5). The provided dataset consist of 186 rasters representing the temporal dynamics in the lake between September 2009 to February 2011 with a temporal resolution of $\sim$ 2.1 days. We implemented a reader to convert the COAST2D simulation output into the VTK unstructured grid format. Specifically, each time step would be written to a separate file, with each parameter represented by an array within that file. As a result, we ended up 186 mesh files, each consisting of $47,000$ quad elements and containing information on flow direction, flow velocity and four chemical concentrations for each cell. Given that representation, it is straightforward to display a temporal sequence for any of the included parameters and use VTK for subsequently applying visualisation algorithms to the data set.

To represent the groundwater flow system, the distribution of hydraulic heads, groundwater velocities and stream path trajectories in the Poyang

Lake Basin has been visualised in the EIS based on the results of the groundwater model developed by Nixdorf (2018) (see Fig. 6). The groundwater regime was simulated in two-dimensional planar direction for low and high water levels in Poyang Lake using the open source THMC FEM code OpenGeoSyS (Kolditz et al., 2012a), which has been applied for groundwater flow simulations on the regional scale under various scientific objectives in previous studies (e.g. Walther et al. (2014); Wu et al. (2011); Nixdorf et al. (2017)). The two-dimensional triangular FEM mesh used for the simulation consists of about $150,000$ Elements with a spatial resolution of about $500\,m$ inside and about $10\,km$ outside of the Poyang Lake Core Region (for details of the model pre- and postprocessing see Nixdorf (2018)). The groundwater flow model computes hydraulic head (Fig. 6a) and groundwater velocity vectors (Fig. 6b) at each node/element of the FEM mesh for December 1999 (low lake water level) and September 2000 (high water level) in VTK format, for subsequent integration into the EIS system.

3.2.3. Hydrochemistry

In general, public information on water quality of surface waters – including meta-data on sampling location and time – are difficult to obtain for Chinese water bodies. Accessible datasets are rarely available in a sufficient spatial resolution, particularly if the investigation aims to focus on large river networks (Nixdorf et al., 2015). However, recently a number of studies has been published, providing data on surface water pollution caused by mining activities monitored along tributaries of Poyang Lake. He et al. (2018) measured surface water contents of arsenic, chromium, copper, uranium and thorium at 13 sampling sites in Fu River as well as in its tributary Lin River.

Jian (2018) investigated seasonal changes of heavy metal concentration (copper, lead and cadmium) in the water, soil and sediments at 13 sampling sites of Le'an River, which is a tributary of Xin River, in order to reveal the impact of the Dexing mining area on the stream ecosystem. The results of this study were included in the EIS together with the study of Li et al. (2018), who measured dissolved concentrations of 15 different heavy metals at 37 locations covering the entire Gan River network. For the EIS, we limited ourselves to two prototypical representations for the chemical data: (1) For Le'an River, we display a spatio-temporal distribution for the concentration of copper in the river during various seasons (the pollution during wet season is shown in Fig. 9c). (2) For the Gan River network, we included a multivariate dataset for a fixed point in time, allowing the user to switch through a linearly interpolated mapping of the 15 metal concentrations (see Fig. 7). The visualisation of chemical concentration in 3D river representations has been kept simple on purpose, to allow domain scientists to intuitively understand the displayed data. The combination of both temporal and multivariate data is not a technical issue, but the two dimensional parameter space (compound vs time) becomes difficult to navigate without a specifically designed user interface. Likewise, a concurrent visualisation of multivariate data, such as via glyphs or small multiples, is not straightforward to understand without being given instructions.

Hydrochemical data for Poyang Lake were integrated in the EIS based on the two-dimensional lake model of Du et al. (2018). The simulation includes information on the distribution and dynamics of total phosphorus, total nitrogen, ammoniacal nitrogen and the permanganate index in Poyang Lake in

a spatial-temporal resolution of $100\,m$ and ~ 2.1 days, respectively. This is identical to the hydrodynamic dataset mentioned previously; see conversion details in section 3.2.2.

4. Construction of the Poyang Lake VGE

In Rink et al. (2018), we proposed a framework for creating Virtual Geographic Environments using Unity as well as a workflow for preparing the data to be included. An illustration of the workflow is shown in Fig. 8 and we will give a brief outline in the following: Based on the intended purpose of the VGE, datasets to be included are selected based on availability and their usefulness in the scope of the case study. Datasets often require preprocessing for fitting seamlessly together with other available datasets. While modification of the data (or their graphical representation) is possible at a later stage of the workflow, it is recommended to use the software products the datasets have been created with as much as possible to preserve the data's inherent structure and parameters, and avoid the creation of processing artefacts. A typical example is using a Geographical Information System for the projection of all datasets into the same coordinate system. Once prepared, all datasets are imported into a VTK-based processing software such as the OGS Data Explorer or ParaView, where graphical representations of each dataset are created. While ParaView is an all-purpose software for scientific visualisation, the Data Explorer offers a number of interfaces and algorithms specifically developed for the handling of environmental datasets. Either framework is used to modify the data in ways that have either not been supported in the original software or which are specific to the graphical

representation of the data. An example of this is the mapping of a raster file (e.g. remote sensing imagery) onto a warped surface representing the region of interest. Also at this stage, artefacts are handled, and data reduction algorithms are used to adequately prepare datasets for visualisation. During the visualisation-stage, suitable representations for each of the datasets will be selected and visualisation algorithms are applied so the interesting aspects of each datasets will become visible or emphasised. Suitable colours and transfer functions are selected, if possible in such a way that the colours will help users to understand the data. Finally, the finished graphical objects representing the original datasets will be imported into the Unity framework where parameters concerning the rendering within the scene will be set. At the lowest level, this includes selecting light sources for the scene or assigning specific shaders to a datasets (Bailey and Cunningham, 2011) (i.e. defining how the dark, shiny, or colourful the object will appear, as well as setting more elaborate rendering effects). In addition, presentation-specific functionality is set up. This includes viewpoints of positions in 3D space the user can select from a menu and will automatically be guided to, picking objects to receive additional information (we can link images (Fig. 4), movies or documents or even interactive graphs to any 3D object), selecting and controlling animations via control menu, or switching simulation scenarios.

As an specific example, we would like to illustrate the above workflow based on the dataset for Le'an river: The course of the $280\,km$ long river is part of the Chinese river network dataset acquired from OpenStreetMap. The data is imported into QGIS, the river has been extracted and projected into the EPSG:16050 (UTM zone 50N) coordinate system used for this case

study (Fig. 9a). The river dataset has then been saved into the shapefile vector format and imported into the OpenGeoSys Data Explorer. Here, adjacent points with a distance of less than $100\,m$ to each other have been removed. This reduces the size of the dataset by more than $50\,\%$ without the difference being visible to the human eye due to the size of study area and the final representation of the river. Now, the dataset is mapped onto the 3D representation of the DEM, so it fits into the geographic context of the case study (Fig. 9b). We applied a VtkTubeFilter, changing the representation of the polyline-vector-data into a triangulated pipe-like structure with a radius of $50\,m$. This is required because the original line structure will always be rendered at a width of one pixel and is thus too inconspicuous to be noticed. The dataset was assigned the colour blue, a colour that is typically associated with water. At each point of the dataset we now added scalar values representing the copper-concentration at different times of the year, acquired via Jian (2018). The higher the concentration, the more the colour of the associated river-segment will turn red. This colour is especially suitable here, not only because red is usually associated as a warning or sign of danger, but the severely high concentration of the copper *actually* gives the river a reddish-brown colour. The transfer function we applied turns yellow at a concentration of $1\,{}^{mg}\!/\!_{l}$, red at $2\,{}^{mg}\!/\!_{l}$ and violet at $3\,{}^{mg}\!/\!_{l}$. We then exported the dataset into the Autodesk FBX format, which can be employed to import data into Unity. Location, mapping and colour are automatically adopted during this process. In Unity, we parameterised the dataset such that it is rendered using a simply Gouraud-shader without casting shadows (which is not necessary as it is being located on the catchment surface) and rendering

backfaces (located at the inner side of the tube) in order to save computing power. An animation was defined to change the colour of the dataset based on the copper-concentration during different times of the year (Fig. 9c), in addition the user can access images of river to get a less abstract view of the situation. A viewpoint was set near Dexing Mine where the Copper enters the river. As a result, that particular point-of-view can be set automatically during a presentation, and an interpolated path along the river will guide the user from Dexing Mine to Poyang Lake.

Depending on the complexity of each of the included datasets, some of the steps described above may not be necessary or other algorithms might need to be applied instead. It's important to note that all of the required algorithms are implemented in OGS, ParaView or Unity and can be executed via user dialogues in the respective software programme, thus significantly reducing the time required for each of the steps. It is worth pointing out that the workflow shown in Fig. 8 is a subset of the data workflow introduced by Kolditz et al. (2012b), based on the structure shown in Fig. 1.

In addition to what had been presented in Rink et al. (2018), the functionality of our framework has been expanded for handling a number of types of datasets that will be presented here briefly:

Previously, it has only been possible to assign transfer functions based on spatial-temporal parameters of FEM-based simulation results. These transfer functions assign (and can interpolate) colour values to encode additional information during the presentation. A generalisation of that algorithm now also allows the assignment of data to geometrical data in OpenGeoSys and has been used, as described above, to visualise the changing concentration

of various chemical compounds in Poyang Lake and its tributary rivers. As demonstrated by Samsel et al. (2017) (and more generalised in Zhou and Hansen (2016)), suitable colour maps and transfer functions are of vital importance for an intuitive understanding of visually presented data. As such, we are using applications such as ParaView (Ahrens et al., 2005) or ColorBrewer (Harrower and Brewer, 2011) to generate colour lookup tables (LUT) that are either based on specific values or ranges (such as the LUTs in Fig. 7 and 9c, based on permissable/critical values for Copper concentration in drinking water) or that can be adequately discriminated with human perception.

We also created animations from remote sensing data acquired over multiple years: Google Earth imagery from 2009 to 2018 is used as texture for the Dexing mining area. It shows topographical changes of area and adds to the visualisation of the water pollution in Le'an river discussed above. As such, it enriches the understanding for a user exploring the data via the Environmental Information System and serves the holistic approach of the framework.

To visualise the hydrological processes simulated via COAST2D and OpenGeoSys and discussed in Section 3.2, we applied and adjusted algorithms provided by VTK: For the groundwater simulation, triangle nodes have been mapped to the elevation of the groundwater head, thus creating a warped surface of the simulated water level. In addition, arrow-glyphs have been generated, where the direction of arrow indicates flow direction and the colour the simulated velocity. A total of $10,000$ arrows positioned on an equilateral grid have been calculated and mapped onto the surface representing the

groundwater head for low and higher water level, each (see Fig. 6b). For the surface water hydraulics of the Poyang Lake, a streamline representation of the flow was selected. Given the complex and drastically changing area covered by the lake and large variations in velocity, representing flow via arrow-glyphs as with the groundwater model results in a confusing visualisation where glyphs are not necessarily located on the lake surface and larger glyphs may conceal smaller ones. In contrast, streamlines preserve the shape of the original graphical object and are a suitable way to visualise eddies in the water (see Fig. 5a).

During a concurrent visualisation of both surface and groundwater flow, the different modes of representation also allow to easily differentiate between data sets. Integrating surface and subsurface water flow fields in one visualisation helps to reveal the complex spatio-temporal pattern of gaining and losing conditions along the lake's shoreline and subsequently may facilitate the understanding of cross-compartment interaction in the Poyang Lake Basin.

In previous studies, we have relied on the visualisation of diagrams for time series of weather and climate data. Here, the occurrence of large storms and extreme rain events required a different representation to meet the request for a multi-compartment approach for hydrological processes. Exemplary data from two extreme weather events (see section 3.2.2) have been used to implement an algorithm for the 3D representation of precipitation data. Given 288–528 raster data sets of precipitation intensity per rain event, we created a point cloud representation for visualising rain. Each pixel p_i from the raster data is given an adjustable height-parameter and thus

forms a bounding box B_i in 3D space. Within B_i, n_{ij} points are randomly seeded, with n_ij being dependent on the amount of precipitation on pixel p_i at timestep t_j. Colours can be adjusted based on height, intensity, or any other parameter derived from the dataset. The result is a vivid impression of rain clouds moving over the region of interest (see Fig. 10).

While such animations are very intuitive, we did also include diagrams showing time series data from observation sites, to allow experts to verify numbers and assess the development of the observed events. For intuitive access, the available timeseries data is linked to the representation of observation sites in the 3D scenes. If these objects are picked via mouse or flystick, a 2D overlay window opens, displaying the time series for that particular site as a diagram. For this case study, we also added an interface to the AL.VIS/Timeseries framework developed by the *WISUTEC Umwelttechnik GmbH*, one of our cooperation partners during the project. This interface allows online-access to the AL.VIS database and shows current measurements at the selected observation site (Fig. 11). AL.VIS/Timeseries is able to import data from different sources for quality assurance, research, analysis and exporting. The used database model is very flexible and can process very long time series with more than 10^6 measured values very fast. Multiple diagrams linked to observation sites in the VGE can be opened concurrently and allow users to investigate the time series data interactively via pan and zoom functionality.

Due to the large extent of the Poyang Lake Basin, we encountered a number of new challenges concerning the VGE for this region. The most challenging issue was related to data volume: A sufficiently fine resolution is

necessary to realistically depict areas of interest and to ensure that geographic features such as river valleys are rendered correctly. This was of special importance due to the requirement for spatio-temporal visualisation of rivers and their pollution in the correct geographical context. Given the size of the catchment, both surface grids and texture data is reasonably large. However, for an interactive and immersive VR application, a sufficiently high frame-rate is required so users won't experience stuttering during animations or missing time steps in the rendering of simulation results. Fortunately, recent versions of the Unity engine support not only very large texture-sizes, but also level-of-detail approaches, where multiple resolutions of surface grids are assembled into a tree structure and cross-fading between data sets is automatically handled by Unity itself. In addition, we included river network representations with a varying number of tributaries included as well as varying diameter of tube-representations of rivers. In addition, we use standard procedures for saving rendering time by making use of backface culling (i.e. only the front-faces of triangles are rendered) or view frustrum culling (i.e. only currently visible objects are rendered). Another issue is related to the visibility of small (or thin) structures within a large context. We have addressed this issue before, but due to the size of the catchment it was of special importance in this case study. For an overview of the river network, it required different representations of rivers, as mentioned before. A large diameter of tube structures in required for the objects to be clearly visible when showing the whole catchment. However, a much smaller representation is needed when zooming in on certain regions of interest. Here, we solved the issue by linking specific representations of datasets to given predefined

viewpoints. If the user is selecting a viewpoint that will show large parts of the catchment, larger representations of the rivers with fewer tributaries are shown. If a viewpoint close to the surface is selected, those datasets become transparent and instead a finer resolution with more tributaries is rendered. The same approach is used for small regions of interest such as the Dexing mining area.

We have used the proposed framework to present complex data collections to a wide range of audiences. The 3D visualisation of multi-compartment data has proven to be an excellent means to present research questions and progress to both stakeholders and the interested public, allowing to present complex processes and relationships in an easy-to-understand and engaging way. The virtual reality approach fosters discussions between collaborating scientists by allowing an in-depth look at data characteristics with a complex context. In our Lab (Bilke et al., 2014), we use MiddleVr as a Unity plug-in to present this case study in our Virtual Reality environment using $6 \times 3\,m$ video wall with additional projections on both sides as well as the floor (Fig. 12). The system is powered by 13 beamers and users are tracked via an array of nine infrared cameras, thus providing an immersive environment during presentations. Users can interact with the scene via a flystick or a gamepad. However, MiddleVr also supports a multitude of other platforms and we have built our applications for regular PCs as well as for head-mounted displays such as the HTC Vive or the Oculus Rift.

5. Conclusions

We presented a holistic analysis of water and solute dynamics in a large catchment, highlighting the importance of visualisation for analysing and understanding complex data collections and simulation results. A wide range of observation data in vector- and raster format have been converted into 3D models and are complemented by previously published simulation results of a groundwater flow model for the Poyang Lake Basin as well as a solute transport model of the lake itself. All data sets have been projected into a unified geographical context for a complementary visualisation within a Virtual Geographic Environment. Highlighting points of interest and visualising phenomena relevant to a hydrological analysis of the region facilitates a deeper understanding of the underlying processes and allows a visual correlation of the integrated data. Additional information such as time series, imagery, or websites is linked to corresponding objects in the scene, creating a 3D Environmental Information System for the Poyang Lake Basin. The application allows for interactive data exploration in Virtual Reality, both in cave-like environments or using head-mounted displays, but can also be run on regular personal computers. The software frameworks used and the algorithms developed are in no way limiting the application to the presented case study and can be easily applied to other regions of interest. This form of presentation gives researchers a comprehensive view of all relevant data sets for any given case study, allows for interdisciplinary discussions between collaborating scientists, supplements presentations of research results and has been successfully used for knowledge transfer during open day events.

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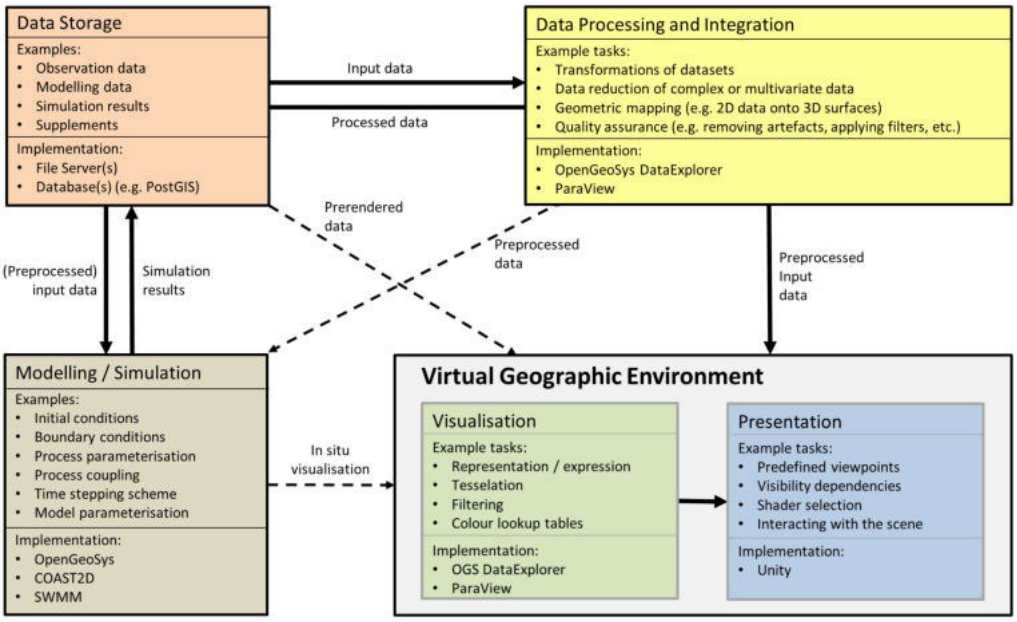


Figure 1: Data life cycle for virtual environments for Earth system modelling. Solid lines mark prevalent types of interfaces, dashed lines mark plausible but somewhat ususual interfaces.

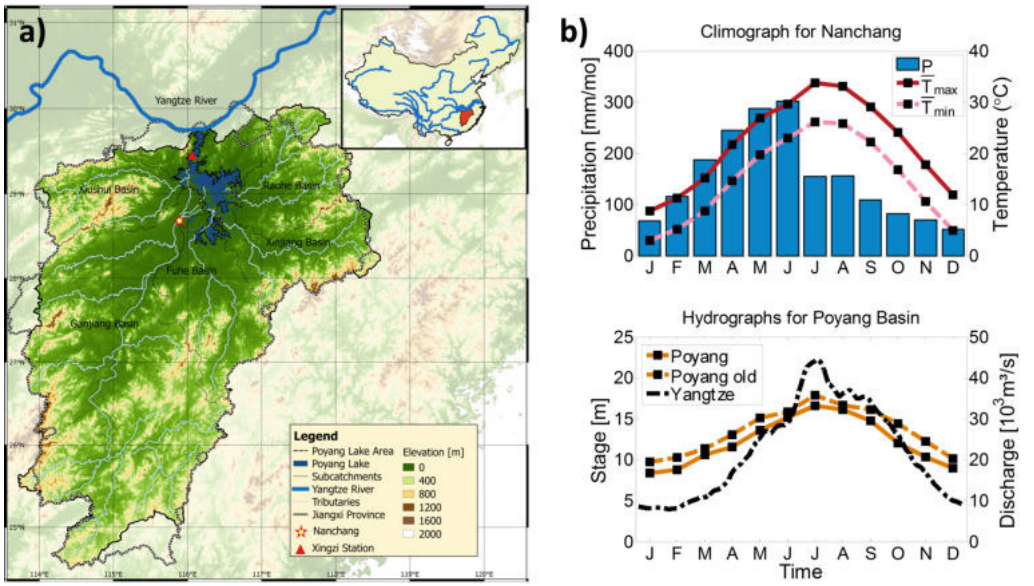


Figure 2: a) Location of Poyang Lake and its catchment b) Climograph for Nanchang City and hydrograph of Poyang Lake at Xingzi station prior ("Poyang old") and post the construction of the Three-Gorges-Dam (Guo et al., 2012; Feng et al., 2016).

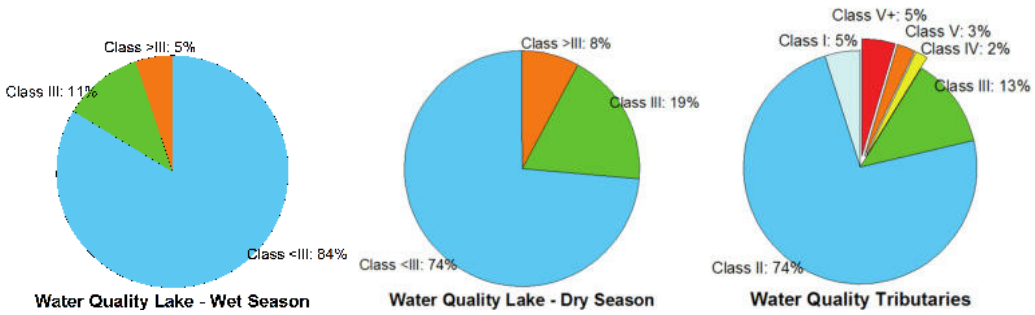
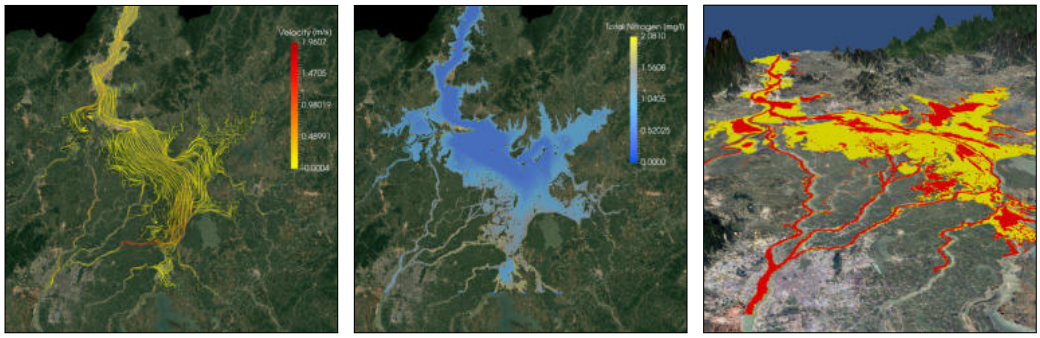


Figure 3: Classification of water quality in Poyang Lake and tributaries according to the Chinese Environmental Quality Standards for Surface Water (Jiangxi Water Resources Department, 2013).

Figure 4: Practical use of the Virtual Reality environment: The user has zoomed in on the Xin River catchment with the river and its tributaries visualised in light blue. Flood hydrographs linked to gauging stations upstream, midstream and downstream (all marked in white) have been opened for further analysis.

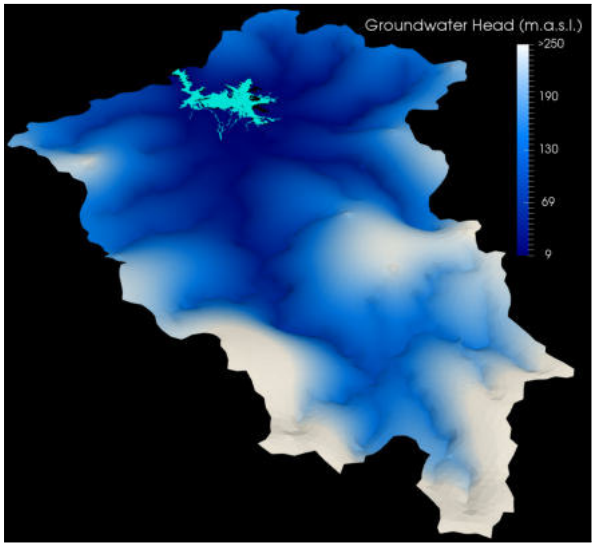


(a) Flow direction and velocity

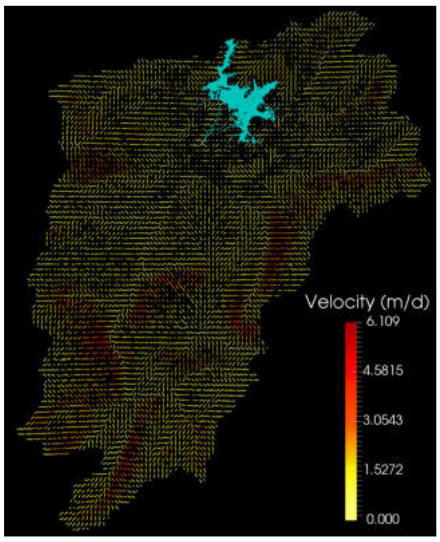
(b) Total nitrogen concentration

(c) Surface area

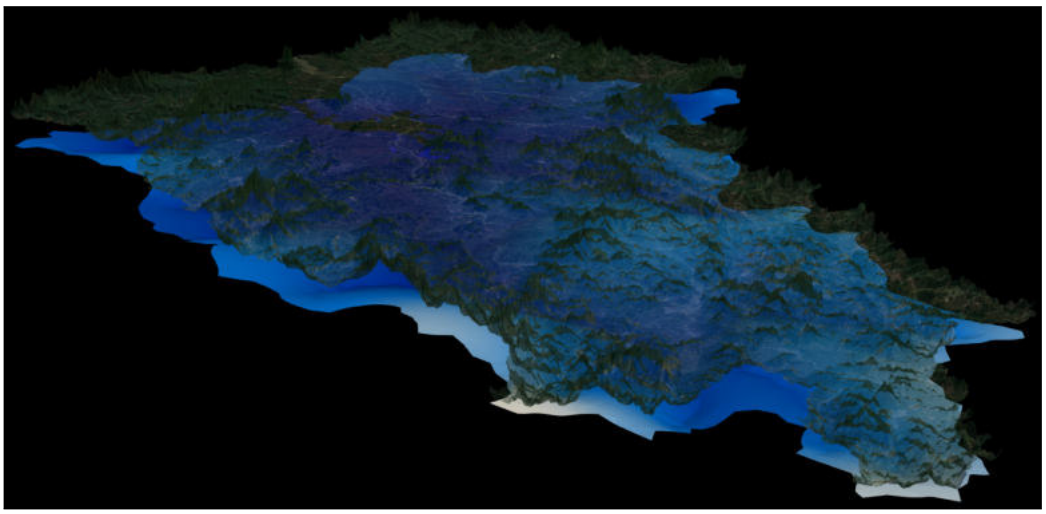
Figure 5: Results of the hydrodynamic model of Poyang Lake developed by Du et al. (2018). **(a)** shows flow direction and velocity of the lake water using trajectories. Observation sites for measuring water quality (green and purple) as well as eutrophic sampling sites (orange) are included in the visualisation scene. **(b)** visualises the distribution and concentration of total nitrogen in the lake. **(c)** illustrates the variation of inundated wetland area in Poyang Lake between May (red) and September (yellow).



(a) Groundwater head (superelevated)

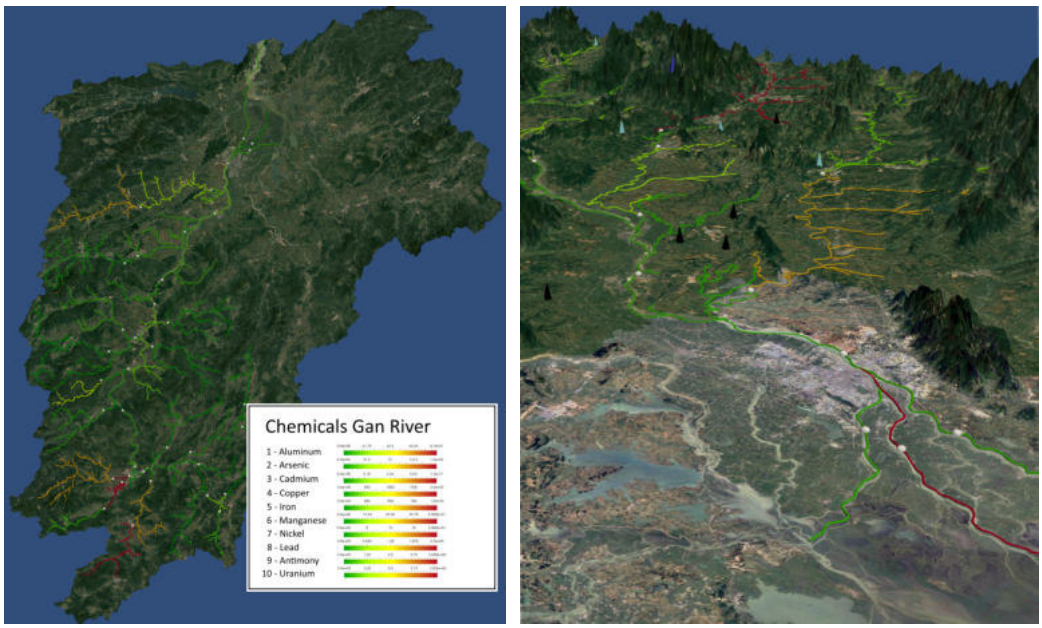


(b) Groundwater flow and velocity



(c) Combined visualisation of groundwater head and surface data

Figure 6: Results of the groundwater flow simulation (Nixdorf, 2018).



(a) Manganese concentration

(b) Lead concentration

Figure 7: Concentration of various metals in the Gan River network. **(a)** Top-down view of the manganese concentration in the river network. Measurement sites are marked in white. Also visible is the overlay showing the legend for the included metals, where green indicates a low concentration, yellow the recommended limit for drinking water and red the critical concentration for drinking water. **(b)** Isometric view westward from Poyang Lake (visible at the bottom). Colours indicate the lead concentration. Cones are marking coal- (black), iron- (light blue) and tungsten-mines (dark blue) located in the region.

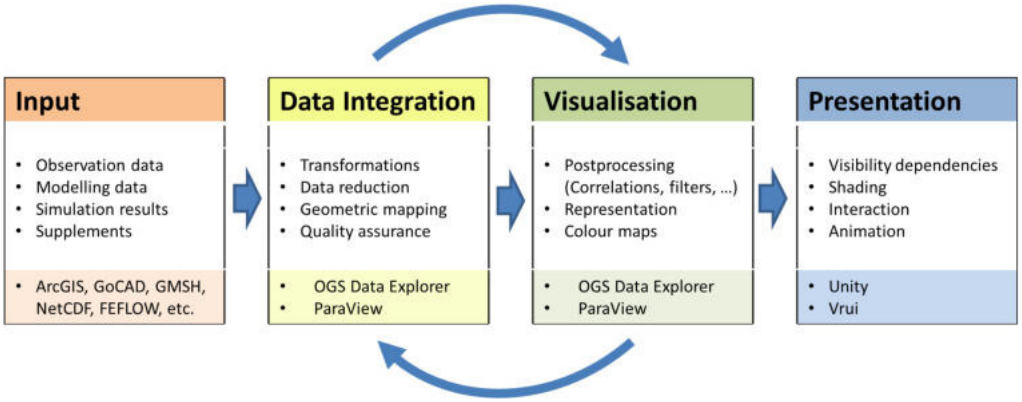
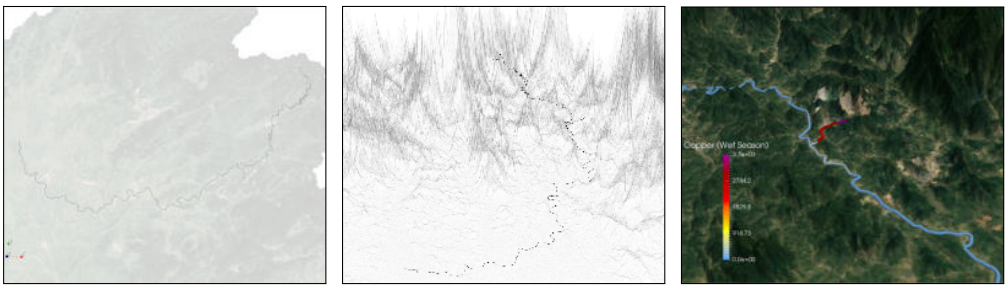
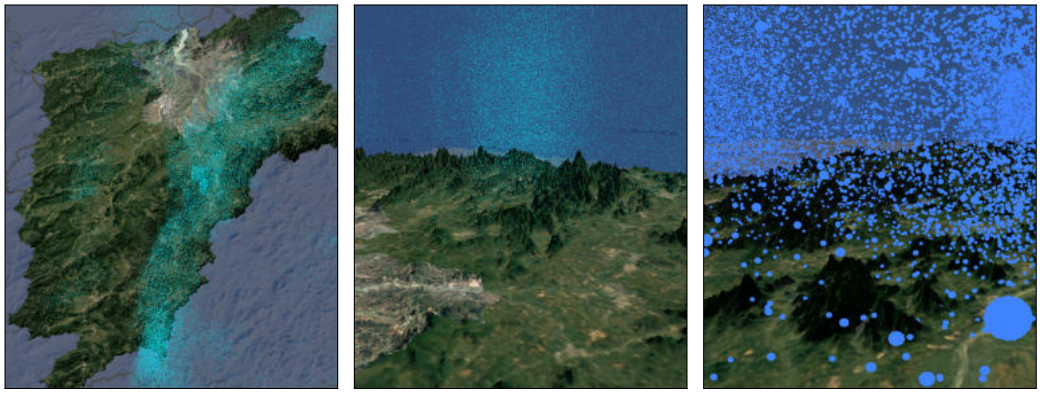


Figure 8: Data life cycle for Virtual Environments for Earth system modelling.



(a) Original data (b) Mapped & superelevated (c) Processed & added data

Figure 9: Exemplarily application of data integration for Le'an River: (a) The original dataset is georeferenced to fit the geographic context, (b) unneeded points are removed from the dataset and polylines are mapped to the digital elevation model (shown here is a 40× super-elevation to illustrate the effect), (c) the dataset is stylised as a tube to be easily visible within the context and given an intuitive colour. Data representing copper-concentration in the river is added and subsequently visualised using a manually adjusted transfer function.



(a) Top-down view (b) Rendering as points (c) Rendering as discs

Figure 10: Visualisation of rain events via a time series of point clouds derived form meteorological raster data. Two approaches have been tested: a simple rendering of points is shown in figs. (a) and (b), whereas points have been rendered as small discs in fig. (c).

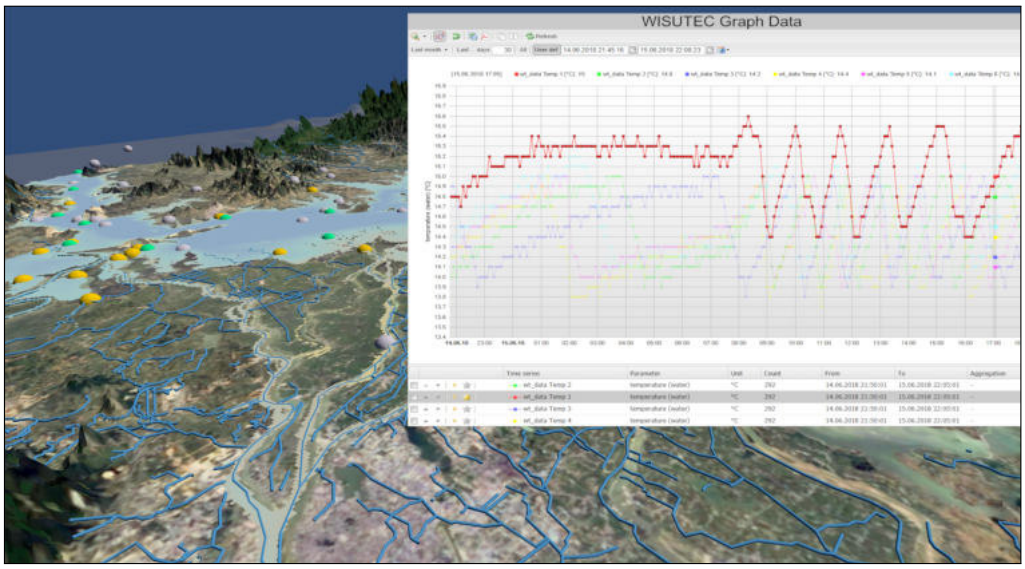


Figure 11: Visualisation of sensor measurements via on-line access to the AL.VIS/Timeseries framework.

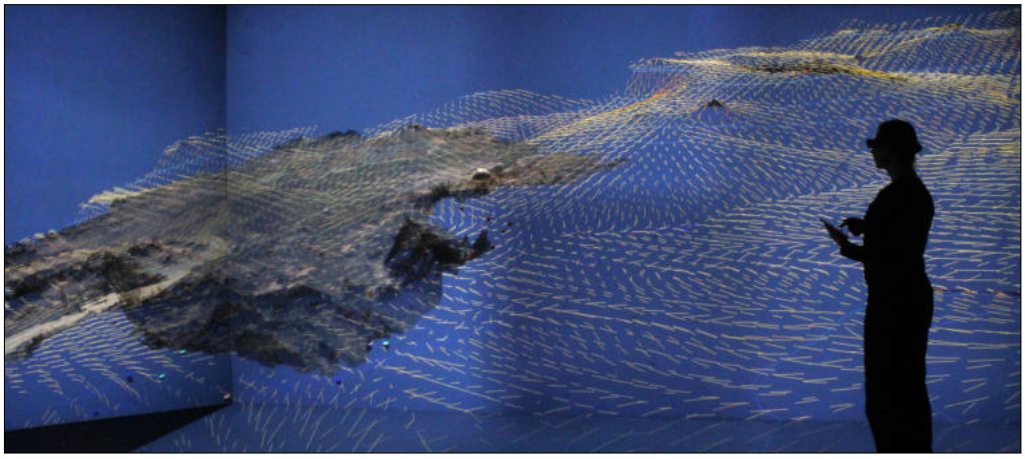


Figure 12: Data analysis of groundwater and lake data in the virtual reality environment.