Environmental Development 7 (2013) 6–16

Contents lists available at SciVerse ScienceDirect

Environmental Development

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

Towards scientific and methodological innovation in transboundary aquifer resource management

Ofelia Tujchneider [a,*], Gregory Christelis [b], Jac Van der Gun [c]

[a] *National University El Litoral & CONICET, Argentina*
[b] *Independet Consultant, Namibia*
[c] *Independet Consultant, The Netherlands*

ARTICLE INFO

Keywords:
Transboundary aquifer management
Science
Holistic methodological approach
Communication
Cooperation

ABSTRACT

Groundwater is both an invaluable and a vulnerable resource. Aquifer resources management, aiming at the responsible exploitation and adequate protection of the groundwater resources, is therefore of key importance and has to be based on sound hydrological, environmental, economic and social principles. Aquifer-wide groundwater projects are carried out to collect the required area-specific information, to understand ongoing processes, to identify the management issues to be addressed and to develop an adequate management strategy and action plan. The quality of the project results depends to a large extent on the science and methodologies adopted in the design and used during the implementation of the projects. In this context, a project was carried out recently to analyse the scientific aspects of—among others—the transboundary aquifer projects within the IW: Portfolio of the Global Environmental Facility (GEF) and to make recommendations for scientific strengthening and innovation. This paper presents the main outcomes of this analysis.

In order to accomplish groundwater resources management goals in the case of transboundary aquifers, a balanced joint strategy is needed. Analysis of documentation on completed and on-going transboundary aquifer projects has shown a wide range of scientific activities that contribute positively to the development of such strategies. This analysis has also identified options for increasing the positive impacts of science on strategy development; some of these options have been pioneered already and

* Corresponding author. Tel./fax: +54 3424592287.
E-mail addresses: ofeliatujchneider@yahoo.com.ar, ofeliatujchneider@gmail.com (O. Tujchneider), gregchristelis@gmail.com (G. Christelis), j.vandergun@home.nl (J. Van der Gun).

2211-4645/$ - see front matter
http://dx.doi.org/10.1016/j.envdev.2013.03.008

deserve wider application other ones are relatively new. Important options are: integrating transboundary aquifer resource management in a wider environmental–socio-economical context (holistic approach); exploring causal chains to better understand the processes of change of groundwater resources; using this improved understanding for optimising groundwater assessment and monitoring programmes; and adaptive management. In addition, to obtain maximum benefit of the scientific results there is a general need to promote effective communication at all levels, between the scientific community and policy-/decision makers, as well as with the local community who have a major role to play in the use and conservation of the resources. All of this should be accompanied by the harmonisation of the legal instruments and co-operation agreements between countries and the communities involved.

Two case studies, one in South America and one in Southern Africa, are added as examples of the setting and approach of the analysed transboundary aquifer projects.

1. Introduction

Besides the continental ice caps, groundwater represents in terms of volume the largest freshwater resource available on Earth. It is extremely important for socio-economic development as well as for poverty alleviation within much of the developing world. The sustainable utilisation and management of this resource must therefore be enhanced, by virtue of its importance. As the management of transboundary waters is a major challenge to the long-term sustainability of ecosystems of global significance, it is important that scientists play a vital role with regard to the identification and evaluation of transboundary groundwaters, as well as in the management and sustainable utilisation of these resources that are currently being exploited.

To substitute the largely sectoral approach that focussed more on the visible and easily quantifiable surface water, a concerted effort by the Global Environmental Facility (GEF) in the late 90s and early 2000s together with implementing agencies promoted a new approach to transboundary groundwater management, better integrated with land-use planning, ecosystem protection and river basin management. Furthermore, UNESCO's International Hydrological programme launched in 2000 the International Shared Aquifer Resource Management Programme (ISARM),that has been successful in contributing to improving relevant area-specific scientific knowledge, including the hydrogeological, legal, socio-economic, institutional and environmental components.

It must be recognised, however, that balanced joint management of a transboundary aquifer is in itself not an easy task. Spatial variations in aquifer characteristics, different groundwater rights of stakeholders within each member state, differences in water quality degradation and conservation, and the potential of conflict, in particular resulting from groundwater's unseen and little understood nature, are issues that need to be addressed. Furthermore, attention should focus on those smaller zones within the aquifer where significant transboundary causes-impacts are likely to be concentrated; these zones should be defined, delineated and further investigated. In the following sections, several other facets of the complexity of transboundary aquifer management are revealed.

The purpose of this paper is to present and share outcomes of the activities of the Groundwater Working Group of GEF's recently finalised IW: Science project. The task of this working group was to critically review the science component of GEF's transboundary aquifer resources projects and to identify options for enhancing the impact of science in such projects (see Tujchneider and Van der Gun, 2012a, 2012b). By its very nature, the analysis is inherently subjective and captures the experience and views of an international interdisciplinary team of professionals.

Most of what follows briefly describes some important science-related findings, together with identified options for scientific and methodological improvement and innovation in Transboundary Aquifer Resource Management projects. A case study of the completed GEF transboundary groundwater project on the Guaraní Aquifer System in South America, is commented on, and an intended GEF transboundary groundwater project in Southern Africa, provisionally entitled 'Sustainable Management of Transboundary Groundwater Resources in the SADC region', is discussed.

2. Integrating transboundary aquifer resource management in a wider context

Groundwater is a cornerstone of many social, economic and environmental systems. However, even in the contemporary accounts of 'integrated' water resources management, groundwater and its unique characteristics are often receiving very limited attention, sometimes they are even overlooked. On the other hand, many groundwater resources management projects—including several that are dealing with transboundary aquifers—are also having a very narrow scope and ignore the fact that groundwater is part of a very complex reality. Groundwater is interwoven with numerous other components of the physical environment and interacts with a large variety of human activities. A few comments on important aspects in this context follow.

First of all, groundwater is part of the hydrological cycle. The components of this cycle interact intensively with each other and most of the water involved passes continuously from one component to another. Groundwater is recharged by rain, either directly or indirectly, by surface water, sometimes even by wastewater or other recycled water used by people, and it discharges into streams and other surface water bodies, into the air by evaporation or evapotranspiration, or into the sea. The regimes of all components of the hydrological cycle are linked, thus no single components (such as the groundwater system) can be properly understood nor controlled without taking the other ones into account.

Land use and groundwater systems are also closely interlinked. Among others, the type of land use affects the replenishment of groundwater in an aquifer by rain or surface water, while drainage and irrigation have their impact on the quantity of groundwater stored, and on pollutants specific for each type of land use that percolate through the soil and modify the groundwater quality. Related to this is the ever-increasing use of the subsurface space (for storage and transport) and subsurface resources (hydrocarbons, minerals, geothermal energy, etc): groundwater conditions are relevant for these uses and - in turn, these uses affect groundwater conditions.

Withdrawal rates of groundwater are not independent of the availability of surface water and other alternative sources of water supply, nor on the impacts of groundwater abstraction on aquatic ecosystems and other environmental functions of groundwater.

In conclusion, groundwater is not an isolated component of the real world, but is subject to a large range of interactions. A holistic approach is required to understand the relevant processes and to harmonise groundwater resources management with other policy fields, such as surface water management, socio-economic development, land use and planning, subsurface use and environmental protection. Incorporating groundwater in integrated water resources management (IWRM) is in most cases a first logical step.

3. Exploring causal chains

Scientists and planners involved in groundwater resources management need to fully understand the processes of change in their object system, including how these are influenced by management measures and by autonomous external factors. Often the cause-effect relationships are addressed in an intuitive way, but such an approach is susceptible to overlooking some of the relevant factors, especially those relatively remote from the analyst's own professional experience or field of interest. Adopting a more formal procedure—causal chain analysis—will reduce or even eliminate this risk.

GIWA (2002) has developed a causal chain analysis methodology that links the following components: root causes, sector activities, immediate causes, 'GIWA' issues, environmental impacts

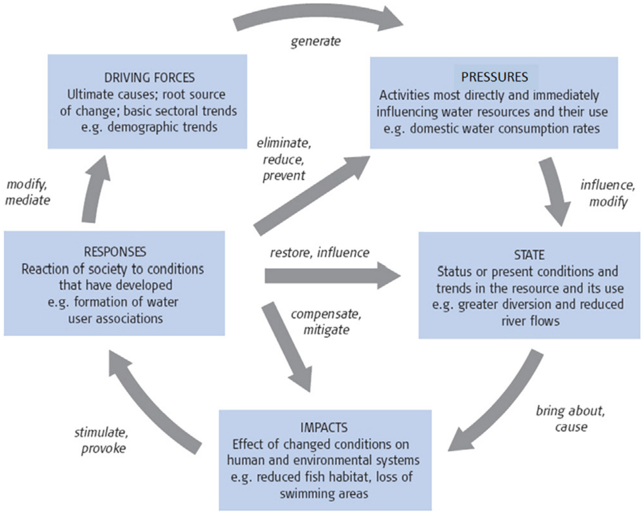

Fig. 1. The DPSIR Framework of Analysis (Source: WWAP, 2006; adopted from Costantino et al., 2003).

and socio-economic impacts. A similar methodology, but with more emphasis on the dynamic interaction between the components of the causal chain, is making use of the so-called DPSIR framework of analysis (Fig. 1).

The figure shown is largely self-explanatory. The driving forces (or 'drivers') in the DPSIR methodology are comparable with the root cases in GIWA's methodology. Typical examples of drivers are population growth, economic development, technological innovation and climate change. They produce or augment pressures on the groundwater system (usually by increased withdrawals, by pollution or by changes in recharge), which results in changes in the state of groundwater in the aquifer. These changes in state (stored volume, groundwater levels, groundwater quality), in turn, have their socio-economic and environmental impacts that trigger responses by individuals and by communities. Such responses may intend to modify drivers or pressures, but they may also focus on influencing the systems' state directly or on mitigation of impacts or on adaptation.

Within the context of transboundary aquifer resources management, causal chain analysis is invaluable for the quality of a transboundary diagnostic analysis (TDA) and for subsequent properly underpinned strategic action plan (SAP). It also gives excellent guidance to assessment and monitoring programmes that should provide the data required for these stages in the planning process and enabling adaptive management.

4. Assessment and monitoring

Managing a natural resources system such as a transboundary aquifer adequately is only possible if sufficient and reliable data and information are available on the realities on the ground. This data and information should include a characterisation of the system to be managed, and also of its state, the use of its resources and the impacts this use and the system's changing state have on individual people, communities and ecosystems. Assessment and monitoring are needed for the acquisition of such data and information (Kukuric et al., 2008).

Assessment produces a time-independent mental image of the system: in the case of groundwater it identifies aquifers and aquitards, explores their limits, defines system parameters such as permeability and porosity, estimates volumes stored and fluxes exchanged with other components of the water cycle, and makes a snapshot of state variables such as groundwater levels and a diversity of water quality parameters. Some assessment activities are rather costly, e.g. geophysical exploration surveys and exploratory drilling programmes. Monitoring, on the other hand, focuses on variation in time and has the purpose of producing time series of relevant variables. In a narrow sense, these are time series of state variables of the groundwater system, but in reality monitoring may have to go beyond this narrow scope in order to facilitate causal chain analysis and a holistic approach to planning and management. One of the main challenges in monitoring is to keep monitoring networks operational over a period of many years.

Assessment and monitoring activities are undertaken for a wide range of purposes, which results in a great diversity in scope and degree of detail. In the category of less intensive assessment and monitoring activities come projects or programmes that have the purpose to identify aquifers that deserve priority in being addressed. An example is GEF's ongoing Transboundary Aquifer Assessment Programme (TWAP) that uses a set of indicators to define these priorities. These indicators are based on field data. At the other end of the spectrum come activities with the objective to plan and implement groundwater resources management at the level of aquifers or parts of aquifers. Such activities, especially if supported by mathematical simulation models and if adaptive management is opted for, require many data with high resolution in space and in time. As previously mentioned, focusing on near-boundary pilot zones is an attractive option in large aquifer systems where the cost of an aquifer-wide assessment and monitoring would become prohibitively expensive.

Data scarcity and limitations in accessibility and quality of the data will have a negative impact on the sustainable management of groundwater resources within the transboundary context. It is important that adequate groundwater monitoring data is generated not only during a project but also beyond, especially if adaptive management is embraced (see next section). This implies that projects also have to pay attention to making arrangements for post-project activities and monitoring.

5. Adaptive management

Managing complex systems such as transboundary aquifer resources systems, taking into account all relevant drivers of change and all system-related socio-economic, ecological, legal and political goals, constraints and impacts, is facing many uncertainties. Postponing decisions and action on the ground until all these uncertainties will have been resolved is no option. Some uncertainties cannot be eliminated at all, and reduction of several other ones is often restricted by the limited time and funds available, while the escalation of problems should be prevented by appropriate action in due time. Consequently, decisions have to be taken and implemented under uncertainty. This calls for a flexible and robust approach that allows strategies and measures to be amended from time to time, without getting out of control. Adaptive management is such an approach (Holling, 1978; Walters, 1986).

Basic to adaptive management, developed during the 1970s at the International Institute for Applied Systems Analysis in Vienna, is learning. Holling (1978) defines adaptive management as '*a systematic approach to improving management and accommodating change by learning from the outcomes of management policies and approaches*'. Sometimes a distinction is made between passive and active adaptive management. The first type uses observed changes in the system's state after implementing measures as a guidance for improving decisions and thus adjusting the management plan. This is in line with common practices in IWRM to adopt a cyclic planning schedule, with periodic plan updates after a certain number of years. Active adaptive management incorporates learning explicitly as part of the objective function; it focuses on learning by experimenting. In other words: management actions are taken not only to manage the groundwater resources system, but also—even primarily—to learn about the processes governing the system.

As far as groundwater management is concerned, passive adaptive management is usually preferable to active adaptive management. This is in the first place because many processes in groundwater systems tend to be extremely slow, which means that it will take an excessively long time before the responses to management measures can be observed, and often these responses (including negative ones) then have become virtually irreversible, at the management time scale. Secondly, groundwater management relies strongly on changing the behaviour of people. It would be unrealistic to expect that people will be prepared to change repeatedly their behaviour for the sake of learning by experimenting. Therefore, a strong strategic vision, underpinned by scientific observation and analysis, is indispensible, while observations on changes over time have to be used primarily for periodic adjustment of assumptions, preferred actions and expected system responses.

6. Communication

Transboundary aquifer resources management requires actions to be taken at field level and the behaviour of the numerous and diverse stakeholders to be harmonised, in tune with the adopted policies and strategies. This can only become reality if there is sufficient and effective communication between all parties involved. Scientists of different disciplines—social and natural sciences alike—have to communicate intensely in order to integrate their observations, studies and views into a reliable overall picture of reality. They have to listen to decision-makers who can inform them on the political boundary conditions and priorities. On the other hand, they have to present their views in such a way that these can be understood by the decision-makers and the local stakeholders, and be used as the basis for informed decision-making. Decision-makers, in turn, have to interact with the local stakeholders to become fully aware of their perceptions, needs and preferences. In addition, they should also acquire sufficient knowledge to understand the information supplied by the scientists and to ask them relevant questions. It is clear that local stakeholders should also actively communicate with the other parties and verify whether their views are duly taken into consideration in the developed management strategies and plans. A prerequisite for adequate communication is mutual trust and respect among all partners involved.

Almost anywhere in the world, there is still much to be done before such ideal communication conditions as depicted above will prevail. What can be done to enhance the contribution of science to communication?

First of all, scientists and their organisations should pay due attention to making the results of scientific work available and easily accessible to other scientists, planners and decision-makers. Too often it is hard to find reports on local scientific work carried out—sometimes it is even questionable whether such reports do exist. One should be aware that sharing scientific information is the only way of making it effective for properly managing the water resources. In addition to reports that should be circulated to the persons and organisations for which they are meant, and to libraries or databases for consultation later on, there are many other ways of disseminating the results of scientific work: web pages on the internet, conferences, workshops, papers in journals, articles in newspapers, programmes on radio/TV and at schools/universities, dedicated videos, social networking (blogs), etc. Many scientists are not yet familiar with using such a wide range of communication methods, but it is a challenge to diversify the approaches to science communication in order to increase the positive impact of the applied scientific work.

Secondly, since time has passed that a scientist communicates scientific results only to fellow-scientists, he/she should be aware that the messages should be tuned properly to the envisaged communication partners, in terms of both content and presentation. This requires that scientists properly take into consideration the information needs of the different partners and also try to understand their views, concerns, preferences and priorities. Planners and decision-makers will primarily need to understand the resources system to be managed, with particular emphasis on a diagnostic analysis and on the predicted effects of possible management interventions. Local stakeholders should acquire a basic notion of trends and tendencies in the area's groundwater system, and of the possibility to influence future conditions by implementing measures and by changing human behaviour. Communication between scientists will focus on the conceptual underpinning and validity of the scientific results obtained, but also on how to integrate the outcomes of different scientific studies into a consistent and reliable picture of reality within the area concerned. This picture should cover those aspects that are most relevant for aquifer resources management and allow for holistic planning of groundwater resources management in tune with other area-specific management activities. In the case of transboundary aquifer resources management, there is the additional hurdle of building trust between neighbouring countries and expanding the communication across international boundaries.

Obviously, there is much scope for improving the effectiveness of science for groundwater resources management. Achieving progress in this respect requires full commitment and also significant and dedicated efforts of all parties involved.

7. Two real world cases

7.1. The Guaraní Aquifer System example

One of the most important examples of GEF Projects related to groundwater resources is the Guaraní Aquifer Project. The stage of preparation of the project commenced during July of 2000 and the execution of the project was from 2003 to 2009. The Project was called Environmental Protection and Sustainable Development of the Transboundary Guarani Aquifer System (GAS). The GEF supported the Project financially, the World Bank and the Organisation of American States acted in its implementation and execution. Also IAEA and Germany´s BGR participated.

The Guarani Aquifer System (GAS) is shared between Argentina, Brazil, Paraguay and Uruguay. Its total area is 1,087,879 km^2, of which approximately 21% is located in Argentina, 68% in Brazil, 8% and 3% in Paraguay and in Uruguay, respectively. The outcrop areas are located at the edges of the GAS and are composed of sandstones. Their area covers 124,650 km^2, and includes both recharge zones (67%) and groundwater discharge zones (33%). In such a huge system there are also different hydrogeological environments (see Global Environmental Facility, 2009).

The main objectives of the project were to improve and consolidate knowledge, to carry out a Transboundary Diagnostic Analysis, to promote public and stakeholders' participation and education, to enhance communication and to evaluate the geothermal energy potential.

According to its plan, the project produced very important documents and the Strategic Action Programme (SAP) as a synthesis of the results and the guide of further actions for managing and protecting the SAG.

Relevant results are:

- The implementation of a geographic information system (SISAG): that includes the information of the different wells in the area, that is available for the countries which share the responsibility of maintaining the system;
- A monitoring Network and Mathematical Modelling (M&M), within selected areas of the four countries;
- The creation of local Management Support Committees for helping in the implementation of the management models.

Other important activities developed successfully by the project are capacity building related to groundwater management and dissemination of knowledge.

The project contributed to highlighting the importance of groundwater resources in the area, at regional and local scale. An important challenge in the future will be the implementation of the Strategic Action Plan, linking activities of the different institutions, addressing each country's priorities in a joint action.

An important agreement for cooperation in management and protection of the SAG was signed in August 2010 by the four countries involved: Argentina, Brasil, Paraguay and Uruguay.

Due to the excellent results of the project there is a possibility to use it as an example for the formulation of other projects related to transboundary aquifer resources management and protection, always taking into account the unique particulars of each system and the innovative methodological tools that can be incorporated Fig. 2.

7.2. Sustainable development and management of transboundary aquifers in SADC

The general aridity and limited surface water resources have resulted in increasing dependency among SADC Member States on groundwater for both domestic and productive water needs. Regional

Fig. 2. Location of the Guarani Aquifer System.

estimates indicate that 70% of the population demand for water (between 144 and 168 million people) is supplied by groundwater. While the Revised SADC Protocol on Shared Watercourse Systems has resulted in the formation of River Basin Organisations within most of the major river basins, it has not yet translated into effective mechanisms to address the challenges of transboundary aquifers.

The main aim of the intended project “Sustainable Development and Management of Transboundary Aquifers within SADC” is to proactively add groundwater into the programme of activities of the African Network of Basin Organisations. Furthermore the key objective is to reduce transboundary development risks within SADC, in particular drought and climate change risks, as well as groundwater-specific risks, by means of building capacity for joint, sustainable utilisation and management of transboundary groundwater resources. Two transboundary aquifers have been identified. The “Stampriet Kalahari/ Karoo Aquifer System” that is shared by Namibia, Botswana and South Africa, and the “Ramotswa Dolomitic Aquifer” that is shared by Botswana and South Africa, have been selected through the SADC–UNESCO ISARM process (see Fig. 3).

The study approach is to achieve simultaneous movement at all levels by addressing key issues of groundwater resources at local and transboundary levels and to upscale the local experience to a river basin level and to the SADC regional level.

The southern part of the Kalahari lies within the Lower Orange River Basin and the so-called “Stampriet Artesian Basin” in Namibia is part of a shared aquifer group that straddles the border between Botswana, Namibia and South Africa. The quality of the water in the aquifers deteriorates in the flow direction towards south-western Botswana and the north-western Cape in South Africa. Water is often brackish to saline in this area, known in Namibia as the salt block, and this was probably due to leakage from sub-artesian layers and evaporation through time. The basin contains two confined regional artesian aquifers in the Karoo sediments, overlain by the Kalahari sediments that often contain an unconfined aquifer system. Studies confirmed that extensive faulting resulted in a complex nature of this aquifer system. Recharge into the system in the north-western part of the basin is from structures such as faults, linked to sinkholes that serve as the main conduits for recharging the confined sandstones. The recharge mechanism in the Botswana/Namibia boundary area is however still unknown.

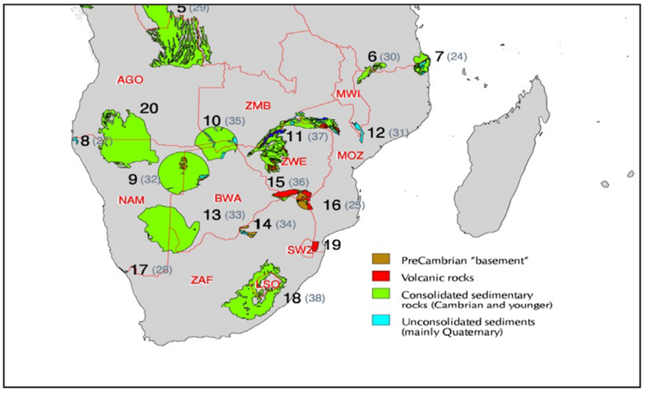

Fig. 3. Map of some of the Transboundary Aquifers within SADC - Stampriet Kalahari Karoo Aquifer (13) and the Ramotswa Aquifer (14).

The Ramotswa Dolomitic TBA in SE Botswana that is shared between Botswana and South Africa has a high vulnerability to pollution. Within Botswana the successful promotion of pit latrines in the 1990s within the village of Ramotswa, situated on top of the dolomitic aquifer, turned out to be an environmental disaster and polluted the shallow aquifer in a very short time period. The intention is to get to a situation of renewed use of the aquifer through regular monitoring in the groundwater protection zones, which have been previously established, and the elimination of the existing pollution problems. The South African side of the Transboundary Aquifer has not been developed, but there is considerable interest in it from national water planners, because of the rising demands within the area. It is now becoming important to synchronise activities on this aquifer for mutual benefit, in particular given its high yield and high vulnerability nature.

With a view towards innovation in the investigation and management of these transboundary aquifers within the DPSIR framework the following observations can be made:

- One of the major driving forces within the project area is the high dependence on groundwater, with most of the area being entirely dependent on this form of the resource. Therefore the need to conceptually understand and to set up a regional groundwater monitoring system with a view to an initial broad quantification of the available resources is clear.
- With regard to pressures, a review is needed of the leakage by natural causes within the Stampriet artesian basin from extensive structural faults, as opposed to human-induced leakage from incorrect drilling techniques. This review should produce clear recommendations on how to understand and possibly reduce the problem. Inefficient irrigation techniques must be improved upon and the possible high losses in leakage from potential mining operations within the confined aquifers within the Stampriet Kalahari-Karoo Aquifers must be understood with a view to good control mechanisms.
- With a view to state, the duties and functions within the River Basin Organisations (RBOs) must be harmonised through the inclusion of a groundwater management body as a component of the RBO tasks. Furthermore an informed consensus on the factors affecting the resource integrity at the national and transboundary level must lead to better understanding and management through a co-operative process of integration of the water resources.
- The impacts of excessive irrigation within the Stampriet Aquifer must be better understood and an integrated ecosystem approach application with standard cost-benefit analyses must be applied.
- With a view to the correct response from the assessment, a comprehensive stakeholder analysis must be initiated at the outset of the project with the harmonisation of the legal instruments and the capacity needed to properly and effectively manage the groundwater resources. Furthermore a comprehensive strategy and mechanisms must be put in place for the effective

management of the transboundary resources, particularly concentrating on the more vulnerable and sensitive areas.

8. Conclusions and recommendations

Groundwater and a considerable part of its context can only be seen through the eyes of science. That is why science and science-based methodologies have to play an important role in any human endeavour to exploiting and using groundwater, to managing the groundwater resources and to preventing any undesired groundwater-related impacts from occurring, now and in the future. From the onset, groundwater projects therefore have relied heavily on the scientific inputs of geologists, geophysicists, hydrogeologists and hydrologists. These inputs were, and still are, focusing on exploring the physical groundwater systems and assessing their dynamics. Engineers, agronomists and economists joined the earth scientists to assist in analysing how to make groundwater exploitation and use most profitable. Over time, in many countries attention has gradually shifted from merely exploiting groundwater resources to managing them, both within national boundaries and in a transboundary setting. This has raised several new scientific issues that call for innovations in transboundary aquifer resources management projects. Such issues include the interaction between groundwater management and other policy fields, understanding cause-effect relationships more fundamentally, the needs for the acquisition of more and better field data, dealing with uncertainty and increasing the impacts of scientific results.

Available reports on transboundary aquifer resources management projects—most of them partly financed by GEF—show that virtually all of these projects have produced valuable scientific outputs, contributing to achieving project goals. Most of the projects have also introduced some scientific or methodological innovations related to one or more of the new scientific issues mentioned above. Nevertheless, such innovations are not yet incorporated in GEF's standard methodology. In addition, several flaws can be observed in current project design and practices, calling for structural steps towards improvement. Consequently, a number of recommendations—based on the work of the Groundwater Working Group of GEF's IW: Science Project—follows.

A first recommendation is to ensure sufficient dissemination and permanent accessibility of the technical and scientific project outputs. Attention should be paid to establishing an appropriate central project database and a repository of project reports and documents; and these should be kept alive after the project's expiration, in one way or another.

Next, a series of recommendations can be made on the scope and design of the projects. Their relevance may vary from project to project, depending on the specific project objectives, but for comprehensive projects meant to produce an overall underpinning and planning for transboundary aquifer resources management the following can be generally recommended. New projects should take a holistic perspective, linking interrelated policy fields (such as land use and water); they should include a causal-chain analysis and ensure that assessment and monitoring activities provide the data required for it; they should show a good balance between natural and social sciences, and preferably integrate the corresponding surveys and studies; they should take into account the different spatial and temporal scales in groundwater resources management and address all issues at their appropriate scale level. Furthermore, most projects should not only focus on socio-economic benefits of groundwater but also take its ecosystem services into account, which can be done by adopting a so-called social-ecosystem approach.

Other recommendations are related to operational aspects and to the management approach to be chosen. In particular, very large transboundary aquifers may require creative approaches to feasible assessment and monitoring programmes, e.g. by focusing on pilot zones. Rigorous scientific standards should be adopted by all projected to verify data used for analysis and to calibrate and validate all models used. Relations between local and international project staff and also the responsibilities of each party should be properly defined. Media plans are required in all projects in order to produce effective science communication, and to trigger interaction between the parties involved. Clever use of indicators may be considered to facilitate communication between parties with very diverse levels of knowledge and professional backgrounds. Finally, transboundary groundwater resources management always takes place under a high degree of uncertainty. Uncertainties can only be reduced to a limited extent. Therefore, a flexible approach to management has to be adopted, allowing for periodic plan adjustment based on what can be learned from observed changes in conditions at field level. Adaptive management represents such a flexible approach.

It cannot be overemphasised how important effective communication and interaction is between the scientific community and decision makers, as well as with the local communities that have a major role to play in the use and conservation of the resources. Therefore, in the transboundary aquifer projects one has to strike a balance between carrying out scientific work and communicating the relevant scientific findings among all partners and stakeholders involved in the management process.

Transboundary aquifer resources management is a continuous, never-ending activity. If projects are used to prepare and initiate the groundwater management process, then adequate provisions should be made for continuity in the future, after the projects will have expired.

It also has to be born in mind that each transboundary aquifer is unique and presents its own specific characteristics and its own challenges and opportunities. The two-presented cases give an impression of different real world conditions at aquifer level.

Acknowledgements

The authors want to acknowledge the full support and collaboration received from the very distinguished colleagues:

- Dr Alice Aureli. International Hydrological Programme (IHP), Chief Groundwaters Resources and Aquifer Systems Section. UNESCO Division of Water Sciences.
- Andrew Dansie. United Nations University. Institute for Water, Environment and Health.UNU-INWEH.
- The members of the Groundwater Working Group of the IW:Science project: Abou Armani, Bo Appelgren, Giuseppe Arduino, Stefano Burchi, Emilio Custodio, Todd Jarvis, Alexandros Makarigakis, Andrea Merla, Shaminder Puri, Fabrice Renaud, Alfonso Rivera, Holger Treidel, Frank van Weert, Mark Zeitoun and Han Zaisheng.
- The anonymous reviewers and the Editors team.

References

Tujchneider, O., Van der Gun, J., (Eds.), 2012a. Groundwater—A Global Synopsis of Groundwater Science and Transboundary Management. Synopsis Report Prepared by the Working Group Groundwater of the GEF IW: Science Project, UNU-INWEH, Hamilton, Canada. ISBN 92-808-6019-4. pp. 20.

Tujchneider, O., Van der Gun, J. (Eds.), 2012b. Groundwater—A Global Analysis of Groundwater Science and Transboundary Management. Analysis Report Prepared by the Working Group Groundwater of the GEF IW: Science Project, UNU-INWEH, Hamilton, Canada. ISBN 92-808-6018-6. pp. 32.

GIWA, 2002. GIWA Methodology: Detailed Assessment, Causal Chain Analysis, Policy Option Analysis. Global International Waters Assessment, UNEP, GEF and Kalmar University, Final version, May 2002.

WWAP, 2006. The United Nations World Water Development Report 2: Water, a Shared Responsibility.

Costantino, C., Falcitelli F., Femia A., Tudini A., 2003. Integrated Environmental and Economic Accounting in Italy. Measuring Sustainable Development—Integrated Economic, Environmental and Social Frameworks. OECD 2004, pp. 209–225.

Kukuric, N., Van der Gun, J., Vasak, S., 2008. Towards a methodology for the assessment of internationally shared aquifers. Paper Presented at the Fourth International Symposium on Transboundary Waters Management, Thessaloniki, 15–18 October 2008.

Holling, C.S. (Ed.), John Wiley and Sons, Chichester, England, ISBN: 0-471-99632-7.

Walters, C.J., 1986. Adaptive Management of Renewable Resources. MacMillan and Co., New York.

Global Environmental Facility, 2009. Acuífero Guaraní. Síntesis Hidrogeológica. Serie de Manuales y Documentos Técnicos del Proyecto para la Protección Ambiental y Desarrollo Sostenible del Sistema Acuífero Guaraní. 102 p.