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Les dossiers thématiques
Issue 14

DEEP GROUNDWATER RESOURCES IN THE SAHARA DESERT AND ARID AND SEMIARID FRINGE AREAS

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Comité Scientifique Français de la Désertification
French Scientific Committee on Desertification

Les dossiers thématiques du CSFD issue 14

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French Scientific Committee on Desertification

The creation in 1997 of the French Scientific Committee on Desertification (CSFD) has met two concerns of the Ministries in charge of the United Nations Convention to Combat Desertification. First, CSFD is striving to involve the French scientific community specialized on issues concerning desertification, land degradation, and development of arid, semiarid and subhumid areas in generating knowledge as well as guiding and advising policymakers and stakeholders associated in this combat. Its other aim is to strengthen the position of this French community within the global context. In order to meet such expectations, CSFD aims to be a driving force regarding analysis and assessment, prediction and monitoring, information and promotion. Within French delegations, CSFD also takes part in the various statutory meetings of organs of the United Nations Convention to Combat Desertification: Conference of the Parties (CoP), Committee on Science and Technology (CST) and the Committee for the Review of the Implementation of the Convention. It also participates in meetings of European and international scope. It puts forward recommendations on the development of drylands in relation with civil society and the media, while cooperating with the DesertNet International (DNI) network.

CSFD includes a score of members and a President, who are appointed *intuitu personae* by the French Ministry of Higher Education, Research and Innovation, and come from various specialties of the main relevant institutions and universities. CSFD is managed and hosted by the Agropolis International Association that represents, in the French city of Montpellier and Languedoc-Roussillon region, a large scientific community specialised in agriculture, food and environment of tropical and Mediterranean countries. The Committee acts as an independent advisory organ with no decisionmaking powers or legal status. Its operating budget is financed by contributions from the French Ministry for Europe and Foreign Affairs, the Ministry for the Ecological and Inclusive Transition, as well as the French Development Agency. CSFD members participate voluntarily in its activities, as a contribution from the French Ministry of Higher Education, Research and Innovation.

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Foreword

Land degradation affects about 23% of the global land area and is increasing at a rate of 5–10 million ha/year, while affecting 3.2 billion people worldwide. In dryland areas, which account for nearly 40% of the land (excluding frozen land), this process is referred to as desertification.

Poorly managed human land use is the main cause of land degradation. Climate change is worsening this trend and accelerating desertification while the key focus of the United Nations Convention to Combat Desertification is to control this process. Curbing soil degradation and restoring degraded land can help combat climate change (e.g. restoring 350 million ha would enable sequestration of 13–26 Gt of atmospheric CO_2) and biodiversity loss. Striving to achieve a land degradation-neutral world is target 3 of United Nations Sustainable Development Goal 15 'Life on Land'. Moreover, restoring land and the services it provides to the planet and to societies is pivotal to the UN Decade on Ecosystem Restoration (2021-2030).

Combating desertification and land degradation is a global challenge underpinned by firm initiatives tailored to local conditions, while requiring cooperation between all actors—civil society organizations, professional organizations, technical and financial partners, public decision-makers, private sector actors, higher education and research institutions. Research has the role of supporting these territory-anchored actions, alongside public and private decision-makers, driven by the most recent scientific knowledge.

The French Scientific Committee on Desertification has decided to fulfil this need by launching a series entitled *Les dossiers thématiques du CSFD* (CSFD thematic reports), with the aim of supplying valid scientific information on desertification, all of its implications and challenges. This series is geared towards policymakers and their advisors in the Global North and South, but also towards the general public, development and environmental science reporters. Moreover, it strives to provide teachers, trainers and trainees with further information on various disciplinary fields. Finally, it intends to contribute to knowledge dissemination of stakeholders in the combat against desertification, land degradation and poverty alleviation—leaders of professional organizations, non-governmental organizations and international solidarity organizations.

These *Dossiers* are focused on diverse topics, including global public goods, remote sensing, wind erosion, agroecology, pastoralism, etc., to review current knowledge in these specific domains. The aim is also to fuel debate on ideas and new concepts, including controversial issues, to highlight commonly implemented methods and outcomes obtained in various projects, while also providing useful references, addresses and websites. The *Dossiers* are endorsed by the Committee.

JEAN-LUC CHOTTE
CSFD Chair
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Preamble

The Sahara Desert—with an area comparable to that of geographical Europe (10 million km^2)—is the largest continuous expanse of dryland in the world. With its semiarid fringe areas, it occupies most of northern Africa, from the Atlantic Ocean to the Red Sea, and accounts for almost half of the total area of the continent. This vast region also hosts some of the largest liquid freshwater reserves on Earth.

In this technical *Dossier* coordinated by Yves Travi—who has devoted most of his career to studying water resources in this region of the world—the aim of the French Scientific Committee on Desertification is to showcase and explain this apparent paradox.

This *Dossier* highlights the fact that groundwater is the second largest liquid freshwater supply on our planet after polar continental ice, and far ahead of lake and river surface waters. It also points out that the presence of these continental liquid freshwater reserves is not directly linked to the climate, but that it also depends on the underground geological structure. Northern Africa has the best groundwater reservoirs in this respect. These are among the largest sedimentary basins in the world, which are filled with rocks that have accumulated over several hundred million years while being several thousand metres thick. Each cubic meter of these porous rocks, or so-called 'aquifer', contains 50 to several hundred litres of usable water. Rather than being saline due to the presence of sedimentary salt layers, as is often the case for deep aquifers, these are freshwater resources.

This *Dossier* nevertheless reveals that, given the arid climatic conditions that now prevail in this world region, these colossal water reserves are generally very poorly supplied, i.e. renewed or 'recharged', under current precipitation (rainfall) regimes. This is a major constraint that does not exist in other parts of the world with higher rainfall rates. If we were to draw a financial analogy, these groundwater reserves could be compared to financial capital and their current recharge rates to interest generated by this capital. Long-term extraction of these groundwater resources could, in theory, only be considered sustainable if the interest, i.e. the recharge, is affected, but not the capital, i.e. the reserves.

Flow rates into these Saharan aquifers (recharge) are therefore very low, or even almost zero in some areas. The quantity of groundwater that naturally emerges from these reservoirs—particularly at oasis sites scattered throughout the desert—is therefore very low overall. Yet this is of paramount importance in these specific locations, for both human communities and ecosystems, since this is the only source of freshwater in this vast region. Moreover, in many cases, current natural outflows, especially in oases, are not in balance with current climatic conditions and—due to the slow underground flow—are the result of more substantial recharge periods dating back several thousands or even tens of thousands of years. Groundwater is hence often referred to as 'fossil' water.

This *Dossier* also explains that during the second half of the 20th century the introduction of modern techniques for pumping groundwater from these aquifers via deep boreholes has enabled a certain degree of economic development in these regions, while in turn enhancing the wellbeing of the communities concerned. In these poorly recharged aquifers, this artificial groundwater extraction method—as opposed to natural artesian outlets in oases—often involves greater extraction relative to the recharge rates, thereby drawing on the capital. This also has more or less long term, i.e. up to several centuries, socioeconomic and ecosystem impacts, as also fully outlined in this *Dossier*.

Yves Travi, along with the other *Dossier* contributors, also offer an excellent outlook on the different types of methods and approaches gradually developed by hydrogeologists, i.e. groundwater scientists, since the second half of the 20th century. These methods have been necessary to gain insight into, develop and manage such large sedimentary aquifers, especially under these specific arid conditions. This region of the world has thus served as a testing ground for many scientific developments (isotopy, groundwater dating, paleoclimatology, numerical model calibration, etc.), which in turn have enhanced knowledge on these rare hydrogeological systems. This *Dossier* therefore also provides an excellent illustration of how the most advanced scientific progress can benefit the economic development of a global region, in this case via hydrogeological knowledge.

The *Dossier* authors stress that further progress is needed, especially to gain access to ever more accurate and reliable groundwater flow simulation models. Yet data and technical tools are already available to decision makers (elected officials, associations, professional representatives, populations, etc.) in the concerned regions, thereby making it possible to quite accurately assess exploitable groundwater flows, as well as to determine the most appropriate geographical locations to tap these resources, and the relatively long-term impacts of the withdrawal process (groundwater depletion, drying up of oases, increased pumping costs, etc.). Scientific and technical knowledge is hence available to decision makers, who thus have all the elements needed to build and make choices among the various groundwater resource use policies. Should the current extent of exploitation of these large reserves be curbed or even halted so as to leave the resources intact for future generations, as may be done for an ore deposit left 'in reserve' for instance? Otherwise, should this capital be used over a few decades to fulfil needs that with hindsight may seem superfluous, especially if no back-up solution is planned? Are trade-off solutions possible—based, for example, on those implemented by certain countries with substantial petroleum or mineral resources—for: current fulfilment of vital and/or high value-added needs; the constitution—based on part of the economic benefits derived from this groundwater capital—of another type of capital, technological or financial, for example, as and effective alternative when the initial water capital runs out? In short, these political choices must primarily be made by the concerned local decision makers. Meanwhile, hydrogeologists must provide technical contributions designed to enlighten these stakeholders in the decision-making process, while still leaving them free to make the political choices themselves. In this respect, groundwater withdrawal is no different from other types of mining—a range of scarce resources are extracted from the ground to meet present needs, without regard to how future generations will be able to obtain the resources they need. This is an ethical and moral issue that urgently needs to be addressed concerning water resources, as well as rare metal and other mineral resources. A new prospective report like that of the Club of Rome in 1972 would now be urgently needed.

This high-quality outreach report on water resources in the Sahara Desert and arid and semiarid fringe areas will be of interest to both groundwater specialists seeking to broaden their hydrogeological knowledge and anyone else eager to learn about water resource issues in this global region and, more broadly, in arid and semiarid regions with large-scale sedimentary basins with low recharge. It will also undoubtedly serve as a benchmark to support policies on groundwater resource usage in this region of the world.

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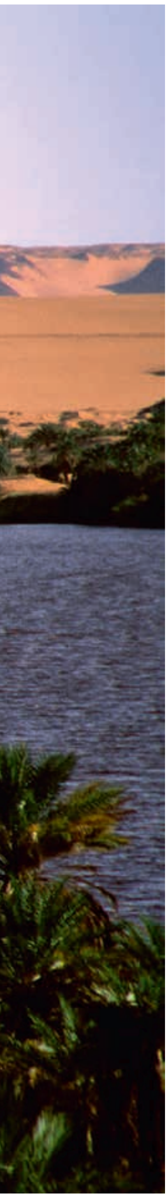
▲ **Katam Lake, Chad.** © Jacques Taberlet



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Introduction: freshwater – a global issue

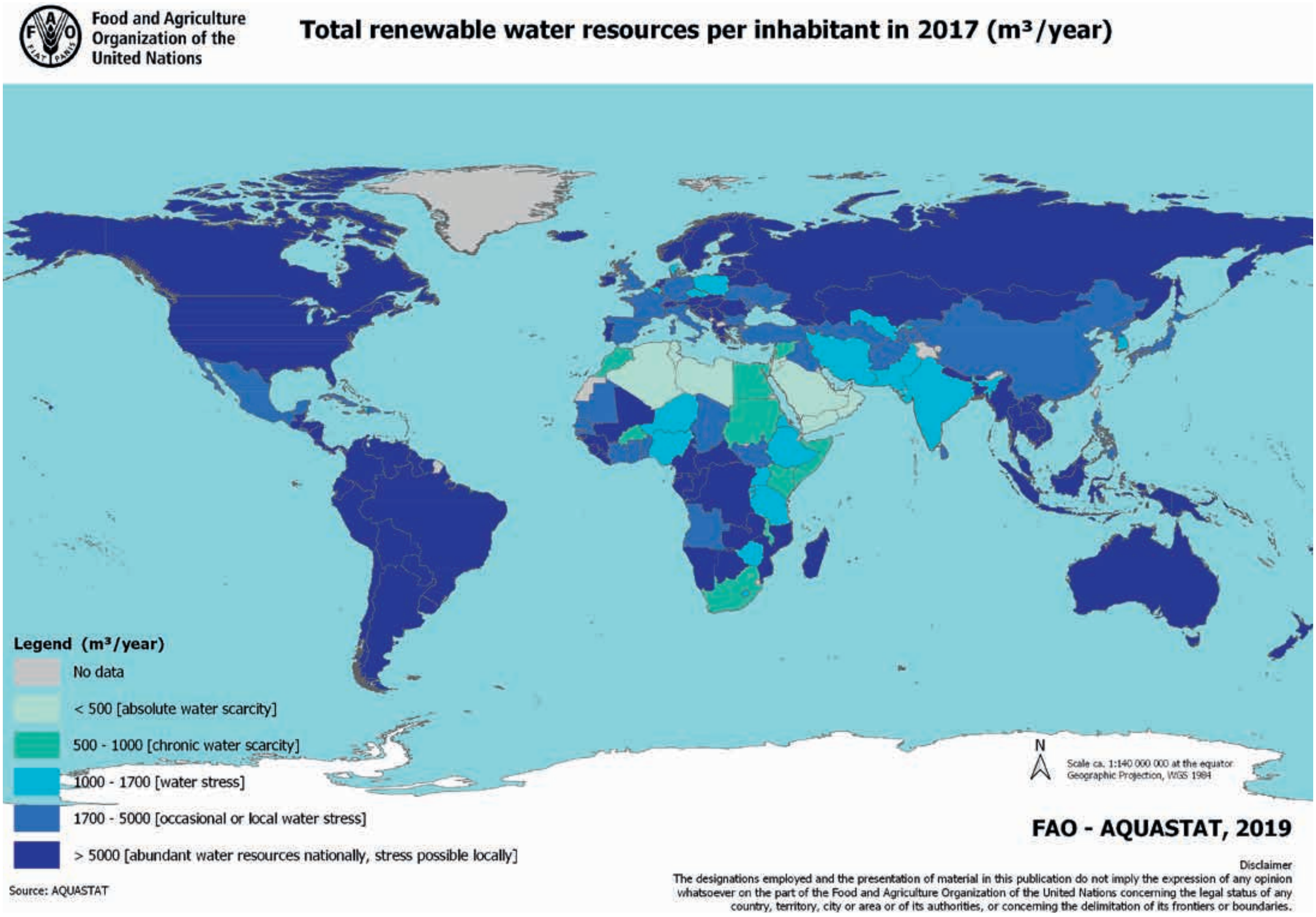
Most water on Earth is found in the oceans. Continental freshwater accounts for just under 3% of this and has two origins—stocks and the renewable water cycle (Marsily *et al.*, 2015). When it rains, part of the water that reaches the ground contributes to so-called 'blue' water that flows on the Earth's surface, in rivers and, after percolation, underground to recharge the water table, or it supplies lakes; the rest is so-called 'green' water that is temporarily stored in the ground and then directly evaporated or absorbed and subject to evapotranspiration via plants. Blue water represents about 32% of global precipitation, or approximately 36,000 km³/year of rainwater (Marsily *et al.*, 2018; Marsily, 2020).

▲ **Irrigation, Tunisia.** Monsfe Hnshir (farmer) highlights the importance of irrigation in his crop plot. Kettana, Tunisia.
Christian Lamontagne © IRD

FINITE RESOURCES?

Blue water resources may be directly used by communities, mainly for domestic, industrial, transport and agricultural irrigation purposes. Domestic water resources are therefore part of a more overall water resource management and conservation objective.

In 2020, blue water withdrawals (all usage types combined) were around 4,700 km³/year worldwide, i.e. 13% of the available water, for a consumption rate of 2,500 km³/year, i.e. 7% of the available water. Irrigation accounted for the main share of withdrawals as it contributed to meeting community food needs.



▲ **Total freshwater resources per inhabitant (m³/year) in 2017.** Source: FAO-AQUASTAT, 2019

The water demand is constantly rising due to world population growth, agricultural intensification and increased industrial water use. By 2050, water needs are expected to increase by about 50%, particularly due to the high agricultural irrigation demand, yet the demand will still be much lower than the available water supply. **There is hence no shortage of freshwater on the global scale.**

DIVERSE REGIONAL SITUATIONS

Yet this global vision does not clearly reflect the reality on the regional scale. Indeed, **freshwater is not equitably distributed worldwide** (see map above), depending on the precipitation abundance or scarcity, in addition to the fact that available freshwater resources are often inadequate for the human population distribution. Water managers can then be faced with various contradictory issues and strategic choices must be made. For instance, depending on the location, drinking water may be hampered by problems of scarcity, transport and/or quality. In areas with shortages, drinking water may be in direct competition with other high water consumption uses (e.g. irrigation), and then strategic choices must be made. Strategies may be needed to, for example, offset a reduction in irrigation water consumption by importing food that can no longer be produced locally.

Given the considerable importance of freshwater resources for humankind, especially in light of climate change, **sustainable management of these resources is becoming a priority**. Among the 17 Sustainable Development Goals (SDGs), adopted on 25 September 2015 by the United Nations Member States, SDG 6 specifically targets water (see Focus opposite).

FRESHWATER GROUNDWATER RESERVES

Renewable resources account for 95% of the water used on Earth, while the remaining 5% comes from groundwater reserves. Overall, these reserves are continuously decreasing due to: (1) excessive groundwater withdrawal for irrigation from a few large-scale aquifer systems, e.g. in India, USA, Pakistan, Iran and Mexico (Döll *et al.*, 2016); and (2) mainly due to the withdrawal of fossil water from large non-renewable aquifers, often the only substantial resources available in the regions where they are located.

This issue is clearly exemplified by the situation in northern Africa because this region hosts many large transboundary aquifers that are not or only barely recharged. These groundwater bodies are often the main, and sometimes only, freshwater resources available and their use may thus be a source of conflict. These aquifers were therefore extensively studied over the 1990-2010 period and subsequently the focus of concrete actions to bring together the concerned countries for joint management. There was then a marked reduction in these initiatives due to the endemic insecurity prevailing in most of the countries. Yet the extent of knowledge gained and actions underway shed light on their possible links with desertification phenomena while also highlighting their hydrogeological functioning. The latter is highly influenced by past climatic conditions—a research field based on isotopic assessment methods and modelling. These two aspects are the focus of the first two chapters in this *Dossier*. The hydrogeology and study of these systems are described in detail in the third chapter based on three examples of large-scale deep aquifer systems: the Chad Basin, the Nubian Sandstone Aquifer System (NSAS) and the North-Western Sahara Aquifer System (NWSAS). Finally, in the last chapter, the issue of the sustainable management of these large systems and the transboundary aspect is addressed through a detailed description of the actions undertaken in the NSAS and NWSAS. This has also provided an opportunity to review the international legal material that applies in this field.

▼ **Dunes in the Grand Erg Oriental, Tunisia.** Vincent Bonneau © IRD

→ FOCUS | An SDG devoted to water

SDG 6 aims to "ensure the availability and sustainable management of water and sanitation for all." This goal specifically calls for universal and equitable access to safe drinking water, hygiene and sanitation by 2030, especially for vulnerable populations. It also calls for sustainable management of this resource, and mentions reducing the number of people suffering from scarce water supplies. This goal mainstreams the notion of transboundary water management, which is essential for sustainable water management while also promoting peace and cooperation. SDG 6 includes eight targets, each of which contributes to the achievement of this goal (see table below).

Targets	Description
Access to drinking water	6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all.
Access to sanitation and hygiene services	6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.
Water quality	6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.
Sustainable water resource management	6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.
Integrated resource management	6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.
Ecosystem protection and restoration	6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.
Cooperation and capacity building	6.a By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies.
Collective water management	6.b Support and strengthen the participation of local communities in improving water and sanitation management.

Fossil water and desertification

Apart from the major river basins, the presence of freshwater in the form of lakes or springs (oases) in arid and desert areas of the Sahara-Sahel belt is often exclusively linked to the surfacing of deep groundwater. The latter is considered as 'fossil' water because it accumulated during the rainy periods of the Quaternary, thousands or even hundreds of thousands of years ago. Human withdrawal of this water (via drainage and pumping) or its natural emptying may result in the drying up and/or salinization of these wetlands and in turn to the disappearance of their biodiversity. **Deep groundwater resource preservation is a key factor in combating desertification.**

▼ **Oum El Ma Lake, Erg Awbari, Libya.** Groundwater resurgence.
© Philippe Crochet

→ FOCUS | A few hydrogeological terms in a nutshell…

Aquifer: a layer or mass of permeable rock with a saturated zone (the entire solid substrate and water therein) that is sufficiently conductive to enable high groundwater flow and harnessing of substantial amounts of water.

Aquifer system: a single aquifer or group of aquifers and semi-permeable bodies ('aquitards'), whose parts are in continuous hydraulic connection, and whose boundaries prevent any marked outward propagation. An aquifer system represents the range of groundwater flow (and transport), according to the distribution of potentials (hydraulic head or water column pressure), as well as the range of propagation of influences of all natural (e.g. recharge, discharge) and artificial (e.g. pumping) origins.

Area of influence: area in which the piezometric surface in an aquifer is impacted, i.e. modified, by drawdowns due to groundwater withdrawal.

Artesian: a well or borehole that exposes groundwater, which rises to the surfaces naturally.

Artesian groundwater flow: a phenomenon whereby groundwater gushes to the surface.

Confined aquifer and confined groundwater: an aquifer overlaid by geological horizons of low permeability, where the contained groundwater has no phreatic surface—it is under higher pressure than the atmospheric pressure throughout. This groundwater is considered as being 'confined' and its piezometric surface is higher than the aquifer ceiling. Hence a drop in the piezometric level will not deplete the aquifer, which is limited by its ceiling, but will lead to hydraulic decompression.

Free or unconfined aquifer: generally a shallow aquifer where the piezometric surface marks the upper limit and the groundwater is considered as being 'free'. The piezometric level freely fluctuates and its pressure matches the atmospheric pressure. The reservoir becomes desaturated when the piezometric level drops.

Groundwater: all water in a saturated aquifer zone, whose parts are hydraulically connected.

Groundwater recharge: external water of many origins supplying an aquifer.

Hydraulic decompression: during withdrawal or natural emptying of an aquifer trapped between two impermeable levels ('confined aquifer'), its piezometric level drops, as for an unconfined aquifer, but without desaturation. Only the internal pressure decreases, thereby leading to a decrease (generally elastic, therefore reversible) in the rock porosity, and also to decompression of the contained water—hence the term 'hydraulic decompression'. These two processes enable water production without desaturation of the environment.

Leakage: groundwater transfer, usually vertical and slow, through a semi-permeable horizon.

Piezometric level: upper level of a static liquid column where the hydrostatic pressure is equilibrated relative to the datum. It is measured by the free water level in a vertical borehole open at the target point (piezometer).

Saturated zone: a two-phase (solid, liquid) system where all pores of the solid substrate are filled with water.

Supply or recharge area: the zone in which continuous or temporary water inflows occur to recharge an aquifer, especially a partially confined aquifer that is not recharged throughout its full expanse.

Unsaturated zone: a three-phase (solid, liquid, gas) system where only some of the pore spaces are filled with water, with soil air occupying the rest.

Well field: an area that includes a number of abstraction sites/pumping wells (interconnected or not) that are arranged so as to minimize interference while being jointly managed for a given use.

For further information: Castany and Margat, 1977; Collin, 2004
http://hydrologie.org

FOSSIL WATER – ANCIENT ENDANGERED RESOURCES

Schematically, from a management standpoint, there are two categories of aquifer systems: (1) those in which groundwater flows and recharges seasonally, i.e. 'renewable' aquifer systems; and (2) those with little or no recharge due to the prevailing climatic and/or geological conditions, i.e. 'non-renewable' or 'barely-renewable' aquifer systems. Sustainable management of these two types of systems relies on different withdrawal schemes.

Renewable aquifers are replenished in their recharge areas directly by rainfall and percolation, or indirectly via surface water. They may also sometimes be recharged by deep aquifers, especially in pumping areas, through vertical leakage between two adjoining and overlapping aquifers caused by a drop in head (or piezometric level) in the surface aquifer. The renewable part of this resource could be considered as the share of average natural flow that could be used under suitable technical, economic and environmental conditions. Indeed, the water 'reserve'—which could initially be tapped if the reservoir is sufficiently thick and the groundwater is close to the surface—can subsequently be recharged in the medium term. **Sustainable management implies that only this renewable part of the reservoir should be tapped.**

> Fossil water accumulated in aquifers in distant geological times—thousands to hundreds of thousands of years ago under climatic conditions that were wetter than nowadays.

These aquifer systems are commonly found in humid and temperate regions, especially in the form of alluvial or colluvial aquifers, or in karst systems with substantial water flow during the hydrological cycle. **They are much less common in arid and semiarid regions where the drainage networks are often restricted to large rivers.** Surface aquifers in Sahelian regions are recharged during the rainy season, but they are highly vulnerable because the reserves are very limited and cannot withstand long periods of drought.

Otherwise, **non-renewable aquifers** are barely or not recharged due to their hydrogeological features, and especially because they are currently located in areas under arid or semiarid climatic conditions, whereas most of them were formed during earlier and more humid geological periods. Precipitation in these regions is often too low and evapotranspiration too high to significantly recharge deep aquifers. In this second category, which generally corresponds to aquifers in large sedimentary basins, the water is considered to be 'fossil water'.

By definition, **fossil water is therefore water of atmospheric origin whose stocks were directly (rainfall) or indirectly recharged via rivers and lakes during wet periods of the Quaternary.** Given the fact that these resources are buried in confined spaces far from recharge areas, the waters are under pressure ('load') and may surface naturally—in the form of springs or diffuse flows that supply rivers and lakes, such as Yoa Lake in northern Chad (see photo below)—or artificially (via boreholes).

Anthropogenic (artificial) withdrawals of these fossil waters essentially amount to destocking operations that often have relatively little impact on natural outflows (at springs and via drainage) during the first years of withdrawal. Regarding deep confined aquifers, this destocking process does not desaturate the reservoir but instead causes hydraulic decompression.

In humid or temperate regions, non-renewable aquifers may occur alongside perennial streams and renewable aquifers, but the latter are preferentially tapped. When there is sufficient decompression, these aquifers may even recharge underlying aquifers (via downward drainage). Their management is therefore somewhat simpler.

Otherwise, abstraction of these non-renewable aquifers does not represent substantial amounts of water on a global scale (32 km^3/year, i.e. about 4% of global groundwater withdrawal). However, **in arid or semiarid regions, non-renewable aquifers are often the main —or even only—water resources that can be tapped. The situation with regard to their use is therefore similar to that of mining, i.e. with a high risk of depletion** (see Focus next page).

◀ **Access to water in Niger. An artesian well.** Wankam, Tillabéri region.
Tahirou Amadou © IRD

▼ **Yoa Lake (370 ha, maximum depth 25 m) near Ounianga Khebir, northern Tchad.** This lake, located between Tibesti and Ennedi, is recharged via several springs which emerge through the fractured sandstone (water with a 300 mg/l mineralization rate).
© Jacques Taberlet

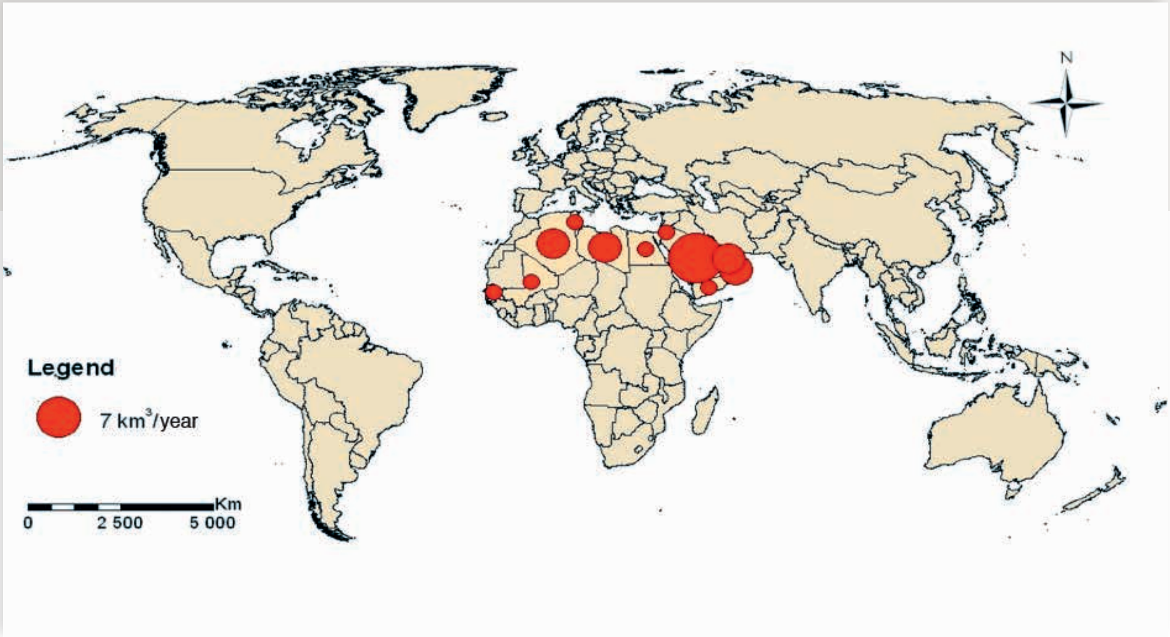
→ FOCUS | Mining fossil water – a feature of drylands?

Almost all groundwater withdrawals worldwide concern renewable resources, yet a small fraction of these withdrawals—but substantial in some countries—corresponds to non-renewable resource mining.

Amount of water produced worldwide via mining
On the basis of available statistics (1995–2005 data), which are relatively old and incomplete, groundwater mining for this recent period is estimated at about 32 km^3/year worldwide (see table opposite).

Share of this production in total groundwater extraction
Total worldwide groundwater withdrawal is about 800 km^3/year, with water mining accounting for 4% of this withdrawal, i.e. relatively low. However, this type of fossil water extraction is focused in a few countries, while being predominant in some of them (see map below).

Producing countries
Groundwater mining is relatively concentrated, i.e. the three largest producing countries—Saudi Arabia, Libya and Algeria—account for nearly 85% of the estimated world total. Note that the economy in these countries is based mainly on mining (hydrocarbon exploitation), so non-renewable resource mining is a normal familiar process, even when it comes to water. Water mining is thus a speciality of arid and hyper-arid regions—almost all of these extractions (98.5%) take place in Arab countries.



▲ **Global non-renewable groundwater resource mining.** Source: Margat, 2006

> Beyond a certain threshold, any extent of fossil water usage is considered excessive, which leads to a gradual disappearance of the aquifer water stock. Tapping of these resources is thus similar to mining.

In the largest producing countries, non-renewable resource extraction is a significant supply, and often the dominant and even only one. This fulfils a major share of the water needs (mainly for irrigation):

- 86% in Saudi Arabia
- 83% in Oman
- 74% in the United Arab Emirates
- 71% in Libya
- 35% in Algeria (~ 100% in the Sahara)

These non-renewable water resource mining operations are major short- and medium-term development factors, but they are clearly likely to raise long-term human, societal and ecological problems.

Source: Margat, 2008
For further information: Marsily *et al.*, 2015; Marsily, 2020

Country	Date of data	Extraction km³/year	Aquifers mined	References
Saudi Arabia	2000	20.47	Arabian Multilayered Aquifer System	Abdurrahman, 2002
Libya	1999-2000	3.2	Nubian Sandstone Aquifer SASS, Murzuk	Bakhbakhi, 2002 OSS, 2003
Algeria	2000	1.68	NWSAS	OSS, 2003
United Arab Emirates	1995-1996	1.57	Arabian Multilayered Aquifer System	ESCWA, 1999
Oman	1998	1.09		ESCWA, 1999
Egypt	2002	0.9	Nubian Sandstone Aquifer	ESCWA, 1999
Yemen	2005	0.9	Tihama Aquifer	Al Asbahi, 2005 (IWC-Env.)
Tunisia	2000	0.46	NWSAS	OSS, 2003
Jordan	1998	0.35	Disi Aquifer	ESCWA, 1999
Kuwait	1998	0.25	Arabian Multilayered Aquifer System	ESCWA, 1999
Mali	2000	0.2	Taoudéni Basin	OSS/UNESCO, 2005
Senegal	2003	0.18	Maastrichtian	OSS/UNESCO, 2005
Bahrain	1995-1996	0.16	Arabian Multilayered Aquifer System	ESCWA, 1999
Qatar	1995-1996	0.15	Arabian Multilayered Aquifer System	ESCWA, 1999
South Africa	-	~ 0.10	Karoo Aquifer	
Mauritania	2003	0.09	Maastrichtian	OSS/UNESCO, 2005

▲ **Global groundwater resource mining.**
Contemporary production according to available data.

▼ **El Guettar, Oasis Tunisia.** Deep borehole reaching fossil aquifers. Located upstream of the oasis, the water flows gravitationally towards the crop plots and houses. Jean-Pierre Montoroi © IRD

SALINIZATION AND BIODIVERSITY LOSS

Regardless of whether fossil water emerges naturally (springs that can supply oases) or artificially (boreholes), its outlet and usage conditions can have a major impact —such as water and soil salinization or the halt of natural gushing of the resource—in fragile environments, such as that of Kufrah Oasis (Libya) or in southern Tunisia.

These aquifers are by definition barely or not at all recharged, so the resources are susceptible to mining, while being endangered in the more or less long term once the (natural) emptying or withdrawals are higher than the water supply. Whether naturally, very slowly, or more rapidly due to heavy withdrawals, the hydraulic pressure decreases in the aquifer (hydraulic decompression), the groundwater piezometric level drops, gradually leading to the disappearance of the springs and in turn of the oases.

Moreover, very substantial water and soil salinization could occur in these environments due to the very high water evaporation rates linked to the high prevailing temperatures. Indeed, salts (dissolved elements) naturally present in groundwater do not evaporate and they accumulate on site. **Salinization is therefore associated with the dynamics of groundwater that serves as a surface water supply and often accompanies drops in groundwater levels and flows.** These changes inevitably have significant negative impacts on biodiversity.

Drying up of wetlands and salinization...

Kufrah Oasis (southern Libya, near the borders of Chad and Egypt) was, for instance, a beautiful freshwater lake in 1924. It then became a salt lake after about 40 years (up until the 1960s), and it has now completely disappeared due to the end of artesian groundwater flow. Nowadays, water is supplied to the palm groves via boreholes several tens of meters deep (see photos below).

▲ **Evolution of the Kufrah Oasis lake from 1924 to present day.**
Top: from Edmunds, Travi *et al.*, 2001
Middle: © W.M. Edmunds
Bottom: © Y. Travi

The drop in the water level of a lake, concomitant to a drop in its supply, can lead to the disappearance of its outlet. As the water is no longer sufficiently renewed, the lake becomes concentrated due to evaporation. Similarly, in places where the water stagnates and becomes shallow, or goes and comes, salt deposits quickly settle (e.g. around Youan Lake, Chad, see photos opposite).

... and biodiversity loss

Very rich permanent and seasonal microfauna and macrofauna communities are present around and within these deserted freshwater bodies. Obviously **the total disappearance or salinization of these water bodies is accompanied by the disappearance of almost all biodiversity.**

Even though some of these natural sites are doomed in the long term due to the natural deep aquifer emptying and decompression, good water resource management can safeguard such aquifers for many years. Salinization can be combated by ensuring good drainage of water bodies, and boreholes can replace natural water inflows, provided that their flow rates are tailored to the hydrogeological conditions so as to preserve the resources as well as possible.

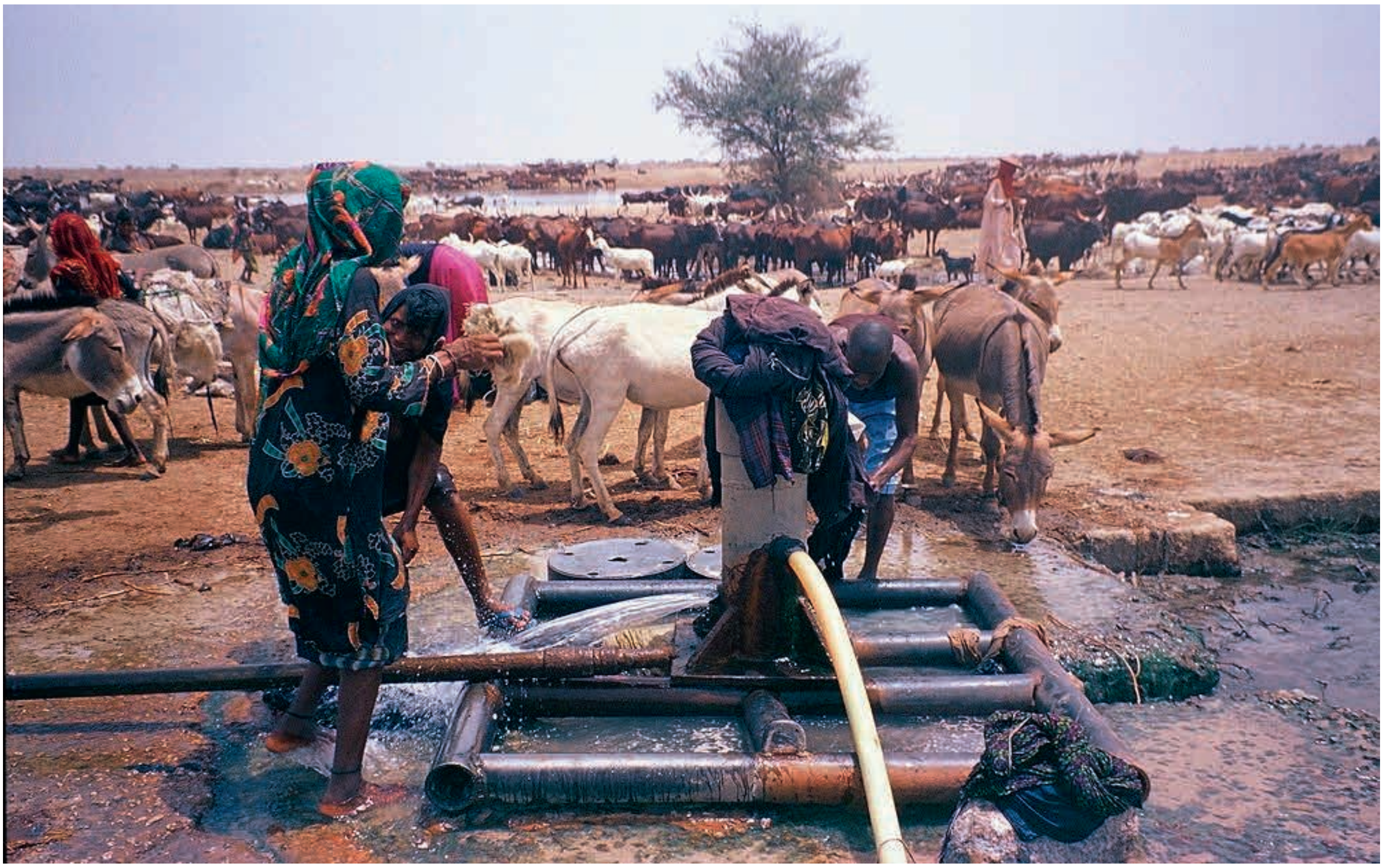
For further information on the description and hydrological behaviour of these lakes; see Van Der Meeren Thijs *et al.*, 2019.

▲ **Zone around Yoa Lake (Chad).** Freshwater spring and nearby salt deposits.
© *Ministère en charge de l'Eau, Bureau national de la commission conjointe de la nappe de grès de Nubie*, Ndjamena, Chad

▲ **Zone around Ounianga Serir, Teli Lake (Chad).**
Salt deposits on the lake shore. © Jacques Taberlet

▲ **Presence of birds in freshwater Bokou Lake, near Ounianga Serir in northern Chad.**
© *Ministère en charge de l'Eau, Bureau national de la commission conjointe de la nappe des grès de Nubie*, Ndjamena, Chad

General features of fossil aquifers



▲ **Artesian well in Lake Chad Basin, Nigeria.** © I. Baba Goni

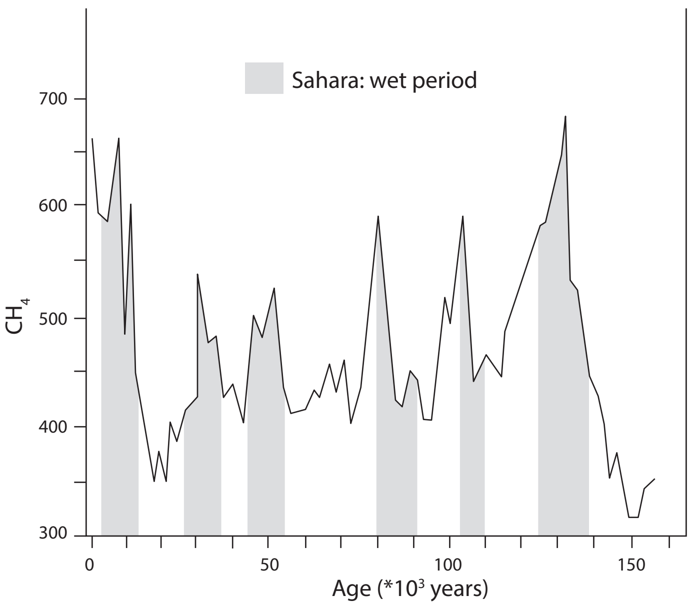
▲ **Fossil lake in the Algerian Sahara region (I-n-Atei), with an alternation of diatomaceous earth and fine and coarse detritus deposits.** Many freshwater fish fossils are found in the diatomaceous deposits, along with wildlife remains, charcoal and prehistoric tools on the paleolake banks. © Yves Travi

PALEOHYDROLOGY – DEEP AQUIFER RELICTS OF HUMID QUATERNARY PERIODS

There is substantial evidence (rock paintings, tools, etc.) of ancient populated areas with abundant water supplies and dense vegetation in Saharan and sub-Saharan regions. Wide rivers, whose beds are still visible in the landscape, flowed northwards towards the Mediterranean, southwards towards the Atlantic or in the direction of vast lake basins. Traces of lakes (sediments or fauna fossil remains) are currently found in the most arid Saharan regions (see photo left and opposite page).

▲ **Rock painting in Libya.** For Tuareg people, the Jebel Akakus is Tadrart, i.e. 'the mountain' in Tamasheq, underlies the highest mountain range in southwestern Libya. The prehistoric Tadrart Akakus area has been classified as a World Heritage Site by UNESCO for its exceptional wealth of engravings and rock paintings. Through the animals and human figures represented, this mainly desert area reflects the temporal evolution of the climate. Christian Leduc © IRD

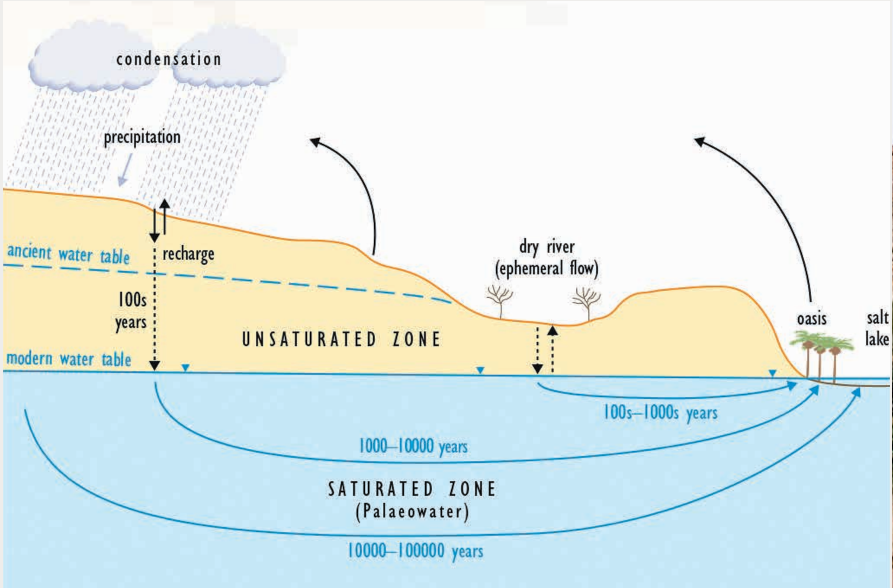
Groundwater resources could have been replenished with water from the central Saharan mountain ranges, which functioned as a 'water tower', or via infiltration from the large lacustrine areas. Dating research has revealed that episodic recharges occurred during various wet periods of the Holocene and late Pleistocene. **Huge volumes of water from these ancient periods are currently stored in deep aquifers in the Sahara and Sahel regions.** Desert oases are the only visible vestiges of the hydrological functioning of these periods. They are the natural outlets of these vast deep aquifers of water—discharged under pressure—that infiltrated several thousand years ago (see Focus next page).



▲ **Climate change patterns (relative to atmospheric methane concentrations) over 150,000 years, and rainy phases in the Sahara Desert**
From Petit-Maire *et al.*, 1991

→ FOCUS | **Oasis – a remnant of wet periods in the distant past**

Oases in desert areas receive groundwater from deep aquifers. This water may come to the surface through fractures associated with various relatively complex geological structures, or via surfacing of the water table (current or ancient) in topographical depressions (see diagram below left).



▲ **Water cycle in arid regions.** Today's rainfall may take decades or centuries to reach the water table, which is adjusting to present drier climatic conditions. From Edmunds, Travi *et al.*, 2001

▲ **Aoué oasis with palm trees north of Guelta d'Archei Lake, Chad.** Marcel Roche © IRD

▲ **Guelta d'Archei Lake southwest of the Ennedi mountain range.** © Jacques Taberlet

FUNCTIONING OF DEEP AQUIFERS IN THE SAHARO-SAHELIAN REGION

Sahara – huge aquifers prevail

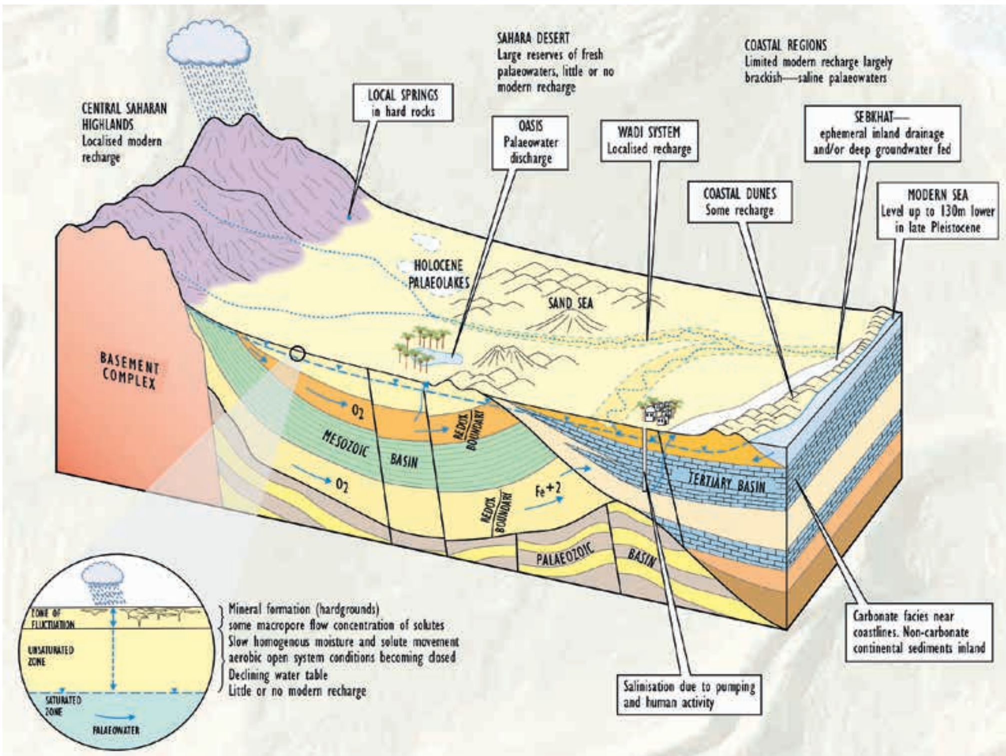
There is less than 100 mm of rainfall yearly throughout most of the Saharan region. Good quality groundwater may, however, be found in many of the large sedimentary basins, but very deep wells are sometimes necessary to tap this drinking water. Geochemical and isotope hydrology research (see p. 23) has shown that these water resources are ancient and formed as a result of rainfall (recharge) in ancient times when the climatic conditions were wetter than today.

Sahelian and Saharan sedimentary basins host substantial fossil groundwater resources.

Groundwater generally flows from the mountain ranges in the centre of the Sahara (Hoggar, Tassili, Tibesti, Air, Adrar des Iforas, Ennedi)—potential recharge areas—towards the centre of the basins where water flow is generally very slow (a few m/year), including a relatively marked vertical upward component (see map and diagram opposite).

▲ Sahara region.

▶ Diagram illustrating the evolutionary patterns regarding landscape elements, groundwater recharge and quality in the African Sahara.
From Edmunds, Travi *et al.*, 2001



▼ Outline of large-scale deep confined aquifers in North Africa.
From Seguin and Gutierrez, 2016

Extensive ancient fossil groundwater resources hence prevail in major sedimentary basins of the Sahara, such as the North-Western Sahara Aquifer System (see. p. 34). These basins include geological series spanning the Cambrian (primary era) to the Quaternary period and contain many permeable freshwater layers up to 2,000 m deep.

The freshwater gradually becomes brackish in the vicinity of the coast, while the continental geological facies give way to marine facies dominated by carbonate rock.

Sahel – smaller aquifers

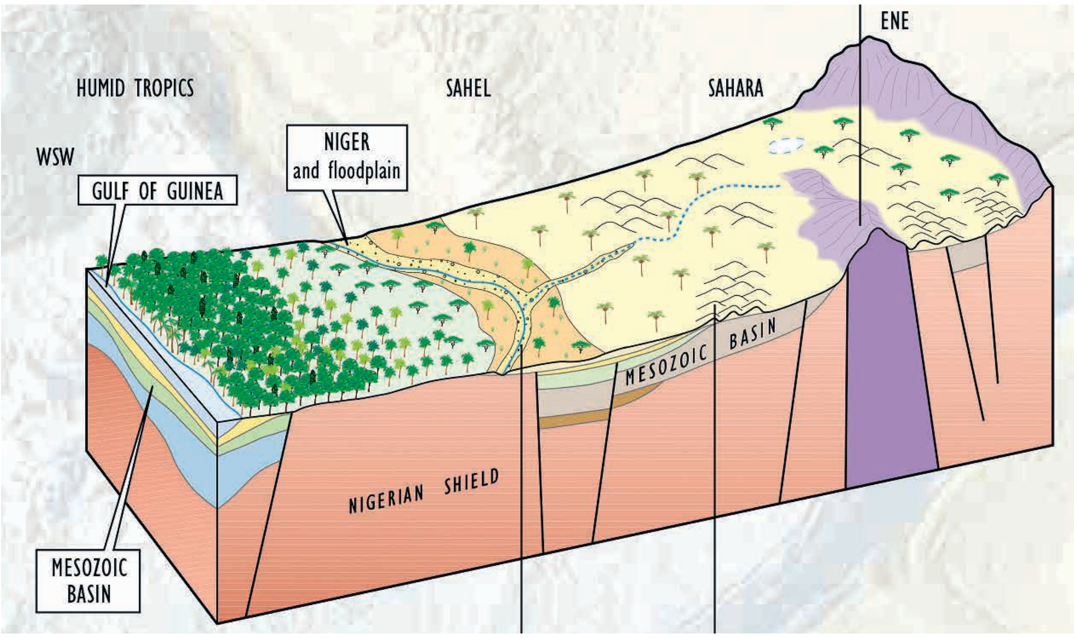
The Sahel separates the humid tropical zone from the Sahara Desert. Like the Nile further east, two major rivers, i.e. the Senegal and Niger, flow through the Sahel, bearing water from the humid tropical zone. Similarly, the Chari River provides the main water supply for Lake Chad.

Several sedimentary basins are located in the Sahelian region (Senegal-Mauritania, Chad, Iullemeden), although they are relatively smaller than those found in the northern Saharan region.

Many of these basins are located in grabens (trenchlike blocks between two normal faults) in the bedrock (African shield, composed of granite, metamorphic rock and ancient sedimentary rock). **The aquifers were markedly recharged during the Pleistocene and, more locally, during the Holocene, and many paleolakes were formed during the last wet periods around 4,000 years before present (BP*).**

Most groundwater in the Sahel—as in the Sahara—is of fossil origin and the only significant recharges currently occur along perennial or seasonal streams.

* The baseline 'present' date is conventionally set at 1 January 1950.



▲ **Diagram illustrating the landscape elements and groundwater resources in Sahelian regions.**
From Edmunds, Travi *et al.*, 2001

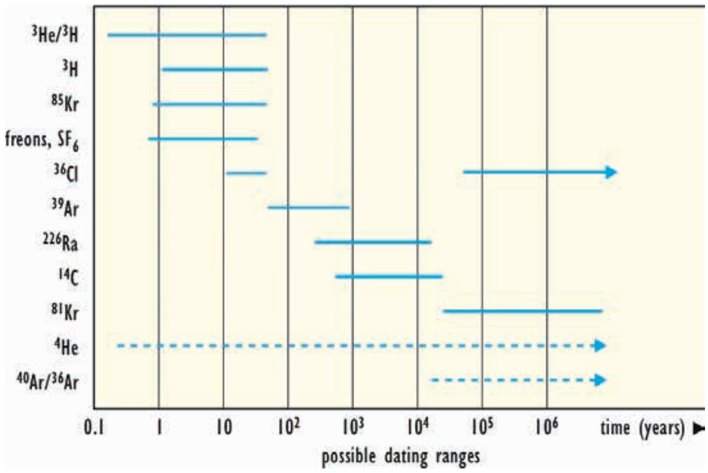
PALEOCLIMATIC INDICATORS AND DATING TOOLS

Isotopic tracer techniques

Scientists use paleoclimatic indicators to piece together ancient terrestrial climatic conditions. Water found above or below the water table can provide useful information to reconstitute past climates and determine aquifer recharge periods. Tracers sensitive to climatic variations (temperature and rainfall) and residence time indicators are used for groundwater dating and thereby highlight the temporal evolution of climatic parameters.

> Groundwater is a legacy of the past and can bear traces of past climatic and temperature conditions, of ancient vegetation and rocks via which it has flowed. It preserves certain features acquired at the time of its initial infiltration and then drains very slowly underground where water up to several million years old may be found.

A range of radioisotopes and chemical elements of anthropogenic origin (e.g. chlorofluorocarbons [CFCs], or so-called freons) can be used to assess water age. These tracers cover periods ranging from a few decades to several tens or hundreds of thousands of years (see adjacent figure). Many of these tracers are hard to use and interpret and must be managed by a specialist.



▲ **Timescales covered by different tracers.**
From Edmunds, Travi *et al.*, 2001

Isotopic tracers are now commonplace, these include the oxygen 18 to deuterium ratio ($^{18}O/^2H$) and carbon 14 (^{14}C) to date ancient waters, or the oxygen 18/deuterium ratio and tritium, or CFCs, for dating recent waters. These tools help determine the residence time of the water and highlight recharge origins and climatic conditions.

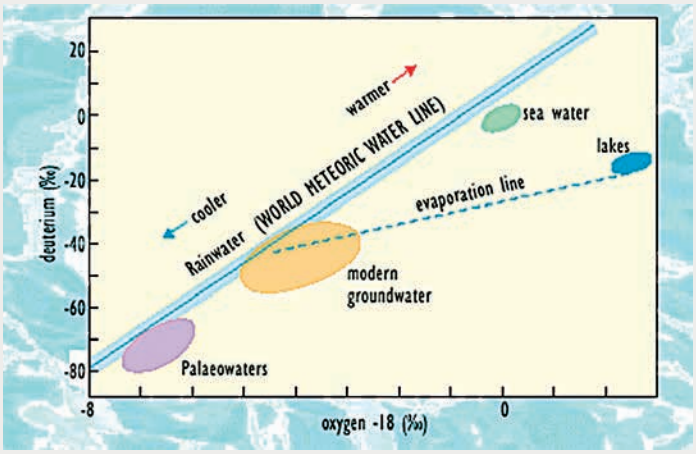
Radiocarbon (or the ^{14}C radioisotope of carbon), associated with the $^{18}O/^2H$ ratio, is probably the most widely used fingerprinting tool in Saharan-Sahelian groundwater studies, as is the case regarding the Azaouad Depression north of the Niger River (see box page 25). Stable oxygen and hydrogen isotopes are used to reconstruct paleoclimates by characterizing the evaporated water and recharge conditions (water origin, temperature and rainfall) (see Focus next page).

Ratios between noble gases (helium, neon, argon, krypton, xenon, radon)—which are used to a lesser extent due to the more complex sampling and analysis conditions—provide information on the atmospheric temperatures of more ancient periods, since their solubility is temperature-dependent. This signature is preserved when the water reaches confined aquifers.

→ FOCUS | Use of water molecule isotopes to fingerprint paleoclimates

Isotopes are atoms of the same chemical element that differ only in the neutron number in their nucleus, so they do not have the same atomic mass. Water is composed of two stable isotopes—$^2H_2{}^{18}O$, (heavy isotopes) and $^1H_2{}^{16}O$, (light isotopes). These isotopes fractionate during meteorological processes (condensation and evaporation) and their ratios change accordingly. The isotopic composition ($\delta^{18}O$ or δ^2H_2) can thus serve as a climate-based groundwater tracer, i.e. more negative values combined with a relative decrease in the heavy isotope (e.g. ^{18}O, depletion) generally reflect colder and wetter climatic conditions while, conversely, relative ^{18}O enrichment reflects warmer climatic conditions or high water evaporation. Regarding evaporation, as fractionation takes place in an unsaturated atmosphere (contrary to condensation), ^{18}O and ^2H fractionate differently—as seen in the diagram, the dots are aligned on an evaporation line with a different slope than that of the ocean vapour line (Global Meteoric Water Line).

For further information: Tweed *et al.*, 2019



▲ **Information derived from the $^{18}O/^2H$ ratio.**

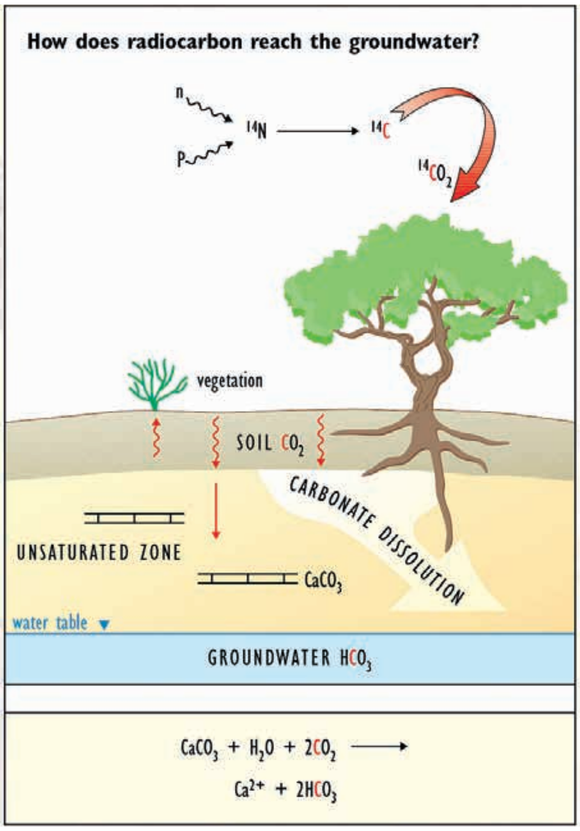
From Edmunds, Travi *et al.*, 2001

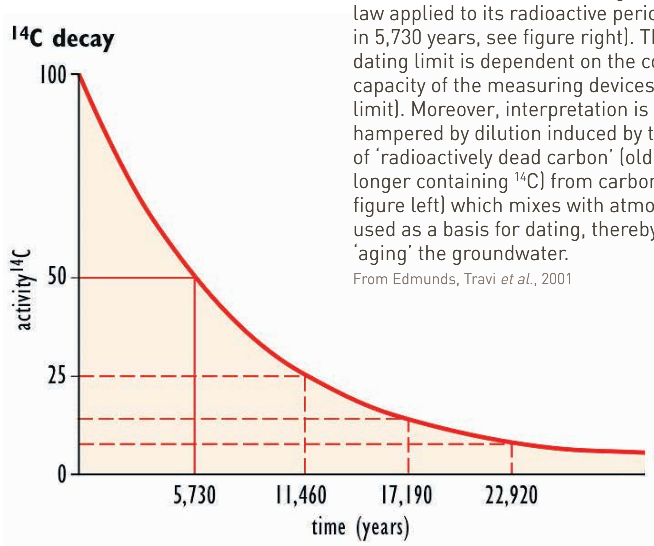
Carbon 14 and krypton 81 – preferred tools for dating very ancient groundwater resources

Groundwater in the Sahelian-Saharan regions may have a residence time in aquifers of many thousands or tens of thousands of years, or even more. Carbon 14 groundwater dating is therefore by far the most widely used method, since its dating scope—with sufficient accuracy—reaches about 35,000 years (see figure below).

Carbon 14 dating is based on measurement of its residual radiological activity. Two main approaches are used for fingerprinting groundwater:

1. liquid scintillation counting of beta particles following extraction of the carbon contained in the different carbonated water soluble forms and transformation into benzene;
2. accelerator mass spectrometry (AMS)—a more recent method that is considered as the most efficient. The carbon 14 fraction is measured directly (atom count) relative to carbon 12 and 13 atoms.





◀ **Carbon 14—the only radioactive carbon isotope—is produced by cosmic radiation in the upper atmosphere and like all carbon atoms reacts with oxygen to form CO_2.**
Once sequestered underground from the atmosphere, carbon 14 gradually undergoes so-called radioactive decay. Its radioactivity decreases over time according to an exponential law applied to its radioactive period (or half-life in 5,730 years, see figure right). The maximum dating limit is dependent on the counting capacity of the measuring devices (detection limit). Moreover, interpretation is often hampered by dilution induced by the dissolution of 'radioactively dead carbon' (old carbon no longer containing ^{14}C) from carbonate rocks (see figure left) which mixes with atmospheric carbon used as a basis for dating, thereby artificially 'aging' the groundwater.

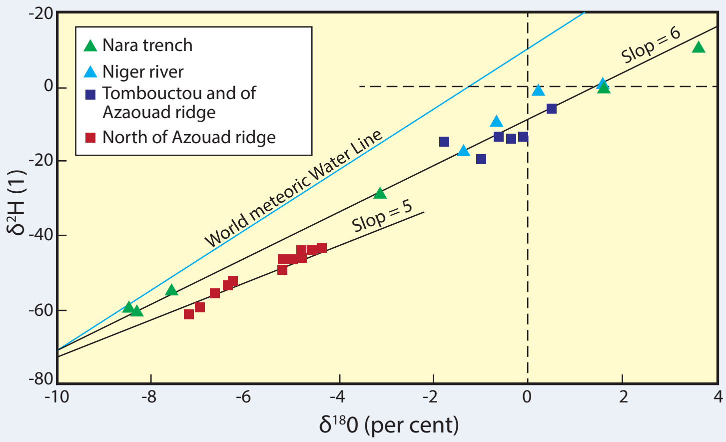
From Edmunds, Travi *et al.*, 2001

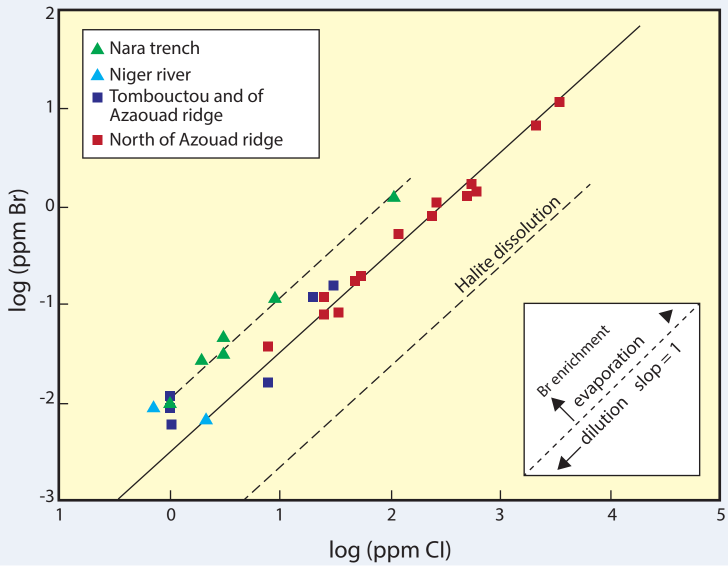
→ EXAMPLE | **Water and carbon 14 isotopes to assess groundwater paleorecharges in northern Mali**

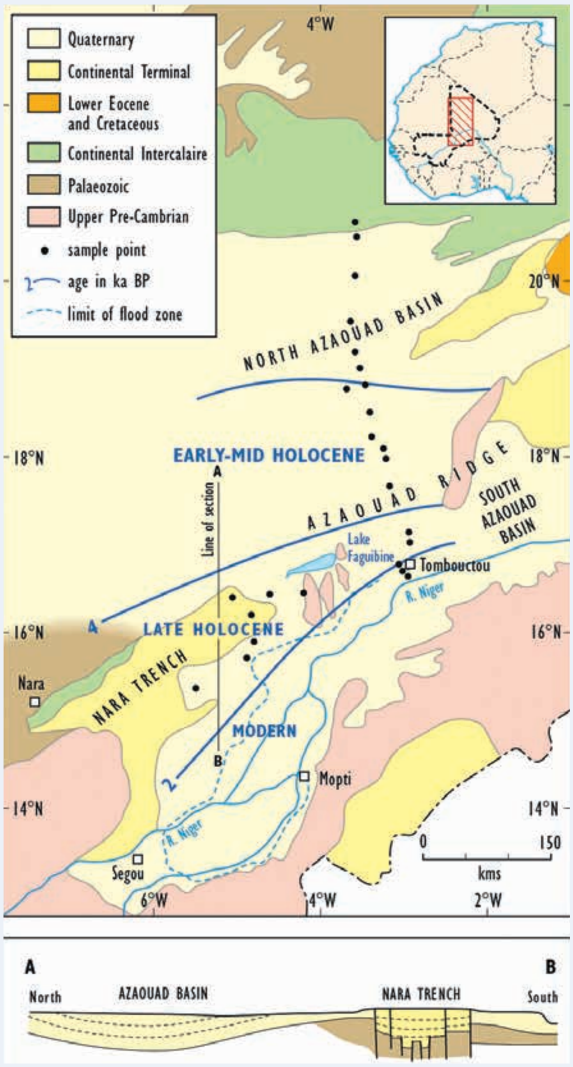
The Azaouad Depression located north of the Niger River in Mali has been recharged during current Niger flooding periods and directly by rainfall during Holocene wet periods.

This has been clearly illustrated by the chemical and isotopic (water molecule isotope) compositions in groundwater with temporally well defined radiocarbon ages (^{14}C dating). The latter show a zonation pattern suggesting that the river migrated from north to south across the Nara trench over a 4,000-year period since the end of the Holocene wet period. The chemical and isotopic signatures suggest that the northward extension of the River's flood recharge was restrained by the Azaouad ridge. Signatures in the southern part are characteristic of the River water, whereas those in the part north of the ridge indicate that recharge occurred exclusively via local rainfall.

From Fontes *et al.*, 1991







▲ **Geological setting and section through the Azaouad Basin, Mali.** © Edmunds, Travi *et al.*, 2001

◀ **Top: isotopic evaporation signatures (slopes 5 and 6).** These differentiate groundwaters of the Sahara (Azaouad ridge) from those of the Sahelian region to the south, recharged via paleorecharge from the Niger River.

◀ **Bottom: Br/Cl ratio.** This distinguishes slightly bromine-enriched waters, related to recharge from the River, from waters with a Br/Cl ratio close to that of rainfall.

Given the limitations of ^{14}C dating with respect to the very ancient groundwaters of the major Sahelian-Saharan basins, interest has been growing in the use of krypton 81, which complements carbon 14 for dating groundwaters more than 35,000 years old, and even up to several hundred thousand years old. Use of this approach—long hampered by the relatively complex sampling and analysis conditions—has increased in recent years with the development of new techniques. Krypton 81 is a chemically inactive noble gas and hence does not require correction, unlike carbon which undergoes chemical change in the system. Moreover, concomitant measurement of krypton 85 allows us to check for potential pollution by current atmospheric gas during the sampling process (Purtschert *et al.*, 2013).

Hydrogeology of large aquifers in northern Africa

▲ **Douz oasis in southern Tunisia.** The town of Douz in southern Tunisia is known as the 'gateway to the Sahara'. It was the most important oasis in the region in ancient times, and a key stopover for caravans on their journeys between the Sahara and northern Tunisia. It is now a popular destination for tourists who come to visit the Grand Erg Oriental sand dunes. Edmond Bernus © IRD

In northern Africa, three main types of geological units prevail: (1) ancient basement complex areas, (2) continental sedimentary basins and (3) coastal sedimentary basins, with the latter being mainly represented by the Senegal-Mauritanian Basin in sub-Saharan Africa.

The major deep aquifers—which are often multi-layered and centrally confined (i.e. intercalated between two quasi-impermeable geological formations)—correspond to the continental sedimentary basins and are located in the two following major geological sequences:

- the Continental Terminal (or so-called Terminal Complex in North Africa), consisting of sedimentary formations of the Cenozoic Age (Middle Eocene-Pliocene, 56–2.6 million years BP), essentially detrital, sandy or sandy-clay;
- the Continental Intercalary, essentially of the Mesozoic Age (252.2–66 million years BP), with predominantly sandstone sedimentary formations with clay intercalations. It is the predominant aquifer in Saharo-Sahelian Africa, while its resources are generally considered as being non-renewable or barely renewable.

WIDE-RANGING AQUIFER SYSTEMS

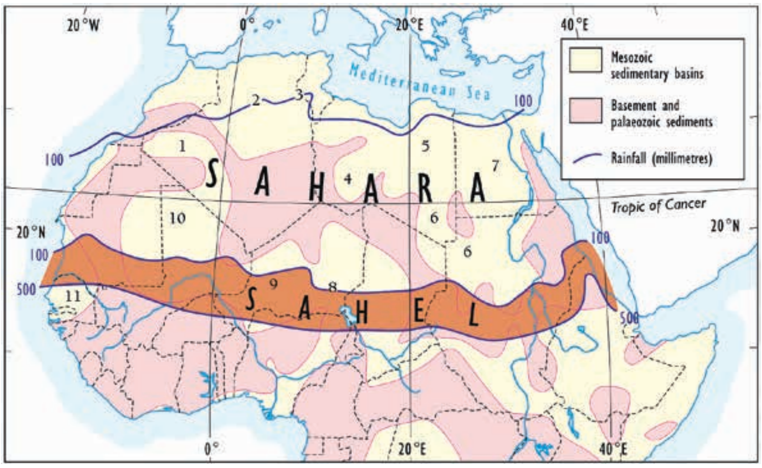
The main continental sedimentary basins of the Saharo-Sahelian zone are schematically illustrated on the adjacent map, while the main aquifers of these basins are shared between several countries (see table next page).

Some of these aquifers have been the focus of numerical modelling*, such as the North-Western Sahara Aquifer System (NWSAS), the Nubian Sandstone Aquifer System (NSAS), as well as the Iullemeden and Taoudeni Aquifer Systems, which are characterized by relatively high recharge flow rates on the southern slopes and via the Niger River.

NWSAS and NSAS—given the geographical position of their borders (potential recharge zone)—can benefit from recharge flows, particularly on the southern sides and via the Niger and Nile Rivers. These recharges are, however, insignificant relative to the reservoir volumes.

Aquifer name	Countries	Area (10^3 km^2)
Nubian Sandstone Aquifer System (NSAS)	Egypt, Libya, Sudan, Chad	2,200
North-Western Sahara Aquifer System (NWSAS)	Algeria, Libya, Tunisia	1,000
Lake Chad Basin	Niger, Nigeria, Chad, Cameroon, Central African Republic	1,500
Taoudeni Aquifer System (TAS) and Iullemeden Aquifer System (SAI)	Benin, Burkina Faso, Mali, Mauritania, Niger, Nigeria, Algeria	TAS: 2,000 IAS: 500
Murzuk Basin	Algeria, Libya, Niger	450
Senegal-Mauritanian Basin	Mauritania, Senegal, Gambia, Guinea-Bissau	340

▲ **Main deep aquifers in northern Africa.** From Seguin and Gutierrez, 2016



▲ **Schematic map of the main sedimentary basins in the Saharo-Sahelian zone.**
▲ 1. Tindouf; 2. Grand Erg Occidental; 3. Grand Erg Oriental; 4. Murzuq; 5. Sirte; 6. Kufrah; 7. Western Desert; 8. Chad; 9. Illumeden; 10. Taoudenni; 11. Senegal-Mauritanian. From Edmunds, Travi *et al.*, 2001

* Terms defined in the Glossary (page 58) are blue and underlined in the text.

NUBIAN SANDSTONE AQUIFER SYSTEM – NSAS

Research history

Most geological, hydrogeological, hydrochemical and isotopic studies of the Nubian Sandstone Aquifer System (NSAS) were conducted in the 1970s and 1980s. These, in particular, included studies conducted over several years by the German Collaborative Research Center (SFB, Technical University of Berlin) in Egypt (Toshka, Dakhla, Bahariya, Farafara) and Sudan (Darfur and East Kordofan), as well as by the British Geological Survey (BGS) in the Sarir and Kufrah Basins in Libya (Thorweihe and Schandelmeier, 1993; Edmunds and Wright, 1979).

The Center for Environment and Development for the Arab Region and Europe (CEDARE) published a review of NSAS knowledge in 2001 (see Focus next page), and proposed a **numerical model** for forecasting modifications in the groundwater quality and balance. Over the 2006-2013 period, a large-scale programme* led to the acquisition of substantial data and the proposal of a new global model, while fostering joint management of this large aquifer system according to UN Shared Aquifer Diagnostic Analysis (SADA) and Strategic Action Plan (SAP) procedures.

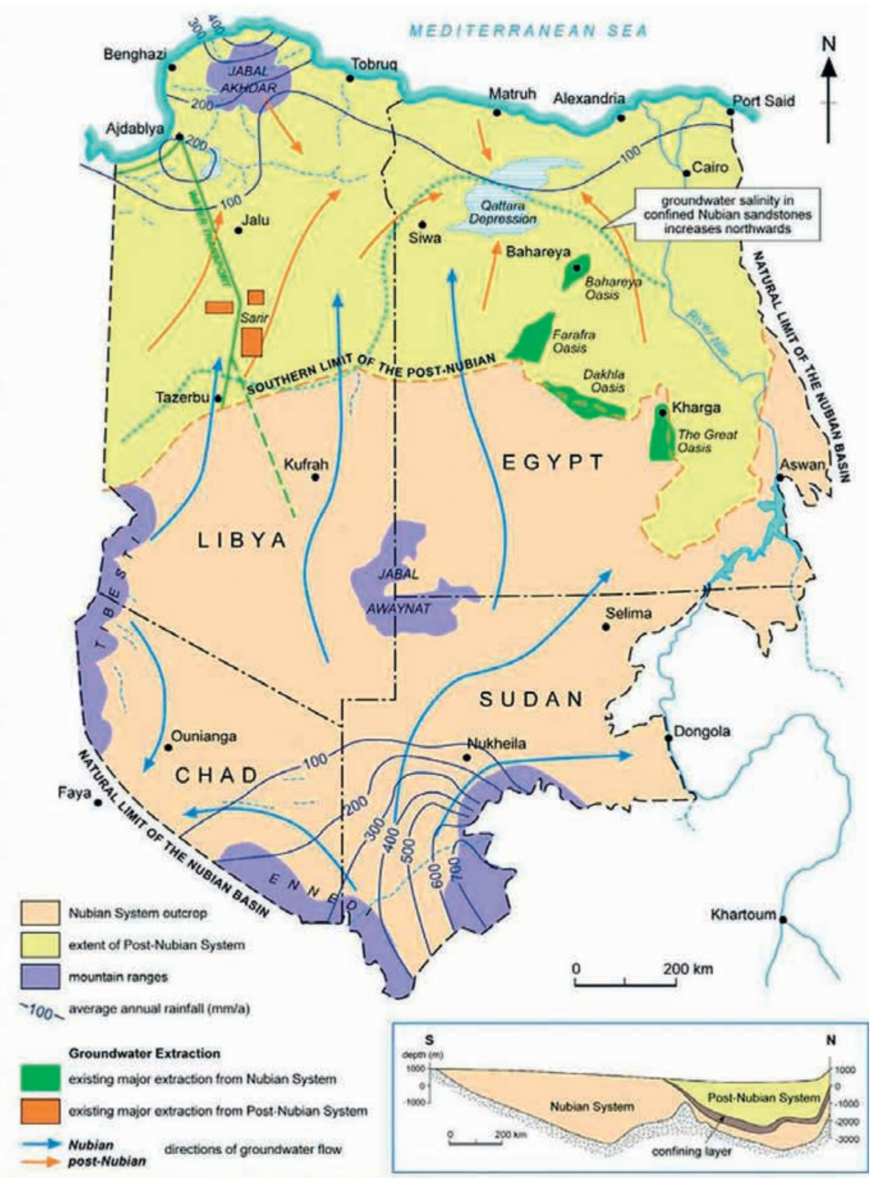
* Programme jointly conducted by the United Nations Development Programme (UNDP), the International Atomic Energy Agency (AIEA) and the United Nations Educational, Scientific and Cultural Organization (UNESCO).

NSAS—which is up to 3,500 m thick in some places—is one of the largest groundwater reserves in the world.

Description of the aquifer system

The Nubian Sandstone Aquifer System spans an area of around 2.2 million km² in four countries: Sudan (376,000 km²), Chad (376,000 km²), Egypt (828,000 km²) and Libya (760,000 km²).

Several sub-basins are shown on the schematic map below, including the Kufrah system, extending from Chad to Libya, and the Dakhla system in Egypt, with major depressions consisting of the Kharga, Dakhla, Farafra and Bahariya Oases.



▲ **Map of the Nubian Sandstone Aquifer System (NSAS).** From UNESCO, 2001

→ FOCUS | CEDARE – Center for Environment and Development for the Arab Region and Europe

CEDARE was established 1992 as an international intergovernmental organization with diplomatic status. This was in response to the convention adopted by the Council of Arab Ministers Responsible for the Environment (CAMRE) in 1991 and upon the initiative of the Arab Republic of Egypt, the United Nations Development Programme (UNDP) and the Arab Fund for Economic and Social Development (AFESD).

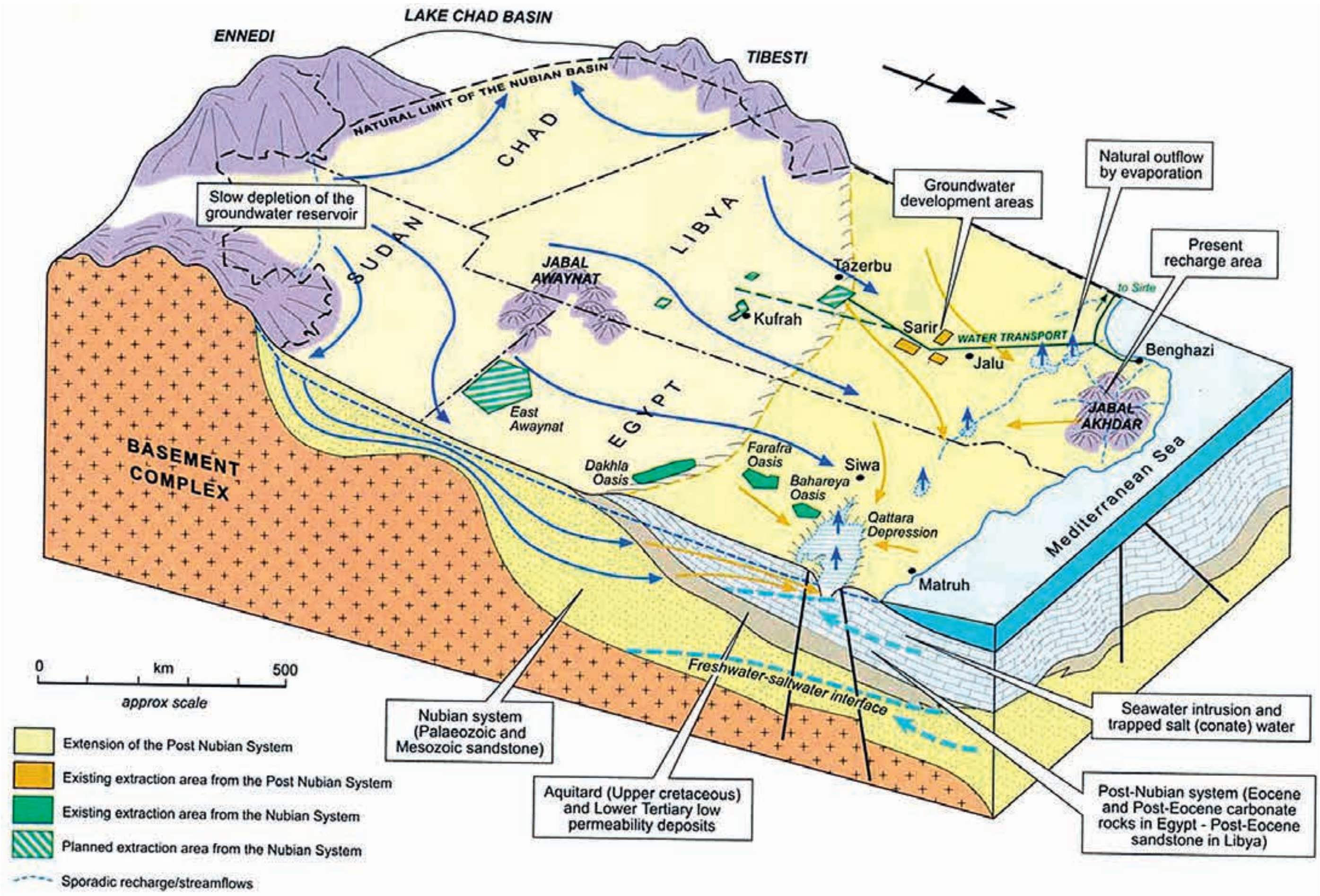
The Centre facilitates collaborations between the Arab Region, Europe and the international community working on environment and development. Its mandate is to work alongside countries and institutions to mainstream and balance economic, environmental and social priorities in policies and actions to ensure a future that is more innovative, community oriented, inclusive and sustainable, while being rooted in environment-friendly principles and human welfare development.

For further information: http://web.cedare.org

The Nubian Sandstone Aquifer System (NSAS) actually encompasses two overlapping aquifer systems:

- The Nubian Aquifer System (NAS) extends across Egypt, eastern Libya, northern Chad and northern Sudan. It is formed by detrital sediments (mainly sandstone) hosting the aquifer. An ancient basement complex (Cambrian) underlies the aquifer rocks that range in age from the Late Cambrian to the Upper Cretaceous.
- The Post-Nubian Aquifer System (PNAS) extends across northeastern Libya and beneath the Western Desert of Egypt. It is more recent and less extensive than the NAS, while being composed of marine sediments (mainly clay, marl and limestone) overlain by continental sediments.

These two systems (NAS and PNAS) are separated by low-permeability layers of the Upper Cretaceous (100.5–66 million years BP) and Lower Tertiary ages. These separation layers are sometimes discontinuous (due to the absence of deposits or erosion) and are thinner in places, thereby enabling a direct connection between the two systems. In the northern part, the water is increasingly salty as it approaches the Mediterranean Sea. The aquifer is no longer confined south of the 26°N parallel.



▲ **Block diagram of the NSAS.** From Salem and Pallas, 2001

State of the knowledge – dating and modelling

Based on climate scenarios, the NSAS groundwater balance and flow regime was first simulated by **numerical modelling** in the late 1970s. The model simulations highlighted underground flow directions and the location of potential aquifer recharge (current or past) and discharge (Egyptian and Libyan oases) areas.

A new model was developed by CEDARE in the early 2000s based on these data. Isotopic (environmental isotopes) and geochemical data were used to specify the model parameters and underpin the recharge and flow regime results. This regional-scale model takes two overlapping levels (NAS and PNAS) into account. Several scenarios based on the increasing aquifer usage between 2000 and 2015 were tested for the 2000–2060 period. This model is currently used to predict changes in the hydrogeological balance and water quality. Many other more localized models, around large wellfields in Libya or Egypt, were developed between the 1970s and 2005.

More recently (2009)*, a new unique paleohydrology-based model (dating of different paleoclimatic recharge periods) has been designed (see Focus next page).

The model simulations generally indicate that the aquifer usage pattern foreseen for the coming years would not jeopardize the overall reserve over a period of several hundred years. Yet there is a risk of local damage near the large wellfields due to excessive local groundwater drawdown (drop in the piezometric level).

The results of many dating studies carried out since the 1970s have highlighted variable groundwater residence times. Many of these findings are biased due to the use of outmoded techniques and complicated sampling conditions. It can however be estimated—based on the most recent studies and taking the results obtained via different techniques into account—that residence times (depending on the groundwater storage volume and the groundwater discharge rate of the system) have ranged from 100,000 to over 2,000,000 years. This reflects the presence of **an enormous reserve, probably one of the largest in the world, and indicates a recharge period that essentially dates back to the early Quaternary, with wet periods occurring after the last Ice Age (around 10,000 years ago) having a limited impact on the recharge pattern.**

Several estimates of the groundwater volume in this large aquifer have been made. The most likely estimate, based on saturated zone modelling and hydraulic parameter calibration, is around **370,000 km³** (see Table below).

* Under projects implemented by the International Atomic Energy Agency (IAEA), with the support of the United Nations Development Programme (UNDP) and the Global Environment Facility (GEF) (2003-2010). For IAEA activities related to water resources, see: https://www.iaea.org/topics/water
Aggarwal *et al.*, 2011; Wallin *et al.*, 2005.

Country	Area (1,000 km²)			Freshwater stocks* (km³)			Extraction (km³/year)		
	PNAS	NAS	Total	PNAS	NAS	Total	PNAS	NAS	Total
Egypt	569	311	880	102,417	52,299	154,716	0.306	0.2	0.506
Libya	350	300	650	11,240	125,309	136,549	0.264	0.567	0.831
Sudan	-	750	750	-	47,807	47,807	-	0.84	0.84
Tchad	-	70	70	-	33,878	33,878	-	0.0	0.0
Total	**919**	**1,430**	**2,350**	**113,657**	**259,293**	**372,950**	**0.57**	**1.607**	**2.177**

* Assuming a 10^{-4} storage capacity for the confined part of the aquifer and an effective porosity of 7% of the unconfined part.

▲ **Groundwater volumes in different countries and pumped water volumes.** From CEDARE/IFAD, 2002

→ FOCUS | **IAEA model based on radiometric dating and paleohydrology data**

The IAEA model—which was developed with the participation of all the countries concerned by NSAS—uses data collected for previous models (CEDARE), but the unique feature is that it is also based on radiometric dating and paleohydrology measurements. This IAEA model is three-dimensional (whereas the CEDARE model was two-dimensional), with two layers, including: (1) the confined NAS and unconfined PNAS in the north, and (2) only the unconfined PNAS in the south.

The IAEA model assumes that the aquifer is a single homogeneous but anisotropic system (i.e. with high horizontal and low vertical permeability). This model was designed using the finite difference method and the Modflow groundwater simulation code, with the geometry inputs derived from topographic data from the CEDARE model and recent Shuttle Radar Topography Mission (SRTM) land surface topography data. The IAEA model covers a larger area than the CEDARE model—encompassing more of Sudan to the southeast, Libya to the west, with a small extension to the Chadian oases—and is intended to reach as close as possible to the natural hydrogeological boundaries of the system.

Model calibration

The IAEA model was primarily calibrated based on the assumption that the aquifer recharges from the surface during wet periods (recharge > discharge) and discharges (recharge <<< discharge) during dry periods. The last high recharge period ended about 10,000 years ago. A simulation starting at 10,000 years BP should thereby reproduce the current state of the groundwater reserves. The benchmark levels were derived from 1960s data (i.e. before the start of intensive abstraction) and were relative to the oasis and **sabkha** elevations, i.e. corresponding to the groundwater elevations. The aquifer horizontal and vertical permeabilities were fitted so that the model could reproduce the current groundwater level.

Once the aquifer response had been calibrated over a 10,000 year period, the model was fine-tuned locally to account for historical observed drops in groundwater level in three catchments in Egypt and Libya. This enabled determination of the proportion of the specific yield of the aquifer (quantity of water extracted per metre of drop in piezometric level/pressure in the aquifer) that could be attributed to its capacity to restore water through hydraulic decompression and aquifer desaturation. The aquifer porosity—which affects the groundwater flow rate—was set for the whole system, while no spatial variations in permeability were taken into account. Only isotopic ages were used to calibrate the porosity. Based on a re-evaluation of the carbon 14 (^{14}C) and chlorine 36 (^{36}Cl) ages, and the recent use of krypton (^{81}Kr), **the groundwater age was estimated to range from 200,000 to 1.5 million years**.

Preliminary results and transboundary impacts

The model, once calibrated, was tested for a 3 million year period by simulating alternating dry and wet periods based on paleoclimatic knowledge. The adjacent figures show a probable lack of flow across the Chad-Libya border, with little groundwater movement northwards across the Libya-Egypt border.

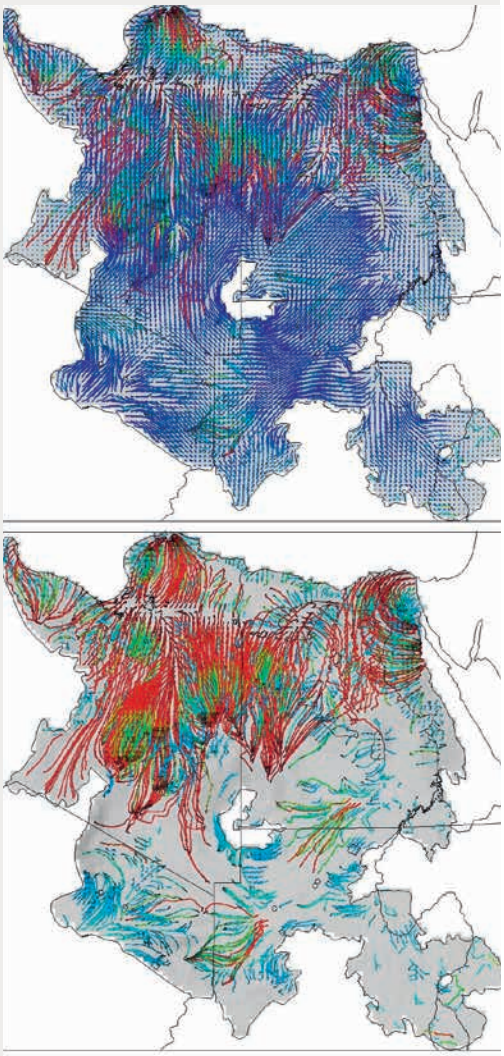
The effect of pumping in several wellfields (Kufrah in the north and East Oweinat in the south) was also simulated over a 200-year period. **The simulations revealed a high local impact on groundwater levels but a very limited regional effect and an absence of transboundary effect.**

The fact that the areas of influence are quite small illustrates **the huge potential of this system**. For example, in areas where the aquifer is especially thick (e.g. Kufrah in Libya), groundwater extraction should be able to continue for tens or even hundreds of years without any marked regional impact.

In the area where the aquifer is thinner (southern Egypt and Sudan), heavy extraction would likely not have any regional and transboundary effects, but it could have a significant local impact.

The model was tested and fitted to ensure its robustness before being made available for use by the concerned States.

For further information: Voss and Soliman, 2014
Nubian News: www.iaea.org/newscenter/news/chad-egypt-libya-and-sudan-agree-on-framework-for-joint-management-of-the-nubian-sandstone-aquifer-system
Nubian Regional Strategic Action Programme: www.iaea.org/sites/default/files/sap180913.pdf



▶ **Flow directions showing natural groundwater flow in the NSAS prior to extraction activities in the 1960s.** Dark blue lines indicate directions relative to ages of around 50,000 years (between groundwater recharges and discharges), while red lines represent circuits of about 2.5 million years. The top figure shows all flow directions and the bottom figure shows only those older than 50,000 years.

DEEP AQUIFERS IN THE CHAD BASIN

Research history

The first major geological and hydrogeological research began in Chad in the first half of the 20th century, which included hydrogeological studies conducted in the Chari-Baguirmi Basin in 1940 and 1941. The first hydrogeological sounding surveys in 1950 highlighted the nature and geometry of sedimentary filling in the Chad Basin. Hydrogeological reconnaissance maps at 1:500,000 scale were produced in 1964 and then synthesized to produce a first synthetic hydrogeological map of the sedimentary basin in 1969 (Schneider, 1969).

The French Office for Scientific Research in Overseas Territories (ORSTOM) also began focusing on Lake Chad and its relationship with surface water in 1965. A hydrological report on Lake Chad Basin (1966-1970) was published in 1972 (LCBC-UNDP-UNESCO, 1972). A 1:1,500,000 geological map and hydrogeological maps of the Republic of Chad were then published in 1992, accompanied by a lengthy explanatory memorandum (Schneider and Wolf, 1992).

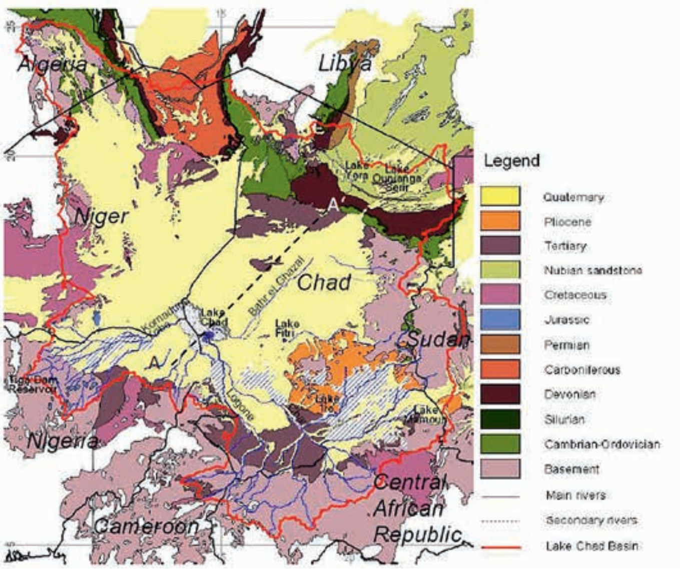
> Substantial groundwater resources could be tapped in Chadian hydrogeological basins. These resources are mainly located in large-scale unconfined sedimentary aquifer systems covering 75% of the country.

The *Schéma directeur de l'eau et de l'assainissement* report (2001) summarizes the main previous research. Thereafter, in-depth hydrogeological, geochemical and isotopic studies were carried out in Chad by the German Federal Institute for Geosciences and Natural Resources (BGR) between 2010 and 2016. These studies mainly concerned the shallow waters of the Logone-Chari, Kanem and Bahr el Gazal floodplains. In 2015, Bouchez *et al.* used ^{36}Cl to determine groundwater residence times in the Continental Terminal aquifer (around 300,000 years), thus challenging previous dating results (around 40,000 years) regarding the same aquifer in the southern part of the basin (in Nigeria).

Isotope hydrology has been used as a research tool since the late 1960s to offset the lack of conventional hydrogeological data. Investigations were initially carried out around Lake Chad and were then gradually broadened to the whole basin (Chad, North Cameroon, Nigeria, Niger) in the framework of IAEA technical cooperation projects and university research. Most of this research, however, concerns the surface aquifer.

Description of the system

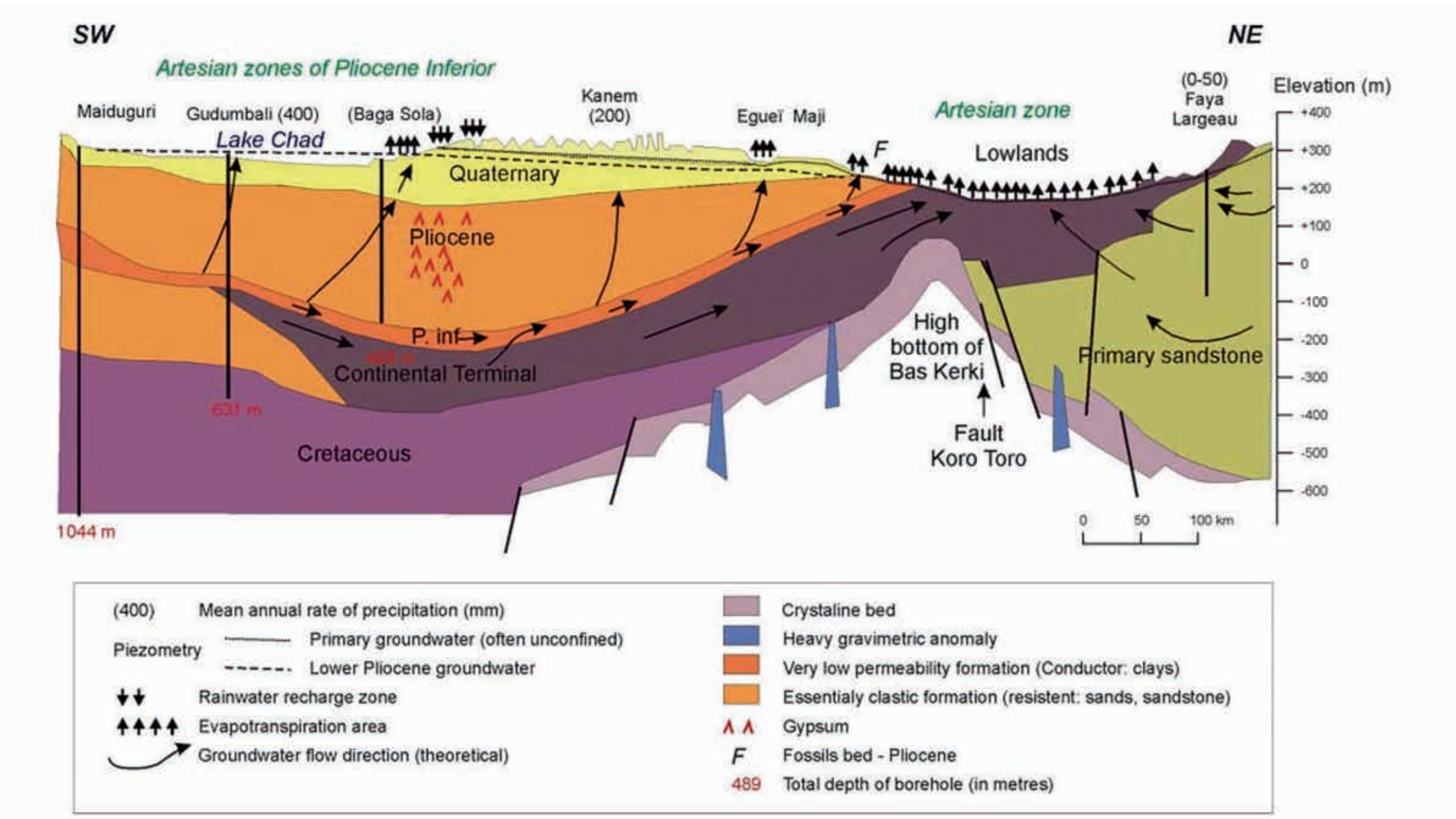
Lake Chad Basin is located in the eastern Sahel region, along the southern edge of the Sahara Desert. It is one of the largest sedimentary drainage basins in Africa, spanning an area of about 2,400,000 km². This transboundary aquifer complex is shared between Chad, Cameroon, Central African Republic, Niger and Nigeria. Unconfined transboundary sedimentary aquifers account for almost three quarters of the total area of the Lake Chad Basin.



▲ **Geology of Lake Chad Basin.** From Schneider and Wolf, 1992; BGR, 2012

The southern part of the aquifer is composed of sedimentary layers that began forming in the Cretaceous period, reaching up to 7,000 m thickness. These layers often consist of sand and sandstone separated by more clayey and sometimes discontinuous horizons. These contain a substantial groundwater reservoir in the form of confined or semi-confined free groundwater (or so-called 'phreatic water'), that is sometimes artesian in lowland areas. From bottom to top, there are four major superimposed aquifers, i.e. Cretaceous, Continental Terminal, Pliocene and Quaternary (see map previous page and diagram below):

- The Cretaceous aquifer (Lower Aquifer in Nigeria) is relatively unknown and overlies the crystalline basement complex.
- The Continental Terminal aquifer includes the Maastrichtian, Paleogene and Miocene in this area. It is confined in the central part of the basin and around Lake Chad, while being free (phreatic) in the Bodélé Depression and in southern Chad.
- The entire Lower Pliocene lies 250–300 m underground. The boundary between this and the Continental Terminal aquifer is often ill-defined. It is artesian around Lake Chad and spans an area of about 60,000 km^2, while water is extracted from this aquifer via several artesian wells in Niger and Nigeria. The Pliocene aquifer begins with a sandy series 10–30 m thick (Lower Pliocene), and then continues with a 200 m thick clay sedimentary layer that separates the Lower Pliocene–Pliocene aquifer from the Quaternary aquifer.
- The N'Djamena groundwater aquifer lies in the Quaternary detritus layers. It is essentially formed by alternation of clay and sand deposits. A clay layer located at about 20 m depth separates two horizons in a discontinuous manner, i.e. an upper horizon that is the focus of water extraction via village wells, and another deeper horizon that is tapped via boreholes. The base of this aquifer entity is located 50–180 m underground. Because of the shallow piezometric levels (5 m on the edge of the Chari River to 80 m in the centre of the piezometric depression of the Chari Baguirmi plain), this groundwater **may be easily extracted and is widespread, so it is currently the main water supply source in the region.**



▲ **Cross-section of Lake Chad Basin from Maiduguri (southwest) to Faya Largeau (northeast).**
From Schneider and Wolff, 1992; BGR, 2012

State of the knowledge

The many studies carried out on this basin have mainly focused on the free phreatic aquifer because of the high surface water resources, while overlooking the deep aquifers. The upper part of the basin is therefore relatively well known (recharge rates, relations with Lake Chad, extractable and renewable volumes).

Otherwise, little is known on the deep Continental Terminal aquifer, mainly because it has yet to be the focus of substantial water extraction. Most boreholes are located in the southern part of the aquifer in Nigeria, where high recharge has been noted—estimated in the 50–130 mm/year range, with an estimated renewable resource rate of 12 million m^3/year. Based on a 10 m drop in groundwater level, the extractable reserve is estimated at 70–145 million m^3/year. Yet these estimates remain highly uncertain due to the absence of modelling (currently complicated by the lack of available data).

A rough piezometric map has confirmed the south-to-north groundwater flow direction. Recent ^{36}Cl dating further confirmed this direction, while estimating a groundwater residence time of over 300,000 years around the centre of the basin (Bouchez *et al.*, 2015).

▲ **Lake Chad impacted by climatic variations. Chad.** François Delclaux © IRD

NORTH-WESTERN SAHARA AQUIFER SYSTEM (NWSAS)

Research history

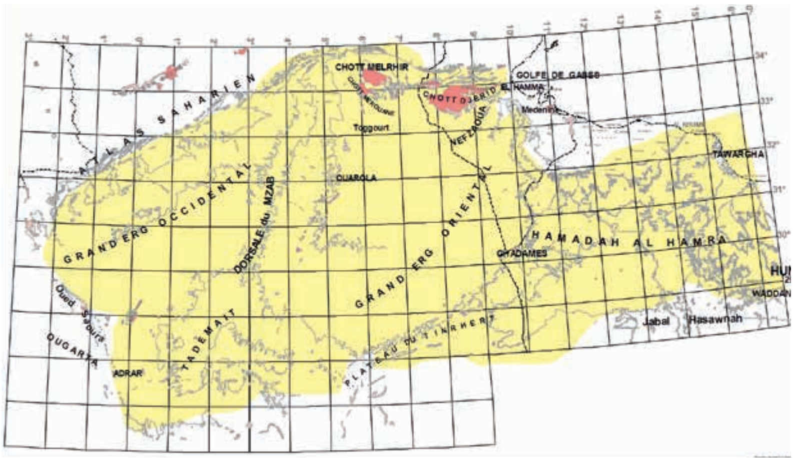
The first studies were published long ago, in conjunction with the rise of oil prospecting in the 1950s. In 1952, a first collection of monographs entitled *Données sur l'hydrogéologie algérienne, la géologie et les problèmes de l'eau en Algérie* (Data on Algerian hydrogeology, geology and water issues in Algeria) was published on the basis of the findings of specific studies and it highlighted many reports on water abstraction works (springs and wells). The structure and nature of the Saharan Mesozoic was also described in detail in the 1960s (Busson, 1967; Conrad, 1969). In 1972, UNESCO funded a project to summarize all available data on the management of present and future water resources in the Tunisian and a large portion of the Algerian sectors of the NWSAS (UNESCO, 1972). The report was used to develop a scalable global mathematical model (i.e. of the whole aquifer system with the possibility of updating the model with newly acquired data; see for example Besbes, 2010) in a joint Algerian-Tunisian project managed by the Sahara and Sahel Observatory (OSS, 2002, 2003, 2008). With contributions from new studies and local modelling, in particular on the Libyan territory, the functioning of the aquifer system was reconstructed, while proposing extraction scenarios. More recently, taking the paleohydrology features into account while conducting surveys with radioactive tracers (^{14}C, ^{36}Cl, ^{4}He, $^{134}U/^{138}U$) combined with hydrogeological modelling, has helped to gain insight into the different Quaternary recharge episodes, as well as to highlight and quantify current recharge rates, thereby bolstering existing numerical hydrogeological models (Baba Sy, 2005; Guendouz and Michelot, 2006; Pettersen, 2014).

Description of NWSAS

The northern Saharan aquifer system roughly covers a 1 million km^2 area, 700,000 km^2 of which are in Algeria, 80,000 km^2 in Tunisia and 250,000 km^2 in Libya. From north to south, it extends from the Saharan Atlas Mountains to the Tidikelt outcrops and the southern edge of the Tinrhert Plateau and, from west to east, from the Guir-Saoura valley to the Hun Graben in Libya (see adjacent map).

Overall, there are two major aquifers, i.e. the Intercalary Continental (IC) and the Terminal Complex (TC), with the latter being relatively equivalent to the South-Saharan Continental Terminal. The basin covered by this large aquifer system can be subdivided into three sub-entities: the two (1) Grand Erg Occidental and (2) Grand Erg Oriental sub-basins—which are **endorehic** flow basins ending in blind **chott** and **sabkha** depressions—and (3) the Hamada El Hamra Plateau.

The Terminal Complex is a non-uniform complex of carbonate formations from the Late Mesozoic (Upper Cretaceous) and detritus deposits from the Tertiary, particularly the Miocene.



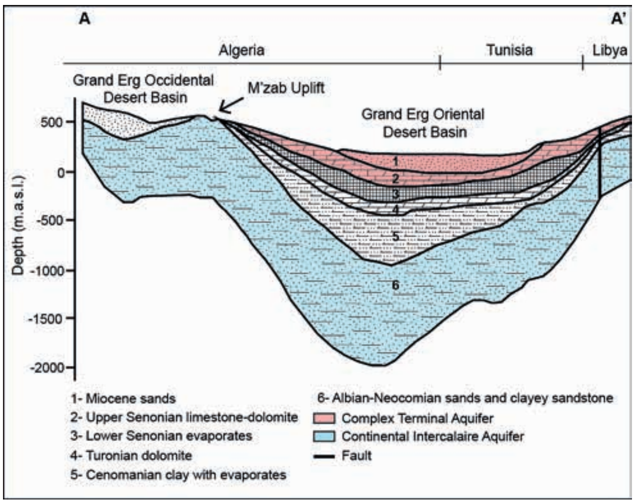
▲ **Map of the northern Sahara region.** The yellow area corresponds to the NWSAS. From OSS, 2003

The **Intercalary Continental** is defined as the continental complex between the Hercynian Folds, which kept the sea away from the Saharan Platform, and the marine incursions of the Upper Cretaceous. This entity is mainly made up of continental Lower Cretaceous sandstone-clay formations. Borehole log surveys revealed an intercalation of post-Paleozoic and Ante-Cenomanian marine or lagoonal sediments within the IC.

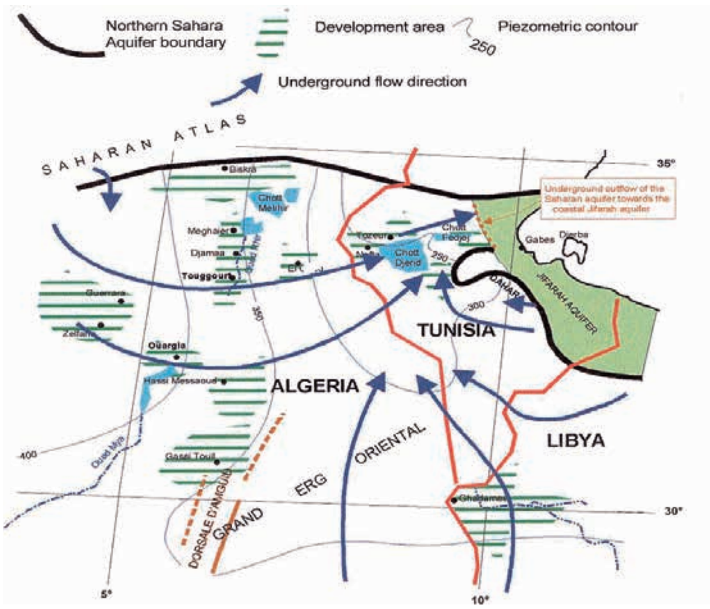
From a hydrogeological standpoint, the Grand Erg Occidental and Grand Erg Oriental desert basins are separated (no spatial continuity of flows on either side of piezometric ridges) by the M'zab Uplift which extends from the Atlas Mountains in the north to the Tademaït Plateau (see above map). The western part of the aquifer system is used exclusively by Algeria. Due to its geological configuration, the IC (unconfined aquifer) is recharged via the Saharan Atlas Mountains in Algeria and in the vicinity of the M'zab Uplift in the east, with underground flows generally oriented in a north–south direction (Moulla *et al.*, 2012).

In the eastern part, the IC can potentially be recharged at the level of (1) the Atlas Mountains in the north and (2) the Tinrhert Plateau in the south. In the former case, this configuration induces west–east flows and south-north flows in the latter, with a common natural outlet at the Tunisian **chotts** and the Djeffara coastal aquifer. The current recharge rate has long been considered negligible, which means this aquifer is non-renewable (Edmunds *et al.*, 2003; Guendouz *et al.*, 1997). This viewpoint is based on numerous recharge estimates carried out between the 1960s and 2000 using different approaches —hydrological and hydrodynamic balances, geochemical and isotopic infiltration tracers and modelling. The recharge values obtained—mostly in the 8–15 m^3/s range—were however often based on incongruous and/or imprecise data.

The **Terminal Complex Aquifer** (equivalent to the Continental Terminal Aquifer in Africa) has a configuration similar to that of the IC, but with the additional possibility of direct recharge from the Eastern Desert sand dunes (ERESS, 1972; Guendouz *et al.*, 2003). There have been fewer recharge estimates focused on this aquifer compared to the IC because of the much lower extraction potential of the TC and its lower artesianism, thereby increasing production costs. Most studies have therefore essentially involved modelling, with TC recharge estimated at 18–24 m^3/s (ERESS, 1972; OSS, 2003).



▲ **West/east cross-section of the NWSAS.** From Kamel, 2012



▲ **Hydrogeological scheme of the IC in the Algerian/Tunisian Grand Erg Oriental.** From UNESCO, 2006

Modelling and management of the NWSAS

Groundwater withdrawals have increased sharply in the northern Sahara (Algeria, Tunisia, Libya) since the 1970s—from 790 million m³/year in 1970, they sharply increased in the 1980s to reach 2.3 billion m³ in 2000 (Baba Sy, 2005). These extraction levels are in line with the findings of the *Étude des ressources en eau du Sahara septentrional* (Study of water resources in the northern Sahara) project (ERESS, 1972), forecasting an increase in withdrawals from 790 million m³/year (1970) to 1.8 or 2.5 billion m³/year in 2000 (depending on the scenario), with extractions taking place at around 9,000 water outlets (74% in Algeria, 14% in Tunisia and 12% in Libya). The overall withdrawal rate over the 1970-2000 period was in the 30–40 billion m³ range.

Based on the withdrawal level of 2000, the NWSAS project then forecasted a total extracted volume of 83 billion m³ by 2050. These estimates should be considered in the light of various estimates of the total aquifer system reserves, i.e. between 60,000 (UNESCO, 1972) and 31,000 billion m³ (Baba Sy, 2005). Note nevertheless that only a fraction of the water in a confined aquifer is extractable, so it is therefore necessary to take the possible effects of decompression (loss of artesianism, resulting in extraction difficulties and high operating costs, settlement of the reservoir, salt water intrusion, etc.) and the geographical distribution of the aquifer and of extraction sites into account.

In the northern Sahara, several models of various dimensions and using different techniques (analogue method, finite elements or finite differences) have been developed. In 2002, in the first phase of the NWSAS project and on the basis of these models and data from many studies, OSS developed a 3D mathematical model using the finite difference technique. This was done by considering a hydrogeological scheme with three aquifer levels separated by two semi-permeable horizons (see chart below). The model was then validated on the basis of piezometric maps previously published by various authors. This model estimated: (1) a global recharge of about 36 m³/s, (2) vertical exchanges between the two main aquifers (from the IC to the CT) of 5.8 m³/s, and (3) that **chotts** and **sabkhas** accounted for 75% of the outlet flows, with the remainder ultimately reaching the Mediterranean Sea.

This model underwent several adjustments to take local specificities and new data into account, particularly regarding its Tunisian part. After calibration, several

HYDROGOLOGICAL CHART OF THE NWSAS		
ALGERIA	**TUNISIA**	**LIBYA**
	Impermeable aquifer ceiling	
Sand aquiferer	Djerid sand aquifer	Lower Miocene sand-limestone aquifer
	TERMINAL COMPLEX AQUIFER – Upper Cretaceous	
Limestone aquifer	Nefzaoua limestone aquifer	Upper Cretaceous Mizdah aquifer
	Semi-permeable	
	TURONIEN AQUIFER – NALUT AQUIFER	
	Semi-permeable	
	INTERCALARY CONTINENTAL AQUIFER – KIKLAH AQUIFER	
Jurassic Triassic Lower Cretaceous	Jurassic Triassic Upper Cretaceous	Upper Jurassic Lower Cretaceous
	Impermeable or semi-permeable substrate	
Paleozoic	Lower Jurassic Triassic	Carboniferous **Cambro-Ordovician**

▲ **Conceptual hydrogeological chart of the NWSAS.** From OSS, 2003 simulations of extraction impacts up to 2050 were performed while considering different scenarios: (1) maintaining the current extraction level, (2) a minimal increase, or (3) a marked increase. Regardless of the scenario tested, the extraction impact was significant, with declines in groundwater levels of several tens of metres—even several hundreds—particularly at pumping stations. These findings underline the potential risk of total artesianism loss, problems of **chott** and **sabkha** salinization, alongside transboundary effects. This global model is relevant for highlighting issues and risks related to tapping of the NWSAS, yet it has shown its limitations as a management and decision tool for decision makers. The studies were then oriented towards sectoral modelling with the aim of defining the regional potential of the aquifer rather than modelling the overall impact of extraction prospects (Besbes *et al.*, 2005).

According to OSS (2003), these forecasted simulations based on a hydraulic approach showed that it was possible to increase NWSAS borehole withdrawals (estimated at 2.3 billion m^3 in 2000) to 7.8 billion m^3/year, “while to a certain extent respecting constraints related to the risk of resource degradation”. This would, however, represent an eightfold higher extraction level than the estimated NWSAS renewable resource rate, therefore leading to significant groundwater drawdown. Moreover, this scenario would only be possible if extraction operations were to be shifted to sectors where groundwater is unconfined at the surface. Hence, 80% of the supplementary withdrawals would have to be done in remote regions that have yet to be thoroughly studied.

▲ **Timimoun Oasis, Algeria.** The town of Timimoun—aka ‘the flamboyant’—is located west of the Tademait Plateau. It is surrounded by a cluster of oases (palm groves) bordering the Grand Erg Occidental Aquifer Francois Molle © IRD

Is sustainable management of large fossil aquifers possible?

▲ **Artesian borehole in Douz, a town in Kebili region, southern Tunisia.** Pierre Deschamps © IRD

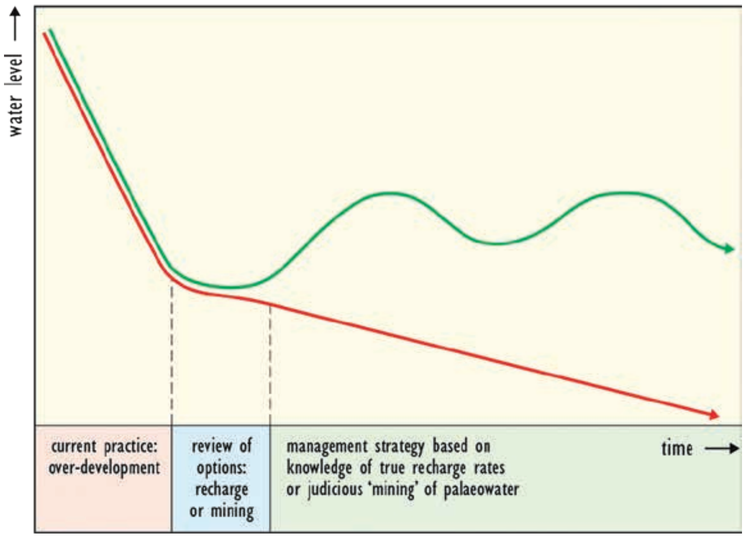
The growing water needs of local communities is an issue in arid and semiarid zones where water resources are scarce. A major challenge is hence to ensure a sustainable water supply, especially via efficient groundwater resource management.

FOSSIL AQUIFER MANAGEMENT

Natural recharge and discharge in an aquifer are generally in equilibrium under natural conditions and over sufficiently long periods, with periodic variations in recharge mainly mirrored by variations in the aquifer water column (rise or fall in the groundwater piezometric level). In fossil aquifers that host considerable water reserves yet have little or no recharge, extraction in addition to natural discharge accelerates the decompression of confined aquifers. This may result in a decrease in the elevation of discharge areas, in turn leading to the disappearance of wetlands or resurgences (springs, lakes, oases, etc.).

In addition to an assessment of the available water volume, thorough knowledge of the groundwater origin and age may help identify extraction strategies that could effectively limit the impact on the resources. As shown in the adjacent diagram, initial overextraction is often possible without any marked environmental impact. Then the issue arises of rebalancing the aquifer, with possible recharge or continued overextraction. The latter must be done with caution, while fostering reasonable extraction around smallholdings and by accounting for the decreased capacity of the aquifer.

However, **effective management is not simply a matter of assessing the overall volumes extracted from the aquifer because the environmental impact is also dependent on the position of wells relative to the aquifer recharge and discharge areas, as well as on the groundwater extraction planning**. These elements must be taken into account in mathematical models which —once developed and validated—help assess extraction scenarios.



▲ **Different groundwater extraction strategies.**
Green line: withdrawal identical to recharge
Red line: groundwater mining
From Edmunds, Travi *et al.*, 2001

Models – a resource management support tool?

The development of mathematical models able to simulate groundwater extraction impacts must primarily be based on full knowledge of the quantitative and qualitative parameters of the systems (flows, geometric limits, hydrodynamic parameters, water quality), and possibly their temporal variations*. In addition to existing data, many activities could thus be carried out or set up: the preparation of geological maps and cross-sections, piezometric measurement and monitoring networks, flow measurements at natural or artificial aquifer outlets, pumping tests and flow measurements, sampling for chemical and isotopic measurements, use of natural or artificial tracers and geophysical surveys.

A conceptual model of the target aquifer system may be developed following validation, synthesis and interpretation of these data, as well as their potential mainstreaming into a geographic information system (GIS). This model represents the characteristics and modes of functioning of the resources considered, and particularly relations with neighbouring entities (aquifers, impermeable areas, surface water, unsaturated areas, etc.). It also expresses the state of hydrogeological knowledge at a given moment as well as the possible uncertainties.

The development of mathematical and numerical tools can help gain in-depth insight into the functioning of hydrosystems and water resource variation patterns according to different extraction scenarios. Mathematical models can specify certain physical parameters that may be hard to grasp in the field (flow velocities, flows, exchanged volumes, etc.), while generating an overall more or less precise assessment of the functioning of the aquifer system in 2D or 3D space, and of its potential quantitative and qualitative temporal variation patterns. This facilitates testing of different extraction scenarios on a global scale, as well as relative to the local impacts of actions or human pressures on these systems.

These mathematical and numerical models—once efficiently validated and calibrated for the target objectives—**can serve as tools to help manage the resource potential according to specific needs or projected economic developments**.

Note, however, that these models are only a more or less accurate representation of the actual situation (highly dependent on the collected data quantity and quality), and that calibration and validation may be illusory given the number of parameters involved. **It is therefore essential to take groundwater extraction plans of monitoring networks into account to be able to monitor changes (flows, piezometric levels) and validate and/or correct hypotheses stemming from the models.**

Decision support tools can be developed to simulate different extraction scenarios. The results may help decision makers build groundwater extraction policies while clearly highlighting the associated benefits and impacts.

* For very old aquifers, modelling can sometimes be carried out in several stages corresponding to different climatic periods.

Groundwater transfer to deficient or vulnerable areas

In addition to the possibility of applying different extraction scenarios on a global or local scale, thorough knowledge of the functioning of aquifer systems can help in planning potential water transfers. Given the heterogeneity of some aquifer systems and their high inertia, more vulnerable areas could be preserved by benefitting from water inflows via piping from less vulnerable parts of the aquifer, as is currently being studied in the Senegal sedimentary basin (see for example below). Water transferred in this way could then be used directly or reinjected into quantitatively and/or qualitatively altered parts of the aquifer.

→ EXAMPLE | **Project to transfer groundwater to the groundnut-cropping area in Senegal**

Deep groundwater enclosed in Maastrichtian sand, sandstone and clayey sandstone throughout the Senegal sedimentary basin is the main source of water in this country. This groundwater is heavily tapped and there is a risk of overextraction in many places.

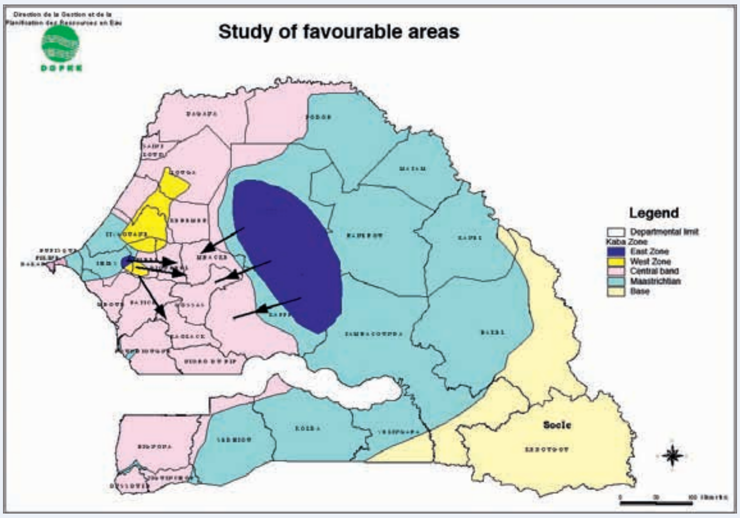
The west-east geological cross-section through the Senegal sedimentary basin (see adjacent map) highlights two distinct parts—the sandstone layers of the Maastrichtian aquifer are relatively shallow in the east but westward they plunge quite sharply under tectonic forces, while becoming more clayey. This rupture has led to the emergence of poorer quality water with a risk of rapid deterioration due to excessive extraction. This zone roughly corresponds to the groundnut-cropping area, characterized by a high human population density in large urban centers such as Touba, Mbacké, Diourbel, Kaolack, Fatick, etc. In these and neighbouring areas, surface groundwater is generally of poor quality with little potential, and communities have to make do with salty fluoridated water from the Maastrichtian aquifer (> 1.5 g/l dry residue and > 2 mg/l fluoride content).

The possibility of groundwater transfer was therefore considered and studies on this issue were carried out in the framework of the *Plan d'action de gestion intégrée des ressources en eau dans le bassin arachidier* (PAGIRE-BA) project initiated by the Senegalese *Direction de la gestion et de la planification des ressources en eau* (DGPRE). Several options were considered, with the most promising logically concerning the eastern section of the Maastrichtian aquifer (see adjacent map). The objectives were to assess the actual potential of the Maastrichtian aquifer in this sector, to determine the extractable quantities and locate withdrawal sites so as to avoid salinisation of this zone, from the saline strip to the west and/or from the underlying saline part of the Maastrichtian aquifer.

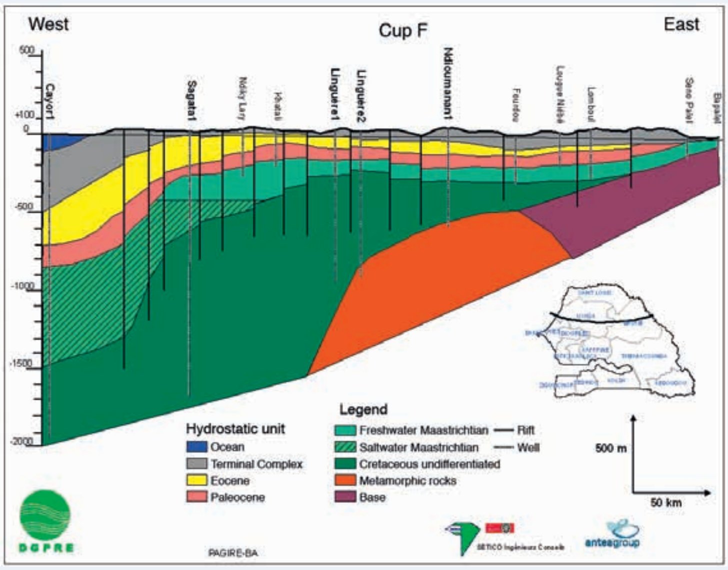
A full series of operations were undertaken, particularly hydrogeological and geophysical prospecting by electrical sounding, the digging of five pits to carry out test pumpings, the installation and monitoring of a piezometric network, and finally a large number of hydrochemical and bacteriological analyses.

The overall collected data led to the development of a mathematical model via which a possible scenario was proposed. Extractable flows sometimes amounted to nearly 100,000 m^3/day by distributing the wells to three extraction sites. Each of the latter consisted of nine wells located east of the edge of the brackish water zone, along a north-south line. The extension of the zones of influence of these wells protects them from contamination by the saltier waters of the western sector.

For further information: www.dgpre.gouv.sn



▲ **Proposed groundwater transfers in the Senegal River Basin.**
From DGPRE, 2015



▲ **West-east geological section through the Senegal sedimentary basin.**
From DGPRE, 2015

ESSENTIAL TRANSBOUNDARY MANAGEMENT

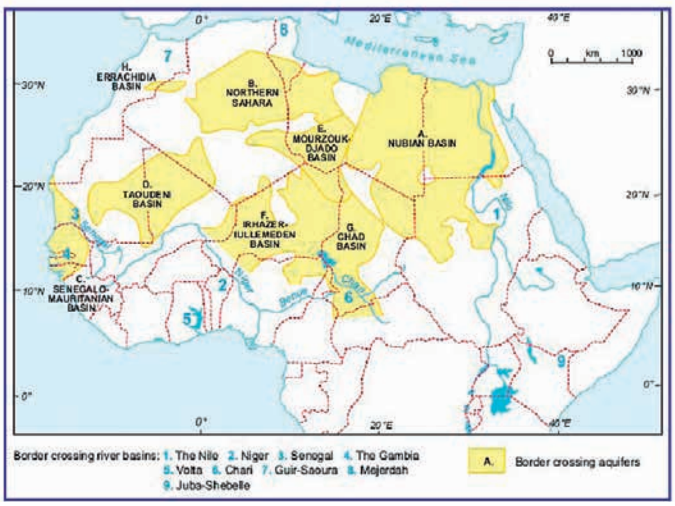
Groundwater meets the needs of over half of the world population, while supporting a range of economic activities, especially agriculture. This resource is subject to increasing pressure and must be the focus of special attention to ensure its sustainable management in line with socioeconomic changes (AFD, 2011). **This is a complex issue as the political decisions required for good groundwater management often concern several sovereign states whose priorities may differ.** There are actually many cases where the hydrological cycle concerning groundwater (recharge, flow, discharge) is located within the territory of two or more States. For instance, an aquifer may be crossed by a border, with a part in one State and another in a neighbouring State, or an aquifer may be hosted in the territory of one State yet its recharge zone is in another, etc. Moreover, sometimes withdrawals from an aquifer in one country may have quantitative and/or qualitative impacts beyond its borders, etc.

Over 270 transboundary aquifer systems have been identified in the framework of the UNESCO International Shared Aquifer Resources Management (ISARM)* programme.

Major transboundary basins in the Saharo-Sahelian zone

Almost all large-scale sub-Saharan aquifers span several countries (see map below). A transboundary approach is thus essential to ensure their effective management.

* See www.isarm.net



▲ **Major transboundary basins in the Saharo-Sahelian zone.**
From UNESCO, 2004

These aquifers correspond to wide-ranging sedimentary basins (from 500,000 km^2 to over 2,000,000 km^2), notably:

- northern Sahara: the Nubian Sandstone Aquifer System (NSAS), the North-Western Sahara Aquifer System (NWSAS) and Murzuk Basin
- southern Sahara: the Senegal-Mauritanian, Tindouf, Taoudéni, Iullemeden and Lake Chad Basins.

Smaller sedimentary basins, ranging from a few hundred km^2 (Maghnia Plain) to tens of thousands of km^2 (Djeffara and Errachidia-Béchar Basins), also host transboundary aquifers. The latter have more modest and partially renewable resources, so extraction has a lower transboundary impact.

Large aquifer systems are usually multi-layered, with series ranging from a few hundred to a few thousand metres in thickness. These systems have enormous reserves when comparing the flow and turnover rates, which could warrant groundwater mining.

As noted in the previous chapter, the state of knowledge regarding these aquifer systems is far from being comprehensive. Exploration or extraction operations are generally carried out at very deep horizons, so prospecting of these aquifer systems has sometimes locally benefitted from circumstantial support of petroleum research studies involving deep explorations. Otherwise, prospecting may be hampered by the absence of at least partial substitute resources, thereby making deep groundwater extraction indispensable. **Monitoring of these aquifers is hence more developed in North Africa countries than in the Sahel.**

A relatively recent framework for groundwater

International water laws emerged very early due to the transboundary nature of certain watercourses used for navigation or other purposes (hydroelectricity production, fishing, etc.). Hence, since the medieval authorization of free movement on some rivers, nearly 3,800 unilateral acts and declarations, bilateral and multilateral treaties have been signed with regard to international water resource use, not to mention international customs (e.g. the equitable use of shared resources principle), general principles of international law (e.g. the obligation not to abuse one's rights) and jurisprudence (e.g. the principle of non-damaging land use). **These mechanisms are intended to foster between-State agreement and negotiation processes.**

Shared groundwater has more recently been taken into account in successive stages, including several initiatives (see Focus next page).

These different initiatives reflect a certain shift in international law which was initially focused solely on surface waters in the vicinity of borders (rivers, lakes), as well as on their role as a territorial element and communication route. The economic aspect then emerged with the notion of resources (agriculture, industry) focused more on meeting human population needs, but often also with a territorial aspect. The affirmation of human drinking water rights (right to life and health) gradually established it as a universal right, thereby necessitating inter-State cooperation.

The specific features of aquifers have had to be taken into account in the process of adapting to groundwater resources which are more fragile in the long term. The most up-to-date benchmark is Resolution 63/124 on the Law of Transboundary Aquifers, which promotes two fundamental international water law rules: (1) equitable and reasonable resource use, and (2) ensuring that no substantial damage will be caused.

Equitable and reasonable (i.e. sustainable or optimal) resource use implies joint management and several factors must be taken into consideration. Article 5 of the Resolution specifies the various factors relevant to the equitable and reasonable utilization of the resource to be taken into account. These relate to socioeconomic needs, as well as to the characteristics and potentials of aquifer systems and their protection.

The damage prohibition rule—essentially developed to deal with transboundary pollution—is harder to implement in terms of the quantitative aspect (water withdrawal volumes) because any extraction will necessarily impact the concerned hydrosystem. This requires good common knowledge of the system, while seeking the least penalizing solution via discussions between the stakeholders (concerned States).

Cooperation between State and non-State stakeholders for rational groundwater resource management may be based on the integrated water resources management (IWRM) concept that has been fostered since 1992. Indeed:

• The Dublin Principles—adopted at the 1992 International Conference on Water and the Environment—stress that, among other things, “water is a finite and vulnerable resource, essential to sustain life, development and the environment”, and that “water development and management should be based on a participatory approach involving users, planners and policymakers at all levels.” The action programme adopted on this occasion includes aquatic ecosystem protection.

• The same year, one of the objectives of the Rio Earth Summit was to organize sustainable management of water resources by establishing modes of coordination between the various users, managers and public authorities.

The IWRM concept is still not markedly applied at the transboundary level due to various natural, administrative and socioeconomic constraints.

→ FOCUS | **International laws on groundwater resources – a few key dates**

1989. The so-called Bellagio Draft Treaty on transboundary groundwater resources was drawn up at the initiative of experts to foster joint management of ground and surface water resources (safeguarding groundwater and recognition of the interrelationships between ground and surface waters), "the community of interest", as well as "optimal use and conservation on a reasonable and equitable basis, including the protection of the underground environment". This project was, however, not followed up, but some of its principles were included in subsequent international instruments.

1992. Adoption, under the aegis of the United Nations Economic Commission for Europe, of the Helsinki Convention on the Protection and Use of Transboundary Watercourses and International Lakes, which this included shared aquifer systems. Parties to the Convention are obliged to cooperate to prevent and control pollution while ensuring rational and impartial use of transboundary waters.

1997. Adoption of the New York Convention on the Law of Non-Navigational Uses of International Watercourses. This Convention, which only entered into force in 2014 and was subsequently ratified by just 36 State Parties (February 2019), only covers shared aquifers connected to a watercourse. It promotes the principle whereby States sharing an international watercourse in their respective territories must utilize it in an equitable and reasonable manner and participate equally in its development and protection. This participation includes the right to use the water resources alongside the obligation to cooperate in its protection and development.

1999. The London Protocol on Water and Health is an appendment to the Helsinki Convention which accounts for the short- and long-term adverse effects on human health and wellbeing of unsustainable water resource management. State Parties must thus ensure equitable access to water, adequate in terms of both quantity and quality, for all members of the population, especially those who are disadvantaged or socially excluded, while also ensuring effective protection of water resources used as sources of drinking water, and related water ecosystems, from pollution from other causes, including agriculture, industry and other discharges and emissions of hazardous substances.

30 November 2012. The Conference of the Parties to the Helsinki Convention adopted a decision that allows countries that are not members of the United Nations Economic Commission for Europe (UNECE) to draw on the provisions of the Convention, despite the fact that it was originally negotiated as a regional instrument by UNECE countries. This extension has thus notably enabled Chad (22 February 2018) and Senegal (31 August 2018)—43 State Parties in February 2019—to benefit from the Convention.

2008. Adoption by the United Nations General Assembly of the Law of Transboundary Aquifers (Resolution 63/124 of 11 December 2008). This resolution is based on the sovereignty of each transboundary aquifer State over the portion of the aquifer located within its territory, with the obligation to exercise its sovereignty in accordance with international law and the principles of equitable and reasonable utilization, which implies not causing significant harm to other States, the continuous exchange of data and information established by States, and the prevention, reduction and control of pollution through the implementation of management and monitoring plans.

This principle was reaffirmed by Recommendation of the 6th Committee of the UN General Assembly on 11 November 2016, which stresses that the Law of Transboundary Aquifers is crucial for the relations between States and that transboundary aquifers, which embody natural resources of vital importance for present and future generations, should be reasonably and equitably managed through international cooperation.

For further information: Berberis, 1987; Sohlne, 2002; AFD, 2011; Simonel *et al.*, 2012; Lasserre and Cardenas, 2016

▲ **Well for groundwater extraction from the Nubian Sandstone Aquifer in Qena wadi (Eastern Desert), Egypt (well planned for a future ranch).**

© R. Guiraud

DIFFICULTIES IN IMPLEMENTING SUSTAINABLE TRANSBOUNDARY GROUNDWATER RESOURCE MANAGEMENT

Overall, groundwater management—especially regarding transboundary groundwater—requires **substantial national and international financial resources to cover capital investment and facility renovation expenditures, in addition to operational, maintenance and servicing costs.** This is an issue in many developing countries where it is very complicated to come up with a homogeneous between-State management approach, sometimes due to long-standing discord or a lack of political will. In addition, technical, financial, institutional and administrative capacities can vary markedly between countries and priority is often given to overcoming economic rather than environmental constraints.

The relevant international laws are currently not binding. They generally call upon States to cooperate and —pending successful negotiations—they provide rules and tools to facilitate cooperation.

Currently it is **more a question of concerted efforts to manage competition issues between different groundwater uses and stakeholders by striving to limit environmental degradation and social conflicts**. This concerted management can be achieved through the creation of intergovernmental organizations, as illustrated by the two examples below.

→ FOCUS | **Surface water and groundwater management organizations in Africa**

- Liptako-Gourma Authority (ALG): www.liptakogourma.org
- Niger Basin Authority (ABN): www.abn.ne
- Volta Basin Authority: www.abv-volta.org
- Senegal River Basin Development Authority (OMVS): www.omvs.org
- Gambia River Basin Development Organisation (OMVG): www.pe-omvg.org
- Lake Chad Basin Commission (LCBC): www.cblt.org
- Permanent Interstate Committee for Drought Control in the Sahel (CILSS): www.cilss.int
- African Water Facility (AWF): www.africanwaterfacility.org

Example of collaborative management – the NSAS situation

Groundwater is tapped from large-scale Nubian Sandstone Aquifer System by four countries: Egypt, Chad, Sudan and Libya. The cooperation process between these four states has progressed slowly via several agreements and the establishment of cooperation instruments, particularly the founding of an international institution (Quadri, 2017).

An intergovernmental management organization...

Egypt and Libya expressed interest in organizing joint NSAS management as early as the 1980s, which led to a 1991 agreement to found a structure (formalized in 1992), i.e. the Joint Authority for the Study and Development of the Nubian Sandstone Aquifer System (JASAD-NSAS). Sudan joined this association in 1996, followed by Chad in 1999. At that time, a *modus operandi* was developed—a Board of Directors, which has been officially based in Tripoli since 2006. It consists of three ministerial-level representatives from each country, along with an Executive Director, an administrative secretariat and technical staff. There is a national office in each member country, with a coordinator and a technical team. Regular meetings are scheduled, while exceptional meetings may be held at the request of one of the Member States. Representatives of international organizations or donor countries may be invited to these meetings.

... to study and monitor the NSAS

From a legal standpoint, the scope of action of JASAD-NSAS is limited to internal regulation and excludes procedural powers for aquifer management. Its funding sources are annual contributions from Member States and grants from national and international institutions and donor countries.

Its main role is the joint monitoring and studying of the aquifer. This involves data collection, preparation of studies and the development of programmes and common aquifer water usage regulations. Its mission also includes studying environmental aspects regarding the state of the aquifer, while striving to encourage Member States to limit their groundwater extraction rates.

Two mainly procedural agreements negotiated by the Center for Environment and Development for the Arab Region and Europe (CEDARE) and ratified in 2000 stress the need for regular ongoing monitoring, data updating and data and information sharing.

Another milestone was achieved in 2006 with the launch of a new programme, i.e. the Regional Action Programme for the Integrated NSAS Management financed by GEF and implemented by UNDP, IAEA and UNESCO (International Hydrological Programme). This project aimed to gain further insight into the functioning and potential of the aquifer and to lay the foundations for a strategic action plan (SAP) based on the rules outlined in Resolution 63/124 (see page 29). Four specific objectives were defined:

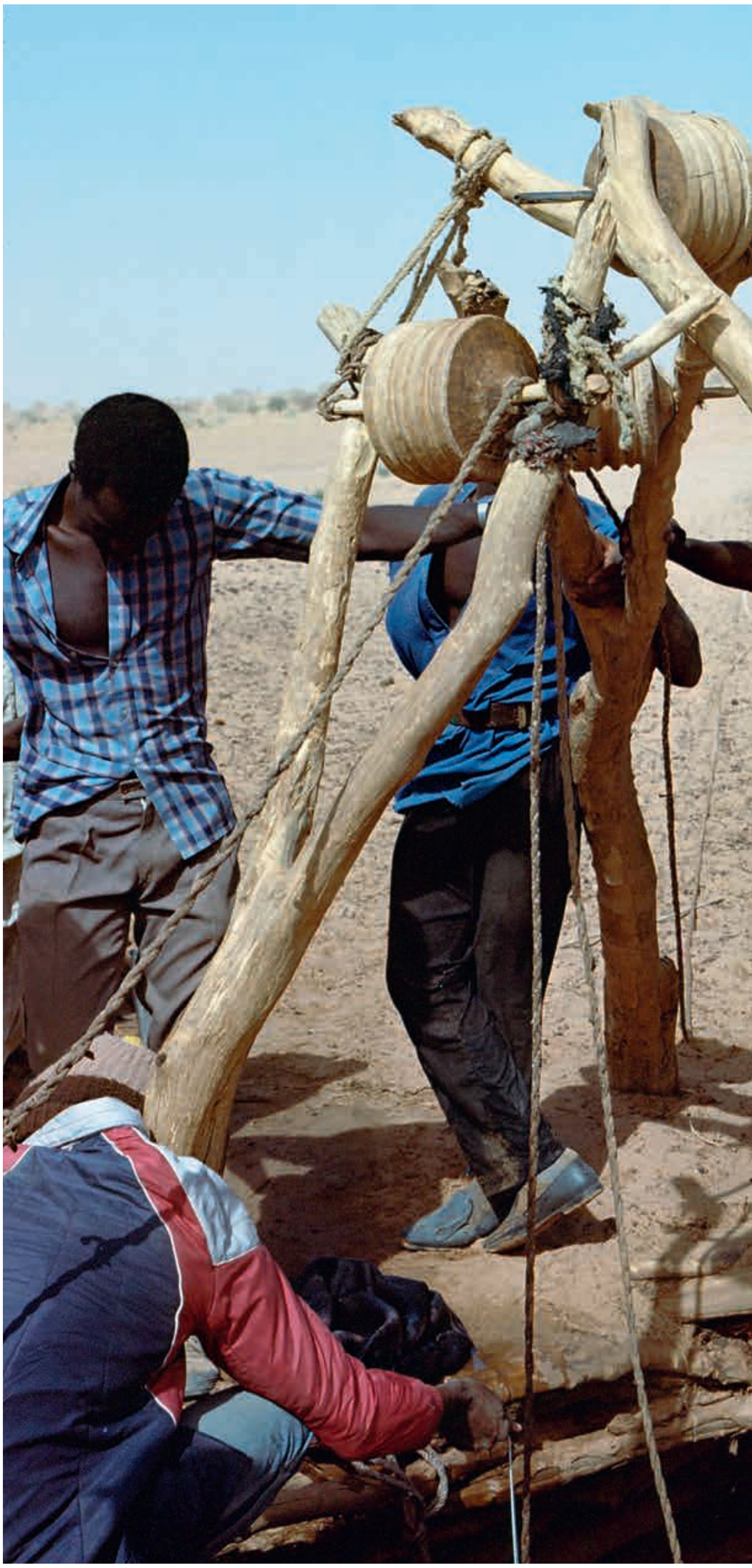
• identify the main hazards and their causes using a Shared Aquifer Diagnostic Analysis (SADA), which highlighted population growth, inadequate national and international governance structures and poverty
• fill knowledge gaps using appropriate technical approaches
• prepare an SAP defining the policy and legal and institutional reforms needed to address the identified risks
• propose an institutional structure to implement this SAP.

A strategic action plan to enhance transboundary cooperation

The SAP—signed in Vienna by the four Member States on 18 September 2013—calls for strengthening of the role and capacity of the Joint Authority and identifying new areas of cooperation. It stresses the need to develop a regional policy regarding measures and management strategies, and thereby to strengthen the institutional and legal aspects related to NSAS management. It recommends the development of a cooperation structure devoted to data exchange and the creation of a network of measurements for the entire aquifer system. Finally, it recommends improving the efficiency of regional offices in the Member States.

The ultimate objective of this SAP is to enable—via legal and institutional procedures—transboundary cooperation to mainstream socioeconomic activities and management plans based on efficient groundwater resource use. The involvement of agriculture and the control and prevention of migratory movements are crucial in this respect.

This last project is a significant step forward for the management of this large transboundary aquifer system, despite the many shortcomings and gaps revealed by the strengths, weaknesses, opportunities and threats (SWOT) analysis carried out in October/November 2011. The actions recommended by this SAP are unfortunately on standby due to the events and civil war that have been under way in Libya since 2014.



▲ **Deep conventional well. Taoudenni Basin, northern Mali.** © Yves Travi

NWSAS situation and the role of OSS

The North-Western Sahara Aquifer System is shared by three countries: Algeria, Libya and Tunisia. The authorities of these three countries became aware of the overextraction risks in the late 1960s.

In 1972, an Algerian-Tunisian programme (*Étude des ressources en eau du Sahara septentrional*, ERESS) focused on preliminary modelling of this aquifer, which generated a first assessment of the impact of current withdrawals and their likely increase. This programme was subsequently updated in 1980.

The specific NWSAS programme was launched within the overall framework of the Sahara and Sahel Observatory (OSS) programme on large drainage basin aquifers after a series of regional seminars and workshops. A programme document signed in Tunis in September 1997 designated OSS as the programme project manager and responsible for fund sourcing. The aim of this programme was to conduct a study of the resource and its uses, to propose a monitoring and joint management mechanism as well as recommendations on the best possible uses of this water.

In May 1999, a first 3-year phase (1999-2002) was launched with the support of the water administrations of the three countries, the Swiss Agency for Development and Cooperation, the International Fund for Agricultural Development (IFAD) and the Food and Agriculture Organization of the United Nations (FAO). This first programme (NWSAS I) was followed by NWSAS II (2003-2006) and NWSAS III (2010-2015).

NWSAS I – hydrogeology, databases and modelling

OSS coordinated this programme while relying on national and international experts for its implementation. This first phase (1999-2002) involved close collaboration between water managers of the three concerned countries, with an NWSAS team set up in Tunis. In addition to dynamic dialogue between the various stakeholders, this first phase enabled:

• significant enhancement of geological and hydrogeological knowledge on the aquifer system

• creation of a database referencing 9,000 boreholes and their main characteristics, including operating rates. This database, with its analysis tools, can function as a real information system, thereby providing a management tool for the three countries

• development of a mathematical model that enhanced the previous models by integrating the Libyan sector and including numerous data recorded and studies conducted between 1972 and 1999. This model could perform simulations and formulate forecasts

• the recommendation to set up a permanent mechanism for consultation between the three countries, yet its legal aspects had yet to be defined.

NWSAS II – setting up a consultation mechanism

This second phase (2003-2006)* led to:

• development of two sub-models (Biskra and Western Basin in Algeria) and the Tunisian-Libyan Djeffara model (Besbes *et al.*, 2005)

• an assessment of agricultural practices

• development of an institutional consultation mechanism between the Member States, with the coordination unit being hosted by OSS. Following several workshops and meetings, the configuration of the mechanism of this structure, its functioning and financing were officially adopted in November 2017 and a coordinator was appointed on a 1-year rotational basis. The coordinator's main mission was to provide a framework for exchange and cooperation between the three countries for joint studies and research activities, defining data exchange protocols, updating models and their implementation, training initiatives, etc.

At the end of the new NWSAS knowledge exploitation phase and the proposal of various hypotheses on water usage, it was essential to carry out an in-depth socioeconomic survey on the situation regarding irrigators and on the real water usage costs. This action was undertaken during the NWSAS III project phase.

NWSAS III – operational recommendations for sustainable water resource management

The third phase of the project (2010-2015) was geared towards formulating operational recommendations for improving the management of the resource, especially for agricultural irrigation, within the framework of sustainable development policies.

* Phase carried out with the support of the Swiss Agency for Development and Cooperation (SDC, Switzerland), the French Facility for Global Environment (FFEM), the Global Environment Facility (GEF), the United Nations Environment Programme (UNEP), UNESCO and the German Agency for International Cooperation (*Deutsche Gesellschaft für Internationale Zusammernarbeit, GIZ*).

→ FOCUS | **Sahara and Sahel Observatory**

The OSS is an organization of international scope with an African vocation which was founded in 1992 and based in Tunis in 2000. Its action spans arid, semiarid and dry subhumid areas within the Saharo-Sahelian region. OSS member countries include 25 African countries, 7 non-African countries and 13 member organizations representing West, East and North Africa, UN organizations and non-governmental organizations.

The OSS mission is to support African member countries in the sustainable management of their natural resources in a particularly unfavourable climate change context. OSS thus invests in:

• implementation of the UN multilateral agreements on desertification (UNCCD), biodiversity (UNCBD) and climate change (UNFCCC)
• promotion of regional and international initiatives related to the environmental challenges of Saharo-Sahelian Africa
• definition of concepts and streamlining of approaches and methodologies related to sustainable land management, water resources and climate change.

The Observatory necessarily focuses on knowledge transfer, capacity building and awareness raising for all stakeholders.

OSS activities and projects are respectively funded by voluntary member country contributions and by grants and donations from development partners.

Effective governance mechanisms and a skilled, multicultural and multidisciplinary team are key assets that enable OSS to provide a high value-added contribution to the international and African institutional landscape.

The OSS action covers a wide range of interventions related to environment monitoring and surveillance in support of the countries' efforts in combating land degradation and desertification, in sustainable water resource management, the resilience of populations, and in safeguarding biological heritage. Several major projects have been carried out in recent years by OSS within water resource framework:

• **NWSAS**: North Africa (Algeria, Libya, Tunisia), North-Western Sahara Aquifer System, a three-phase project carried out between 2000 and 2015, successively boosting knowledge on the system, generating management tools and enhancing water use, particularly for irrigation.
• **CREM**: Maghreb (Algeria, Morocco, Tunisia), Regional Cooperation for Sustainable Management of Water Resources in the Maghreb, carried out in two phases (2014-2018 and 2019-2020, 2020–2021) for the establishment of a regional water resource management strategy.
• **NB-ITTAS**: West and North Africa (Algeria, Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Guinea, Mali, Mauritania, Niger and Nigeria), ABN-OSS project, Improving IWRM, knowledge-based Management and Governance of the Niger Basin and Iullemeden-Taoudeni/Tanezrouft Aquifer System.
• **GICRESAIT**: West and North Africa (Algeria, Benin, Burkina Faso, Mali, Mauritania, Niger and Nigeria), Integrated Concerted Water Resource Management of the Iullemeden, Taoudéni/Tanezrouft and Niger River Aquifer Systems (2010-2017), assessment of the potential and monitoring of water resources of these two large aquifer systems, started in 2004 with the SAI study.
• **IGAD**: East Africa (Djibouti, Ethiopia, Eritrea, Kenya, Somalia, Sudan, South Sudan, Uganda), Mapping, assessment and monitoring of shared water resources in the IGAD subregion project implemented by OSS (2007-2012) for a joint vision of transboundary water resource management.

Support for consultation mechanisms:

- NWSAS: the coordination unit of the NWSAS consultation mechanism has been hosted at the headquarters since 2008. Its main missions are to support the countries in the implementation of the main technical activities aimed at facilitating dialogue between the countries.
- SAIT: Establishment of a consultation mechanism for integrated management of the shared groundwater of Iullemeden and Taoudéni/Tanezrouft aquifers at the Meeting of Ministers held in Abuja on 27 March 2014. The principle of creating this framework for the management of these water resources was adopted with a Memorandum of Understanding that had already been signed by four countries (Benin, Mali, Niger and Nigeria).

Many documents (maps, atlases, technical and documentary reports, databases, GIS, Geoportal) have been published by OSS on these different projects.

For further information: www.oss-online.org

For operational reasons, the project was the focus of three agreements signed with the three cooperation partners, i.e. the African Water Facility, the French Facility for Global Environment (FFEM) and the Global Environment Facility (GEF).

The NWSAS III project had a twofold objective:
- enhancement of hydrogeological knowledge regarding the water resources based on socioeconomic data describing the actual farm functioning situation (see Focus next page)
- proposal of alternatives for agricultural redeployment in the area and operational recommendations for sustainable agriculture, including water and soil resource conservation. This latter point was addressed by developing the installation of a number of agricultural demonstration pilots throughout the NWSAS.

Six irrigation water management issues were identified and selected by the water authorities of the three concerned countries, around which the demonstration pilots were set up. The latter had different specific objectives, such as the safeguarding *foggaras* (underground galleries used for irrigation in the Sahara), soil degradation control, production system restoration or preservation, the development of geothermal water resources, treatment of soils affected by salinization or streamlining of brackish water usage. The results obtained in the six pilots were validated in three national workshops and one regional workshop (OSS, 2012, 2015) (see Focus next page).

▲ **Deep borehole drilling rig.** © Edmunds, travi *et al.*, 2001

▼ **Artesian borehole at Rtem, Tozeur region (Tunisia) abandoned and not plugged.** example of poor management. Pierre Deschamps © IRD

→ FOCUS | **NWSAS III: socioeconomic data and agricultural demonstration pilot results**

To draw up a quantitative and qualitative inventory of irrigated agriculture throughout the basin, 3,000 farms spread over 10 zones (five in Tunisia, four in Algeria and one in Libya) were the focus of detailed surveys to describe their functioning and the behaviour of irrigating farmers. Regarding this latter point, considering the different water access conditions (private, collective or free), two variables seemed especially relevant, i.e. the water salinity incidence and the cost to farmers (see Table below).

	Mean NWSAS	Private access	Public access	Free access	Algeria	Libya	Tunisia
Water consumption per hectare and per farmer (m^3/ha)	12,686	10,516	14,746	21,735	13,520	9,134	13,266
Water cost ($/$m^3$)	0.036	0.045	0.028	0.004	0.036	0.028	0.040
Water productivity ($/$m^3$)	0.413	0.484	0.350	0.274	0.405	0.341	0.458
Gross margin per ha	3,909	4,270	3,176	4,683	4,632	2,861	3,478
Importance of livestock production (% of agricultural income)	17.72	19.7	12.94	30.85	14.9	27.9	9.4
Average irrigated area	4.2	6	2.6	0.85	5.1	6	1.8
Percentage price elasticity regarding the water demand (consumption variations when prices rise by 100%)	-12	-27	-8	-	-45	-25	-33
Percentage salinity elasticity (water productivity variations when salinity rises by 100%)	-75	-67	-80	-	-53	-52	-35

▲ **Summary of results per water access category.** From OSS, 2015

The higher cost of private water access, and more generally the higher cost to farmers, led to a reduction in consumption and a search for alternative water-efficient cropping systems. Salinity had a significant economic impact, thereby warranting investments to combat it (drainage, land reclamation, demineralization, etc.). The overall results could provide a basis for development policies (water pricing, land tenure, investments, etc.).

A hydro-economic model was developed to support decision makers. The model simulates scenarios and for each one it defines: 1) the maximum volume that could be pumped from the aquifer, and 2) the maximum income that could be generated.

Agricultural demonstration pilots: the six pilots (two in each of the three countries) aimed to test technical solutions to improve water productivity, in relation to water scarcity, salinization, irrigation inefficiency and soil degradation issues.

The cost-effective technical solutions implemented (solar energy, underground drainage, demineralization, localized irrigation combined with rational intensification of cropping systems) substantially improved the water productivity. Examples include solar energy usage and irrigation system modifications in the Reggane Oasis (Algeria) or the restoration of soils altered by salinization and hydromorphy in Kebili (Tunisia.) These results have had a significant educational role in boosting awareness on the value of water among farmers, who are now more inclined to pay for irrigation water while investing to achieve greater efficiency.

Moreover, the pilots have also played a social role in promoting dialogue among farmers and fostering innovation dissemination and the social acceptability of innovations. These dynamics have proven promising and could help renew interest in irrigated agriculture in some regions across the Basin

For further information: OSS, 2015

▲ **Solar-powered borehole, Senegal River Valley, Thialaga (Senegal).** Kirsten Simondon © IRD

What future for deep aquifers in Saharo-Sahelian regions?

▲ **Lake Trouna, Libya.** This is one of the 22 lakes of Ramlah d'El Daouda. © Jacques Taberlet

The large deep aquifers of the Saharan region and its arid and semiarid fringes contain considerable quantities of freshwater. The favourable geological structures have enabled this groundwater—partly trapped and under pressure—to rise to the surface, thereby creating freshwater 'islands' in the desert, in turn enabling the development of human societies and oasis agriculture. Modern deep groundwater extraction techniques have currently led to the development of many regions, while enhancing the livelihoods of local communities. These reserves were, however, largely formed during wet periods of the past and are often barely or not replenished and are therefore *a priori* vulnerable.

In recent decades, these large-scale aquifer systems have been the focus of extensive studies using conventional hydrogeology tools and novel methods developed over this period. This research has led to the design and development of hydrogeological models to simulate the future evolution of these large aquifer systems according to different scenarios. **These systems—considering the enormous quantities of water they contain—generally do not seem threatened in the short or medium term.** However, extraction activities are not uniformly distributed and some sectors where these activities are concentrated have already experienced local technical and environmental problems. It would therefore be essential to develop regional models that could be applied to improve extraction planning, yet models can

only produce a more or less accurate representation of the actual situation (simulations are highly dependent on the quantity and quality of the collected data). **It is hence necessary to maintain current monitoring networks while continuing to acquire data so as to validate the forecasts and fine-tune the models.**

Overextraction of these aquifers—which are shared by several countries—could give rise to serious economic and political issues in the long term. It may seem difficult to decide to deprive local populations from the benefits of these resources in order to safeguard them for future generations for a period that is still hard to evaluate. **Yet management of these resources must necessarily be the focus of political decisions to save water and prioritize its usage.** These approaches must be bolstered by the strengthening of regional and international cooperation to enhance knowledge on these aquifer systems and develop modern techniques that could boost the cost-effectiveness and thereby save groundwater, especially with regard to agriculture, as is already under way in the NWSAS. It would also be essential to develop a global approach to water management policy by including food security and the 'virtual' water concept (e.g. equivalent imported or exported water resources for agriculture). These issues are particularly well described and developed in the book of Besbes *et al.* (2019)* on water security in Tunisia.

* Mustapha Besbes, Emeritus Professor at the National Engineering School of Tunis, and foreign associate of the Academy of Science in Paris, is a specialist in water resources in arid countries. He was regularly consulted during the different stages of the NWSAS project.

For further information...

BIBLIOGRAPHY

Abdurrahman W., 2002. *Development and management of groundwater in Saudi Arabia*. GW-MATE/UNESCO Expert group meeting, Socially sustainable management of groundwater mining from aquifer storage. Paris, 6 p.

AFD, 2011. Toward a joint management of transboundary aquifer systems. Methodological guidebook. *À savoir*, 3. Paris, 122 p.

Aggarwal P.K., Froehlich K., Gofiantini R., 2011. Contributions of the International Atomic Energy Agency to the development and practice of isotope hydrology. *Hydrogeology Journal*, 19: 5-8.

AGW-Net, BGR, IWMI, Cap Net, RAOB, IGRAC, 2015. *Intégration de la gestion des eaux souterraines dans les organismes de bassin transfrontalier en Afrique*. Training manual published by AGW-Net, BGR, IWMI, Cap Net, RAOB and IGRAC. 241 p.

Al Asbahi, Qahtan Yehya A.M., 2005. *Water resources information in Yemen*. UN Intersecretariat Working Group on Environment Statistics (IWC-ENV), International Work Session on Water Statistics, Vienna (June 20-22 2005). http://unstats.un.org/unsd/environment/envpdf/pap_wasess3a3yemen.pdf

Baba Sy M., 2005. *Recharge et paléorecharge du système aquifère du Sahara septentrional*. PhD dissertation in Geology, Université de Tunis El Manar, 261 p.

Bakhbakhi M., 2002. Hydrogeological framework of the Nubian sandstone aquifer system. In: Appelgren B. (ed.), *Managing shared aquifer resources in Africa (ISARM Africa). Proceedings of the internatonal workshop, Tripoli (Libya), 2-4 June 2002. IHP-VI, Series on Groundwater n°8*. UNESCO, Paris: 177-201.

Berberis J.A., 1987. Le régime juridique international des eaux souterraines. *Annuaire Français de Droit International*, 33: 129-162.

Besbes M., Bouhlila R., Pallas P., Pizzi G., Ayoub A., Babasy M., El Barouni S., Horriche F., 2005. *Étude sur modèles mathématiques de la Jeffara tuniso-libyenne*. OSS report, OSS, Tunisia.

Besbes M., 2010. *Actualisation du modèle SASS. Rapport final*. OSS / Mécanisme de concertation du SASS.

Besbes M., Chahed J., Hamdane A., 2014. *Sécurité hydrique de la Tunisie : gérer l'eau en conditions de pénurie*. Éditions L'Harmattan, Paris, 358 p.

Besbes M., Chahed J., Hamdane A., 2019. *National water security. Case study of an arid country: Tunisia*. Springer Nature, Berlin, 272 p.

BGR, 2012. *Groundwater needs assessment in the Lake Chad Basin. Report*. Berlin, 14 p.

Bouchez C., Deschamps P., Goncalvez J., Hamelin B., Sylvestre F., Doumnang J.C., Mahamat Nour A., Baba Goni I., Favreau G., Genthon P., Seidel J.L., 2015. Investigation of ^{36}Cl distribution: towards a new estimation of groundwater residence times in the confined aquifer of the LCB? *Procedia Earth and Planetary Science*, 13: 147-150.

Busson G., 1967. *Le Mésozoïque saharien. 1ère partie : l'extrême Sud-tunisien*. Éditions du CNRS, Paris, 196 p.

Castany G., Margat J., 1977. *Dictionnaire français d'hydrogéologie*. BRGM Service géologique national, Orléans, 249 p.

CBLT-PNUD-UNESCO, 1972. *Synthèse hydrologique du bassin du lac Tchad, 1966-1970*. Rapport technique, UNESCO, Paris, 218 p. + maps.

CEDARE/IFAD, 2002. *Programme for the development of a regional strategy for the utilization of the Nubian Sandstone Aquifer System. Volume II: Hydrogeology*. CEDARE, Cairo, Egypt.

Collin J.-J., 2004. *Les eaux souterraines. Connaissance et gestion*. BRGM Éditions / Hermann, Orléans, 170 p.

Conrad G., 1969. *L'évolution continentale post-hercynienne du Sahara algérien (Saoura, erg Chech-Tanezrouft, Ahnet-Mouydir)*. Centre de recherche sur les zones arides. Série géologie n°10, Éditions du CNRS, Paris, 527 p.

DGPRE, 2015. *Projet de mise en œuvre du Plan d'action de gestion intégrée des ressources en eau dans le bassin arachidier (PAGIRE-BA). Rapport de synthèse des études*. DGPRE, Senegal, 21 p.

Döll P., Douville H., Güntner A., Müller-Schmied H., Wada Y., 2016. Modelling freshwater resources at the global scale: challenges and prospects. *Surveys in Geophysics*, 37: 195-221.
DOI: 10.1007/s10712-015-9343-1

Edmunds W.M., Wright E.P., 1979. Groundwater recharge and paleoclimate in the Sirte and Kufra basins, Libya. *Journal of Hydrology*, 40(3-4): 215-241.

Edmunds W.M., Travi Y., Zuppi G.M., Gasse F., Dodo A., Goni I.B., Djoret D., 2001. *Groundwater: a renewable esource? Focus on Sahara and Sahel*. GASPAL (Groundwater as Palaeoindicator) (EC ENRICH, ENV4- CT97-0591), British Geological Survey, Oxfordshire, 20 p.

Edmunds W.M., Guendouz A.H., Mamou A., Moulla A., Shands P., Zouari K., 2003. Groundwater evolution in the Continental Intercalaire aquifer of southern Algeria and Tunisia: trace element and isotopic indicators. *Applied Geochemistry*, 18(6): 805-822.

ERESS, 1972. *Étude des ressources en eau du Sahara septentrional. Rapport final*. 1 map, 12 plates. OSS, Tunis, 78 p.

ESCWA, 1999. *Updating the assessment of water resources in ESCWA member States*. Rep. E_ESCWA_ENR_1999_WG.1_7-EN, Economic and Social Commission for Western Asia, Beirut, 147 p.

Fontes J.C., Andrews J.N., Edmunds W.M., Guerre A., Travi Y., 1991. Paleorecharge by the Niger River (Mali) deduced from groundwater geochemistry. *Water Resources Research*, 27(2): 199-214.

Guendouz A., Moulla A.S., Edmunds W.M., Shand P., Zouari K., Mamou A., 1997. Palaeoclimatic information contained in groundwaters of the Grand Erg Oriental, North-Africa. In: *International symposium on isotope techniques in the study of past and current environmental changes in the hydrosphere and the atmosphere, Vienna, 14-18 April 1997*. IAEA-SM-349-/43: 555-571.

Guendouz A., Moulla A.S., Edmunds W.M., Zouari K., Shands P., Mamou A., 2003. Hydrogeochemical and isotopic evolution of water in the Complex Terminal aquifer in Algerian Sahara. *Hydrogeology Journal*, 11: 483-495.

Guendouz A., Michelot J.L., 2006. Chlorine-36 dating of deep groundwater from Northern Sahara. *Journal of Hydrology*, 328(3): 572-580.

Kamel S., 2012. Application of selected geothermometers to Continental Intercalaire thermal water in southern Tunisia. *Geothermics*, 41: 63-73.
DOI: 10.1016/j.geothermics.2011.10.003

Lasserre F., Cardenas Y.V., 2016. L'entrée en vigueur de la Convention de New York sur l'utilisation des cours d'eau internationaux : quel impact sur la gouvernance des bassins internationaux ? *Revue québécoise de droit international,* 29-1: 85-106.

Margat J., 2006. *Exploitations et utilisations des eaux souterraines dans le monde.* BRGM-UNESCO copublication, Paris, 52 p.

Margat J., 2008. *Les eaux souterraines dans le monde*, Éditions BRGM, Orléans, 44 p.

Marsily G. de, 2020. Will we soon run out of water? *Annals of Nutrition and Metabolism*. 2020;76 (suppl 1):10-16. https://doi.org/10.1159/000515019 (www.karger.com/ANM).

Marsily G. de, Abarca-del-Rio R., 2015. Water and Food in the Twenty-First Century. *Surveys in Geophysics*, 37: 503-527. DOI: 10.1007/s10712-015-9335-1

Marsily G. de, Abarca-del-Rio R, Cazenave A, Ribstein P., 2018. Allons-nous bientôt manquer d'eau ? *La Météorologie, Revue de l'atmosphère et du climat.* 101: 39-49.

Moulla A.S., Guendouz A., Cherchali M.E.H., Chaid Z., Ouarezki S., 2012. Updated geochemical and isotopic data from the Continental Intercalaire aquifer in the Great Occidental Erg sub-basin (south-western Algeria). *Quaternary international,* 257: 64-73.

OSS, 2002. *Système aquifère du Sahara septentrional : de la concertation à la gestion commune d'un bassin aquifère transfrontière. SASS project. Internal report.* Tunis, 58 p.

OSS, 2003. *Système aquifère du Sahara septentrional. Gestion commune d'un bassin transfrontière. Études et rapports.* SASS project. Tunis, 147 p.

OSS, 2008. *Système aquifère du Sahara septentrional. Gestion concertée d'un bassin transfrontalier.* Coll. Synthèse, n°1. Tunis, 49 p.

OSS, 2012. *Système aquifère du Sahara septentrional, « SASS III ». Rapport d'activités année 2012.* Tunis, 39 p.

OSS, 2015. *Pour une meilleure valorisation de l'eau d'irrigation dans le bassin du SASS. Diagnostic et recommandations.* Tunis, 32 p.

OSS/UNESCO, 2005. *Ressources en eau et gestion des aquifères transfrontaliers de l'Afrique du Nord et du Sahel.* ISARM Africa, UNESCO IHP-IV Series on Groundwater. N°11. Paris, 134 p.

Petit-Maire N., Fontugne M., Rouland-Lefevre C., 1991. Atmospheric methane ratio and environmental change in the Sahara an Sahel during the last 130 kyrs. *Paleogeography, Plaeoclimatology, Palaeoecology*, 86(1-2): 197-206. DOI: 10.1016/0031-0182(91)90009-G

Pettersen J.O., 2014. *Traçage isotopique (^{36}Cl, ^{4}He, ^{234}U) et modélisation hydrogéologique du système aquifère du Sahara septentrional. Application à la recharge Quaternaire du Continental Intercalaire.* PhD dissertation, Géosciences de l'environnement, Université d'Aix Marseille, France. 329 p.

Purtschert R., Sturchio N.C., Yokochi R., 2013. Krypton dating of old groundwater. In: Suckow A., Aggarwal P.K., Araguas-Araguas L. (eds.). *Isotope methods for dating old groundwater.* IAEA, Vienne: 91-124.

Quadri E., 2017. *The Nubian sandstone aquifer system. A case of cooperation in the making.* XVI World Water Congress. International Water Resources Association (IWRA). Cancun, Mexico, 29 May-3 June 2017. 10 p.

Raimond C., Sylvestre F., Zakinet D., Moussa A. (eds.), 2019. *Le Tchad des lacs. Les zones humides sahéliennes au défi du changement global.* Collection Synthèses, IRD Éditions, Montpellier, France. 368 p.

Salem O., Pallas P., 2001. The Nubian sandstone aquifer system (NSAS). In: Puri S. (ed.). *International shared (transboundary) aquifer resources management - Their significance and sustainable management.* IHP-VI, IHP Non Serial Publications in Hydrology, UNESCO, Paris, 74 p.

Schneider J.L., 1969. *Carte hydrogéologique de la République du Tchad.* BRGM, France.

Schneider J.L., Wolf J.P., 1992. *Carte géologique et carte hydrogéologique au 1500000 de la République du Tchad, mémoire explicatif.* Document du BRGM. 209, vol. 1 et 2. Orléans, 689 p.

Seguin J.-J., Gutierrez A., 2016. Les ressources en eau du continent africain : rareté et abondance. *Géosciences*, 21: 58-66.

Simonel N., Requier-Desjardins M., Baba Sy M., Latrech D., Dodo A., 2012. La gestion des ressources transfrontières en eau souterraine à l'échelle supranationale. Une étude du système aquifère du Sahara septentrional et du système aquifère Iullemeden en Afrique. In: Maganda C., Petit O., Peter Lang S.A. (eds.), *Strategic Natural Resource Governance: Contemporary Environmental Perspectives*: 99-127. Regional Integration and Social Cohesion. hal-02178756

Sohlne J., 2002. *Le droit international des ressources en eau douce : solidarité contre souveraineté.* La documentation française, Paris. 608 p.

Thorweihe U., Schandelmeier H. (eds.), 1993. *Geoscientific research in Northeast Africa.* Balkema, Rotterdam, 793 p.

Tweed S., Leblanc M., Cartwright I., Bass A., Travi Y., Marc V., Nguyen Bach T., Dang Duc N., Massuel S., Kumar U.S., 2019. Stable isotopes of water in hydrogeology. In: Maurice, P. A. (ed.) *Encyclopedia of water: science, technology and society.* Wiley: Hoboken, NJ. DOI: 10.1002/9781119300762.wsts0154

UNESCO, 1972. *Étude des ressources en eau du Sahara septentrional (ERESS) : Algérie, Tunisie - (mission). Rapport sur les résultats du projet, conclusions et recommandations.* Paris. Available at UNESCODOC, document code: TR/UNESCO/UNDP(SF) REG.100

UNESCO, 2001. *Internationally shared (transboundary) aquifer resources management. Their significance and sustainable management. A framework document.* IHP-VI, Non Serial Documents in Hydrology. November 2001, UNESCO, Paris.

UNESCO, 2004. *Proceedings of the International workshop on managing shared aquifer resources in Africa, Tripoli, Libya, June 2-4, 2002.* Ed. Applegreen, B., ISARM-Africa. IHP-VI, Series on Groundwater. No. 8, 238 p.

UNESCO, 2006. *Non-renewable groundwater resources. A guidebook on socially-sustainable management for water-policy makers.* IHP-VI, Series on Groundwater. N°10, 104 p.

Van der Meeren T., Deschamp P., Sylvestre F., Kemkong B., Moussa A., Schuster M., Verschuren D., 2019. Les lacs d'Ounianga. Mieux comprendre leur dynamique hydrologique et écologique par une approche interdisciplinaire. Chapitre 6. In: *Le Tchad des lacs. Les zones humides sahéliennes au défi du changement global*. Collection Synthèses, IRD Éditions, Montpellier, 368 p.

Voss C.I., Soliman S.M., 2014. The transboundary non-renewable Nubian Aquifer System of Chad, Egypt, Libya and Sudan: classical groundwater questions and parsimonious hydrogeologic analysis and modeling. *Hydrogeology Journal.* 22(2): 441-468.

Wallin B., Gaye C.B., Gourcy L., Aggarwal P., 2005. Isotope methods for management of shared aquifers in Northern Africa. *Ground Water. 43: 744-749.*

WEBSITES

(nonexhaustive list)

International organizations

CEDARE - Center for Environment and Development for the Arab Region and Europe
http://web.cedare.org/

FAO - Food and Agriculture Organization of the United Nations
www.fao.org/land-water/water

GEF – Global Environment Facility
www.thegef.org/topics/international-waters

FFEM – French Facility for Global Environment
www.ffem.fr/en/page-thematique-axe/aquatic-ecosystems-0

IFAD – International Fund for Agricultural Development
www.ifad.org/en/water

IAEA – International Atomic Energy Agency
www.iaea.org

IGRAC - International Groundwater Resources Assessment Centre
www.un-igrac.org

ISARM - International Shared Aquifer Resources Management
https://isarm.org

United Nations – Water Action Decade: 2018-2028
https://www.un.org/sustainabledevelopment/water-action-decade/

OIEau – International Office for Water
www.iowater.org

OSS - Sahara and Sahel Observatory
www.oss-online.org

UNDP – United Nations Development Programme – SDG 6
www.undp.org/sustainable-development-goals#clean-water-and-sanitation

UNEP - United Nations Environment Programme
www.unenvironment.org/fr/explore-topics/water/about-eau

UNESCO – United Nations Educational, Scientific and Cultural Organization
https://en.unesco.org/themes/water-security/hydrology/groundwater

International cooperation agencies

AFD – French Development Agency
www.afd.fr/en

Research institutions and laboratories

BRGM – French Geological Survey
https://www.brgm.fr/en/challenges/groundwater-management

CIRAD – French Agricultural Research Centre for International Development
www.cirad.fr/en

CNFSH - *Comité National Français des Sciences hydrologiques*
https://hydrologie.org

IRD – French National Research Institute for Sustainable Development
https://en.ird.fr

Networks

RIOB – International Network of Basin Organizations
www.riob.org/en

Ritimo - *Réseau d'information et de documentation sur le développement durable et la solidarité internationale (site « Partage des eaux »)*
www.partagedeseaux.info/English

▲ **Dromedaries at a watering hole in the Great Eastern Erg, Tunisia.** Vincent Simonneaux © IRD

Glossary

Chott. A saline depression, or lake, in desert regions of Algeria and Tunisia that remains predominantly dry but may sometimes be flooded.

Endorehic. Surface water that does not reach the sea or ocean but instead drains into a basin or lake with no outlet, or is lost by infiltration and/or evaporation during its flow.

Numerical modelling. This involves building a set of mathematical functions describing a phenomenon. Changes in the physical system may be predicted by modifying the initial variables.

Sabkha. In North Africa, a flat saline bottom of a blind depression, without vegetation, in which saline mineral deposits form during dry periods. These sites may become flooded with rainwater or rising groundwater during rainy periods.

List of acronyms and abbreviations

BGR	German Federal Institute for Geosciences and Raw Materials - *Bundesanstalt für Geowissenschaften und Rohstoffe*
BGS	British Geological Survey
BP	Before present
CEDARE	Center for Environment and Development for the Arab Region and Europe
CI	Continental intercalaire
CNRS	French National Centre for Scientific Research
CREM	Regional Cooperation in the Water Sector in the Maghreb Project
CSFD	French Scientific Committee on Desertification
CT	Continental terminal (or so-called '*complexe terminal*' in North Africa)
DGPRE	*Direction de la gestion et de la planification des ressources en eau*, Senegal
ERESS	*Étude des ressources en eau du Sahara septentrional*
FAO	Food and Agriculture Organization of the United Nations
FFEM	French Facility for Global Environment
GEF	Global Environment Facility
GIS	Geographic information system
IAEA	International Atomic Energy Agency
IAS	Iullemeden Aquifer System
IFAD	International Fund for Agricultural Development

IRD	French National Research Institute for Sustainable Development
ISARM	International Shared Aquifer Resources Management Programme
IWRM	Integrated water resources management
JASAD-NSAS	Joint Authority for the Study and Development of the Nubian Sandstone Aquifer System
LCBC	Lake Chad Basin Commission
NAS	Nubian Aquifer System
NBA	Niger Basin Authority
NSAS	Nubian Sandstone Aquifer System
NWSAS	North-Western Sahara Aquifer System
OSS	Sahara and Sahel Observatory
PAGIRE-BA	*Plan d'action de gestion intégrée des ressources en eau dans le bassin arachidier*
PNAS	Post-Nubian Aquifer System
SADA	Shared Aquifer Diagnostic Analysis
SAP	Strategic action plan
SDGs	Sustainable Development Goals
TAS	Taoudeni Aquifer System
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization

CSFD
Les dossiers thématiques

Abstract

95% of the freshwater used by mankind worldwide—mainly groundwater—derives from renewable water resources (i.e. the share of rainfall not taken up by plants or evaporated). The remaining 5% is from the groundwater stock accumulated during excess recharge periods. Globally, this stock is constantly declining due to overexploitation linked to an imbalance between natural or human discharge (especially for crop irrigation) and groundwater recharge, or simply due to the complete absence of recharge. This is the case regarding the large Saharo-Sahelian aquifers, which are often the only substantial water resources available in this region.

These nonrenewable, so-called 'fossil', groundwater resources were generally formed during the wet Quaternary Periods. The age and conditions of their recharge have been studied using isotope hydrology (climatic markers and dating) combined with abundant evidence of a vast hydrological system (fossil hydrographic networks, lake sediments) and of human, animal and plant life.

In the Saharan zone, the dwindling rainfall pattern over the last few millennia and the natural discharge of these large aquifers have gradually led to formation of the desert as we know it today. Currently, only a few oases remain that are supplied by groundwater pushed to the surface under pressure. These fragile environments are threatened by the overuse of groundwater resources. Many often transboundary studies have been conducted since the 1970s to gain insight into the functioning of these aquifers and to come up with ways to manage them sustainably.

This *Dossier* considers the deep groundwater resources in the Saharo-Sahelian zone in terms of the availability of fresh water worldwide and highlights the importance of preserving them to combat desertification. It focuses on the general features of these major aquifer systems, while underlining their geological and paleohydrogeological specificities. The study methods are then described based on three examples of major deep aquifer systems: the Chad Basin, the Nubian Sandstone Aquifer System (NSAS) and the North-Western Sahara Aquifer System (NWSAS). Finally, the rational management of these large-scale systems and transboundary aspects are addressed while outlining the initiatives undertaken on the NSAS and NWSAS.

Keywords:
Deep aquifers, Saharo-Sahelian region, paleohydrogeology, transboundary management, water resources, oasis

Résumé

95 % de l'eau douce utilisée par les hommes au niveau mondial, essentiellement d'origine souterraine, proviennent de la ressource en eau renouvelable (part des précipitations qui n'est ni consommée par les plantes puis évapotranspirée, ni évaporée). Les 5 % restants proviennent du stock d'eau souterraine emmagasinée lors des périodes de recharge excédentaire. À l'échelle mondiale, ce stock décroît continuellement du fait d'une surexploitation liée à un déséquilibre entre la vidange, naturelle ou provoquée (notamment pour l'irrigation agricole), et la recharge ou tout simplement du fait de la quasi-absence de recharge. C'est le cas des grands aquifères de la région saharo-sahélienne, souvent seule ressource régionale d'importance disponible.

Ces réserves d'eau souterraines non renouvelées, souvent qualifiées de « fossiles », sont en grande partie héritées des périodes humides du Quaternaire. L'âge et les conditions de leur recharge ont pu être étudiés à l'aide de l'hydrologie isotopique (marqueurs de conditions climatiques et datations) associée à de nombreuses traces d'un vaste système hydrologique (réseaux hydrographiques fossiles, sédiments lacustres) et de vie humaine, animale et végétale.

Dans la partie saharienne, la raréfaction des précipitations au cours des derniers millénaires et la vidange naturelle de ces grands aquifères ont conduit progressivement le désert à reprendre ses droits. À l'heure actuelle, seuls subsistent quelques oasis alimentées par l'émergence des eaux souterraines sous pression. Ces milieux fragiles sont menacés par la surexploitation des ressources en eau souterraines. De nombreuses études, associant souvent plusieurs pays, ont ainsi été entamées depuis les années 1970 pour mieux comprendre le fonctionnement de ces aquifères et tenter de les gérer durablement.

Ce dossier replace, tout d'abord, les eaux profondes de la zone saharo-sahélienne dans le contexte de la disponibilité en eau douce sur la planète et souligne l'importance de leur préservation pour lutter contre la désertification. Il s'intéresse ensuite aux caractéristiques générales de ces grands systèmes aquifères, souligne leurs spécificités géologiques et paléo-hydrogéologiques et décrit les méthodes d'étude, en s'appuyant sur trois exemples de grands systèmes aquifères profonds : le bassin du Tchad, le système aquifère des grès nubiens (NSAS) et le système aquifère du Sahara septentrional (SASS). Enfin, la question de la gestion rationnelle de ces grands systèmes et son aspect transfrontalier sont abordés en décrivant les actions entreprises sur le NSAS et le SASS

Mots clés :
Aquifères profonds, région saharo-sahélienne, paléo-hydrogéologie, gestion transfrontalière, ressources en eau, oasis

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