



MARCH 2007

CONTENTS

ISSUE FOUR

This is the fourth issue of the Forum for Groundwater, making it a full year old already. If, as they say, the first year of any publication is the trickiest, then the success so far bodes well for the future.

A constant focus on African groundwater issues can make it seem that groundwater elsewhere in the world is well understood and has few problems. This is not the case:

In this issue, Brigid Ó Dochartaigh discusses some of the groundwater problems facing farmers at Chahaertan oasis, Inner Mongolia, China.

Jeff Davies diverts his attention to Bangladesh to illustrate the classic properties of unconsolidated sedimentary aquifers.

Gideon Tredoux explains various approaches to Managed Aquifer Recharge (MAR), an area where African examples – such as the scheme at Atlantis - are at the forefront of international innovation.

Max Karen and Jim Anscombe share an important further aspect of their experience in Zambia – a new way of dealing with high iron concentrations in groundwater.

And finally, Laurra Olmsted introduces a brand new organization, Hydrogeologists without Borders, from whom we hope to hear much in future.

As usual, the Forum for Groundwater is available to download from the following websites, together with back issues:

<http://burdon.wwgw.org/>

<http://www.waternet.co.za/groundwater/>

"Forum for Groundwater" is coordinated by the IAH Burdon Network and the CSIR Water Resources Competence Area. Views and opinions expressed in this Forum are those of the individual authors. It is intended to be a discussion forum for those interested in groundwater, with an emphasis on African groundwater.

The Forum is compiled quarterly by: Jude Cobbing, CSIR Groundwater Research Group, PO Box 395, Pretoria 0001, RSA. Tel: +27 12 841 3857 email: [jacobbing@csir.co.za](mailto:jcobbing@csir.co.za) If you would like to contribute to the Forum, please contact Jude (above). We are always looking for short articles on aspects of groundwater in Africa, particularly by those working in or interested in Africa. General comments are also very welcome.

Groundwater degradation in an irrigated oasis in Inner Mongolia, China

– Brigid Ó Dochartaigh

An innovative system for removal of iron from iron-rich groundwater in Africa – Max Karen and Jim Anscombe

An introduction to the Unconsolidated Sedimentary Quaternary Aquifers of Bangladesh – Jeff Davies

Hydrogeologists without Borders: – a new Organization – Laurra Olmsted

Managed Aquifer Recharge (MAR) – an interview with Dr Gideon Tredoux



Groundwater degradation in an irrigated oasis in Inner Mongolia, China – *Brigid Ó Dochartaigh*

Alxa League, in the westernmost part of the Inner Mongolia Autonomous Region, is one of the driest areas of China, with significant water resource problems. There are only two permanent rivers in the 270,000 km² League, and with a scattered population of over 170,000, groundwater is a vital resource. The average land elevation is 1000 to 1400 m, but a number of mountain ranges rise to over 3000 m. Deserts (sandy and stony) cover about 30% of the League area. The average annual rainfall ranges from less than 100 to 200 mm, rising to over 400 mm in mountain ranges. Rainfall is highly variable on daily and seasonal scales, with more than 80% occurring between May and September, typically as 10 to 15 separate rain events. Annual evaporation is much higher than rainfall, ranging from 2500 to 4000 mm, although winter evaporation rates (when temperatures can fall to -30° Celsius) are low.

The largest groundwater resources in Alxa League exist in alluvial basins adjacent to mountain ranges, where high runoff from summer rainfall events causes local recharge, both by sheet runoff and by infiltration through the beds of ephemeral rivers (wadis). Direct rainfall recharge over aquifer basins is small by comparison, but is particularly important in desert areas, feeding flow to permanent lakes which are a characteristic part of the desert landscape.

The irrigated oasis of Chahaertan, in the Left Banner of Alxa League (the most populous and economically developed of the three Banners in the League) covers an area of 30 km². It lies on a moderately to highly permeable Quaternary fluvial sand and gravel aquifer deposited in a faulted Tertiary sedimentary basin, to the northeast of the Helan mountains, which are the highest in Alxa League. Estimated average annual recharge to the basin is less than 50 mm, but this rises to over 300 mm in the area around the oasis, largely because of focussed recharge from a significant wadi network.

The oasis was first developed in the late 1960s to encourage the expansion of irrigated agriculture as part of the economic development of the region, supported by government initiatives. Most development occurred by the mid 1980s. Today about 6000 people live and work in the oasis, producing mainly maize, sunflowers (for oil), and watermelon, with smaller amounts of cotton, chillis, and wheat. Most of the crops are marketed, locally and nationally, but some are grown for local use as livestock fodder, mainly for sheep and goats. The oasis also supports a number of former herders who have recently begun to stall-feed their livestock, following the advent of grazing bans across much of the non-irrigated land in Alxa League. The aim of these bans is to try and restore vegetation thought to have been degraded by over-grazing. Although relatively small, Chahaertan oasis is one of only a few such agricultural areas in Left Banner, and is therefore an important part of Alxa League's economic activities.

Groundwater abstraction is intensive, with more than 150 production wells typically sited less than 500 m apart. Most are pumped at 60 to 80 m³/hour almost continuously during the growing season from May to August. The total estimated annual abstraction from the oasis is 20 million m³/year. A study carried out in autumn 2006 showed that groundwater levels in the oasis have fallen by up to 0.5 m/year for at least 20 years, indicating that abstraction has been unsustainable for much of the lifetime of the oasis. Groundwater level falls have been partially mitigated by a high level (around 50%) of irrigation returns. But groundwater modelling carried out during the recent study indicates that unless abstraction is reduced, water levels will continue to decline, and individual wells may have to be abandoned within 10 to 25 years.

The natural quality of the groundwater below the oasis is relatively good, but it is highly contaminated by nitrate – derived largely from local fertiliser use – with concentrations of up to 600 mg l⁻¹ as NO₃. Nitrate concentrations vary across the oasis, controlled partly by landuse (higher beneath areas with more cultivation) and historical development (higher beneath the oldest parts of the oasis). Age dating indicates that typically only 10 to 20% of abstracted groundwater is modern, representing largely wadi recharge and irrigation returns, while most is more than 50 years old, representing a mixture of wadi and local rainfall recharge and groundwater flow from upgradient of the oasis.

In the 1980s there was active management of the groundwater resource in Chahaertan, particularly with regard to water level monitoring. Excellent records are available for 1984 to 1994, when water levels were typically measured every 10 days in seven designated monitoring wells. But since the mid 1990s there has been little or no groundwater monitoring or management, as the government organisations with responsibility for water resources faced growing funding pressures, and as many of them underwent reconstruction and the transferral of key technical staff to other areas. Today there is still little groundwater management, despite acknowledgement at national government level of the significance of the water resource problems facing much of China, and at regional government levels that the Chahaertan oasis, and the other oases in Alxa League, are experiencing severe groundwater quantity and quality problems. A new hydrology bureau set up in 2004 has responsibility for groundwater resources across Alxa League, but has so far done little to collect new groundwater level and quality data from Chahaertan, citing a lack of funding and technical staff.

The recent study referred to in this report, carried out by the British Geological Survey as part of the Alxa League Environmental Rehabilitation and Management Project, a 5 year AusAID (Australian government aid) programme, was done in collaboration with Chinese government departments, and the results have been shared with the relevant organisations. These results include: recommendations to reduce abstraction from the oasis, and to reduce nitrate leaching by more effective irrigation and nitrogen budgeting; for ongoing monitoring of groundwater



FORUM FOR GROUNDWATER



levels and quality; and for regular assessments of groundwater conditions to identify the effectiveness of these mitigation measures. Hopefully, these recommendations will help to ensure that the importance, and the vulnerability, of the scarce groundwater resources in Chahaertan and other oases in Alxa League are fully recognised by funding and management organisations alike, and that groundwater will once more be actively managed. This will help to ensure the long term protection of an important regional economic and environmental resource, and the livelihoods of thousands of people.



Measuring water level and flow rate at a production well in Chahaertan oasis



Sampling groundwater from a well outlet pipe to an irrigation pond, showing the contrast between sandy un-irrigated soil in the foreground and irrigated sunflower and maize fields behind

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An innovative system for removal of iron from iron-rich groundwater in Africa – Max Karen and Jim Anscombe

Iron rich groundwater poses a serious problem in many parts of the world. In rural Africa this problem can affect large numbers of people who rely on handpumps for a safe, reliable water supply.

High concentrations of iron in groundwater cause water discolouration and can impart an unpleasant taste to water as well as causing staining of food and laundry. Iron is not known to cause directly detrimental affects to human health, however in many places it can cause health problems indirectly since people will return to unprotected sources due to the unpleasant taste and colour of the groundwater.

The image below shows a reliable handpump with a good yield situated next to a health centre in North Western Zambia. The high levels of iron have led to the borehole being rejected for potable water supply. This has led to the local community returning to using water from unprotected sources.



Iron-rich groundwater causing iron staining at a handpump

As part of the North Western Province Rural Water Supply Project this issue was first highlighted during the initial hydrogeological survey of the area. This indicated that large numbers of boreholes contained high levels of iron.

Within the project area levels of iron above 1mg/l were found to cause discolouration. At levels of iron above between 2mg/l and 3mg/l many boreholes were found to have been abandoned by the local community/health centre they were constructed to provide safe water to.

The issue has been dealt with in two ways. The first was to carry out a study of existing iron filtration methods around the world. The results of the study were used to design a filter that was installed early in the project to assess its performance in terms of both iron reduction and crucially maintenance and operation.

The image below shows the same borehole after the iron filter has been installed. The formerly rejected borehole is now in constant use.



The same borehole after iron filter installation

The iron levels from the inlet to the filter are monitored regularly using portable iron photometers. The levels were further quantified during a trace element sampling programme carried out in order to identify if there were any other potentially toxic elements. The results were analysed at the British Geological Survey laboratories at Wallingford, UK. The result below from the unfiltered inlet to the filter and the filtered outlet, indicate that the iron filters are removing iron to well below acceptable limits.

FORUM FOR GROUNDWATER



Borehole Name	Iron Filter	Fe (mg/l)
Mafuliwanjamba RHC	INLET	6.910
Mafuliwanjamba RHC	OUTLET	0.212
Chilemba BS I	INLET	10.600
Chilemba BS I	OUTLET	0.235
Kivuku	INLET	4.410
Kivuku	OUTLET	0.013

Table of iron concentrations at boreholes fitted with iron filters, showing reductions due to the filters

The second way that the issue has been dealt is geophysical. During the in-house geophysical siting programme boreholes with high iron levels were surveyed using resistivity sounding. A preliminary assessment of the results indicates that there is a link between boreholes with high levels of iron, and conductive layers of below 40 Ω m, below 30m depth. This is interpreted in the geological context of an association with clay.

The project now goes into production. The method for dealing with boreholes with high iron will be to drill a second borehole if iron levels are above 1mg/l, if the second borehole also has high iron levels the borehole with the lowest iron concentration will be selected and an iron filter will be installed.

The filtration system will be modified so that it can be incorporated into the civil works that will be constructed next to each new borehole. The crucial issue however is the sustainability of the filter. Based on monitoring data and the fact that the communities themselves were put in charge of the maintenance of the handpumps it is believed that this problem can be solved.

Max Karen (maxkaren23@hotmail.com) and Jim Anscombe (waterdoc777@hotmail.com) are independent hydrogeological consultants who have worked all over Central and Southern Africa on rural water supply projects.





Hydrogeological Environments: Unconsolidated Sedimentary Quaternary Aquifers of Bangladesh - J Davies

Impact of Quaternary Climate Change

The Ganges, Brahmaputra and Meghna (GBM) delta system of Bangladesh is located at the junction of the Indian, Tibetan and Burmese tectonic plates. The main landforms include (Figure 1):

1. Northern hills and fan deltas
2. Late Pleistocene tracts and main valley fluvial floodplains
3. Main delta area, south of the Ganges-Maghna rivers

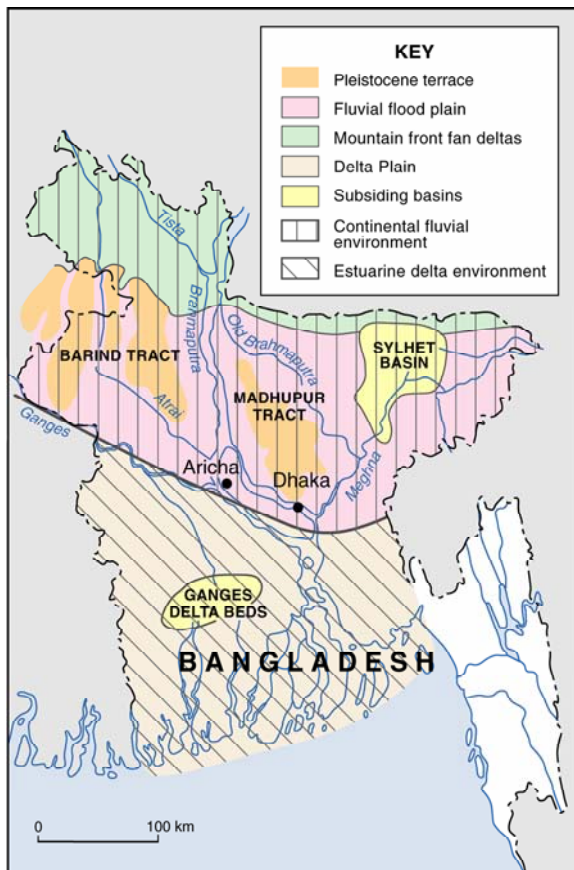


Figure 1 Principal landforms in Bangladesh

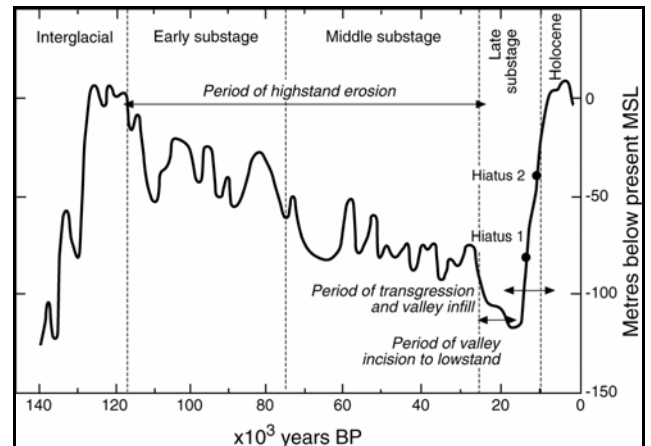


Figure 2 Quaternary changes in sea level

Much of the delta area lies at less than 6 m above sea level, whereas the Barind and Madhupur Tracts lie at 15-40 mamsl. The nature of the prolific aquifers of the GBM area and their development for domestic and agricultural purposes, including installation of 4.5 million hand pumped boreholes and thousands of shallow and deep irrigation boreholes, are described in Rahman and Ravenscroft (2003). The Pleistocene and Holocene age sediments that form these aquifers were deposited during cycles of fluvio-glacial and sea-level change, the last being 120 Ka in duration (Figure 2).

For most of the latter period the main rivers of the area flowed southward through the main delta (Fig. 3). In response to sea level decline by 30 ka BP channel incision accompanied by channel switching had occurred (Fig. 4). By the Glacial maximum at 20 Ka BP, sea level had declined to about -130 metres below that at the present day. Coarse fluvio-glacial sediments, derived from Himalayan fans, were deposited within the incised main valleys by high flow rivers (fig. 5). Within the fluvial floodplain areas the major river channels underwent repeated cycles of incision and infilling during the last million years. Finer, less permeable sediments were deposited during the Holocene period by lower gradient meandering rivers in these areas. Within the main delta area, stacked river channels of the Brahmaputra and other rivers indicate occupation of the same channel trend during successive cycles of glaciation within the tectonically subsiding area. In the delta, thick sequences of fine grained over-bank flood silts and clays occupy the areas between the stacked channel piles.

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Figure 3 Main Holocene river flows

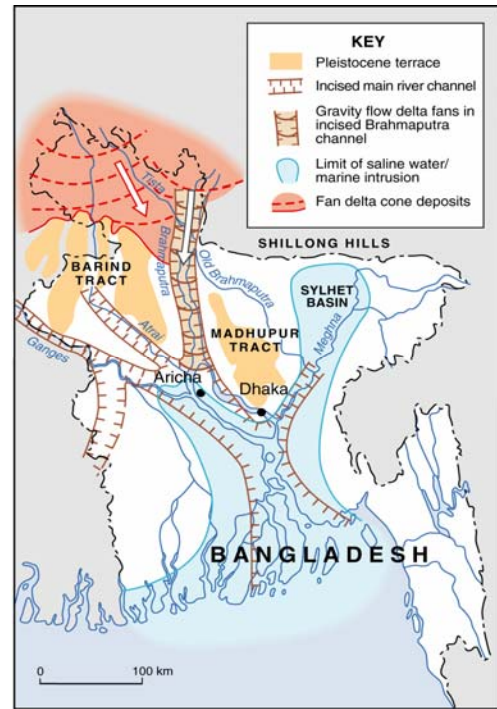


Figure 5 Deposition of coarse fluvio-glacial material

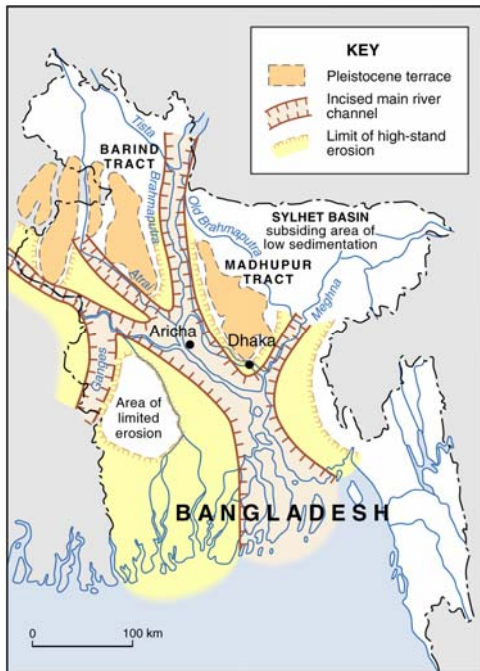


Figure 4 Channel incision and channel switching



Figure 6 High yielding irrigation tubewell, with monitoring piezometers in the foreground



Figure 7 Reverse-circulation drilling rig

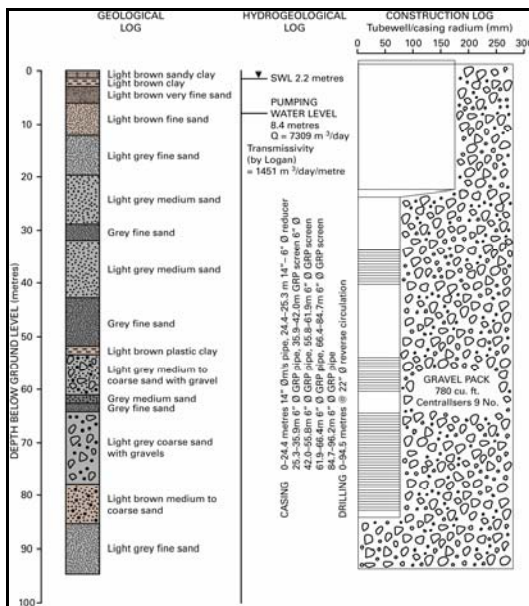


Figure 8 Typical borehole log

Groundwater Development

Hydrogeological data were obtained from some of the 15,000 reverse circulation drilled deep tubewells installed to supply water for crop irrigation and large town domestic use. Deep tubewells, each 80 to 120 m deep, have been installed into the shallow Late Quaternary aquifer, each nominally yielding 56 l/sec of groundwater for the irrigation of 100 acres of rice (fig 6). Similar deep tubewells supply water by reticulation to the large towns.

A typical reverse circulation drilling rig comprises a Hydreq Minor rig mounted on a Ford 4x4 tractor with a high capacity suction pump (fig. 7). During deep tubewell drilling, sediment samples are obtained and described at 1.5 m intervals to define the location of screenable horizons. A typical borehole log records lithology penetrated and construction (fig. 8). Test pumping is undertaken to define tubewell efficiency.

Recently, deeper 200-300 m boreholes have been drilled using the direct circulation mud flush method to tap the Deep Quaternary aquifer to provide arsenic free water to larger towns. Although lithological samples were obtained during the drilling of these boreholes and some were geophysically logged using resistivity and natural gamma equipment little detailed information on the hydrogeological nature of the deep Quaternary aquifer has been forthcoming. Unfortunately, several thousand boreholes recently drilled to depths of about 300 m using a water flush drilling system designed to provide arsenic free water to rural communities from the deep aquifer system have produced little additional hydrogeological data.

Aquifer Distribution

The low regional topographic gradient of the GBM area is mirrored by the low hydraulic gradients within the main aquifer systems of 0.08 m/km. The rates of groundwater flow through the aquifer systems are also affected by sediment age. The permeability of the older the sediments is reduced by weathering, diagenesis, compaction, cementation with red-brown iron oxides and decomposition of micas to grey smectitic clays, as found in the fluvial sands and silts of the Pleistocene age- Madhupur and Barind Tracts.

Aquifer recharge occurs during the annual April-October monsoon period when high rainfall, river floods and tidal rise are experienced. Such climatic events combine to cause annual flooding, often of catastrophic scale.

The distribution of main aquifer units in the Quaternary age fluvial and deltaic sediment sequence are shown on a north-south cross section of GBM in Bangladesh (fig 9). These include:

Fan Deltas - Late Pleistocene to Holocene age coarse-grained sands, gravels and cobbles of the Tista and Brahmaputra mega-fans and basal fan delta gravels along the incised Brahmaputra channel.

Shallow Aquifers - Late Pleistocene to Holocene age braided river coarse-grained sands and gravels deposited along the incised Palaeo-Ganges, lower Brahmaputra and Meghna main channels. The sediments in the incised channels have high transmissivity ($3000 \text{ m}^2\text{d}^{-1}$) and porosity of about 20 %. The surrounding sediments have medium/low transmissivity ($300 \text{ m}^2\text{d}^{-1}$) and high porosity (60 %).



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Deep Aquifers - Early to Middle Pleistocene age stacked fluvial main channel medium to coarse grained sands at >150 m in the Khulna, Noakhali, Jessore/Kushtia and western moribund Ganges Delta areas in the subsiding delta basin.

Delta Area Dupi Tila Aquifer - Early to Middle Pleistocene-age red brown medium to fine-grained sands underlie Holocene age grey medium to fine grained sands.

Pleistocene Tract Dupi Tila Aquifer - Early to Middle Pleistocene-age coarse to fine-grained fluvial sands underlie the Madhupur and Barind tracts.

Key references:

Rahman, A.A. and Ravenscroft, P. (editors) 2003. Groundwater Resources and Development in Bangladesh: Background to the Arsenic Crisis, Agricultural Potential and the Environment. The University Press, Dhaka, Bangladesh. BGS and DPHE, 2001.

Kinniburgh, D.G. and Smedely, P L (eds) Arsenic contamination of groundwater in Bangladesh Volume 2: Final Report. British Geological Survey Report WC/00/19. BGS Keyworth.

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The large numbers of handpumps installed within the shallow aquifer systems of Bangladesh appear to be most affected by arsenic contamination. The occurrence of arsenic in the shallow Quaternary aquifers of Bangladesh is discussed in BGS and DPHE (2001). Seasonal groundwater movement due to climatic and abstraction controls is also most evident within these systems.

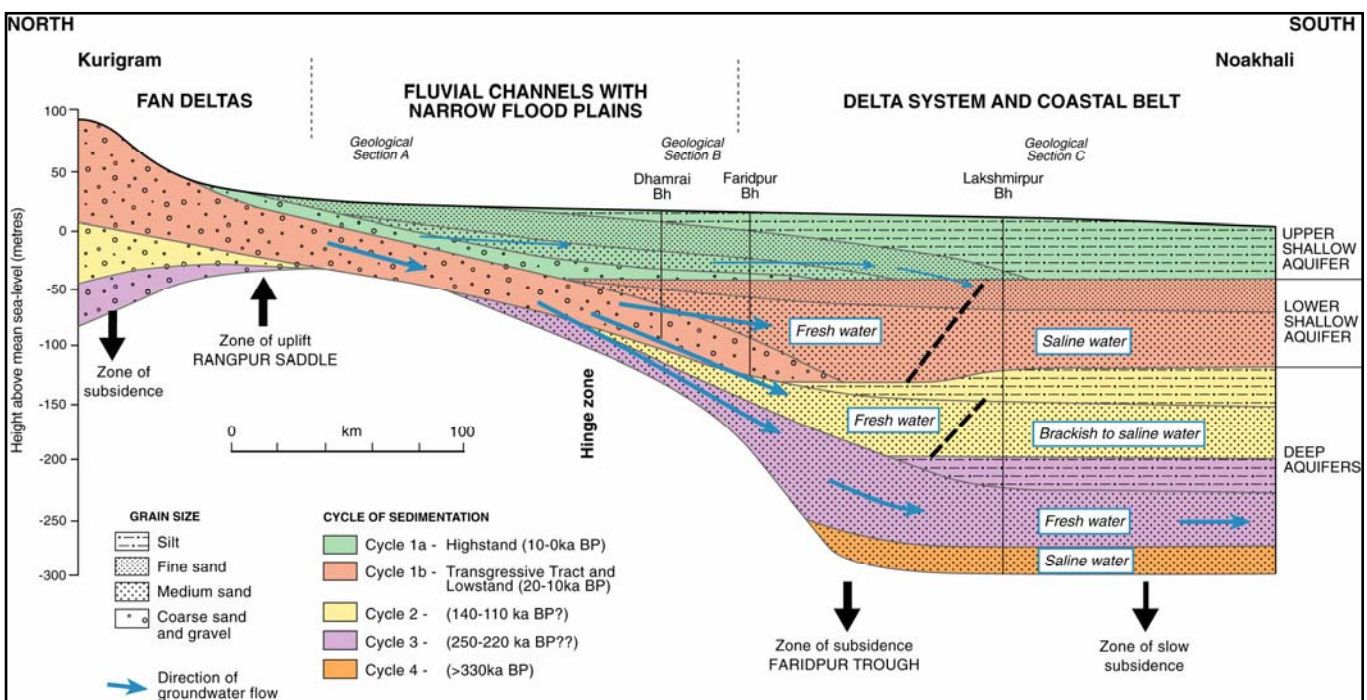


Figure 9 Distribution of main aquifer units in the Quaternary age fluvial and deltaic sediment sequence



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Hydrogeologists without Borders: – a new Organization – *Laura Olmsted*

In 2005 a group of hydrogeologists in Canada initiated a new organization: Hydrogeologists Without Borders (HWB); (www.hydrogeologistswithoutborders.org). HWB's members share a concern about the importance of groundwater in developing countries. HWB places a particular emphasis on potable water supply in the most impoverished areas of the world and seeks to build hydrogeologic capacity to apply local solutions to the development, use, management and long-term protection of groundwater resources. By January 2007, the organizational structure of HWB had been established, a list of volunteers numbered more than 80, and a business plan had been developed outlining their vision and goals. Currently, HWB is based in Canada but has the potential to grow internationally.

The goals of HWB include:

1. Provide immediate **hydrogeologic assistance** to developing countries that lack hydrogeologic expertise.
2. Support the development and sustainability of **hydrogeology capacity building** in developing countries. This will be accomplished primarily through support of existing hydrogeology MSc programs at universities in developing countries. The CARA Network (www.caraqua.org) in Latin America has already educated approximately 80 MSc level hydrogeologists through three programs (Costa Rica, Nicaragua and Guatemala). Three new CARA MSc programs will begin in 2007 (El Salvador, Honduras, Bolivia)
3. **Partner** with organizations (Canadian, overseas or international) involved in hydrogeology programs or projects in developing countries.
4. **Educate and raise awareness** of the importance of, and the issues pertaining to, groundwater in developing countries.
5. Establish and maintain the financial and administrative systems necessary to support the **operation of the HWB organization**.

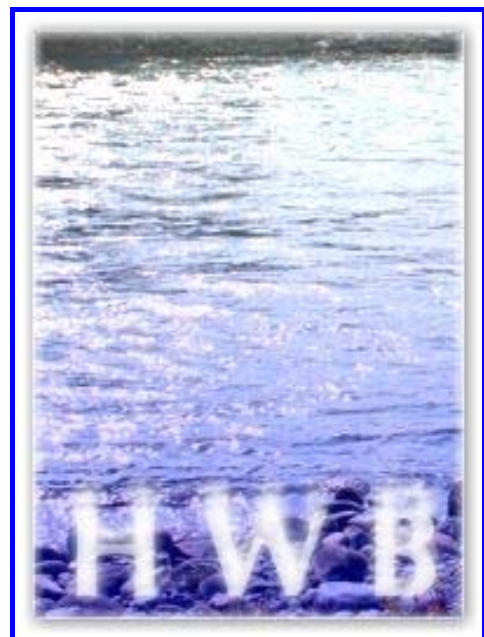
In association with the **International Year of the Planet Earth** (2007-2009), HWB is currently working to establish a consortium of interested parties to increase the hydrogeological capacity within SSA countries. HWB plans to adapt the CARA Network model to first strengthen 2 or 3 regional SSA hydrogeology MSc programs by assisting with faculty training, enhancing equipment/book supplies, improving laboratories, and by funding full-time MSc students from the entire SSA region. Over the longer-term, MSc hydrogeology programs will eventually be established and supported in each country, if applicable. The MSc programs will be two years intensive full-time study,

providing a strong scientific foundation in the first year, followed by curriculum covering the social, economic, institutional, legal and political aspects of integrated water resource management, with an emphasis on groundwater.

The MSc programs will be strongly connected to each country's priority development issues such as potable water supply, sanitation, and watershed management. The MSc programs will train professional hydrogeologists who will work for government agencies, other universities, international organizations, NGOs or in the private sector. The SSA hydrogeology MSc programs will be partnered with MSc programs in North America and Europe. The NA/Europe universities would take the lead in finding funding to strengthen their own international aid programs. The NA/Europe university programs will train professors of the SSA hydrogeology MSc programs, assist with curriculum design and delivery and seek bi-lateral project funding from their own governments or international programs. Professional short courses and technical workshop training will augment the MSc programs. HWB will support the SSA hydrogeology programs by developing projects and partnerships for SSA hydrogeology MSc programs, providing volunteer hydrogeologists to assist SSA universities, and by developing an ongoing hydrogeology MSc student scholarship fund for students in programs in developing countries. Other partners might include national geological surveys or NGOs that have an interest in capacity building. At the current time we are looking for organizations or individuals who would like to partner in this consortium.

For more information, please contact Laura Olmsted at lolmsted@matrix-solutions.com or David Bethune at bethuned@ucalgary.ca.

Laura Olmsted (lolmsted@matrix-solutions.com) is a hydrogeologist working in Canada. She is a member of the Burdon Groundwater Network, and one of the initiators of the HWB project.





Managed Aquifer Recharge (MAR) – an interview with Dr Gideon Tredoux (CSIR, South Africa)

This interview sprung from questions Jude Cobbing (JC) put to Dr Gideon Tredoux (GT) around the issue of enhanced or managed recharge to aquifers. Dr Tredoux has been involved with these systems for many years, and is in an excellent position to shed some light on what is now an important part of groundwater management in many parts of the world.

JC: *What does MAR stand for, and what exactly does it mean?*

GT: In the international groundwater community directly involved in *Artificial Groundwater Recharge* (AGR) the term *Managed Aquifer Recharge* (MAR) has become firmly embedded. Hence the series of International Symposia on Artificial Groundwater Recharge have become known as ISMAR, e.g. ISMAR6 will take place in Phoenix, Arizona in October 2007. It was largely intended to move away from the concept of doing something "artificial" in order to ensure easier acceptance of this water management technique in the non-hydrogeological community. However, in South Africa the hydrologists use the abbreviation MAR for mean annual runoff and this is well entrenched. Thus, in the South African context MAR is not considered an ideal term for artificial groundwater recharge.

MAR or AGR mainly encompasses the management actions for storing (surplus) surface water in an aquifer. However, in certain cases it is employed as a first step in the treatment of river water for potable purposes, e.g. in dune filtration systems (Netherlands) river bank filtration (Europe), or the reclamation of wastewater, e.g. the Soil Aquifer Treatment (SAT) as it was called in Israel. Gradually the use of the aquifer matrix for removing non-degradable compounds and metals is being phased out, especially in Europe. On the other hand, in some parts of the world deep well injection of wastes into saline aquifers is still being practised.

In Australia the term Aquifer Storage and Recovery (ASR) has been coined for the injection of water, often of slightly impaired quality e.g. urban stormwater runoff, into a borehole for storage and recovery from the same borehole, generally for non-potable purposes.



ASR infrastructure at Bolivar, South Australia

If the water is abstracted from another borehole nearby, increasing the travel distance and potential improvement in quality, it is called Aquifer Storage, Transfer, and Recovery (ASTR).

In the more arid parts of the world, farmers are largely dependent on groundwater and the more enterprising ones considered ways and means to extend their supplies. Constructing dams in ephemeral streams, up gradient of boreholes or wells, often solved this problem. In India these structures are called "percolation tanks". However, the dams easily silted up and, in view of the excessive evaporation, the idea originated that a dam filled with sand, i.e. a "sand storage dam", could serve as a reservoir from which little or no evaporation would occur. In 1953, Dr Otto Wipplinger published an extensive study of the subsurface storage of water in such artificial sand aquifers in Namibia and particularly the construction and efficiency of such systems to serve as water supply sources. It can be visualized that the sand dam serves as an artificially constructed 'aquifer' and if the steps in raising the dam wall are small enough, coarser material will be trapped which could form an excellent aquifer. The storage and infiltration facility may also be located off-stream as in the case of the Nahaley Menashe scheme in Israel where the runoff from three ephemeral rivers are diverted into a basin for sedimentation and then led into an infiltration basin in the dunes to recharge the unconfined coastal aquifer.

JC: *Is MAR used anywhere in Africa? How successful are these schemes?*

GT: Larger scale artificial groundwater recharge systems are mainly known from the extreme northern and southern parts of Africa. The Atlantis Water Resource Management Scheme (AWRMS) has been in operation for the longest period. Groundwater exploitation at Atlantis, a town with more than 240 000 inhabitants (in 2006) close to Cape Town, commenced in 1976 and the introduction of artificial groundwater recharge started in 1979 when urban stormwater and treated wastewater was recharged to the



sandy aquifer via infiltration basins. On average storm water and wastewater infiltration augments the natural recharge of the groundwater by 1.5×10^6 to 2.5×10^6 m³/yr. Water quality management is a key feature of the system and this includes separate treatment of domestic sewage and industrial wastewater as well as separation of stormwater from residential and industrial areas. Only secondary treated domestic sewage is considered suitable for recharge and is blended with the stormwater runoff after passing through a series of maturation ponds. The peak flow of the stormwater and wastewater blend is of low salinity and is recharged in a part of the aquifer where groundwater salinity is lower. The treated industrial wastewater, softening plant regenerant brine, and industrial area stormwater, together exceeding 2×10^6 m³/yr, are discharged into the coastal recharge basins. These are located down gradient of the production well field as the water quality is not considered suitable for recycling. The longer term sustainability of the system is presently being studied in great detail as the AMRMS has recently become one of eight test sites for the European Community research project "Reclaim Water".

At Polokwane in the Limpopo Province of South Africa, the fractured granitic gneiss aquifer is being recharged indirectly via the alluvium in and alongside the Sand River bed. The aquifer is used for town supply to Polokwane. The flow in the river consists of floodwater and treated wastewater. Recharge of the aquifer in this way is unintentional and concern exists that the aquifer will become polluted with organic compounds derived from the wastewater. This may jeopardize the longer term viability of the system.

At Kharkams in the Northern Cape Province an ephemeral spring dissipating into the alluvium was intercepted for injection into a production borehole in granitic rocks. This operation only augments the water supply by some 0.02 Mm³/a. However, in that very arid environment it constitutes a significant improvement in the reliability of supply. In addition, the low salinity spring water significantly improves the quality of the water in the aquifer.

In Namibia, the Omaruru River Delta (Omdel) Scheme, located 35 km from the coast, was constructed in 1993 to augment the water supply to the central Namib Desert area, which includes the towns of Henties Bay, Swakopmund, and Walvis Bay, as well as the uranium mining operations at Rössing. The river runoff is collected in the Omdel Dam with a capacity of 40 Mm³ and after settling of the silt and clay the water is allowed to flow along the river for some 6 km to recharge basins constructed in the river bed. The first recharge activity took place in 1997/98 when approximately 50% of the inflow of 18 Mm³ was recharged. Further recharge events followed the floods of 1999/2000 and later. Overall the scheme can be described as successful as it preserves flood water for recharge, most of which would have been lost to the sea. Improving the yield of the scheme is being considered by the relevant authorities.

Following several extended pilot scale tests, artificial recharge of the Windhoek Aquifer is entering full scale operations (2007). The pilot tests were preceded by detailed geological, structural, and hydrogeological investigations of the quartzitic aquifer providing water to Windhoek. The pilot scale injection tests were carried out using potable water from the water supply system. This water was further treated with activated carbon for removing traces of organic compounds. High injection rates were achieved and it was evident that injection was feasible. The concept of water banking makes the injection scheme economically attractive as it reduces the risks associated with the city water supply in periods of drought. Based on the results of the pilot scale tests, a full-scale system has been designed and will be implemented in various phases. Phase I involving injection into five boreholes at a rate of 5 Mm³/yr is starting in 2007. The actual injection volumes will depend on the periods of availability of surplus potable water. The economic viability of the scheme has been proven by considering all the alternatives, e.g. of importing water from the Okavango River in the north, or desalinated water from the coast.

In Egypt large scale MAR systems are being planned following large scale pilot tests in the period from 2001 to 2004. This is being planned in collaboration with experts from the Netherlands and will serve agricultural needs as well as potable water supplies. For agriculture treated wastewater recharge is considered.

In contrast to the larger schemes for town supply described above, Kenya has concentrated on small scale systems in rural areas. By March 2005 some 320 sand dams were in operation while a series of another 500 dams was planned for the Kitui area, eastern Kenya. On average the construction of a sand dam in the ephemeral rivers amounts to 6 000 Euro and it provides a water supply to 50 families. A local NGO, Sahelian Solution Foundation (SASOL) is instrumental in planning and guiding construction of the dams.

JC: *What are common problems experienced with MAR systems?*

GT: MAR systems employ infiltration basins, trenches, or injection boreholes. All these systems suffer the problem of clogging of the filtration surface or even the aquifer matrix, depending on the type of clogging. In the case of physical clogging, the infiltration rate of basins may be restored by simply removing the top layer. In the case of a borehole it is more difficult and sometimes even irreversible and control of suspended matter is vital in such systems. Clogging may also be caused by air entrapment, chemical precipitation, algae, bacterial growth, etc. Regular monitoring of the recharge water, the receiving water body, and related factors is essential. In certain cases slight disinfection may be of great value.

Water resource managers are generally concerned that the recharged water may be lost. If it is taken into account that high quality potable water is generally used for



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recharge, it is a legitimate concern. For this reason it is essential that the geology, hydrogeology, and hydrochemistry are well understood and detailed knowledge of the characteristics of the particular groundwater system and the unsaturated zone obtained. Finally, pilot infiltration or injection tests are essential for testing the feasibility of recharging the aquifer. In fact, Water Resource Planning Systems of the South African Department of Water Affairs and Forestry has commissioned the development of a strategy for 'A National Approach to Implement Artificial Recharge as Part of Water Resource Planning'. This will ensure that artificial groundwater recharge is considered as a management option already in the planning stage of any water resource development.

A less common but real problem is the occurrence of nuisance compounds such as pyrite or even toxic minerals such as arseno-pyrites in the aquifer matrix. The introduction of oxygenated water into the aquifer will oxidize and mobilize these and may cause the system to fail.

Legal requirements may put restraints on the development of systems and may control the quality of the recharge water. For this purpose the aquifer ecology needs to be understood and the impact of the "foreign" water needs to be evaluated.

JC: *What, in your opinion, is the future of MAR in Africa, and in other parts of the developing world?*

GT: Overall, MAR or AGR should form part and parcel of groundwater development schemes as many of these are being over pumped well in excess of the natural recharge. In South Africa where the Water Act of 1998 prescribes that the reserve requirements of a water resource needs to be determined, it makes sense to have an MAR plan to increase the sustainability of the resource and to ensure an adequate reserve.

JC: *Do you think that MAR has a role to play in adapting to climate change?*

GT: In 2002 the Dutch had already started using "MAR-SSS", which was called Management of Aquifer Recharge and Subsurface Storage. This was eventually shortened to MARS, where the "S" denoted "Storage". Although this has not found wide acceptance in hydrogeological circles, it underlines the importance of subsurface storage particularly as a response to climate change and the increasing aridity expected in many semiarid areas.

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