Application of Big Data and Technologies for Integrated Water Resources Management - A Survey

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***Abstract* – Problems related to water are of highest relevance, and their importance is likely to increase in future. Tools of Integrated Water Resources Management (IWRM) address those problems. New technological developments on various fronts, concerning measurement, data transfer and storage, as well as data processing, modeling and visualization enable the advanced use and application of IWRM tools. Mainly we provide an overview on the development in various fields of IWRM and briefly include information about an ongoing project that involves some of the new technologies, in particular the long-range wide area network (LoRaWAN) for data transfer from hydrological sensors.**

Index Terms* – *Integrated Water Resources Management (IWRM), Big Data, Smart Technologies

I. Introduction

Water has been termed the blood of the earth [1]. In the very beginning of human civilization the management of water resources has been the driving force of technological, societal and administrative development [2]. Since then the hydro-sector has played an important role in technological progress and will do so in the future. As limited water resources are threatened by climate change and growing competition its relevance is even likely to increase [3].

Water is a key component in the UN-sustainable development goals [4]. Aside from the 'Clean Water and Sanitation' target, where water is directly addressed, water is also crucial for Target 11 ('Sustainable Cities and Communities') and for Target 13 ('Climate Action'). In order to reach those targets tools for integrated water resources management (IWRM) are most important [5,6], in their current state, and even more how they develop further dealing with big data.

The Global Water Partnership (GWP) defines IWRM as a process, which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment [7]. 'IWRM promotes the way forward for efficient, equitable, and sustainable development and management of the world's limited water resources and for coping with conflicting demands. Implementing IWRM at the river basin level is an essential asset in managing water resources more sustainably leading to long-term social, economic, and environmental benefits' [5]. However, understanding IWRM as an end in itself has been criticized [8,9]. As IWRM is a broad process, requiring change in multiple sectors and at multiple levels, there is no specific blueprint that can be applied to any given situation [10].

Here we focus on the technical side of IWRM. From the viewpoint of hydrology the key of IWRM is the concept that water and other environmental compartments cannot be considered as isolated, but have to be understood being connected. This holds especially for the various hydrological compartments as surface water, seepage and groundwater, which are connected with the humidity of the atmosphere. The combination of the water compartments is the key component of the technological aspects of IWRM. Surface and subsurface water are connected [11,12,13,14]. Both these compartments have to be conceived as a single water body. This holds even more if technical installations of IWRM like constructed wetlands or managed aquifer recharge with treated wastewater connect the surface and the sub-surface [15]. Moreover, anthropogenic recharge sources as leaky utility lines, storm sewer systems and storm-water catchments can be significant [16,17,18], as well as over-irrigation of lawns, parks, and golf courses [19].

Draught risk and flooding, also flash floods, are topics of high relevance addressed by IWRM [20,21,22,23]. IWRM deals with issues on water quantity as well as on water quality [24].

IWRM tools have to deal with the supply and distribution of water, but also with wastewater, stormwater, flood and draught management, with seepage through the soil and groundwater. Depending on the site in question hydropower and irrigation [25], as well as technical installations as dams, managed aquifer recharge, or constructed wetlands may have to be considered by IWRM. Ecosystem preservation is a target, directly connected with water availability. In order to cope with the different and sometimes competing requirements of the various activities, a cooperated and synchronized approach is needed.

Big data has become a 'buzz-word' in science and industry [26], which is not clearly defined. However, it not only concerns the database and the pure amount of stored information [27]. It also includes the technologies that are used to produce the data sets and thus enable big data. Thus we maybe better speak of big data technologies [28]. Among those technologies are remote sensing, geo-information systems (GIS), smart sensors, network technology, hard- and software development, etc. Following recent terminology we will refer to these also as smart technologies, and deal with those briefly in the sequel. The aim of the tools is to enable and support well-informed decision-making and problem solving.

II. Data

We distinguish between parameters and variables, which is especially relevant from the perspective of modelling. As models play a crucial role in the entire concept, it is convenient to generalize the distinction. For specified values of parameters models calculate distributions of variables. For models parameters are thus input values, while variable distributions are computed and are thus output values of models (see below III.E).

Typical variables and parameters in hydro-systems are:

- surface water table
- air pressure
- humidity
- rainfall
- evaporation
- wind speed
- wind direction
- groundwater table
- temperature
- concentrations
- pH
- turbidity
- alkalinity
- organic matter content
- total dissolved solids
- redox state
- soil water saturation

The latter parameters are all related to the chemical, biochemical or biogeochemical characterization of water. Concentrations of specific chemicals have to be considered in case of pollutions.

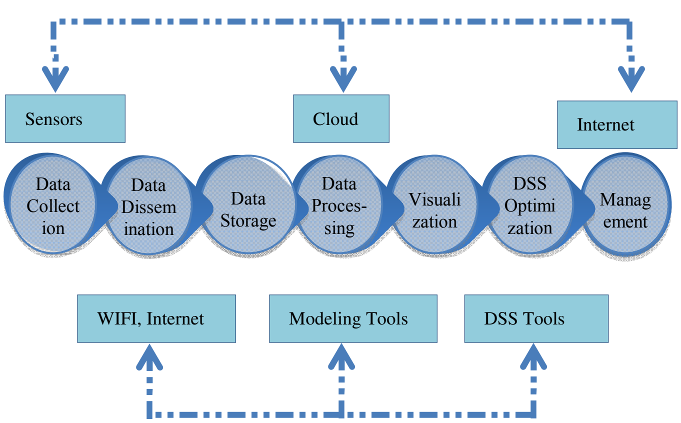

Fig. 1. Schematic representation of IWRM technologies and tools, modified from [29]

III. Smart Technologies

Smart technologies concern monitoring and collection, data dissemination, storage and organization, data processing, visualization, decision support (DSS) and management. The sketch in Fig. 1 illustrates the order, in which the different tasks appear, the tools and where they operate.

A. Monitoring

Monitoring is an essential prerequisite for all following steps of IWRM. Variable values need to be measured with sufficient frequency, and then transferred and stored. Smart sensors nowadays automatically measure variables, and store time-series locally. Different variables may vary on very different time scales. Meteorological parameters may change after some minutes, while the water table of a river is usually constant over hours. Groundwater tables and temperatures only show changes from one month to the next. Thus there may be long periods in which the parameter is marginally changing. Smart sensors report changes only, if a relevant change of data is observed.

For smart management within a watershed or sub-watershed a sufficient and comprehensively distributed network of sensors for various variables or parameters needs to be installed [30]. An example set-up of a smart monitoring network for measuring water quality is reported from India [31]. A detailed description of a smart network for aquifers can also be found [32]. Special sensors for monitoring aquifer conductivity are currently in development [33]. Sensor networks can collect real-time data and transfer them using low-cost innovative communications and protocols (see below III.C).

The size of a sensor network is limited, due to practical, operational or financial reasons, making remote sensing an alternative option.

B. Remote Sensing and Satellite Data

Remote sensing is based on the measuring of the upwelling electro-magnetic radiation from the land surface [34]. From these measurements spatial distributions of parameters or variables are derived. The measurements are obtained airborne by airplane flights or from satellites. As satellites circulate around the earth in a repeated course, the latter option offers the possibility to obtain data about the temporal change of a distribution.

The hydrological variables for which distributions are obtained by remote sensing are:

- Precipitation
- Surface soil moisture
- Surface skin temperature
- Snow cover
- SWE (snow water equivalent)
- Water level
- Evaporation

Moreover water quality data can also be obtained. From different space missions more and more remote sensing data are available every year to obtain distributions of the mentioned variables [35,36]. The data from the different missions differ in spatial and temporal resolution, and in public availability.

Users of satellite data have to take into account that satellite data of hydrological entities have undergone a calibration and validation process, in which their output is compared with some field measurements. This procedure has some inherent problems, as one time areal observations are compared to temporarily resolved data at a point. For satellite precipitation products (SPP) extensive review studies on this comparison are available [37,38].

C. Data Transfer

Measured data have to be transferred to a database for storage. In smart technical solutions that is usually performed via wireless data transfer. The communication between sender and receiver can be organized via cloud indirectly or directly to a central data management unit. Dissemination of data can also be performed using radio transmitters or other wireless technology, one of which is the long-range wide area network (LoRaWAN).

LoRaWAN [39] it is a private and spread spectrum modulation technique that allows sending data at low rates to long ranges. It includes a network layer to send data to any base station connected to a cloud platform. The wireless connection extends up to 10 km range, which is a significant advantage over the other wireless technologies like bluetooth that operates only over few meters. LoRaWAN is a low powered system that is supplied either by small solar panels or by batteries. Using LoRaWAN it is feasible to have different devices shared to a single hub. LoRaWAN may be the best choice in areas, where a cellular signal cannot be found constantly and a modem will not operate.

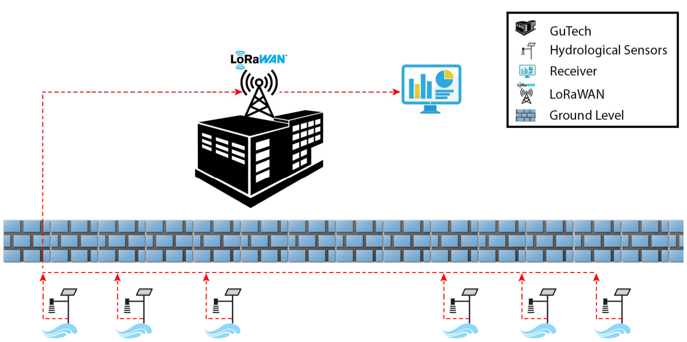

Fig. 2. Concept of long-range wide area network for hydrological sensors

The sketch in Fig. 2 illustrates the concept of LoRaWAN of hydrological sensors that is currently set up at the GUtech university campus. The server and gateway are installed at the roof, to which sensor stations at different locations in a radius of 10 km can connect. The hydrological parameters measured are: air pressure, groundwater table, groundwater electrical conductivity (salinity) and groundwater temperature. It is aimed to include further and different sensors and stations in the network, in order to demonstrate the feasibility of the set up for environmental sensor networks [40].

D. Storage and Organization

There are various storage options for the measured data. Cloud storage surely has advantages concerning the accessibility from arbitrary locations, however issues of security, privacy and ownership of data should be clarified prior to massive deployment of cloud storage and computing [41]. For security and backup reasons data have to be stored somewhere at least at two locations.

A central data management facility is not necessarily required. Network solutions are probably easier to realize, as different organizations are usually involved. In any case the data and communication should be organized in a way, that all measured data can be accessed by all certified users with different types of end user facilities, i.e. by the technician in the field for online monitoring, the modeller for connecting the simulation software with the database, as well as someone from the managing department.

In BIG data the problem of standardization becomes relevant, because commonly several different institutions are involved in the management of hydro-resources, that in the course of their history have developed different data standards. In many administrations hydrological data are located in various different branches of the local, regional and state administration. Ministries responsible for water, for the environment, for irrigation, for urban development, etc., gather, store and administrate data. In order to utilize big data, different databases have to be combined and modified according to a common standard. Only then the IWRM technologies are enabled to deal with competing interests in the water sector appropriately. Bai *et al.* [42] describes problems related to data standardization in China, which can serve as an example for the problem in general.

E. Data Processing

Data processing includes tools of various complexities, ranging from simple plausibility checks to sophisticated modelling. Statistical methods operate directly on the measured datasets. Outliers can be filtered out and missing data added. Accidental, biased and gross errors can be corrected by semi-analytical mathematical methods using autoregressive models [43].

Modelling tools operating with parameters and observed data are developed for various purposes. Most numerical methods deliver spatio-temporal distributions of variables. One may distinguish between conceptual (empirical models) and physically based models [36]. The latter are performed solving partial differential equations, which are derived from basic principles of physical laws: the shallow water Saint-Venant equations for overland water flow [44] and Darcy's Law for groundwater [45].

Flow models concern flow of water on the earth surface, and following the concept of integration, may include infiltration and seepage through the unsaturated zone and of groundwater in aquifers. On the spatial scale models usually operate on watersheds or sub-watersheds [5]. The temporal scale varies significantly with the purpose. Flood events are simulated for periods of days or weeks, using time-steps as small as minutes [46]. Changes of long-term water balances, for example caused by global warming, deal with years or decades.

If water quality is addressed the transport of contaminants or other chemical or biochemical species has to be considered. Transport models are usually linked with flow models and consider various simultaneously operating processes, as advection, diffusion and dispersion, decay and degradation, as well as ad- and absorption, etc. A case study on water quality modeling for sustainable wastewater management illustrates the case [47].

Calibration is an important step towards a valuable model set-up. Within the IWRM framework calibration is performed using observed data from the database. Values of parameters are determined by a fitting procedure in an inverse modelling procedure. Measured values of variables are used as input parameters, while parameter values are obtained as output – in comparison to usual (forward) modelling the role of variables and parameters is exchanged. The computer implementations for inverse modelling utilize forward modelling tools, minimizing the 'error' between measured and modelled variable values and thus solving optimization problems [48,49].

Real world measurements contain errors both due to the accuracy limit of the sensor and due to inaccuracy concerning the position of the measurement, which have to be taken into account in the model calibration. The simple consideration of a measured value thus does not make and may even cause instabilities in the models. In the method of data assimilation measurement errors of all type can be taken into account, assuming a statistical error distribution [36,50]. Assimilated data typically include the measurements and previous forecasts. Stepping iteratively from one time instant, at which measurements are available, to the next, this way of calibrating accumulates information from past observations into later forecasts.

Models that are calibrated on assimilated observed data allow scenario calculations and may deliver valuable predictions. In order to test the validity of a model, numerical results for a time period, that was not included in the calibration process, are checked with field measurements. One speaks of a validation test, and if the fit is good, the model is qualified as validated. Different variants of validation, graphical as well as statistical, have been classified in a more detailed study [51]. For both calibration and validation the issue of performance measures is highly relevant. An extensive study on hydrological models led to the recommendation of combining graphical and statistical measures and to the formulation of guidelines, including performance thresholds [52].

F. Visualization

Big Data deliver huge datasets. Continuously operating sensors deliver long time series. Remote sensing and models produce variable values for a large number of nodes within a grid or mesh. In order to obtain an understanding, the data have to be visualized.

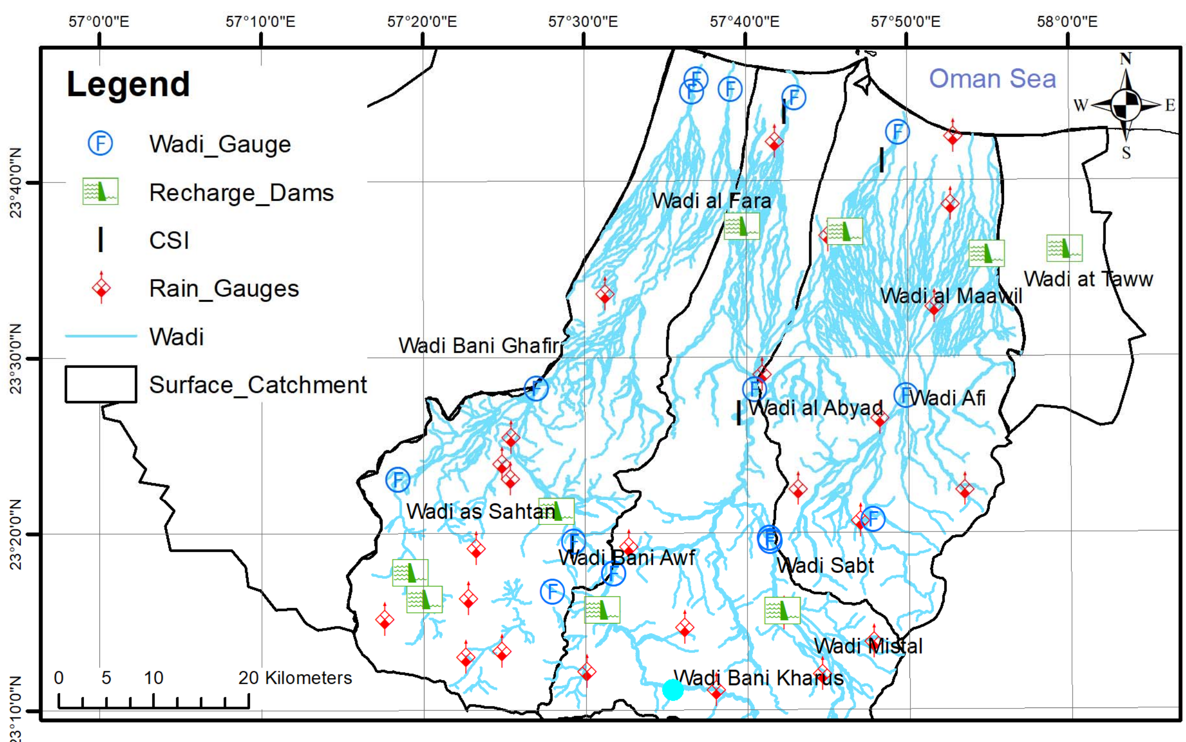

Fig. 3. GIS illustration showing wadis Fara, Bani Kharus and Maawil in Al Batinah (Oman), watershed boundaries and measuring stations

Geo-information systems (GIS) have become a common tool to present spatially distributed variables in geographical maps. Nowadays GIS is a standard state-of-the-art tool for presenting IWRM options and/or results. An example from the authors' project is given in Fig. 3. For the South Batinah region in Oman depicted are: watersheds with their boundaries, wadi channels, recharge dams and water treatment facilities (CSI). Regular measurements are taken at wadi and rain gauges, shown in the map, by the Ministry of Regional Municipalities and Water Resources (MRMWR) of Oman. Time series of past measurements are available from the MRMWR on request.

GIS requires data that are related to geographical coordinates. Ki [53] distinguishes between GIS and Big Data visualization, but recognizes also an overlap between them. In mathematical packages, like MATLAB or R, algorithms are developed and improved that enable advanced options for big data visualization in which the geographical component is missing.

Aside from the mentioned tools for general data visualization, there are special illustration options of specialized software. For example tools for numerical modelling are equipped with methods to produce appealing output, showing colour maps, contour plots, streamlines, flowpaths and/or velocity fields.

G. *Decision Support and Optimization*

Final aim of big data and IWRM tools is to support well-informed decision-making. In order to do so data and tools have to be available to decision makers. Software tools, so-called decision support systems (DSS) are developed for this special [54]. 'Information technologies can act as technical artifacts and can facilitate stakeholder communication, supporting decision making in a complex societal context' [55].

Decision makers mostly have to choose between various alternatives. Thus the costs and various consequences of the alternative options need to be known and evaluated. Validated models can be used to simulate alternative options, simulated in various scenarios. The evaluation of the model output can provide key information for decision makers. A study on riverbank filtration [56] and a review on the Nile basin [57] demonstrate the operation of a DSS on the local and on the catchment scale.

H. *Software Integration*

In order to connect the various computational components, related to the above mentioned fields integrated software architecture has to be designed and installed. Several approaches have already been proposed [58,59]. The latter introduce an integrated information system (IIS) for regional environmental monitoring and management based on Internet of Things (IoT). The IIS demonstrates a new paradigm also for the integration of big data in IWRM. Current and future developments of the IoT are surely crucial to make data from the physical world available for resources management tasks. The architecture has to fulfil two requirements. It has to be based on the data structure of the real world components, like sensors and smart phones (1), but also to take into account the needs of the end-users (2) that may be very different. An example: for long-term water resources management it may be sufficient to have monthly or yearly averages of the relevant variables, while flood management at peak time relies on time steps in the scale of several minutes. Due to the transient state of development in all related fields it is probably impossible at current state to design an architecture and implement an integrated software system that fulfils all needs.

IV. DISCUSSION

Smart technologies deliver tools for the integrated management of the hydro resources. They offer the chance to compare options, to balance between competing interests and to come to well founded decisions.

Advanced technical tools for IWRM are currently available or are in development. Smart sensors are available that can be combined to powerful networks. More and more satellite data can be accessed, partially without any charge. Wireless communication and cloud storage of big data enable that powerful tools for modelling, simulation and visualization can be utilized. Finally these can be integrated in tools for decision-making and optimization. In all of these areas the technologies, methods, hard- and software are in rapid development.

Regarding the current state of development the technology is probably in its early phase, related to its inherent potential for solving problems connected with water resources management.

Exploiting the full potential of the big data and IWRM connection is probably less a problem of technological innovations and development, but more a problem of society. Technical options as outlined here will only be successful, if legal, political, economic and cultural conditions are met [7,60]. It seems to be more difficult to gather various interests and to convince different interest groups to work towards a common goal. However the various stakeholders will be less reluctant to change, if attractive tools are made available from the technical side. Major challenges in this respect are [36]:

- Collect easily real-time data and measurements through sensor networks and low-cost innovative communications and protocols.
- Make better-informed decisions through the use of advanced analytics, which translate the raw data into actionable intelligence.
- Improve the efficiency, performance and optimization of infrastructure through real-time management systems.

New components are developed in all fields within the entire information architecture. Data transfer from multiple sensors by LoRaWAN can contribute to the system as a cheap and reliable technology within its range. The authors will report about their findings after the installation of the network at GUtech is completed and working experience has been gained.

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