A MULTI-DISCIPLINARY APPROACH AND TOOLS FOR COMPARATIVE AND IN-DEPTH ASSESSMENTS OF TRANSBOUNDARY AQUIFERS

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ABSTRACT

Groundwater is a vital source for drinking water, irrigation, industry and the sustainability of wetlands, springs and river flows. In recent decades, groundwater use has increased tremendously. Climate change and population growth are likely to result in a further increase in groundwater use. To sustainably manage groundwater a good understanding of the resource and factors affecting it is crucial. Many actors have an impact on groundwater and to minimise disparity between those stakeholders it is important to provide stakeholders wide access to information on the resource. Assessing and sharing information on transboundary aquifers provides a particular challenge as it involves cooperation between countries which may have different approaches to assessing groundwater and different data protocols.
A methodology is presented for the assessment of transboundary aquifers; it covers hydro(geo)logical, socio-economical, environmental, legal and institutional aspects. Results can be presented as indicators for comparative assessments of multiple aquifers. In-depth assessment at the aquifer level provides relevant information to develop specific management actions. To facilitate dissemination of results between (international) stakeholders, a web-based Information Management System has been developed, which gives access to thematic maps and underlying data, enabling stakeholders to perform their own analyses in support of sustainable groundwater governance.

Keywords: groundwater, transboundary aquifers, assessment, information management, governance

1. INTRODUCTION

Water is a vital natural resource, contributing to human health and economic development and supporting many ecosystems. Groundwater plays an essential and increasing role in global drinking water supply and food security (Wijnen et al., 2012); it delivers about 50% of all drinking water worldwide (WWAP, 2009) and over 40% of all irrigation water (Siebert et al., 2010). Specific industries may also heavily depend on groundwater. Over-abstraction, contamination and degradation of recharge areas are threats to the sustainability of aquifers worldwide (Wijnen et al., 2012). The utilisation of groundwater is subject to socio-economic, institutional, legal, cultural ethical and policy considerations (UNESCO-IHP, 2000). Contamination of aquifers and degradation of recharge areas are similarly affected by these different factors. Responding appropriately to the demands and changes on groundwater resources therefore requires a holistic understanding of the groundwater system (Wagener et al., 2010). To provide such holistic or integrated understanding, assessment of groundwater systems has to take into account all relevant hydro(geo)logical, environmental, socio-economic, legal and institutional aspects as advocated amongst other by UNESCO-IHP (2001). Sustainable management of groundwater is the shared responsibility of diverse groups of stakeholders who use groundwater, may pollute groundwater or are affected by changes in the groundwater system. For all these stakeholders to act in an effective way and on an equal footing, they all require access to relevant information. Or as Wijnen et al. (2012) pose: "Information, knowledge and communications functions are essential components of groundwater governance".

Governance of transboundary aquifers is particularly challenging: Legal and institutional settings tend differ between countries, there is a multitude of governmental and non-governmental stakeholders and data are often fragmented and scattered. Since the launch of the Internationally Shared Aquifer Resources Management (ISARM) initiative (UNESCO-IHP, 2000), multiple initiatives have been undertaken to improve data and information on transboundary aquifers, like WHYMAP (2006), UNESCO-IHP (2009), UNECE (2011) and IGRAC (2015). But there was no systematic and internationally accepted methodology for the assessment of transboundary aquifers available. This is remarkable, since the quality of project results depends to a large extent on the science and methodologies used during the implementation of projects (Tujchneider et al., 2013). Neither have previous efforts been made to set up a system to store the results of assessments for sharing with stakeholders in such a way that the often complex geographic and socio-economic relations between factors become clear and stakeholders can perform their own analyses to define interventions.

In presenting a methodology for a multi-disciplinary assessment of transboundary aquifers together with a transboundary aquifer information management system, the authors hope to contribute to mainstreaming this approach to multi-disciplinary assessment and data sharing as a tool in support of sustainable governance of these vital fresh water resources.

2. MULTI-DISCIPLINARY ASSESSMENT METHODOLOGY

2.1 Objectives

Different assessments serve different purposes. Classic hydrogeological assessment includes describing the geometry and hydraulic characteristics of the aquifer, as well as the groundwater quantity, flow patterns and quality. This type of assessment is often executed to establish the development potential and aims to answer questions like 'what are favourable sites for new boreholes/wells?' and 'what are potential sustainable borehole yields?', or aims to analyse a specific issue like groundwater pollution. The multi-disciplinary assessment methodology we propose can be applied at two levels, each with its specific objective. The level 1 assessment, which is an indicator based assessment, enables comparisons between different aquifers at the regional or even global scale, and by doing so provide guidance when setting priorities for further research and/or interventions. The level 2 assessment is an in-depth assessment for individual aquifers and aims to provide the information needed to define specific interventions for that aquifer. Both levels of assessment make use of the same types of data:

2.2 Data to be collected

Data on transboundary aquifers are often very limited and difficult to obtain. Therefore the aim was to limit the data as much as possible to those data which are essential to describe the status of the aquifer. The data are grouped in the different multi-disciplinary themes (table 1).

Table 1: List of data to be collected, grouped in themes (from IGRAC, UNESCO-IHP, 2015)

	Parameters, variables and information to be collected	**P***
A – Physiography and climate		
A.1	Temperature**	1
A.2	Precipitation**	1
A.3	Evapotranspiration	1
A.4	Land use**, incl. groundwater irrigated agriculture, groundwater dependent ecosystems, etc.	3
A.5	Topography: Elevation data**	2
A.6	Surface water network**	3
B – Aquifer geometry		
B.1	Hydrogeological map	3
B.2	Geo-referenced boundary of the Transboundary Aquifer	1
B.3	Depth of water table/piezometric surface	2
B.4	Depth to top of aquifer formation	2
B.5	Vertical thickness of the aquifer	2
B.6	Degree of confinement	2
B.7	Aquifer’s cross section	3
C – Hydrogeological characteristics		
C.1	Aquifer recharge, incl. artificial and induced recharge, return flow from irrigation, extent of recharge zones and source of natural recharge.	
C.2	Aquifer lithology	3
C.3	Soil types	2
C.4	Porosity	3
C.5	Transmissivity and vertical connectivity	2
C.6	Total groundwater volume	2
C.7	Groundwater depletion	1
C.8	Natural discharge mechanism	2
C.9	Discharge by springs	2
D – Environmental aspects		
D.1	Groundwater quality – natural (suitability for human consumption)	1
D.2	Groundwater pollution – anthropogenic	1
D.3	Solid waste and waste water control, incl. waste water being collected in sewerage systems, waste water treated, solid waste being stored in controlled fields.	3
D.4	Shallow groundwater table and groundwater-dependent ecosystems	2
E – Socio-economic aspects		
E.1	Population (total and density)**	1
E.2	Groundwater use, incl. total volume groundwater abstraction, groundwater abstraction for domestic use, groundwater abstraction for use in agriculture and livestock, groundwater abstraction for commercial and industrial use	
E.3.	Surface water use, incl. total volume of surface water use, surface water for	

	domestic use, surface water use for agriculture / livestock, surface water for commercial and industrial use	
E.4.	Dependence of industry and agriculture on groundwater	3
E.5.	Percentage of population covered by public water supply	3
E.6.	Percentage of population covered by public sanitation	3
*F. Legal and institutional aspects****		
F.1.	Transboundary legal framework, incl. existence, scope and extent of agreement	1
F.2.	Transboundary institutional framework, incl. existence, mandate and capacity of institutions	1
*G. Implementation of measures – Law and regulations****		
G.1	Control of groundwater abstraction, incl. permits, fines, taxes, subsidies, awareness programmes etc.	2
G.2	Control of groundwater quality, incl. permits, fines, regulations, obligatory studies, awareness programmes etc.	2

* P: Priority. 1: data used to calculate core indicators (see table 2); 2 data used to calculate additional indicators (see table 2); 3 relevant data but not feeding into indicators.

** This type of information may also be available from global datasets

*** Methodology for legal, institutional and implementation is currently being revised by UNESCO-IHP.

2.3 Indicators to generate overviews and additional insights

Indicators have been designed to capture and categorise ‘primary concerns’ on groundwater, like maintaining the integrity of groundwater quantity and quality; optimal benefit from use and environmental functions of groundwater; minimal negative impacts of changing boundary conditions and ‘secondary concerns’ focusing on conditions for groundwater management and control like awareness, legal framework, plans and regulations, institutions, stakeholders attitudes, governance, etc., superposing the social impacts and responses for adaptation to climate change (UNESCO-IHP, IGRAC, WWAP, 2012). Table 2 lists the indicators which have been developed. A distinction was made between core (C) and additional indicators (A) to provide focus in situations where there is very little data available. The set of core indicators is considered to be the minimal required set to describe the most relevant aspects of the aquifers. The indicators are calculated from the data in table 1 with priority 1 (core indicators) and priority 2 (additional indicators).

Table 2: Assessment indicators (from: UNESCO-IHP, IGRAC, & WWAP, 2012)

#	Indicator*	c/a*
Defining or constraining the value of aquifers and their potential functions		
1.1	Mean annual groundwater recharge	C
1.2	Annual amount of renewable groundwater resources per capita	C
1.3	Natural background groundwater quality	C
1.4	Aquifer-buffering capacity	A
1.5	Aquifer vulnerability to climate change	A
1.6	Aquifer vulnerability to pollution	A
Role and importance of groundwater for humans and the environment		
2.1	Human dependency on groundwater	C
2.2	Human dependency on groundwater for domestic water supply	A
2.3	Human dependency on groundwater for agricultural water supply	A
2.4	Human dependency on groundwater for industrial water supply	A

2.5	Ecosystem dependency on groundwater	A
2.6	Prevalence of springs	A
Changes in groundwater state		
3.1	Groundwater depletion	C
3.2	Groundwater pollution	C
Drivers of change and pressures		
4.1	Population density	C
4.2	Groundwater development stress	C
*Enabling environment for transboundary aquifer resources management***		
5.1	Transboundary legal framework	C
5.2	Transboundary institutional framework	C
*Implementation of groundwater resources management measures, law and regulations***		
6.1	Control of groundwater abstraction	A
6.2	Groundwater quality protection	A

*: Full definitions of the indicators are presented in UNESCO-IHP & UNEP (2016)
**: The indicators on the enabling legal and institutional environment and the indicators on implementation of groundwater resources management measures currently being revised by UNESCO-IHP.

2.4 From problem recognition to policy implementation

The comparative indicator based assessment (level 1) provides a method to relatively easily get an insight into the status of aquifers and the most urgent issues which need addressing, based on limited amounts of aggregated data. The level 1 assessment is therefore suited to select priority aquifers and/or themes within a region. These priority aquifers or themes can be assessed in an in-depth level 2 assessment. As the level 2 assessment brings together detailed information on spatial distribution of parameters as well as time series, this in depth assessment is suited to locate and determine the extent of issues within a transboundary aquifer. Based on this, specific interventions to improve sustainable management and/or development of an aquifer (governance interventions) can be developed. Depending on the issues identified these interventions can range from management interventions (e.g. optimise irrigation to stop or reverse groundwater depletion), data acquisition programmes (e.g. monitoring groundwater use), to improving the enabling environment for groundwater management (e.g. setting up a transboundary joint management body, improving domestic legal and institutional capacity or improving stakeholder engagement). Table 3 summarises the relationship between the different levels of assessment and governance interventions.
Following this 3-phase approach, the knowledge on key characteristics of the transboundary aquifers is steadily improving as new investigations are carried out. In-depth assessment of an aquifer will unlock new information that can also be used to improve and update information for the indicators (level 1). In combination with repeated level 1 assessments the methodology thus also allows for a mechanism to analyse trends in the development of indicators over time, thereby enabling analyses of the effectiveness of governance interventions.

Table 3: Relationship between level 1 and level 2 assessments and governance interventions

Phase 1: Level 1 assessment	**Problem recognition**
	• Identification and basic characterization of transboundary aquifer • Aggregated data per transboundary aquifer and national segment • Comparative indicator based assessment

	Outcome: *Selection of priority aquifer(s) or theme(s) for further research and resource allocation*
Phase 2: Level 2 assessment	**Problem analysis/identification**
	• In-depth assessment of aquifer(s) • Joint fact-finding and assessment of the selected transboundary aquifer(s) based on spatially distributed data and time series (not aggregated) • Locate and determine extent of issues within a transboundary aquifer (either of transboundary nature or shared problems)
	Outcome: *Scientific and technical basis for interventions / actions*
Phase 3: Governance interventions	**Actions to improve sustainable management and development of the transboundary groundwater resources (governance)**
	• Agreements on criteria and targets • Transboundary Policy formulation • Joint monitoring programmes • Etc.
	Outcome: Policy implementation

3. CASE-STUDIES

The methodology has been applied in two projects; the Transboundary Water Assessment Programme (TWAP) and in the Groundwater Resources Governance in Transboundary Aquifers (GGRETA) Project.

3.1 Background on TWAP project – level 1 assessment

TWAP was an indicator based assessment of all transboundary waters of the world; from the open ocean and large marine ecosystems to transboundary rivers, lakes and aquifers. In the groundwater component of TWAP, UNESCO-IHP together with IGRAC coordinated the level 1 assessment of 199 transboundary aquifers. Aggregated data on the aquifers were collected via networks of national experts using questionnaires. These data were used to calculate the core indicators describing the status of each aquifer. A global water use model was used to calculate the quantitative and socio-economic indicators including scenario analyses for 2030 and 2050 (Riedel, 2015). One of the reasons to conduct TWAP was to provide donors like the Global Environmental Facility (GEF) a tool for setting priorities in resource allocation (UNESCO-IHP, UNEP, 2016), and to create a baseline for future repeat assessments.

3.2 Background GGRETA project – level 2 assessment

In the GGRETA project an in-depth (level 2) assessment was conducted for three selected transboundary aquifers (Trifinio aquifer - El Salvador, Guatemala, Honduras; Stampriet-Kalahari/Karoo aquifer - Namibia, Botswana, South Africa; and the Pretashkent aquifer - Kazakhstan, Uzbekistan). The main goal of GGRETA is to enhance cooperation on water security, prevent transboundary and water-use conflicts, and improve overall environmental sustainability. The project aims to reinforce the capacity of member states in managing groundwater resources; strengthen cooperation among countries sharing the aquifer; and develop a long term strategy for the monitoring and governance of the transboundary aquifer

(UNESCO-IHP, SDC, 2016). The assessments were coordinated by UNESCO-IHP together with IGRAC whilst teams of national experts played crucial roles in collecting, harmonising and analysing relevant data and information for the purpose of the assessment.

4. RESULTS

4.1 Transboundary Aquifer Information Management System

As part of TWAP and GGRETA, a web-based Transboundary Aquifer Information Management System (TBA-IMS) was developed to store, publish and share data and information from the level 1 and level 2 assessments. The TBA-IMS is a map based system which allows the upload of thematic maps resulting from the assessments. Users can analyse thematic maps, create overlays, perform queries and download data and information for further analyses or reporting purposes. All data from the level 1 assessment are publically accessible in one portal. For the level 2 assessments it is possible to set up a dedicated viewer per transboundary aquifer, including functionality to create a password protected environment with access for authorised partners only. This functionality allows for cooperation and sharing of data between countries without compromising the fact that some countries may consider data on transboundary groundwater resources too sensitive to be publically shared. The password protected environment also provides an ideal platform for sharing draft data between (international) project partners.
The TBA-IMS uses OGC international standards for sharing geospatial data (OGC, 2016), and the system's web map server allows sharing of map layers and data with external Geographic Information Systems (GIS) managed by other organisations. In the same way, data from external sources can be visualised and analysed in the TBA-IMS.

4.2 Results from TWAP – Comparative indicator based, level 1 assessment

In TWAP the methodology has been applied to the assessment of 199 transboundary aquifers: A structured data base on transboundary aquifers across the world has been set up, capturing aggregated data collected by national experts using questionnaires, as well as capturing the results from global modelling. The questionnaire survey confirmed that limited data are available on transboundary aquifers. Nevertheless it was possible to calculate at least some of the core indicators for most transboundary aquifers. To some extend the lack of data could be compensated using results from the global modelling (quantitative and socio-economic indicators). For each aquifer an information sheet has been developed which summarises available data and indicators and also includes a map and (if available) cross-section of the aquifer.

4.3 Results from GGRETA – In-depth, level 2 assessment

In the GGRETA project three aquifers have been assessed. For all three aquifers teams of national experts collected as much as possible of the required data, constructing maps of spatially variable data and tables and graphs of time dependent data. Before uploading the results into the TBA-IMS, data were as much as possible harmonised. Even though extensive efforts were made to bring together as much as possible the available data from all kinds of different sources (like different ministries, departments and universities) all three assessments to some extend were limited by the lack of data. Nevertheless many thematic maps were constructed for the aquifers and uploaded into the TBA-IMS and for each TBA an assessment report was compiled providing guidance for future action.

5. DISCUSSION

5.1 The value of a Transboundary Aquifer Information Management System

Having set up a structured and publically accessible database on transboundary aquifers across the world, as was done under TWAP, is an important achievement in itself as it allows a broad audience of donors, scientists and other professionals access to data which were previously inaccessible; it clearly identifies and highlights the need for more and better information on transboundary groundwater; and it has laid the foundation to analysing trends and the effects of interventions once repeat assessments have been carried out. The TBA-IMS for the level 2 assessment with work spaces set up per transboundary aquifer is a tool to support decision makers and other (international) stakeholders involved in the governance of the transboundary aquifers. It has the potential to engage a wider group of stakeholders and limits disparities with regards to data and information. The password protected environment also provides an ideal platform form sharing draft and/or sensitive data and information between (international) project partners and as such facilitates international cooperation. The extent to which the TBA-IMS can really fulfil its functions in the future largely depends on the amount of data in the system and if data gets updated and added.

5.1 The importance of a structured approach to Transboundary Aquifer Assessment

The structured approach to the assessments proved to be very useful. It provides focus to the experts involved in the assessment; it clearly highlights important data gaps and as such provides guidance for future research and monitoring programmes. Some national experts indicated that even the questionnaire itself already provides important guidance as it summarises which data are crucial to inform policies and which data should therefore be collected / monitored.

5.2 Indicator based, level 1 assessment

The indicator based approach requires data to be aggregated. This proved to be challenging to national experts, especially when their spatial coverage of data is limited and in the case of very large aquifers. Lack of data was also challenging, although to some extend data gaps could be compensated with results from global modelling. The methodology has been successful to characterise large numbers of transboundary aquifers in a relatively short time span. Combining indicators on for example groundwater development stress and human dependency on groundwater provides clear guidance as to what aquifers require interventions to avoid that groundwater will be a factor limiting development, and as such the indicators meet their objectives. Despite the fact that the set of 10 core indicators requires limited information, it may be useful for future comparative assessments to define an even smaller set of core indicators and to look into further simplification of the indicators in order to limit issues with lack of data.

5.3 Level 2 assessment

Like in TWAP the methodology provided clear focus, and response from national experts was generally positive. Despite the fact that different countries sometimes use different coordinate systems, terminologies, different units and categorisations it was possible to harmonise most of these data. The existence of a common TBA-IMS was instrumental in facilitating data exchange and harmonisation, although in one case the international sharing of data on groundwater is still considered to be too sensitive. In general the methodology proved to be robust enough to be applied to three transboundary aquifers in three distinctly different climatic, geological and socio-economic and political settings. Lack of data was also a limitation for the level 2 assessment. But at the same time the structured approach allows to clearly highlight these data gaps and provide focus for future research and monitoring programmes. The assessments have been successful in describing the general state of the transboundary resources. Countries involved are now in the process of defining follow up measures: further research, joint monitoring programmes and in one case study the possibilities to set up a mechanism for future joint action related to the monitoring, management and governance of the shared resource is being discussed.

6. CONCLUSIONS

The multi-disciplinary assessment methodology provides a systematic approach for the assessment of transboundary aquifers at various levels of detail. The methodology has proven to be suitable to perform a comparative indicator based assessment between multiple aquifers, as well as to perform in-depth assessments of individual aquifers. In both levels of assessment lack of available data has proven to be a limiting factor. The advantage of a structured and standardised approach to transboundary aquifer assessment is that it reveals specific data gaps more clearly thereby providing focus to future research and monitoring programmes.

Having one methodology for a comparative indicator based (level 1) assessment and an in-depth (level 2) assessment has the advantage that data and results can easily be stored in structured databases; the outcomes of a level 1 assessment can provide clear priorities for level 2 assessments; level 2 assessments in turn can feed back into updating the indicators of the level 1 assessment; and over time this will allow for analyses of trends and impacts of interventions, provided the indicators of the level 1 assessments get updated at intervals.

The TBA-IMS has the potential to become an important tool to support both research on and governance of transboundary groundwater. The extent to which the TBA-IMS will fulfil this role in the future will depend on the amount and quality of the data in the system. To achieve this, international organisations involved in developing the methodology will have to invest in mainstreaming this methodology. The TBA-IMS is maintained by IGRAC and as it is IGRAC's core mission as a UNESCO centre to facilitate sharing of data and information on groundwater, this system has the potential to become a major publically accessible repository of data on transboundary aquifers and groundwater in general.

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