

# Global Monitoring of Groundwater Resources

<sup>[1]</sup>Neno KUKURIC, <sup>[1]</sup>J Sophie A VERMOOTEN

<sup>[1]</sup>IGRAC, P.O. Box 80015, 3508 TA Utrecht, The Netherlands, e-mail: neno.kukuric@tno.nl

**ABSTRACT** Groundwater is monitored in many parts of the world but there is still no systematic monitoring of global groundwater resources. The International Groundwater Resources Assessment Centre (IGRAC) intends to establish a sustainable global groundwater monitoring system and to use monitored data for a periodic assessment of the global groundwater resources. The Global Groundwater Monitoring System (GGMS) will be a “network of networks” including all those international organisations that are willing to extend existing networks to groundwater monitoring. The GGMS will use aggregated values rather than point observations, primarily because of its areal representativity and the limited accessibility of observations. A web-based application is being developed to assist the GGMS representatives in aggregation procedure and reporting. It is a task of IGRAC to subsequently combine (harmonise), process and disseminate the global groundwater monitoring outcomes. Finally, there is work in progress to combine these terrestrial measurements with remote sensing measurements, leading to a better assessment of global change of groundwater resources.

**KEYWORDS:** Global Groundwater Monitoring, GIS, Remote Sensing,

## 1. INTRODUCTION

Assessment of the global groundwater resources is the core mission of the International Groundwater Resources Assessment Centre (IGRAC). The change of groundwater in time makes the groundwater assessment a dynamical process and the groundwater monitoring a necessary precondition for the assessment. Groundwater is monitored in many parts of the world, mainly by measuring groundwater levels, groundwater abstraction, spring discharge and water quality. The results of these point measurements are sometimes interpolated and combined with other information to produce various groundwater (related) maps covering aquifers, regions and whole countries. There is, however, no systematic monitoring and assessment of groundwater change on global scale.

IGRAC intends to establish a sustainable Global Groundwater Monitoring System (GGMS) and to use monitored data for a periodic assessment of the global groundwater resources. The term ‘system’, rather than ‘network’ is used to avoid an impression of an apart, global network of monitoring wells. GGMS will be a “network of networks” including UNESCO, WMO, IAH and all other international organisations willing to extend existing networks to groundwater monitoring. IGRAC has made an inventory of existing networks and it is in the process of establishing a People Network – a network of GGMS representatives (see Chapter 2).

The GGMS will use aggregated values rather than point observations, primarily because of its areal representativity and in general limited accessibility of observations. Aggregation will be carried out by GGMS representatives, involving their knowledge of hydrogeological conditions, measurement practice, historical records, socio-economical setup, and other factors relevant for derivation of reliable figures. Establishment of an aggregation procedure is very much related to complexity of monitoring variables (e.g. derived variables, spatial and temporal variability, etc.). The procedure and the selection of the variables are addressed in Chapter 3.

A web-based application is being developed to assist the GGMS representatives in application of the aggregation procedure and reporting. They will need only a browser to use this application, retaining complete control over their own data. Besides, the GGMS representatives will have a prominent place in the GGMS application, recognising their valuable contributions. A GGMS application prototype is explained in more detail in Chapter 4.

Once the aggregation is completed, the information is stored in the GGMS database to be quality controlled, combined and harmonised, showing eventually the state and the change of global groundwater resources. The most adequate analysis and presentation forms need to be selected and developed as GGMS application functionalities. As complementary to these terrestrial measurements,

IGRAC is exploring possibilities to use remote sensing observations for monitoring the change of global groundwater resources. The closing part of this paper (Chapter 5) contains some additional thoughts on possible use of GGMS, also in conjunction with remote sensing and global hydrological models.

## **2. THE CURRENT NETWORKS AND THE ‘GGMS PEOPLE NETWORK’**

The GGMS will be a network of networks. The purpose is neither to create a new separate global network of monitoring wells nor to redesign existing groundwater monitoring networks. Only existing network will be used for the GGMS. While setting up the GGMS, the first major step is therefore to obtain an overview of all the networks presently available on a global, regional or national level gathering groundwater related data. Beside these networks, it is also valuable to gather experience on how other global monitoring networks were set up in the past. Organisations having experience on this subject are therefore also incorporated in the overview (see chapter 2.1). Finally, the success of a global network is very much dependent on international cooperation. Hence, the overview also comprises the international networks that might assist in developing the GGMS People Network (Chapter 2.2).

### ***2.1. The Networks***

Technical and human networks related to groundwater monitoring exist at different levels, such as local, national, regional and global. (by regional we mean here world regions).

#### *National and local networks*

National organisations responsible for managing groundwater monitoring network at national or local level are not listed here. Regarding these national and local networks, their current state worldwide has recently been assessed by UNESCO (Vrba, 2007) in the framework of an IGWCO (Integrated Global Water Cycle Observations) workshop. Eleven countries representing more than half of the global population living in areas with many large aquifers were chosen for this assessment. The assessment shows that groundwater quantity and quality is monitored in these countries, mostly through monitoring wells and at springs. Unfortunately the wells often serve more purposes (e.g. abstraction of groundwater) resulting in data collection which does not represent the overall groundwater state of the aquifers. The assessment also revealed that most of the wells monitor only one aquifer. The observations in these countries are carried out manually as well as using sensors at some places. The frequency of measurement is variable, ranging from weekly to trimestrial. Groundwater quality (chemical) analysis is usually carried out ones to twice a year, mostly at the level of Drinking Level Standards (DWS). In some countries only major ions are analysed. GIS environments are already in use in most of the countries for data control, evaluation and mapping. The accessibility of the data to other users is very dependant on the countries

#### *Regional and global networks*



The inventory presented in table 1 shows a list of organisations that are involved in the set up and or management of global or regional human and technical networks. For each organisation, the name of the programme, dataset or network is given. The three remaining columns show the information and expertise that is likely to be present at these organisations. That could be:



- 1) Groundwater data available in specific databases, possibly accessible to the GGMS;
- 2) Extensive experience in data collection procedures worldwide, potentially valuable for setting up the GGMS procedure? and/or
- 3) Worldwide people network, for example the network of representatives of UNESCO IHP (International Hydrological Programme), essential for setuping up the GGMS People Network?

The list is not exhaustive and will be updated when receiving feedback from these organisations. In addition the possibilities of adding our GGMS to exiting programmes and projects will be investigated.

Table 1. Inventory of datasets, programmes and network with a linkage to GGMS

: Groundwater data available, **P**: Useful procedures, : People networks

Organisation	Programs, datasets, & networks		<b>P</b>	
<b>GLOBAL SCALE</b>				
<b>WMO</b>	CHy (Commission of Hydrology)			<b>X</b>
Hydrology and Water Resources Programme (HWRP)	WHYCOS (World Hydrological Cycle Observing System)		<b>X</b>	
	INFOHYDRO			<b>X</b>
<b>WMO</b>	GEWEX (Global Energy and Water Cycle Experiment)			
World Climate Research Programme (WCRP)				
<b>WMO, UNEP, UNESCO, ICSU</b>	GCOS (Global Climate Observation System); GTN-H (Global Terrestrial Network – Hydrology)		<b>X</b>	<b>X</b>
<b>UNEP</b>	GEMS/Water (Global Environment Monitoring System); Gemstat	<b>X</b>	<b>X</b>	
<b>UNEP</b>	GEO-3 Data Compendium	<b>X</b>		
<b>UNESCO</b>	IHP (International Hydrological programme)	<b>X</b>		<b>X</b>
<b>UNESCO</b>	ISARM			<b>X</b>
<b>UNESCO</b>	FRIEND		<b>X</b>	<b>X</b>
<b>UNESCO, WMO</b>	HELP			<b>X</b>
<b>IPCC</b> (Intergovernmental Panel on Climate Change/ UNESCO-UNEP initiative)	IPCC Data distribution Centre		<b>X</b>	
<b>IGOS</b> (Integrated Global Observing Strategy) partnership of UNESCO, WMO, UNEP, etc.)	IGWCO (Integrated Global Water Cycle Observations)			<b>X</b>
<b>RAMSAR</b>	RAMSAR Sites Information Service		<b>X</b>	
<b>IAH</b>	Commission on Hydrogeology in Developing Nations - BURDON Commission			<b>X</b>
23 UN Organisations (coordinated by UNESCO)	WWAP			<b>X</b>
<b>Deutscher Wetterdienst</b>	GPCC (Global Precipitation Climatology Centre)		<b>X</b>	
<b>BfG</b> (German Federal Institute of Hydrology)	GRDC (Global Runoff Data Centre)		<b>X</b>	
<b>BGR</b>	WHYMAP (World-wide Hydrogeological Mapping and Assessment Programme)	<b>X</b>		<b>X</b>
<b>FAO</b>	FAOSTAT, AQUASTAT, wastewater database, world river sediment database, climwat		<b>X</b>	<b>X</b>
<b>WRI</b> (World Resources Institute)	Earthtrends	<b>X</b>	<b>X</b>	<b>X</b>
<b>IAEA</b> (international Atomic Energy Agency)	GNIR (Global Network of Isotopes in Rivers)		<b>X</b>	<b>X</b>
<b>Earth Institute</b> (Columbia University)	International Earth Science Information Network (CIESIN)			<b>X</b>
<b>Pacific institute</b>	The World's Water			<b>X</b>
<b>University of New Hampshire</b>	Water systems analysis group		<b>X</b>	<b>X</b>
....				
<b>REGIONAL &amp; NATIONAL SCALE</b>				
<b>UNESCO</b>	IHP- Latin America & the Caribbean	<b>X</b>		<b>X</b>
<b>UNESCO</b>	IHP-Arab States	<b>X</b>		<b>X</b>
<b>UNESCO</b>	IHP- Asia and The Pacific	<b>X</b>		<b>X</b>
<b>UNESCO</b>	IHP- Africa	<b>X</b>		<b>X</b>

Organisation	Programs, datasets, & networks		P	
UNESCO	IHP – Europe and N. America	X		X
UNESCO, WMO	Regional programs of HELP and FRIEND		X	X
UNESCO + Regional Organisations	Regional ISARM networks			X
UNESCO	IHP National Committees	X		X
CRU	Climate data / climate monitor online		X	X
UNECE	Core-Group on Groundwater			X
WMO World Climate Research Programme (WCRP)	GAME (GEWEX Asian Monsoon experiment)	X		
European Commission	Eurostat		X	
EEA (European Environmental Agency)	Waterbase - Groundwater	X		
OAS/OEA (Organisation of American States)	Office for Sustainable Development and Environment			X
SADC (South African Development Community)	Groundwater Programme, Water sector coordination unit, SADC Water Resources Database	X		X
CCOP (Coordinating Committee for Geoscience Programmes in East and Southeast Asia)	Groundwater programme, Asian Well Database	X	X	
ACSAD, ALECSO, UNESCO-Cairo	Arab Wadi Hydrology Network			X
ACSAD (Arabic Centre for the Studies of Arid zones and Dry lands)				X
UNESCWA (United Nations Economic and Social Commission for Western Asia)	R &D on Water Resources, Treatment and desalination			X
IWRN Inter American Water Resources Network	Network of networks in the Americas			X
JRC (Joint Research institute), ies (Institute for Environment and Sustainability)	WISE, data portals, INSPIRE		X	X
...				

## 2.2. The People Network

The main challenge of this IGRAC initiative is to set up a ‘GGMS people network’ that will secure continuous input of required groundwater data and information. The global people network should be a sustainable people network composed of groundwater specialists, skilled regional or national representatives. These representatives must be able to provide or produce sound aggregated information. These regional aggregations of groundwater point measurements are usually more than a numerical interpolation and averaging procedure. They need to be carried out by regional experts, making use of their knowledge of hydrogeological conditions, measurements practices, historical records, social –economic issues and setup and other factors relevant to deriving reliable figures.

The setting up of a global people network is an incremental procedure requiring careful planning. Firstly each of the organisations presented in the table will be contacted and asked for their expertise and feedback. Depending on the response of this inquiry, a list of potential members of the ‘GGMS people network’ will be defined. The potential members will then be formally invited to join the network and participate in this challenging initiative. The participation and commitment of the members is essential to its success. Strong incentives are therefore required to ensure the sustainability of the network. A visible recognition of the participating organisations and individuals in the IGRAC monitoring programme is the first steps in that direction. The setting up of the network will be carried out in close cooperation with IGWCO/UNESCO/GARS Working Group on Groundwater and the

UNESCO led GRAPHIC Project (Groundwater Resources Assessment on Humanity and Climate Change).

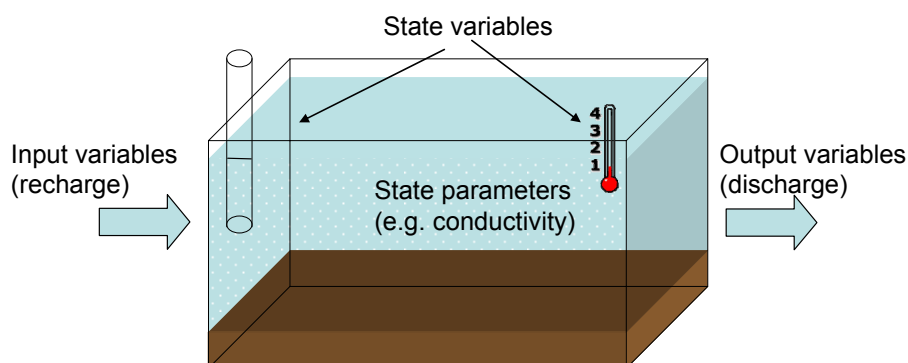
### 3. GLOBAL MONITORING VARIABLES AND AGGREGATION PROCEDURES

The main arguments to use aggregated instead of observed values are the (limited) areal representativity of point observations and their (limited) accessibility. For the purpose of GGMS (assessing the regional and global change), a good areal estimate is more representative than a point measurement (even very accurate one). Besides, in many countries the measurements (“raw data”) are considered strategic information, being hardly accessible internationally.

Aggregation should be carried out by a regional specialist (a GGMS representative) using point measurements (if available) as well as her knowledge of regional hydrogeology, measurement practice, historical records, socio-economical setup, and other factors relevant for derivation of reliable figures. The use of this knowledge and proxy information is that what makes the estimation of areal values much more than a simple averaging.

Establishment of an aggregation procedure is very much related to selection and complexity of monitoring variables. For example, a spatial variability of a variable will certainly influence the size of aggregation area (the grid cell size), whereas the temporal variability determines the frequency of observations. Besides, some variables can be directly measured (e.g. groundwater level), whereas others need to be derived (groundwater recharge).

A system approach can be used to present aquifer and its monitoring variables in a simple way (Figure 1). An aquifer system has the input variables (recharge), the output variables (discharge) and the state variables (such as groundwater level, temperature, concentration, etc.), showing the state of the system. [Aquifer also has the system matrix and the parameters (e.g. porosity), describing the structure of the system.]



*Fig. 1. An aquifer system*

Aquifer recharge (system input) is usually estimated indirectly using precipitation and evapotranspiration data. Estimation of aquifer storage change is primarily based on observed groundwater level/head data. Groundwater discharge is sometimes difficult to monitor (e.g. discharge to rivers, lakes, sea), but the concentrated discharge (springs and abstractions) are widely monitored. Springs and the (monitoring and abstraction) wells are also the points of groundwater quality sampling (temperature, pH, TDS, EC and various chemical characteristics).

The list of global monitoring variables has yet to be prepared; the intention is to do this in a workshop of IGWCO/UNESCO/GARS Groundwater Working Group, to be held in autumn this year. Most likely, the list will start with the groundwater level, probably include groundwater abstraction, groundwater use and groundwater quality variables and it will certainly not be exhaustive.

Definition of the global monitoring variables is not as simple as it looks. For instance, groundwater head/level is measured all over the world, but with a large variety in density and frequency of measurements. Moreover, there are several possible ways to express change in groundwater head/levels in the context of global monitoring:

- If measured values from the wells are available, their monthly or yearly difference can be interpolated and aggregated.
- If no (or a very few) measured values are available an approximation of groundwater level/head change could be made, based on proxy information (precipitation, demography, etc.). The expected groundwater head change could be then expressed using the terms like no change/stable, slight lowering, substantial lowering, etc.
- The change does not have to be substantial in absolute terms (i.e. centimetres, meters) in order to have a large environmental and/or socio/economical impact. Accordingly, a magnitude of impact could also be estimated, using the terms such as high, low, none. To perform this estimation, a combination of various parameters might be required (level/head, abstraction, crop yield, etc.).

The main criterion for selection of a monitoring variable will be its potential usage, especially regarding derived variables. If possible, those should have a direct added value for the country representative (besides being useful for a regional/global analysis). For instance, one could derive a variable assessing the threshold value between sustainable exploitation and the mining. In this way, one could obtain global overviews of the (un)sustainable exploitation of major aquifers and develop global warning tools that then can be regionalized. Critical metadata to attain this would be the ratio between exploitation and recharge values, the latter based on precipitation data, for instance.

The right choice of global variables is crucial for the motivation and involvement of regional specialists in the GGMS People Network. Therefore, it will receive a due attention in all stages of the GGMS development.

#### **4. GGMS WEB-BASED APPLICATION**

The purpose of the GGMS application is to assist the GGMS representatives in estimation of groundwater variables, and in making the estimation available for further regional/global analysis. The latter activity is actually a reporting, usually performed using a kind of input data forms. In the GGMS application, the reporting is simplified to one click on save button, whereas the data estimation receives the main attention.

The main components of the GGMS application are the interactive user interface and the database where all the collected information is stored and kept. The most important advantages of such application are addressed below.

Firstly, the user has and retains the control over own data, this being provided through the direct access to the database. In this way, often disputed “delivering” of data to an international organisation is weakened if not completely dismissed.

The members of GGMS People Network will have a prominent place in the application, recognising their valuable contributions. Besides individual homepages and archives, an internal and a public forum facility will be made available promoting the internal (within the GGMS People Network) and external cooperation.

The GGMS application is being developed as web-based application, hence available from every computer having a browser and an Internet connection. GGMS representatives without a broadband Internet connection are also supposed to use this light application without any noticeable disadvantage.

A prototype of the application has already been developed using ESRI ArcGIS (version 9.2) and Oracle database. The results are encouraging, although the user interface is still not as simple as it should be. The basic application steps are shown in Figure 2. After logging in, the user selects the monitoring area and the variable to be estimated; subsequently, she can plot or retrieve representative measurements and/or proxy values (e.g. precipitation isolines) to be used in estimation of aggregated values (Figure 3). The values are assigned per grid cells, simply by selecting the value (the colour) at the legend palette and clicking into the designated cell (Figure 4).

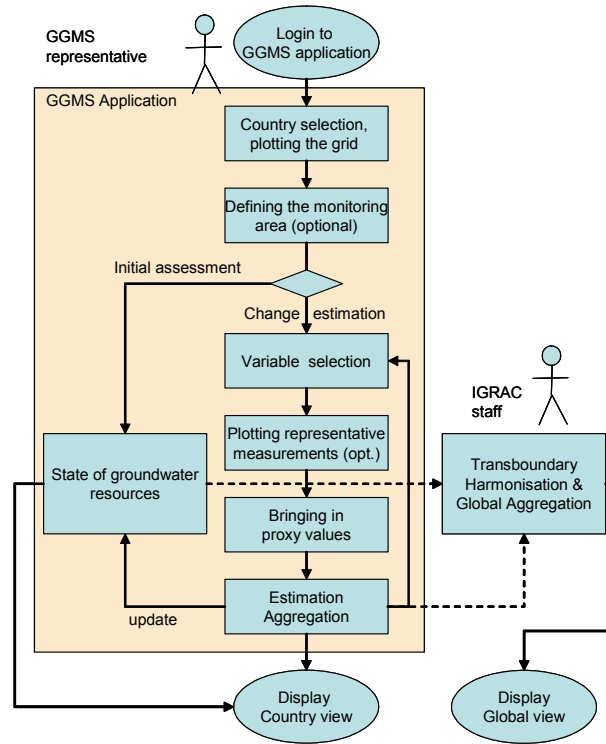


Fig. 2. A GGMS concept

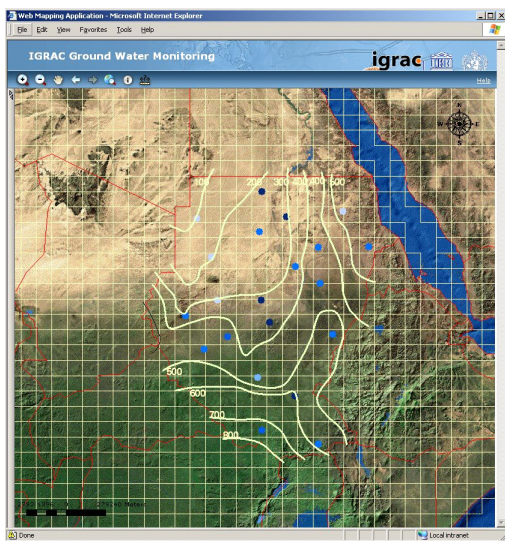


Fig. 3. Proxy data in GGMS

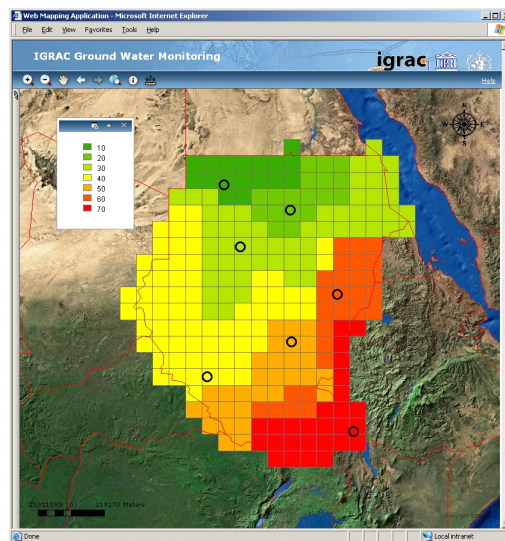


Fig.4. Aggregated values

Once the values per country are estimated, IGRAC will carry out transboundary harmonisation and perform further aggregation - if required. The operational GGMS will also have extensive selection and visualisation options, allowing for an appropriate spatial and temporal analysis of groundwater change.

## 5. WORLDWIDE USE OF GGMS

In principle, the global groundwater monitoring should start when the GGMS People Network is established, the variables selected, aggregation procedure defined and the GGMS application fully operational. In practice, however, this will be an incremental process; all the ingredients are required, but the monitoring will start in a several countries, with one or two variables, using the “country view” (Figure 2) in the application. Hopefully, an operational (part of) GGMS will contribute to expansion of People Network, including new countries and bringing in new information. In meantime, IGRAC will work on harmonisation and quality control procedures and further development of the web-application.

Especially harmonisation of transboundary values is a sensitive issue and needs to be carried out in close cooperation with related countries. The network established, and the experience gained in the framework of UNESCO/IAH ISARM programme ([www.isarm.net](http://www.isarm.net)) will be here a very valuable asset.

The value of the GGMS will grow in time, as the content of the system increases. The GGMS is primarily intended for groundwater specialists and the decision makers at national at international level, but it can be also used by NGOs, schools and universities, international consultants and the general public. It will provide a direct input for UN World Water Assessment Programme (WWAP) and a significant contribution to some other programmes (e.g. GEO, Group on Earth Observations) and projects (e.g. GRAPHIC).

As complementary to the above described terrestrial measurements, IGRAC is exploring possibilities to use remote sensing observations for monitoring the change of global groundwater resources. The most promising method is GRACE (Gravity Recovery and Climate Experiment), dealing with gravity field change and the change in terrestrial water storage. The scale of the implementation and a specification of the groundwater storage component are the main GRACE challenges at this moment (Rodell and Famiglietti, 2002). An IGWCO/UNESCO/GARS workshop has been planned for the October this year at IGRAC to explore possibilities of joint use of GGMS, GRACE and global hydrological models.

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