Engineering 5 (2019) 828–832

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

Environmental Information Systems: Paving the Path for Digitally Facilitated Water Management (Water 4.0)

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1. Introduction

The availability of reliable information describing our natural and anthropogenic environment—and its changes in particular—is crucial for understanding the complexity of structures and processes within environmental systems. Modern remote sensing and monitoring methods provide an increasing amount of environmental data that can be used for a variety of management purposes [1,2]. In the past, geographical information systems (GISs) were widely used to collect and present data within a geographical context for various purposes, particularly in order to combine information from different fields, such as the environment and health (see Refs. [3,4] for two examples). In addition, web-based tools have been linked to GIS methods for the online availability of data [5]. Attempts to build information systems for various purposes are not new; for example, in the 1990s, so-called expert systems were designed for the management of environmental data [6]. Mainly driven by comprehensive databases, these expert systems were hampered by missing concepts and tools for collaborative work, as well as by technical restrictions at that time.

General research on environmental information systems (EISs) started about a decade ago, underpinned by political commitment such as the request for shared EIS by the European Commission, which aimed to facilitate regular environmental assessments and state-of-the-environment reporting [7]. Gu et al. [8] proposed a virtual environment to support decision-making processes based on Water Flow Model for Lake Catchment (WATLAC) lake simulation results. Melville [9] presented a research agenda on information systems for environmental sustainability scenarios. More recent works deal with the development of EIS, such as for precision farming in agriculture [10], the linking of terrestrial and marine environments along coastal systems [11], the economy [12], and investigations on the effect of information uncertainty [13].

Recently, a number of works have appeared concerning extensions of the EIS concept to address socioeconomic aspects and data policies [14]. Jung E and Jung EJ [15] introduced an EIS for decision-making and assessing the impact of natural disasters in Korea. They integrated the EIS through a service-oriented architecture (SOA) in order to use the EIS approach on different scales, such as nationwide and in selected regions. Moreover, a number of new comprehensive works on EIS fundamentals have been published 2018 [16–18], underpinning the growing overarching awareness of this topic within the scientific community.

Most of the approaches mentioned above extend standard GIS functionality by adding approaches from data management or information visualization. However, this type of approach ignores the fact that complex hydrological systems consist of transient three-dimensional (3D) processes.

In contrast, employing virtual geographic environments (VGEs) for data exploration, analysis, and decision-making takes the complex nature of the data into account. Su et al. [19] developed a real-time, dynamic, and interactive 3D visualization framework for large-scale marine water environmental data. The utilization of virtual reality (VR) methods to render environmental processes in a more realistic geographical context [20,21] is a logical conclusion with respect to the nature of the hydrological or atmospheric input data, the multi-variate nature of the parameter space, and the need to explore and understand both observational and simulation data in order to design water management concepts. In this context, scientific visualization plays an important role, particularly for data validation, when integrating and combining heterogeneous information from various data sources [22–24]. VGEs can be applied for operational aspects in hydrology and water resources management such as water scarcity identification [25], early flood warnings [26], and water pollution control [27].

The ongoing big data debate is focusing attention on the use of information science in many domains, including environmental science and technology. Big data and the associated Industry 4.0 paradigm are, therefore, accelerating the process of building meaningful information systems, and are also invoking concepts such as machine learning and artificial intelligence in order to further improve the value of data.

https://doi.org/10.1016/j.eng.2019.08.002

The concept of EIS goes far beyond the established use of GIS to present existing data in a geographical context. The EIS concept includes the ability to predict changes within our environment using a continuous data stream for model validation. In addition to conceptual work on EIS, the technical development of tailored workflows for the optimal usability of available environmental data for a specific purpose is of great importance.

2. Methodology

The development of a corresponding "Water 4.0" framework [28,29] is a somewhat new topic that has been presented at conferences in both information and environmental sciences [30,31].

The present work contributes to both ① further developing the concept of cyber–physical systems (CPSs) and ② demonstrating their application for two challenging water management case studies in the Chaohu Lake and Poyang Lake watershed within Sino-German cooperation projects [32,33].

The concept for digitization in water resources management is illustrated in Fig. 1. The real water system is represented by a so-called "digital twin"—the virtual water system (VWS)—which must contain all important characteristics and features of the real system, depending on the specific purpose for application. As an example for the first case study (Section 3.1), the VWS includes the existing infrastructure of the water supply and wastewater treatment. In order to obtain ongoing information, it is essential for the virtual system to include interfaces to real-time monitoring and remote-sensing information. The VWS needs two main capacities: algorithms for ① continuous data integration (including online data) and for ② modeling of hydrological processes (quantity and quality) to forecast the behavior of the water system. This includes both short- and long-term predictive algorithms for fast and slow processes, respectively, such as the sewer network, flooding, and groundwater. To be specific, the VWS needs to represent feedback between surface and subsurface aquatic compartments in order to be a meaningful digital twin for both operational and long-term water management purposes. Automated control of water infrastructure is one of the practical challenges of the Water 4.0 concepts. VWSs, which capture all the important features of a real water system, are an important prerequisite to achieve this goal.

Scientific visualization plays a key role in the VWS concept during the integration of large amounts of heterogeneous environmental data within a realistic geographical context [22], and when addressing aspects of uncertainty in both data and models [34].

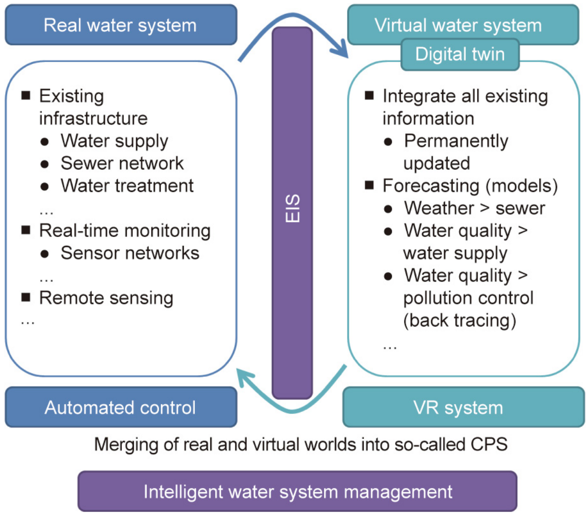

Fig. 1. Concept of building an EIS for water-supply purposes. ">" means affecting.

3. Demonstration examples

In order to illustrate the methodology introduced above, we present two demonstration examples dealing with water resources management: ① the case of Chaohu Lake, involving water supply for a fast growing city, and ② the case of Poyang Lake, involving the safeguarding aquatic ecosystems.

3.1. Chaohu EIS

The EIS for Chaohu Lake (Chaohu EIS) is dedicated to water supply purposes, as the city fully depends on Chaohu Lake as its main water resource. The challenge for this EIS was to combine data and processes for three aquatic compartments: the lake, the urban water system, and the groundwater. Fig. 2 [32] depicts the corresponding workflow for data collection from the available monitoring devices. Data integration includes both hardware (SensoMaster[†] [35]) and software components (the AL.VIS[‡] [36] web interface for data visualization). The entire workflow is embedded into a 3D VR environment[††] [37] (OpenGeoSys DataExplorer, Fig. 3 [32]).

Visualization is an important tool for realizing EISs. The structure and complexity of the data requires a realistic geographical context and the possibility for interactive data exploration [38,39]. The final product is built using Unity [40], to ensure a fully functional, interactive, and platform-independent application for both personal computers and VR environments such as head-mounted displays or video walls. Detailed information on the Chaohu EIS can be found in Ref. [32].

3.2. Poyang EIS

The EIS concept is very flexible for addressing several aspects of water management at different scales. A prototype of an EIS for Poyang Lake (Poyang EIS) was developed in order to represent hydrological processes in the Poyang Lake Basin, such as the seasonal variations of the lake area due to the complex runoff-generation processes in the catchment and the interaction with the water-level dynamics of the Yangtze River (Fig. 4) [41].

Forming a highly dynamic lake–river–wetland system of unique size, Poyang Lake hosts exceptionally high biodiversity and provides a wide range of habitats supporting species that include rare migratory birds [42,43]. As a part of the lower Yangtze River Basin, the lake's aquatic ecosystems are very sensitive to the water-level changes of the river itself. Analyzing the lake's resilience has become very important with regard to large water construction measures along the Yangtze River, such as the Three Gorges Dam or the South-to-North Water Diversion Project. High-precision EISs can be used for both planning purposes and environmental impact assessments. The Poyang EIS integrates hydrometrical data on water quality and quantity from gauging stations in the river network, numerical model results on the water level and flow characteristics of the surface water body and the interacting groundwater in the wetlands, and remote-sensing-derived hydrological information into one system for the scale of the entire Poyang Lake Basin (162 225 km^2). More information on the Poyang EIS can be found in Refs. [41,44].

[†] From AMC—Analytik & Messtechnik GmbH Chemnitz.

[‡] From WISUTEC Umwelttechnik GmbH.

[††] From Helmholtz Center for Environmental Research (UFZ).

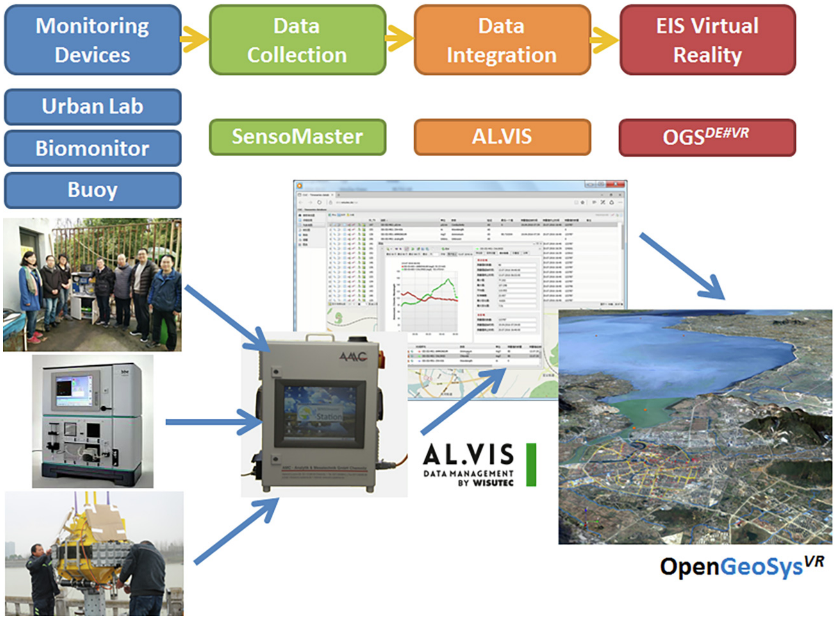

Fig. 2. Chaohu EIS data workflow. Reproduced from Ref. [32] with permission of Springer Nature Switzerland AG, © 2019.

Fig. 3. Chaohu EIS: showing Chaohu City with its infrastructure; for given data points online photos and simulation results can be interactively displayed. Reproduced from Ref. [32] with permission of Springer Nature Switzerland AG, © 2019.

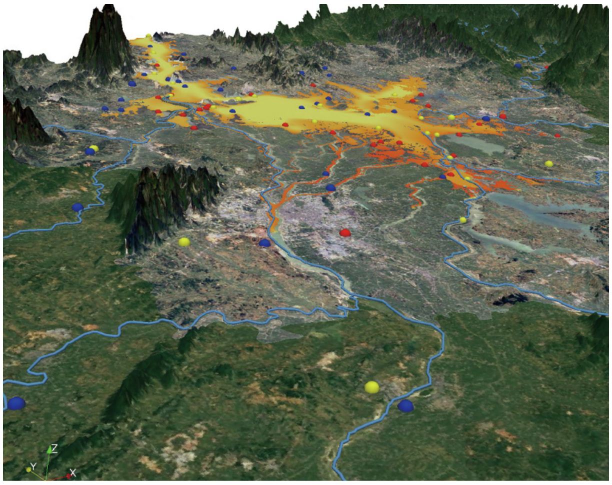

Fig. 4. Poyang EIS: showing water quality aspects (colored water body) as well as observation and measurement locations (colored spheres) [41].

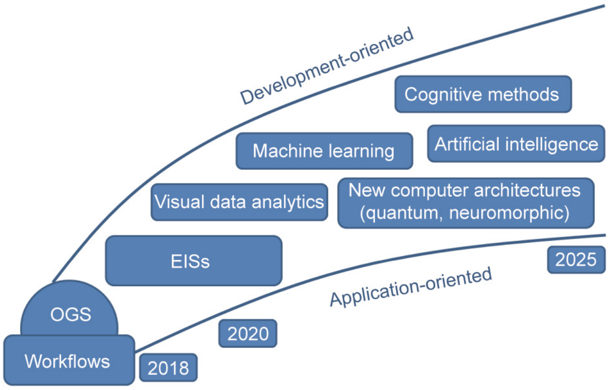

Fig. 5. EIS perspectives. OGS: OpenGeoSys.

4. Concluding remarks and perspectives

Water 4.0 mainly focuses on the automatic operational management of water systems for the control and optimization of existing infrastructures. The realization of this concept is still in its infancy. Practical case studies are important in order to prove and further advance the general concept. The success of Water 4.0 concepts will depend not only on progress in computer sciences, but also—and mainly—on the involvement of practitioners, stakeholders, and policy makers.

The concept of EISs relies on Water 4.0, but goes one step further concerning the predictability of hydrological environments by including established modeling tools as well.

Fig. 5 depicts a perspective from the viewpoint of the analysis platform OpenGeoSys [45], where workflows have been implemented for various environmental applications, including urban energy infrastructures (i.e., geothermal systems [46–48]), hydrological applications [49,50], and waste management [51]. Future applications will benefit from the exploration of modern concepts from information science and technologies, such as visual data analytics, machine learning methods, and artificial intelligence.

New developments in computer hardware need to be taken into account in order to use the available computational power for more refined and precise process simulations (e.g., exascale computing). As such, the development path needs to be guided by both development- and application-oriented principles.

Combining environmental sciences with information technology—through EIS and Water 4.0 concepts and particularly through application studies—will further pave the way for digitally mediated water management, and is a promising new research field for the Sino-German cooperation in environmental research [52].

Acknowledgements

The material of the paper is based on a keynote speech at the International Summit Forum of the Chinese Academy of Engineering (CAE) on Water Pollution Control from 2018 October 24–25 in Hangzhou, China. We are very grateful to the Chinese Research Academy of Environmental Sciences (CRAES) for their kind support concerning the conference attendance. The authors also greatly acknowledge the financial support from various grants: the German Federal Ministry of Education and Research (BMBF) for funding the Chaohu Lake project in the frame of the Chinese Major Water Program (02WCL1337A-E), the Sino-German Center for Science Promotion (CDZ) for the Poyang Lake project (GZ1167), the Helmholtz Association for supporting the establishment of Center for Environmental Information Science (HIRN 0002), and the Chinese Academy of Sciences (CAS) for providing support to various activities through the CAS President's International Fellowship Initiative (PIFI).

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