Groundwater resources sustainability indicators

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Abstract The UNESCO/IAEA/IAH Working Group on Groundwater Resources Sustainability Indicators has been charged with the development of the following activities under the International Hydrological Programme (sixth phase): to prepare a list of groundwater indicators that can be computed at the national and global level, to develop indicator profiles and capacity building materials and to work with case study countries to implement groundwater indicators. In the proposed list of 10 groundwater indicators each of them describes a specific aspect of the groundwater system and/or processes, and is based on aggregation of selected variables, both quantitative and qualitative. Indicators are focused on social, economic and environmental aspects of groundwater resources policy and management, and act as an important communication tool for planners, policy-makers and the public. A balanced scientific and policy-based approach has been employed in deriving groundwater indicators. A DPISR framework was applied in finalizing the set of groundwater indicators.

Key words groundwater; groundwater quality; indicator; sustainability management; vulnerability; water demand

INTRODUCTION

The first UN World Water Development Report (WWDR, 2003) provided a useful theoretical and practical insight into indicator development. As part of the activities of the sixth phase of the International Hydrological Programme (IHP), the UNESCO/IAEA/IAH Working Group on Groundwater Indicators has reviewed the issues arising in the WWDR and has developed a new group of groundwater indicators. These indicators, although simple, try to be both scientific and policy-relevant.

The Working Group concluded that the main functions of indicators are: simplification, quantification, communication, and the capability to compare different regions and technically different aspects. Indicators provide information on the system or process under consideration in an understandable way. The most common use of indicators is describing the state of the resource (*descriptive*). Regular measurement of indicators provides time series (*showing trends*) that may provide information on the functioning of the system or its response to management. They therefore act as important *communication* tools for policy-makers and the public, and also permit evaluation of the effect of specific policy actions and promote the development of new actions. An indicator value can also be compared to a reference condition and so it can be used as a tool for *assessment*. Finally, indicators can be used for *predicting* the future. When models are linked to specific indicators, a time series can be extended into "*estimated*" scenarios.

THE CONCEPTUAL APPROACH

The major indicator development models appear to have been shaped by four approaches: *bottom-up*, *top-down*, *systems* and *cause-effect*. The last one is also known as the Pressure-State-Response (PSR), Driving force-Pressure-State-Impact-Response (DPSIR), or Driving force-Pressure-State-Exposure-Effect-Action (DPSEEA) approach. With the *bottom-up approach*, primary available data are aggregated along several hierarchical levels into indicators using intuitive and mathematical methods. Water resources specialists tend to be critical of this approach as being too reductive. It is widely used in data-rich situations, which in many countries is not common. The *systems approach* analyses the inflows, stock and outflows of a hydrological system before defining the indicator. This approach has been applied in developing sustainability indicators and relies on specific indicators dealing with human and natural systems.

The DPISR framework has been employed in finalizing the set of indicators contained within this report (Fig. 1) (EEA, 2003). The DPSIR methodology ensures establishment of the relationship between policy and economic issues and the most burning issues in groundwater development and management.

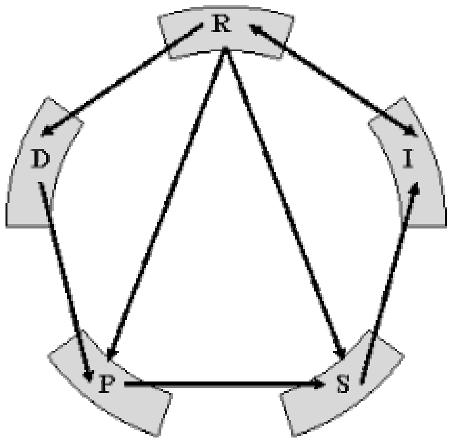

Fig. 1 The general framework used in this report (DPSIR: D, Driving forces; P, Pressures; S, States; I, Impacts; R, Responses).

GROUNDWATER—A SIGNIFICANT COMPONENT OF THE HYDROLOGICAL CYCLE

Two aspects need to be taken into account with respect to groundwater: (a) it has to be seen within the broader context of the hydrological cycle and aquifers as a significant hydrological component of watersheds and basins; and (b) it should be integrated within the context of broader economic and social dimensions, particularly related to its use.

In nature, groundwater is a key element in many geological and hydrogeochemical processes, geotechnical factors conditioning soil and rock behaviour, and a component which sustains spring discharge, river baseflow and many lakes and wetlands. The use of groundwater has increased significantly in the last decades due to its widespread occurrence, overall good quality, high reliability during drought seasons, and generally low development costs. Currently, with a global withdrawal rate of 600–700 km^3 $year^{-1}$ (Zektser & Everett, 2004), groundwater is the world's most extracted raw material. Particularly in rural areas of developing countries, in arid and semiarid regions, and in inland areas, groundwater is the most important and safest source for drinking water.

However, the lack of managerial control over groundwater resources development and protection in many regions has led to uncontrolled aquifer exploitation and pollution. Overexploited aquifers affect springs, streams baseflow, potentiometric water levels, groundwater storage, surface water–groundwater interfaces and wetlands, and may also cause land subsidence. Degradation of groundwater quality, owing to extensive aquifer exploitation and groundwater pollution, is recorded in many countries. More often, groundwater quality is affected by saltwater intrusion into coastal aquifers, by downward and upward influx of water of poor quality into exploited aquifers, by irrigation return flow, or by discharge of pollutants from the surface into shallow aquifers. Groundwater vulnerability to human impacts is recognized as a serious worldwide social, health, economic, and environmental problem.

Sustainable development of resources and environmentally sound protection of groundwater are complex processes, the successful solution of which is closely linked to water planning, policy and integrated water resources management. These aspects, in turn, are influenced by social and economic constraints and should be attentive to the ethical, cultural and historical traditions of society. The main objective of those processes is to ensure quantity, quality, safety and sustainability of groundwater as: (a) a strategic source for life (for drinking and other sanitary purposes) and economic development (e.g. agriculture, industry), and (b) an important component of the ecosystem. Groundwater has also intangible value related to cultural and religious aspects. In many developing countries groundwater is the key to poverty alleviation.

GROUNDWATER INDICATORS

Groundwater indicators, based on monitoring and assessment programmes, support data for planning and sustainable management of groundwater resources, provide simplified information about the current status and future trends in the groundwater system, help to analyse the extent of natural processes and human impacts on groundwater system in space and time, and can be a suitable instrument to facilitate communication with the public.

In the proposed list of indicators, each of them describes a specific aspect of the groundwater system and/or process and is based on the aggregation of selected variables both quantitative and qualitative. Indicators can be combined into an index, which provides compact and targeted information for groundwater planning, policy and management. The index is dimensionless and various weighting and rating systems are applied in its construction. Proposed groundwater indicators are based on measurable and observable data and provide information about groundwater quantity and quality (contemporary state and trend). They are focused on social (groundwater accessibility and its use), economic (groundwater development and abstraction) and environmental (groundwater vulnerability, depletion and pollution) aspects of groundwater resources policy and management.

Ten groundwater indicators are proposed to be applied at the global or national scale (Table 1).

FUTURE DEVELOPMENT OF GROUNDWATER INDICATORS

Development of groundwater indicators is a quasi-scientific process of presentation of groundwater resources state and trends to the various users in a simplified and understandable form. However, limitation of groundwater data at the national level is the key problem in developing groundwater indicators in many countries at present. Data and information scarcity have resulted in insufficient knowledge of groundwater systems of important national and transboundary aquifers. The following examples of data insufficiency could be particularly mentioned:

(a) In comparison with surface water, groundwater monitoring programmes are generally less developed. In particular, groundwater quality monitoring programmes at the national scale are in operation in a few countries only, and representative coverage by such monitoring results is scarce at present.

(b) Data reliability and mutual comparability are often low, because groundwater monitoring methods and sampling procedures are far from being standardized, both at the international and national scales.

(c) Exchange data and information on the international scale is limited till now. Transboundary contamination problems are registered in many parts of the world, however, internationally coordinated effort to collect and process jointly data to facilitate its utilization in pollution control is often missing.

Another problem is data utilization from wells drilled for other purposes, which location and design (especially screening) are not adequate to the groundwater monitoring objectives. Such wells may connect aquifers of different water origins and quality. They also may induce downward influx of pollutants when situated close to the pollution source, or can be affected by pumping of water for irrigation or water supply.

An additional data-related issue is associated with the fact that indicator and database development are two mutually linked and dependent activities. Data availability drives the establishment of the indicators, which, in turn, reinforces the development and collection of data required for more sophisticated formulation of groundwater indicators. However, data availability varies significantly for countries and regions. It therefore seems unlikely that values of some of the proposed

Table 1 Simplified description of groundwater indicators.

Indicators	Importance
Renewable groundwater resources (m^3 $year^{-1}$ per capita) Inhabitants	Estimates the total amount of good (healthy) water for drinking, agriculture, industry, and ecosystems that exists in the country or other administrative unit. The amount of available water per population becomes an important factor for the social and economic development of a country or region.
Total abstraction groundwater ×100% Groundwater recharge	Excessive abstraction of groundwater without the understanding of recharge rates can often cause problems such as depletion of the resource or even subsidence. This indicator may force managers to link abstraction to groundwater recharge estimates.
Total abstraction groundwater ×100% Exploitable groundwater resources	The term "exploitable groundwater resources" means the amount of water that can be annually abstracted from a given aquifer under current socio-economic constraints and ecological conditions. Another indicator to identify problems of excessive abstraction and social and economical impacts.
Groundwater as a percentage of total use of drinking water on country level	This indicator expresses how important groundwater is for drinking water supply at a country or other administrative level. It can reflect the social and economic conditions of the society, accessibility of water resources, investments in water development, and economic value of water.
Groundwater depletion ∑ area with groundwater depletion problem ×100% ∑ are of the studied aquifers	Declines in hydraulic heads, associated with other hydraulic issues, can reflect problems of overexploitation that can produce an undesired impact on groundwater (excessive depletion of river base flow, ecological impacts in wetlands, land subsidence and intrusion of water of poor quality into the aquifer).
Groundwater vulnerability	The concept of aquifer vulnerability is based on the assumption that the physical environment provides some degree of protection against natural and human impacts. This indicator supports groundwater protection policy and management. Four classes of groundwater vulnerability are proposed based particularly on evaluation of soil and unsaturated zone properties.
Groundwater quality ∑ area of aquifers natural quality problem ×100% ∑ are of the studied aquifers or/and ∑area with increase concentration of SP ×100% ∑ are of the studied aquifers (specifically: chloride, nitrate, and electric conductivity)	These indicators provide information about the present status and trends in groundwater quality and help to analyze and visualize quality problems in space and time. For anthropogenic problems, the indicators are restricted to identification of diffuse source problems, such as on-site sanitation and bad agricultural practices.
Groundwater treatment requirements	This indicator describes whether groundwater can feasibly be made potable (drinking water), or usable for other purposes with treatment. Three categories are proposed according to how extensive a treatment groundwater requires.
Number of farmers dependent on groundwater for agricultural activities / Total population of the country	Groundwater has emerged as a powerful instrument of equitable social and economic development in many rural areas of countries, especially in Asia but, also, in parts of Africa and Latin America.

groundwater indicators can be calculated on a worldwide basis at present. When there is an intention to coordinate socio-economic and environmental data collection and to harmonize associated spatial and temporal scales, the relevant UN systems (e.g. UNESCO, FAO, IAEA, UNEP, UNECE, WWAP) can be very helpful in bridging some of the gaps. It is suggested that this task starts with: (a) drafting an overview of existing data including an indication of their quality and reliability; (b) drafting an overview of data gaps; (c) defining required variables and collection of relevant data; and (d) creating a GIS database and tools for data integration, processing and assessment. This is, however, a collaborative process and the Groundwater Indicators Working Group continues the sharpening of its vision towards this objective.

The immediate concern has to be focused on the improvement and/or establishment and operation of national groundwater monitoring programmes in order to reach valuable and internationally comparable data about groundwater quality and quantity and other social, economic and environmental components needed for formulation of groundwater indicators. In countries or regions where groundwater data sets are not currently adequate to calculate relevant variables and develop groundwater indicators, only qualified estimation of variables can be made and groundwater indicators will be presented solely in a simplified form. In cooperation with the UN international community, such countries will be encouraged to develop groundwater monitoring networks and programmes and, thus, improve their policy and management of groundwater resources. Building up of groundwater monitoring and assessment programmes is a scaling (from local to regional, national and global), hierarchical, step by step process, which has to be promoted and implemented within national and international water policy and management plans. This process will be supported by the UN member states, which are the key suppliers of groundwater data and, at the same time, the main users of groundwater indicators.

Many groundwater data and information are collected as a result of the IHP and other UN Programmes and projects (e.g. FRIEND, HELP, ISARM, IGRAC, WHYMAP, HYCOS, GEMS). The databases from UNESCO, FAO (Aquastat), IAEA, UNEP, WMO, and WHO are also important sources of information. Within the UNESCO and IAEA common programme (JIIHP), the indicator formulation will be supported particularly by data relevant to the non-renewable aquifers. Under the auspices of the WWAP, groundwater indicators will be integrated within the context of broader economic and social dimensions and will support the progress towards a sustainable development, protection and management of water resources at the global level.

To summarize what has been said with respect to the future development of groundwater indicators, two aspects have to be particularly emphasized:

(a) Formulation of some indicators is affected by uncertainty, which is inherent for several methods of groundwater indicator development. In many countries and in large transboundary aquifers, the required data sets are not yet available and the processes in the groundwater system can only be estimated. Uncertainty analysis helps to identify which data have to be observed and which monitoring methods have to be applied to acquire mutually comparable groundwater data. Establishment and/or improvement of groundwater monitoring networks and data gathering will also support a more accurate and scientific-based formulation of groundwater indicators in future. Hence, the recommendation is to start the process of developing groundwater indicators, even if groundwater data availability is currently limited and some groundwater variables can be based only on qualified estimation.

(b) There is not any urgent need to develop all proposed groundwater indicators at the country or case study levels. In countries where groundwater data sets are not sufficient for formulation of some indicators, their development will be postponed. However, such gaps in groundwater data accessibility will alert governmental institutions about the need to establish and/or to improve existing groundwater monitoring activities. Such groundwater policy will be reflected in the gradual improvements of databases needed for a more precise calculation of groundwater variables and formulation of indicators.

Finally, the development of indicators is still in its infancy. The process of their creation and implementation is only beginning. In order to understand the inter-relationships between different indicators, it is necessary to have much more data, reflection, public consultation and good case studies. This paper represents the start of this vital process. There is much to be done, particularly in the area of groundwater resources, as they are a fundamental source for poverty alleviation and health promotion all over the world. For instance, the first driving force indicator in Table 1 (groundwater renewable resources/inhabitants (m^3 $year^{-1}$ per capita)), needs to be further analysed in its relationship to the DPSIR chain. What are the interactions between population growth and climate change with respect to the formulation of this indicator? How does it impact other related indicators in issues such as disease, death, hunger, damage to ecosystems, etc.? Therefore, the need to advance towards a systemic approach to the development of indicators is a very urgent task.

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