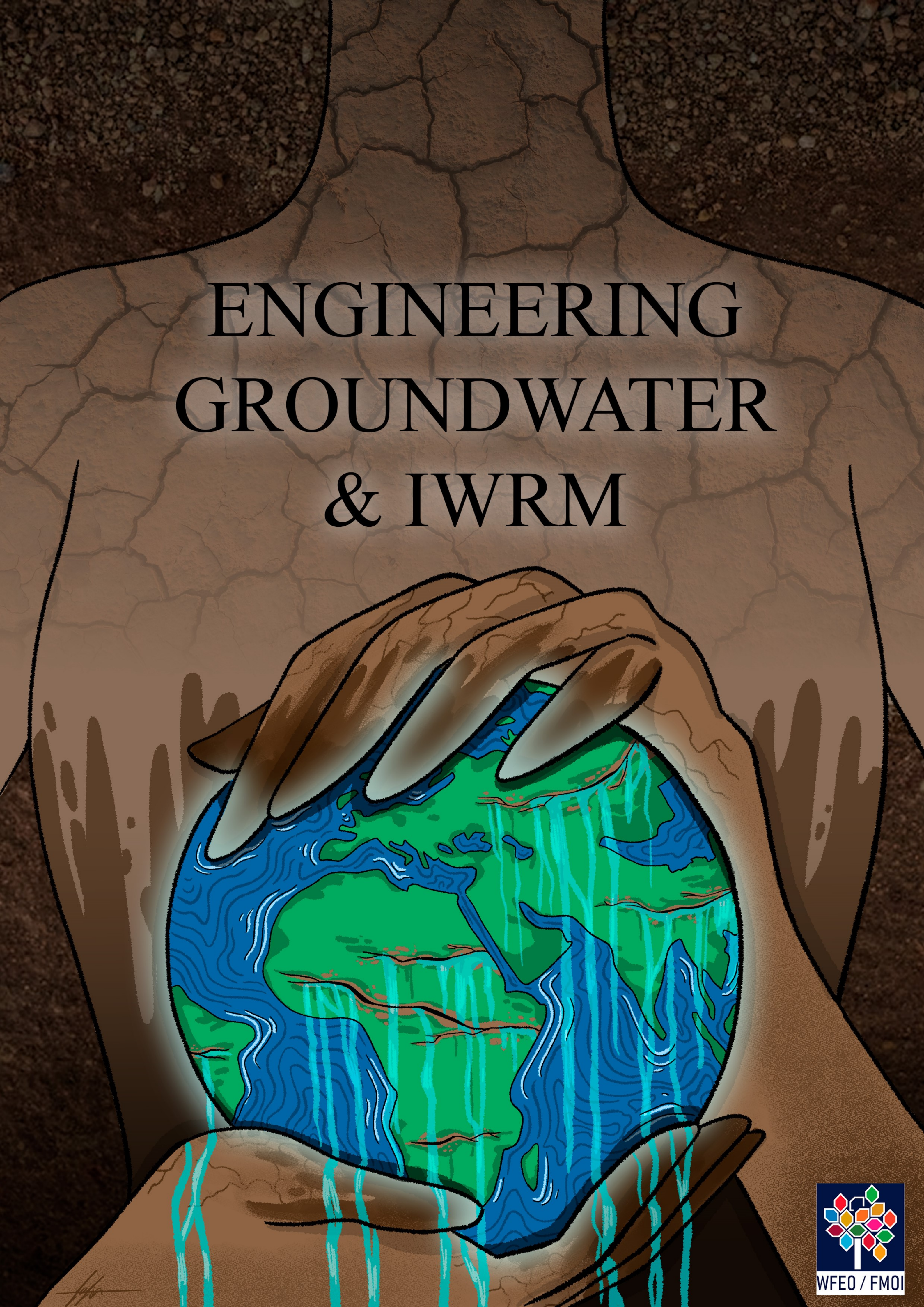
ENGINEERING GROUNDWATER & IWRM



ENGINEERING, GROUNDWATER, AND INTEGRATED WATER RESOURCES MANAGEMENT

World Federation of Engineers Organizations

Standing Technical Committee on Water

WFEO / FMOI

LEAVE NO ONE BEHIND

FOREWORD

by Prof. Dr. José Vieira, President of the World Federation of Engineering Organizations

Water, as a prerequisite for life, is a critical resource and assumes a special focus in terms of sustainable development and its management faces major challenges related to climate change and human activities.

Groundwater is the most abundant source of freshwater on earth, accounting for approximately 99%, and is a sustainable and affordable source of drinking water especially for rural populations in most parts of the world. Due to the fact that the soil constitutes an immense natural filter many aquifers provide water that requires no treatment other than disinfection. This aspect is very important in low-income regions where the cost of a borehole is relatively modest if water is at no great depth. Groundwater is also crucial for agriculture and ecosystems equilibriums. It is estimated that groundwater contributes to 38% of the world´s irrigated crop production.

However, rapid population growth and industrial and agricultural development put increasing pressure on this “hidden treasure”. Urban coverage reducing the aquifer recharge and overexploitation due to intense pumping can result in its dewatering and consolidation, giving rise to ground subsidence and to salt intrusion in coastal aquifers. On the other hand, the entry of pollutants into the aquifer is a very serious threat to water quality due to the great difficulty in removing them.

Global water problems, including droughts and floods, pollution caused by natural and anthropogenic-driven events such as extreme rains, rising sea and river levels, bushfires, and untreated domestic and industrial effluents, are key challenges which require an integrated water resources planning and management considering surface water and groundwater as a single, interconnected resource. Water engineers can provide the necessary expertise and support to address these global challenges applying scientific knowledge and innovative technical solutions.

Recognizing the importance and cross-cutting role of water with most of the UN Sustainable Development Goals (SDGs) and its decisive contribution to achieving the goals of the 2030 Agenda, WFEO established the Standing Technical Committee for Water (CW) in 2022, hosted by “Instituto de la Ingeniería de España” and “Ordem dos Engenheiros”, the WFEO National Members of Spain and Portugal, respectively.

Understanding the relevance of groundwater for human health, food security and ecosystems, it is surprising how little visibility is given to it in the SDGs. The contributors to this publication are world-renowned experts with long experience in groundwater research and development projects that not only provide serious warnings about the challenges and threats related to the quantity and quality of groundwater but also showcased engineering practices for proper integrated water resource management, giving special visibility to the “invisible” groundwater.

This publication provides a comprehensive perspective of groundwater in the context of integrated water resources management and in the framework of sustainable development goals. I am sure that it will serve as a reference in groundwater management, especially for young engineers.

I commend Ignacio González-Castelao Martínez-Peñuela, Chair of CW, and the authors for devoting their generous effort and expertise to the preparation of this publication, which makes a great contribution to expressing the engineering approaches for sustainable development.

STANDING TECHNICAL COMMITTEE ON WATER OF THE WORLD FEDERATION OF ENGINEERING ORGANIZATIONS

By Ignacio González-Castelao Martínez-Peñuela (Editor), Chair of the Standing Technical Committee on Water

The World Federation of Engineering Organizations (WFEO) is an international organization for the engineering profession. Founded in 1968 under the auspices of UNESCO, WFEO brings together national engineering institutions from some 100 nations and represents more than 30 million engineers.

WFEO is the internationally recognized and chosen leader of the engineering profession and cooperates with national and international professional institutions in leading the development and application of engineering to constructively solve global and regional problems for the benefit of humanity.

Given the growing importance of water in the global agenda and its cross-cutting nature to all the United Nations Sustainable Development Goals, the WFEO approved in 2018, coinciding with the celebration of its fiftieth anniversary, the creation of the Working Group on Water (WGoW), chaired by our college Tomás Sancho. This Working Group was jointly sponsored by the "Instituto de la Ingeniería de España" (IIE) and the "Ordem dos Engenheiros" of Portugal (OdE).

Once concluded the activities of the WGoW, the WFEO General Assembly, held in Costa Rica in March 2022, approved the transformation of this Working Group into a Standing Technical Committee on Water (CW), also at the proposal of the IIE and OdE. The CW covers all WFEO initiatives in water engineering and its relations with United Nations bodies and agencies, mainly with UN-Water and UNESCO. Its activity is framed within the scope of the contribution of engineering to Sustainable Development Goals.

The Committee's work covers the four years 2022-2026, with a commitment to release several thematic papers, being this document the first of this series.

I would like to express my gratitude to all the authors for their generous effort and dedication in the preparation of this document, and also to our artist who illustrated the cover.

In March 2023, the world came together at the United Nations Water Conference 2023, convened by the United Nations General Assembly. The outcome of this conference is the "Water Action Agenda", which has been materialized through various commitments, pledges, and actions. This document is WFEO's first commitment to the "Water Action Agenda".

ACKNOWLEDGMENTS

This document results from a collective, disinterested, and generous effort made by the authors and the Standing Technical Committee on Water of the World Federation of Engineering Organizations. The authorship of the report is as follows.

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Disclaimer

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1 Introduction

Ignacio González-Castelao

Water is a universal good indispensable for life, and its quantity and quality affect many sectors, giving this resource a social, environmental, and economic dimension. It is a good that knows no borders and is available in many regions of the planet, but probably in many places the most accessible freshwater is the one that cannot be seen, groundwater.

The vast majority of planet's freshwater resources are found in aquifers (99%), and one-third of humanity depends on groundwater for its subsistence. It provides almost half of the world's drinking water, and nearly 70% of the groundwater withdrawn is used for agriculture, supplying 38% of the world's irrigated land. It is the world's most extracted raw material. Annually, over 200 times more groundwater is abstracted from the earth than oil. Groundwater is vital not only for humans but also for the ecosystems that depend on it and biodiversity.

These resources are also threatened by climate change, but mainly by human activities. Population growth and current lifestyles are depleting these resources to provide us with more food and goods. Groundwater is more protected than surface water from pollution, but this has not prevented humans from contaminating this water. The value of groundwater goes far beyond the mere quantitative and should not be judged only by this data.

This report aims to highlight the relevance of groundwater and how, from an engineering perspective, it should address the management of this resource.

First, a summary description of global groundwater resources is provided in the chapter "Groundwater status", where the relevance of this resource becomes evident.

This resource is interlinked with most of the Sustainable Development Goals (SDG), and its contribution to achieving the targets of the 2030 Agenda is extraordinary. Therefore, it is surprising that this resource is undervalued or under-represented in the SDGs. Groundwater is invisible, but it is also to the SDGs. The chapter "Sustainable development goals and groundwater" shows this resource's real value in relation to the SDGs, indicating those targets with which it is strongly interlinked.

The chapter "Groundwater and climate change" shows how climate change can affect this resource. However, it also highlights that, on some occasions, non-climatic factors can impact aquifers more than climate factors.

The previously mentioned threats to groundwater require a better understanding (knowledge and data) of this resource, more protection and adequate management. Our reliance on this resource makes it necessary to perform not only mere combined management with surface water or integrated management of all resources (conventional and non-conventional). It is essential to achieve integrated management of all these resources together with the soil and land use. All this is described in the chapter "Groundwater and Integrated Water Resources Management".

Groundwater is also crucial in mining, considered the only industrial activity that can become a water producer for itself. Elements of groundwater management are also used in mining activity, where water not only influences the rock cycle but is also present in the extraction of minerals, where it can cause geotechnical behavior problems. Mining requires very often dewatering systems for its activity, systems that can allow meeting external water demands after mine closure. In any case, the flows and volumes drained in many mines may be surprising for those far from the mining world.

Considering that 60% of the world's freshwater flows cross national borders and that approximately 468 transboundary aquifers and aquifer systems are identified, governance over the integrated management of these water resources becomes more complex, making cooperation between countries essential. There are 153 countries (and areas) sharing transboundary waters. The specificities of the management of these aquifers and best practices are discussed in the chapter "Transboundary aquifers".

Groundwater is the primary resource in remote regions and fast-growing cities. It is an essential resource to ensure the human right to water for people, especially for the most vulnerable groups, who depend on them to ensure their drinking water supply for water consumption, hygiene, and food preparation. The current conditions of many aquifers have a profound impact on the populations that depend on them, especially on these groups, where not only the water security of these populations is at stake but also their food security and health. In light of this situation, the last chapter, "Vulnerable groups", focuses on the situation of these groups and several development programs and actions aimed at fully realizing the human right of access to water.

Engineering plays a relevant role in all the above matters, adapting scientific knowledge to the needs of society and the environment. Thus, contributing to sustainable, intelligent, and inclusive development.

2 Groundwater status

João Paulo Lobo-Ferreira

2.1 Introduction

Water has always been the main natural resource on which humanity has depended. Great civilizations arose along the large rivers. The irregular distribution of water resources in time and space was then imposed as an implacable law of nature. Humans have adapted as much as possible to taking advantage, sometimes remarkably, of the cyclical extremes of river flows. Over time they sought to control and manage water resources, building dams and canals to conduct water for supply and irrigation.

Groundwater constitutes water bodies below the surface, saturating the interstitial spaces in geological formations. Depending on the characteristics of geological formations where they occur, groundwater may constitute aquifers if these formations can store and provide water in economically usable conditions. The designation of hydrogeological formations refers to the generality of groundwater geological formations. An aquifer system is considered a spatial domain, limited in surface and depth, in which there are one or several aquifers, whether or not related to each other, but constituting a functional unit for research or exploration. The most important aspects to consider for an aquifer system are its transmissivity, storage (which relates to the storage coefficient and the dimension of the aquifer system), recharge volume and water quality.

The growing development of the world economy and the population's standard of living and the population explosion, registered mainly since the last century, have, however, imposed enormous pressure on traditionally exploited water resources, sometimes close to bursting. The superficial ones located in rivers, lakes, and reservoirs alone, no longer satisfy the growing water needs. Groundwater resources, which are more challenging to capture and, today, eventually to store and capture, have only recently begun to be exploited on a large scale. Their volume, significantly higher than surface resources, makes them an excellent source once the hydrological laws that govern them are known. A large number of regions around the world are now mainly supplied with groundwater.

However, as with surface resources, progressive degradation of their quality began to be observed. In addition to rivers, lakes, and seas, the soil has always served as a receptacle for most liquid tributaries and solid waste from human activity. Contrary to what happened with surface waters, the problem of groundwater pollution, however, never significantly concerned decision-makers, either at central, regional, or local levels. This is perhaps because of ignorance of the potential dangers of groundwater pollution. This type of pollution is, however, for various reasons, much more severe in the medium to long term than for surface water.

First, the groundwater runoff velocities are significantly lower than the surface runoff. In seconds, what happens on the surface normally takes a day or more underground. Thus, the problem is usually only detected too late when much of the underground environment is already polluted. Secondly, the porous underground medium partially retains the pollutants, releasing them very slowly, making it difficult to wash the soil completely. And third, because the volumes affected are substantially higher.

It became urgent to know the mechanisms that govern underground flows. Concerning the aspects of quantity, great progresses have been taken and the current state of knowledge is vast. In terms of quality, only a little more than four decades ago, detailed studies were initiated to understand the phenomena in question.

2.2 Groundwater resources and recharge under climate change conditions

Groundwater is found almost everywhere (Figure 2-1) but varies enormously regarding quantity, quality, and recharge. The distribution of the various hydrogeological types mapped shows that, as a global average, half of the land surface (47 %) of the continents (excluding the Antarctic) is made up of local and shallow aquifers with minor occurrences of groundwater (in these areas groundwater is limited to the alteration zone of the bedrock that may also contain local productive aquifers). Approximately 35 % of the land subsurface host relatively homogeneous aquifers, usually in large sedimentary basins that may offer good conditions for groundwater exploitation. 18 % of the land subsurface comprises aquifers in a geologically complex setting with highly productive aquifers in heterogeneous folded or faulted regions close to non-aquifers.

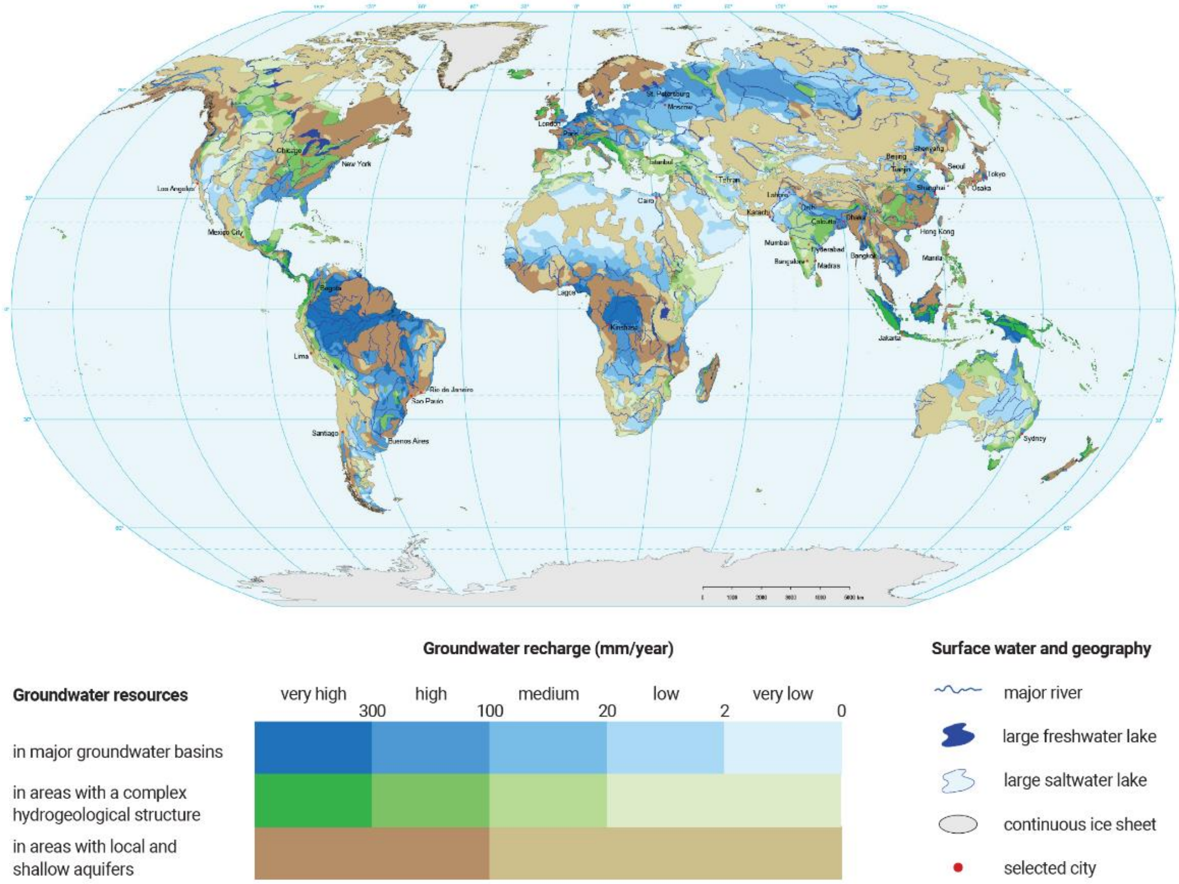

Figure 2-1: Groundwater resources of the world. Illustration from the United Nations World Water Development Report 2022 (United Nations, 2022).

Besides the increase in the rates of groundwater exploitation worldwide, the main variation in regional groundwater availability comes from the decrease in aquifer recharge. This causes changes in the piezometric level and the interfaces between surface and groundwater with changes in the discharge rates from aquifers to rivers, dependent ecosystems, to groundwater and at the interfaces between fresh and saltwater in coastal aquifers and estuarine areas. The increase in extreme precipitation phenomena, even with identical average annual volumes, can also cause a decrease in groundwater recharge because the soil's infiltration capacity is more frequently exceeded, favoring surface runoff instead of recharge. This subdivision varies from continent to continent, as outlined in Table 2-1.

	Major Groundwater basins		Complex hydrogeological structures		Local and shallow aquifers	
	(million km²)	*(%)*	*(million km²)*	*(%)*	*(million km²)*	*(%)*
Africa	13.48	44.9	3.31	11.0	13.22	44.1
Asia	14.54	32.0	7.84	17.3	22.98	50.7
Australia, New Zealand	2.60	32.5	2.90	36.3	2.49	31.1
Europe	5.15	53.0	1.82	18.8	2.74	28.2
Central-/South-America	8.35	45.0	2.02	10.9	8.18	44.1
North America	3.21	15.0	5.75	26.9	12.40	58.1
World (excl. Antarctica)	47.32	35.6	23.64	17.8	62.02	46.6

Table 2-1: Groundwater Resources of the World – Statistics. Illustration from WHYMAP network (BGR & UNESCO, 2022)

Several of the world's major aquifers are under increasing water stress, and 30% of the largest groundwater systems are being depleted (United Nations, 2022), with irrigation water abstraction the main factor in groundwater depletion worldwide. Unsustainable water abstraction is a primary concern in the Asia-Pacific region, as some countries draw unsustainable proportions of their freshwater supply – exceeding half of the total water availability – and 7 of the top 15 groundwater extractors in the world are in Asia and the Pacific (ESCAP United Nations, 2018). Research suggests that groundwater use will increase by 30% by 2050 (ESCAP United Nations, 2018).

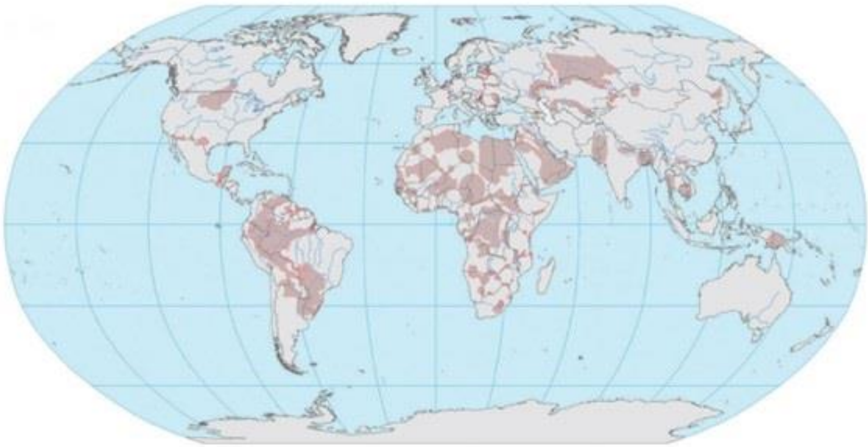

Figure 2-2: Transboundary aquifer systems around the world. The map shows the pattern of inventoried aquifer systems before March 2012. Illustration from UNESCO/IGRAC (Margat & Van der Gun, 2013). For an enlarge version of this image click here or scan the QR code and refer to pages 45-46 (UNESCO-IAHP ISARM Programme, 2009).

Significant concerns are groundwater depletion (losing the buffer against rainfall variability) and changes in soil moisture (and runoff) due to changing land surfaces for urban settlements or agriculture. About 2 billion people depend on groundwater supplies, with approximately 468 identified transboundary aquifers and aquifer systems (UNESCO-IAHP ISARM Programme, 2009).

During the twentieth century, an unprecedented "silent revolution" (Llamas & Martínez-Santos, 2005) in groundwater abstraction has taken place across the globe, significantly boosting irrigated food production and rural development. The global groundwater abstraction rate has tripled over the past 50 years and continues to increase at an annual rate of 1–2%. Groundwater is now a significant source of water for human consumption, supplying nearly half of all drinking water in the world (UNICEF and World Health Organization, 2011). The abstraction of groundwater accounts for approximately 26% of total global water withdrawal and around 43% of all water consumed in irrigation; two-thirds of the total amount is abstracted in Asia (Figure 2-3) with India, China, Pakistan, Iran and Bangladesh as major consumers (Siebert, et al., 2010). Some major aquifer systems still contain large volumes of groundwater but are no longer coupled to contemporary recharge (Foster & Loucks, 2006).

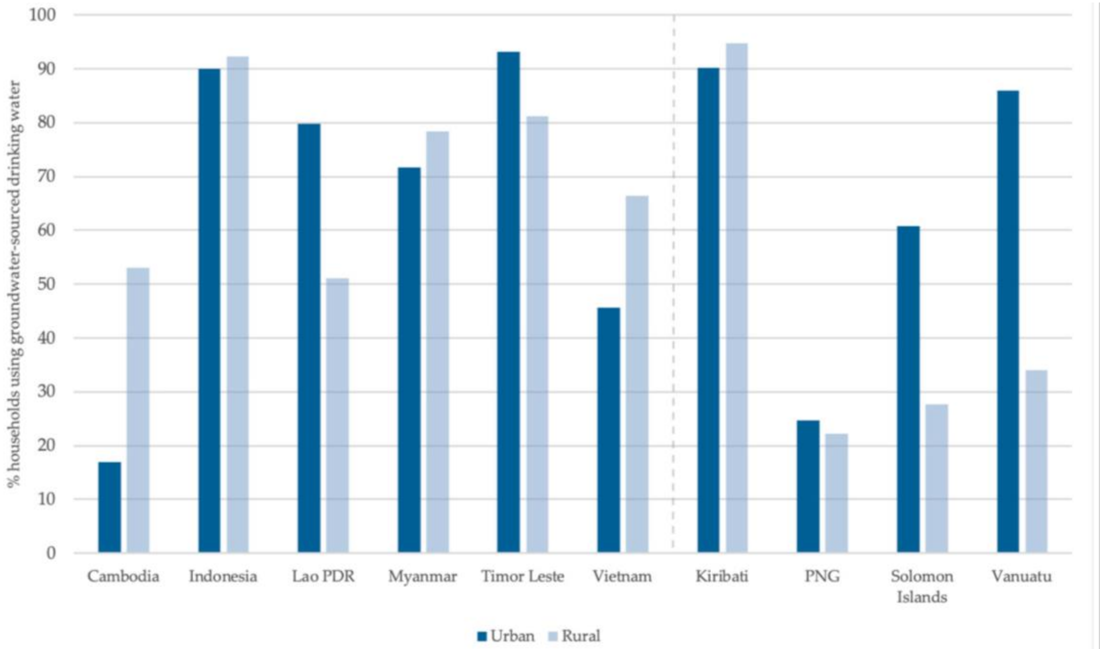

Figure 2-3: Proportion of selected Asian countries' households using groundwater as their primary source of drinking water in urban and rural areas. Illustration from Water (Carrard, Foster, & Willetts, 2019).

Non-renewable groundwater resources and the development of accessible groundwater circulation in these 'fossil' aquifers involve irreversible depletion. Groundwater abstraction rates have not peaked but are dominated by agricultural use in irrigated areas. Numerous groundwater systems in the world's arid and semi-arid zones are not resilient enough to accommodate storage depletion under intensive groundwater development. This is true not only for non-renewable groundwater, but also for many aquifers currently being recharged. The result is a progressive depletion of aquifer storage, made apparent by steadily declining groundwater levels. However, the shallow groundwater circulation that is exploited for all human demands is highly vulnerable. Gradual changes in local groundwater quality have been documented around the world. The most ubiquitous changes are caused by human pollutants, such as sewage, liquid and solid waste, chemicals used in agriculture, manure from livestock, irrigation return flows and mining residues. A second category results from the migration of poor-quality water into aquifer zones, including saline intrusion in coastal aquifers or upward migration of highly mineralized groundwater because of groundwater abstraction. Climate change and associated sea level rise are expected to constitute another threat to groundwater quality in coastal areas. Despite real concerns about unsustainable abstraction rates and aquifer pollution in many parts of the world, groundwater development still presents many opportunities and will continue to do so if carefully managed. Nearly all Arab countries can be characterized as water scarcity. The region's non-renewable shared aquifers, or "fossil" aquifers, are being increasingly exploited, and saltwater intrusion from over-pumping groundwater makes a significant challenge to managing coastal aquifers.

An indicator expressing the degree of pressure on renewable groundwater as a consequence of withdrawal is the renewable groundwater development stress indicator (RGDS). It is the ratio of the annual groundwater abstraction from renewable groundwater resources over the mean annual recharge in the area concerned, expressed as a percentage. It will therefore become clear that the numerical value of the RGDS is identical to that of the GDS (groundwater development stress) indicator in those areas where all groundwater withdrawal is from renewable groundwater. Figures 2-4 and 2-5 show the global pattern of the renewable groundwater development indicator and zones of very significant groundwater depletion.

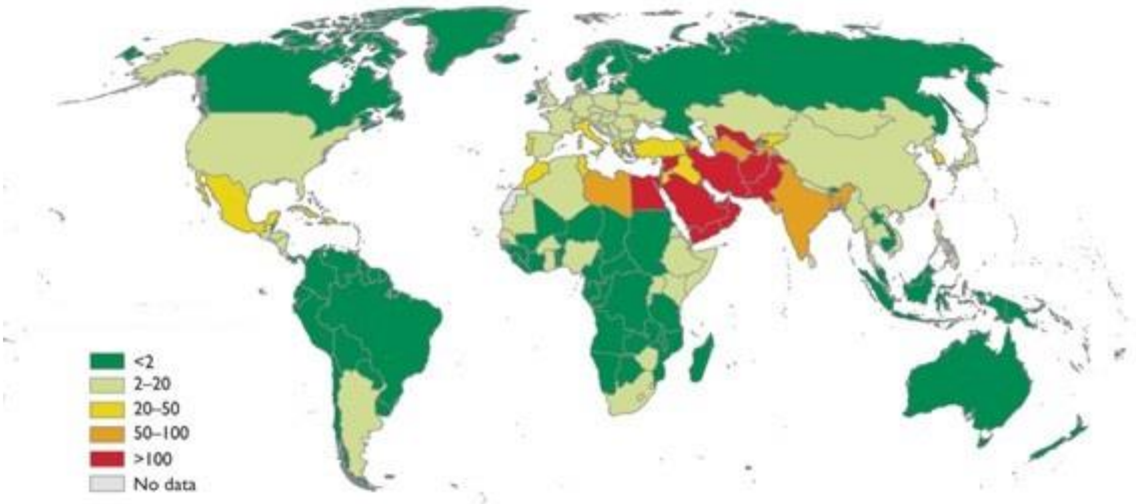

Figure 2-4: Renewable groundwater development stress indicator (Girman, et al., 2007) at country level (RGDS 2010). Lower values of the stress indicator in green areas and higher values in red areas. Illustration from UNESCO/IGRAC (Margat & Van der Gun, 2013).

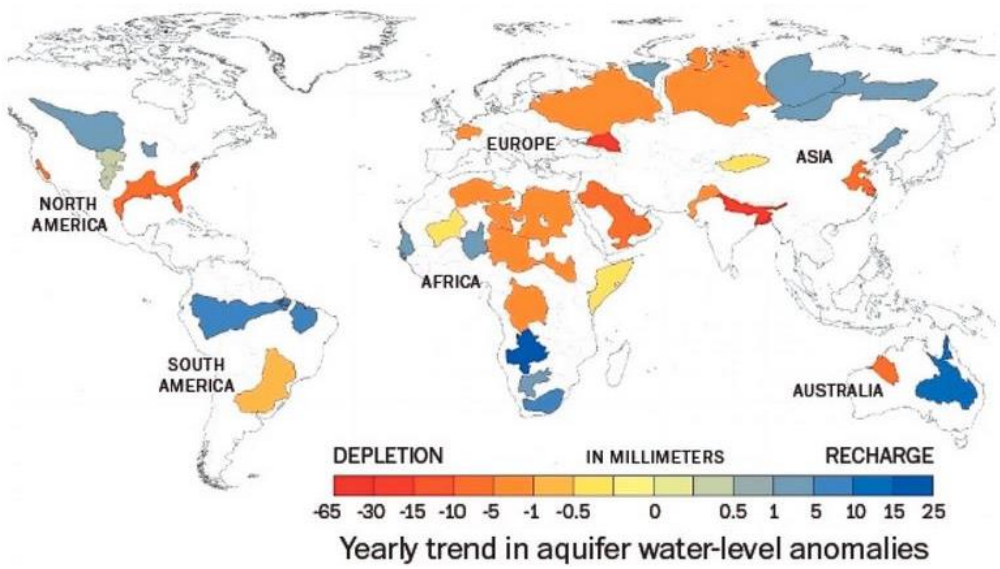

Figure 2-5: Zones of very significant groundwater depletion during the twentieth century due to over-abstracting renewable or mining non-renewable groundwater resources. Illustration from Groundwater Depletion Worldwide (Deep Resources, 2015). Source: Water Resources Research. More than half of Earth's 37 largest aquifers are being depleted, according to gravitational data from the GRACE satellite system.

According to American Geosciences, North America groundwater level declines have been registered in several major aquifer systems (American Geoscience Institute, 2022).

In Southern Europe, groundwater level declines have also been registered, eventually due to precipitation pattern changes (Lobo Ferreira, Leitão, & Oliveira, 2014). This will strongly affect natural groundwater recharge rates. European Union Watershed Management Plans have shown for Southern Europe that for some aquifers, the relationship between current and expected annual average recharge for 2071-2100 is expected to be less than 50% of today´s natural recharge values.

The decline in groundwater levels in southern Europe is due to the influence of climate change on precipitation series and the impact of new, more persistent forms of precipitation. This can lead to large floods and, subsequently, to more extended periods of drought, even if annual precipitation maintains similar average values.

Climatic conditions, such as rain, temperature, and atmospheric humidity, affect the volumes of water used by plants in evapotranspiration and those transferred to recharge aquifers. Under conditions of climate change, hydrological and hydrogeological parameters tend to be modified, directly impacting evapotranspiration (which increases) and recharge (which decreases). Not to forget, changes in the vegetation cover can affect the volumes of evapotranspiration, surface runoff, the water content in the soil and finally, the recharge of aquifers.

2.3 Groundwater quality and the dispersion of pollutants

A chemical or biological material becomes a possible groundwater-polluting agent when introduced into the underground environment. Materials introduced to the surface, such as agricultural fertilizers or effluents from wastewater treatment in the soil, are first subjected to vertical percolation through the unsaturated zone of the soil and only then enter the saturated zone. Materials from other activities can be directly introduced into the saturated zone. For example, those coming from deep wells to reject industrial tributaries are mentioned. Once embedded in the underground system, the materials move in suspension or dissolution, dragged by the flow. The flow network influenced by regional hydrogeological characteristics can also be affected by human activity, for example, exploration, aquifer recharge, or open pit mining activities. The degree of attenuation of the polluting effect of materials included in the underground water system after entering the underground environment depends on the type of contaminant and the type of aquifer flow. The effects that act as pollution retention and attenuation mechanisms can be divided into physical, chemical, and biological effects.

Groundwater pollution is a serious threat to this resource. Recovery from pollution is not easy, as removing pollutants is difficult, meaning that they can accumulate.

2.4 Regional perspective on groundwater resources availability and quality control

Europe´s groundwater making the invisible visible was the World Water Day theme for 22 March 2022. This provided an overview of the state of groundwater in the European Union (EU) (Figures 2-6 and 2-7). Groundwater stores almost one-third of global freshwater resources and, in the 27 EU Member States, supplies 65% of drinking water and 25% of water for agricultural irrigation.

According to Member States' second river basin management plans (2016), 24% of the total groundwater body area was of poor chemical status and 9% of poor quantitative status in the EU-27. A combined assessment of chemical status and quantitative status shows that 29% of the total groundwater body area lacks sufficient capacity to meet the needs of ecosystems and people, owing to deterioration of groundwater quality or quantity. Also, groundwater is under increasing pressure from pollution, abstraction, and climate change.

Pressures will likely increase due to population growth and water demand in a changing climate. While the EU environmental policy framework helps ensure sustainable management of groundwater resources and preserve the natural ecosystems dependent on them, implementing policy provisions needs to be further accelerated. The European Union Water Framework Directive aims to protect inland surface waters, transitional waters, coastal waters, and groundwater. It also aims to achieve specific environmental objectives by implementing programs of measures specified in River Basin Management Plans.

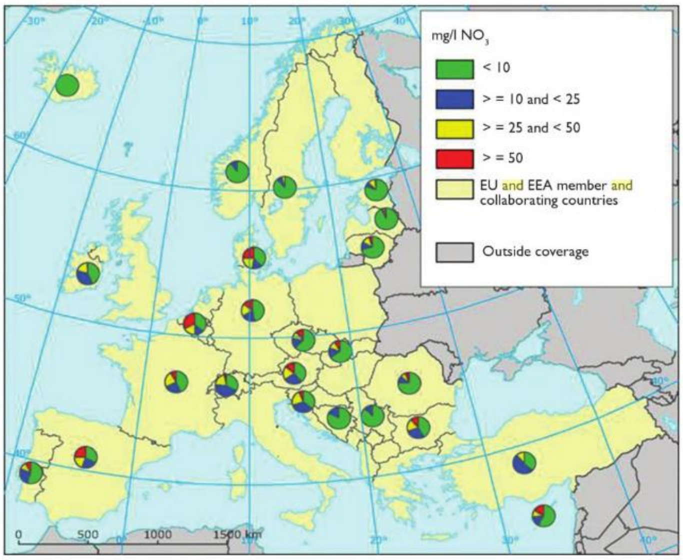

Figure 2-6: Average annual groundwater nitrate concentrations in groundwater, by country and by concentration class. Illustration from European Environmental Agency (EEA, 2010). For an enlarge version of this image click here or scan the QR code.

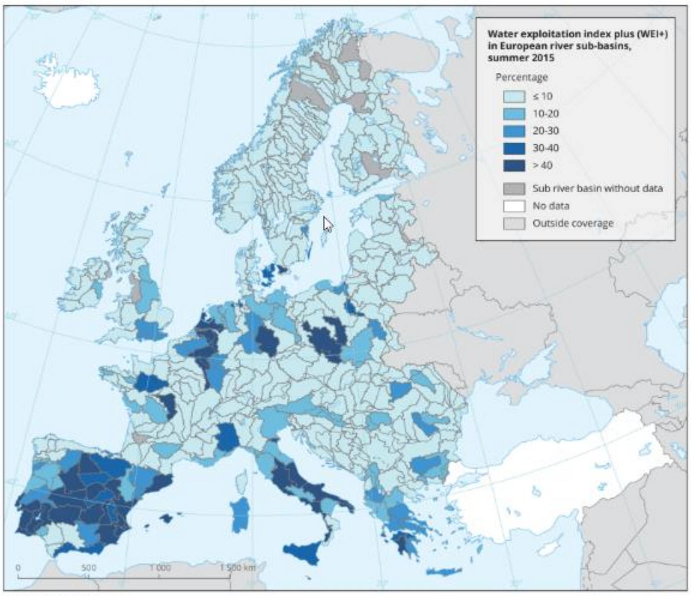

Figure 2-7: Water exploitation index plus (WEI+) in European river sub-basins, summer 2015. Illustration from European Environmental Agency (EEA, 2010). For an enlarge version of this image click here or scan the QR code.

In Asia, groundwater resources are crucial but also a reliable water supply source (Carrard, Foster, & Willetts, 2019). Groundwater overexploitation occurs in many areas of Asia, such as Gujarat, India, North China plain and some area of Pakistan, resulting in groundwater level decline, reduction of well outputs, and seawater intrusion in coastal aquifers, besides land surface subsidence and the movement of polluted waters into the aquifer. In some cases, overexploitation lowered the water table to such a depth that existing wells had to be dismantled. China, India, Japan, Maldives, the Republic of Korea, Sri Lanka, and Thailand are some of the countries facing problems related to excessive groundwater extraction in certain locations (Zaisheng & Hao, 2012).

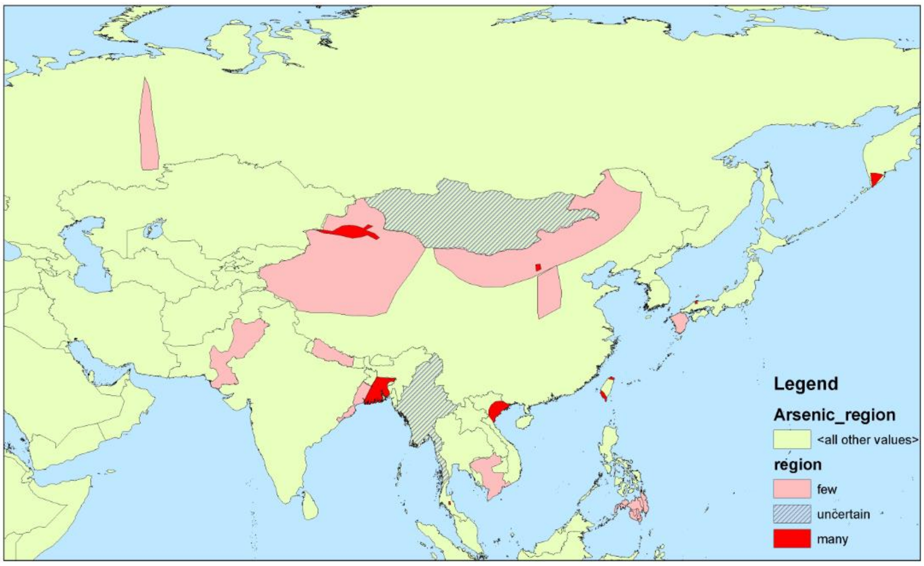

Figure 2-8: Arsenic in groundwater in Asia. Illustration from IGRAC. For an enlarge version of this image click here or scan the QR code.

Han Zaisheng and Wang Hao (China Geological Survey and the China University of Geosciences) mention relevant problems of groundwater quality in Asia related to salt content (in arid and semi-arid Asian regions), saltwater intrusion in coastal aquifers, high levels of arsenic contents in multiple shallow aquifers in Bangladesh and China. Fluoride is a common constituent of groundwater, being endemic in some areas of the northern part of China. Natural sources are connected to various types of rocks and volcanic activity. Agricultural (use of phosphate fertilizers) and industrial activities (clays used in ceramic industries or burning coal) also contribute to high fluoride concentrations in groundwater. The drinking water supply in those groundwater-affected Asian regions must be treated with appropriate methods. High contents of arsenic and fluoride in groundwater are also relevant problems in many other regions of Asia, e.g. high fluoride contents in groundwater have emerged as an important environmental problem in India, Pakistan, Viet Nam and Indonesia (Zaisheng & Hao, 2012).

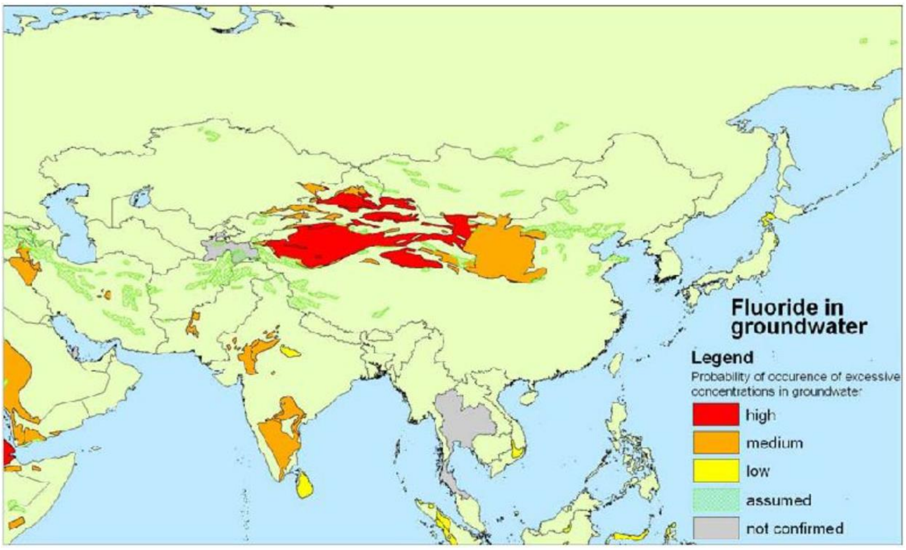

Figure 2-9: Fluorine in groundwater in Asia. Illustration from IGRAC. For an enlarge version of this image click here or scan the QR code.

Groundwater is widely considered an essential source of drinking water in low-income regions. Therefore, it plays a critical role in realizing the human right to water. However, the proportion of households using groundwater compared with other sources is rarely quantified, with national and global datasets more focused on facilities rather than resources used. This is a significant knowledge gap, particularly considering efforts to expand water services in line with the inclusive and integrated agenda of the Sustainable Development Goals. Understanding the prevalence of groundwater reliance for drinking is critical for those involved in water services planning and management, so they can better monitor and advocate for managing water resources that support sustainable services for households. New developments in Asia support the case for governments and development agencies to strengthen engagement with groundwater resource management as foundational for achieving sustainable water services for all. Significant projects have been and still are under development towards groundwater assessment. For example, the "Mapping Groundwater Resilience to Climate Change and Human Development in Asian Cities" project being developed to assess the state of groundwater in major cities. (Groundwater Asia, 2022). The project aims to improve understanding of the impacts of climate change and human development on groundwater resources and local demand. Also, it will address policy recommendations for sustainable groundwater development and management to support adaptation and build resilience. There are four key objectives: to develop a framework for the assessment of the resiliency of groundwater to climate change and human development in urban environment change; to assess the impact of climate change and human development on groundwater recharge and quality of four Asian cities (Bangkok in Thailand, Ho Chi Min City in Vietnam, Lahore in Pakistan and Kathmandu in Nepal); to map resiliency of groundwater of those four Asian cities to climate change and human development; and, to develop evidence-based guidance on assessing how groundwater can support adaptation and build resilience to climate.

In Africa, groundwater resources assessment and quantitative maps have been computed (Figure 2-10). The total groundwater volume in Africa is estimated to be 0.66 million km^3 with a range in uncertainty of between 0.36 and 1.75 million km^3. Only some groundwater volume estimated by the aquifers' saturated thickness and effective porosity is, however, available to be abstracted.

Figure 2-10: Hydrogeological map of Africa showing estimated groundwater recharge, from less than 5 mm/year (in yellow) to more than 500 mm/year (in blue). Illustration from BRGM, the French geological survey (BRGM, 2022). For an enlarge version of this image click here or scan the QR code.

Groundwater is one of Australia's most important natural resources. It is a major water source for urban areas, agriculture, and industry. It is used throughout the country and, for many regions, is the only source of water available -numerous townships, farms, and mines are reliant on groundwater-. The Hydrogeology Map of Australia (Jacobson & Lau, 2022) defines the sedimentary basins and fractured rock provinces that make up Australia's regional hydrogeological divisions. These hydrogeological provinces have been further classified according to whether they are a fractured rock or sedimentary basin, the distribution of aquifers within the province and the productivity of the aquifer. The Great Artesian Basin covers one-fifth of the continent. Although it gives a broad national overview of Australia's major groundwater resources, Figure 2-11 does not show the many other crucial groundwater resources that occur over smaller areas and are equally important for sustaining communities, agriculture, and the Australian economy.

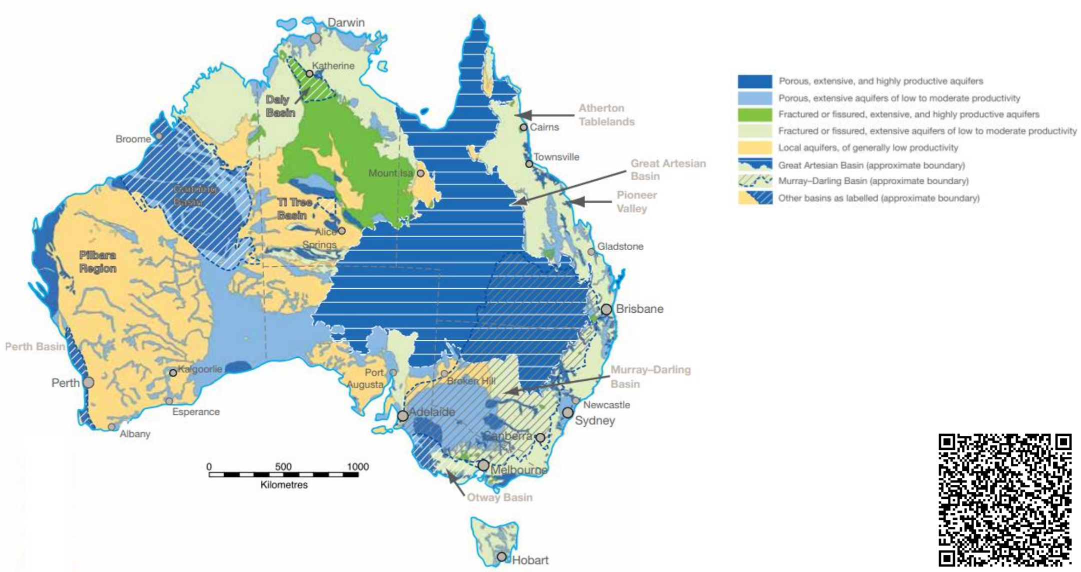

Figure 2-11: Map of Australia's groundwater resources, showing generalized hydrogeology and the locations of some iconic groundwater basins. Illustration from National Centre for Groundwater Research and Training Australia (Harrington & Cook, 2014). For an enlarge version of this image click here or scan the QR code and refer to page 5.

Figure 2-12 presents a map of North America Groundwater Resources produced by BGR & UNESCO (BGR-UNESCO, 2022). For North America, groundwater is an essential drinking and irrigation water source. In the United States, even 60% of all water used for irrigation comes from groundwater resources. This dependency on groundwater, however, comes with its risks as well. Longer periods of extreme droughts, combined with increasing water demand, can lead to overexploitation and, eventually, depletion of aquifers. A recent example is the California drought affecting the High Plains and the California Central Valley aquifers. Natural Resources Canada also worked closely with the U.S. Geological Survey and the international community to develop the WaterML2 data standards and best practices, including GroundwaterWML2 (Open Geospatial Consortium, 2022). Combined with the adoption of other data access standards and technologies from the Open Geospatial Consortium, this has resulted in the ability to seamlessly retrieve groundwater level data from either the Groundwater Information Network or the National Groundwater Monitoring Network of the United States (Brodaric, Booth, Boisvert, & Lucido, 2016).

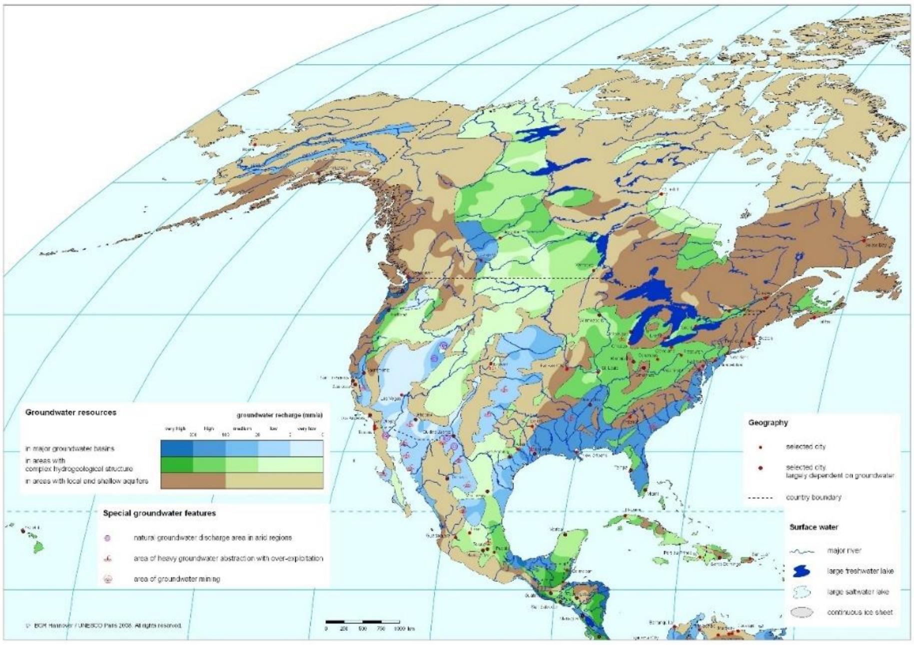

Figure 2-12: Groundwater resources map of North America. Illustration from World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) (BGR-UNESCO, 2022). For an enlarge version of this image click here or scan the QR code.

Groundwater resources in South America (Figure 2-13) have been addressed by many authors, e.g. by Aldo da C. Rebouças. Reliance on groundwater has significantly increased in South America over the past 20 years, partly as a response to the growing costs and other constraints in storing and treating surface water and partly because the economic advantages of groundwater use are now better understood. Nevertheless, groundwater withdrawn from aquifers (taken for use) is difficult to estimate because most come from uncontrolled private and public wells. The vulnerability of groundwater to overexploitation and water quality degradation was not widely understood until recently. Moreover, the difference between the nature of groundwater and surface water prevents the direct transfer of experience gained in managing transboundary rivers and lakes to managing transboundary groundwater basins. In South America, as in almost all parts of the world, people must realize they can no longer follow the philosophy of using and discarding water. This approach is not merely another alternative for many urban areas but the only one available.

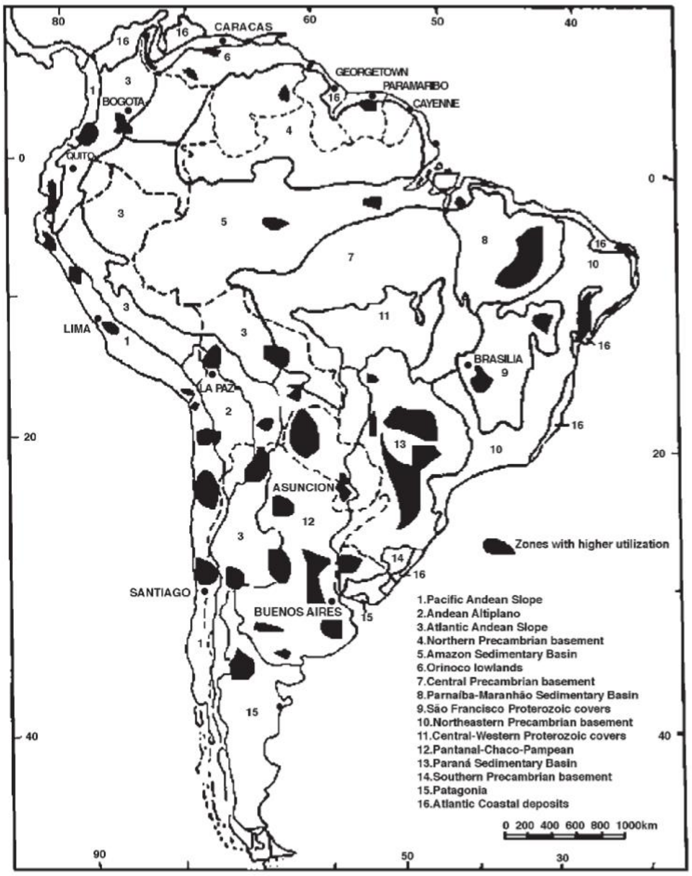

Figure 2-13: South America — Hydrogeological provinces and zones with higher utilization of groundwater. Illustration from Groundwater resources in South America (Rebouças, 1999). For an enlarge version of this image click here or scan the QR code.

2.5 Conclusions

The global volume of liquid freshwater is estimated to be 10.6 million km³. Approximately 99% of this consists of groundwater (Shiklomanov & Rodda, 2004). Freshwater withdrawal from streams, lakes, aquifers, and human-made reservoirs has increased enormously during the last century and is still growing in most parts of the world. The rate of increase was significantly high (around 3% per year) during 1950–1980, partly due to a higher population growth rate and somewhat rapidly increasing groundwater development, particularly for irrigation. The increase rate is approximately 1% per year, in tune with the current population growth rate. Groundwater supplies about 25% of all freshwater abstracted on Earth, but its share in consumptive water use is much higher, as are the overall benefits it provides. The United Nations World Water Development Report 2022 (Groundwater: making the invisible visible) mentions that the total global groundwater withdrawal during 2017 is estimated at 959 km³ (United Nations, 2022). Groundwater withdrawal rates have more or less stabilized in the United States of America, most European countries and China. Asia has the largest share in global freshwater withdrawal (64.5%). It is followed by North America (15.5%), Europe (7.1%), Africa (6.7%), South America (5.4%) and Australia & Oceania (0.7%). A breakdown of groundwater withdrawal by water use sector shows that 69% of the total volume is abstracted for use in the agricultural sector, 22% for domestic uses, and 9% for industrial purposes. These percentages vary between the continents.

Coastal aquifers are a critical resource of fresh water whose quality has declined due to the increase in water needs, a direct consequence of urban, industrial, and agricultural accelerated development (Lobo Ferreira & Oliveira, 2004). Intensive and prolonged exploration in abstractions very close to the sea, where there is no source of compensation for these extractions by natural or managed aquifer recharge of the aquifer, causes the advancement of the freshwater-saltwater interface towards the wells and their subsequent contamination.

As the variability and some negative impacts of climate change are rapidly increasing, both in scale and intensity, it becomes important to foster "innovation in water action", incorporating permanent and appropriate "technological solutions" to hydrogeological and climate change. The aim is to increase water availability for critical economic sectors, improve human health and well-being, and increase the sustainability of ecosystems and biodiversity. One of these solutions is promoting aquifer recharge management (MAR), a technically robust, safe, and sustainable alternative. In this context, the selection of the project MARSOL (Marsol, 2022) by the European Commission Horizon 2020 Research Programme was because MAR has become one of the best technical solutions for modern integrated management of Water Resources, aimed at mitigating the negative impacts of Climate Change.

Recent research on groundwater recharge demonstrates the influence of precipitation distribution series on natural groundwater recharge. Climate change scenarios point to an increase in the number of extreme events and a worsening of these events, more and worse droughts and flood. All these issues should be addressed in more detail by carrying out specific studies in different aquifers to obtain more support for future decision-making.

3 Sustainable development goals and groundwater

Ignacio González-Castelao

Water is one of the most important natural resources for life, the formation of different landscapes and ecosystems, and development. Therefore, only effective and efficient management of this resource can make it possible to achieve the goals of the three dimensions of sustainable development (social, environmental, and economic).

Figure 3-1: Relationship between Sustainable Development Goals and Dimensions. Illustration prepared by the author, based on information published by UN-Water (UN-Water, 2016).

Sustainable Development Goal 6 “Water and sanitation” (SDG 6) is interlinked with the entire 2030 agenda. The linkages between this SDG and the other SDGs can produce positive synergies and generate conflicts. However, most of the relationships of SDG 6 with the rest of the SDGs are positive because achieving its targets makes it possible to reach those of the other goals.

How these linkages interact is not static but can vary between regions, countries, or even from one river basin to another.

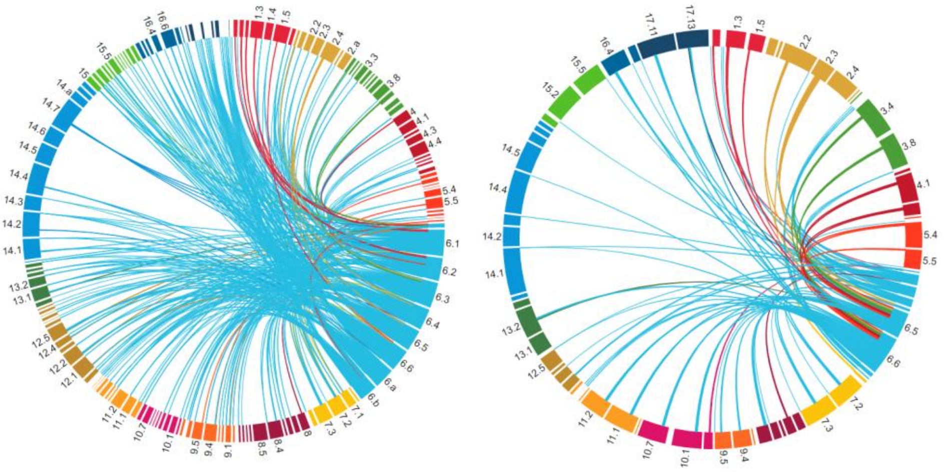

Figure 3-2: SDG 6 interlinkages with the rest of the SDGs. Synergies (left image) and trade-offs (right image). Illustration from KnowSDGs Platform (European Commission, 2022). For an enlarge version of this image click here or scan the QR code and select goal 6 (Synergies/Trade-offs).

Integrated planning and management of water resources and territory are the meeting point for these relationships between the different objectives and goals and the framework for resolving potential conflicts through all stakeholders' participation.

Surprisingly, groundwater, which accounts for most of the planet's freshwater and is the source of supply most used by rural populations, rapidly growing cities, for agricultural irrigation and in industry, has so little relevance in the SDGs.

As the International Groundwater Resources Assessment Center (IGRAC) has rightly pointed out, groundwater should be considered an integral component for providing universal access to safe drinking water in the context of the SDGs and not as a "last resort" resource (Conti, 2015).

Groundwater has a much more significant role in achieving UN's Sustainable Development Goals than shown in the SDGs themselves (Global Groundwater Statement, 2022). It is not only engaged in ensuring safe drinking water and sanitation for all (SDG 6) but also has a crucial direct (climate, energy, food, health, hygiene, ecosystems, and biodiversity) and indirect (poverty reduction and inequalities, education, gender equity, and peace) contribution to most of the goals and targets (IGRAC, 2022).

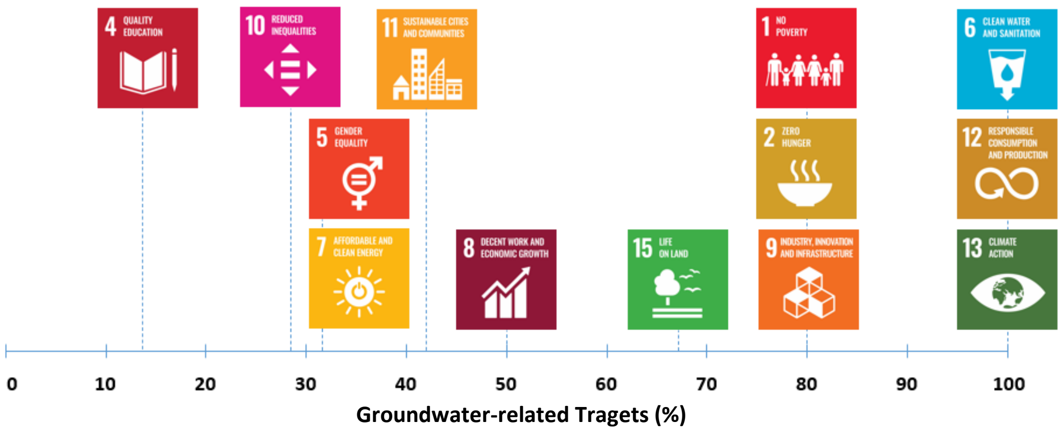

Figure 3-3: Percentage of groundwater-related targets per SDG. Illustration prepared by the author, based on information published by UNU-INWEH (Guppy, Uyttendaele, Villholth, & Smakhtin, 2018).

Groundwater is related to a greater or lesser extent with fourteen SDGs. However, there are three goals that all its targets are related to groundwater (SDG 6 -clean water and sanitation-, SDG -12 responsible consumption and production-, and SDG 13 -climate action-). Also, there are three SDGs to which this resource is not related under the current target-setting framework: SDG 14 (life bellow water), SDG 16 (peace, justice, and strong institutions) and SDG-7 (affordable and clean energy). However, this does not mean that they are unrelated. Although the indicators established to measure the targets do not consider groundwater, out of the 169 targets, there are 53 that have an explicit or thematic interrelation with this resource, having a direct link with 23 of them (Guppy, Uyttendaele, Villholth, & Smakhtin, 2018).

Figure 3-4: SDG Targets that have a direct link with groundwater. The colored circle in the Target logo indicates the type of interlinkage: reinforcing (green), mixed (yellow) and conflicting (red). Illustration prepared by the author, based on information published by UNU-INWEH (Guppy, Uyttendaele, Villholth, & Smakhtin, 2018).

Next, the links between groundwater and these 23 targets are described, although indirect relationships include more targets and other SDGs.

As is the case between SDG 6 and the other SDGs, most of the linkages are positive synergies, with very few conflicts.

The most visible direct links are with the SDG 6 targets, but only one of the eight SDG 6 targets explicitly refers to groundwater. It is “6.6 - by 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lake”. However, none of the indicators explicitly refer to groundwater.

Target 6.1 (safe and affordable drinking water) and target 6.5 (implement integrated water resources management) can only be achieved with groundwater resource development and proper management. Most of the world's population in rural and urban areas depends on groundwater exclusively or in conjunction with surface water, especially in arid and semi-arid regions.

There is a close relationship between drinking water availability, groundwater quality and sanitation/wastewater management. This relationship involves targets 6.2 (end open defecation and provide access to sanitation and hygiene), 6.3 (improve water quality, wastewater treatment and safe reuse) and 6.4 (increase water-use efficiency and ensure freshwater supplies). Access to sanitation and hygiene cannot be achieved at the expense of groundwater quality, as it happens in rural and peri-urban areas, where this problem is more pronounced.

Groundwater contamination can come not only from sanitation and untreated wastewater management but also from irrigation returns and chemical, industrial, mining, or pharmaceutical pollutants present in a variety of waters, which are of increasing concern. The protection of groundwater bodies is essential to prevent their deterioration, which can be seen as a form of groundwater depletion (Conti, 2015). Therefore, achieving target 12.4 (responsible management and use of natural resources) is crucial.

Groundwater management must go beyond mere combined management with surface water. Integrated management of all water resources must be carried out by incorporating non-conventional resources if target 6.5 (implement integrated resources management) wants to be achieved. But going further into integrated management, it should also be multisectoral, including soil and land management (chapter five provides a more detailed explanation of how this integrated resource management should be). Before management and for good decision-making, it is necessary to have data on this resource, information that is often difficult and expensive to obtain (more resources are needed). An example of this need is that monitoring several SDG 6 targets, such as 6.3 (improve water quality, wastewater treatment and safe reuse), indicates that the estimation is based on data from less than half of all countries, many of which come from a relatively small number of measurements (UN-Water, 2022).

Governance usually prioritizes supply-side groundwater management. Still, it is essential that the demand side implements efficiency measures in the use of this resource to reduce its consumption, avoiding overexploitation of aquifers and associated ecosystems (Target 6.4 - increase water-use efficiency and ensure freshwater supplies-).

Groundwater depletion and degradation is an increasingly pressing problem in many parts of the world. Water must be protected at its source, as well as the ecosystems that depend on it (Target 15.1 -conserve and restore terrestrial and freshwater ecosystems-), especially those that depend on groundwater (6.6 -protect and restore water-related ecosystems-), such as springs, wetlands, rivers, lakes, lagoons, and estuaries.

Ensuring access to basic services (drinking water) for all men and women, particularly the poor and vulnerable (Target 1.4 -equal rights to ownership, basic services, technology, and economic resources-), is an issue that can only achieve by considering water withdrawal from aquifers, as Target 11.1 (safe and affordable housing -including basic services-) more focused on the urban population. Unequal access to groundwater is often linked to land ownership and control. Groundwater systems are more resilient to extreme weather events and other types of catastrophes than surface water, so guaranteeing access to this resource for vulnerable sectors is a priority from a social perspective (Target 1.5 -build resilience to environmental, economic, and social disasters-).

World population growth and our consumption patterns make increased food, fodder and fiber production inevitable. To meet the growing demand for food, it is estimated that the irrigated area will have to increase by 17% by 2050 (Bruinsma, 2009). Currently, 70% of the world's water demand is for agriculture, and 43% of irrigation water comes from groundwater (Siebert, et al., 2010). This percentage is higher in arid and semi-arid areas. In this scenario, groundwater is fundamental in meeting Target 2.1 (universal access to safe and nutritious food). However, it should not be forgotten that increased irrigation can decrease the quantity and quality of aquifers (due to the leaching of nutrients and pesticides and salinization). To avoid these problems, it is crucial to increase agricultural productivity in water consumption (Target 2.3 -double the productivity and incomes of small-scale food producers-). Increase in food needs must be carried out differently from what has been done so far in some countries; it must be done in a way that is sustainable for the environment and ecosystems (Target 2.4 -sustainable food production and resilient agricultural practices-). For this, it is essential to achieve disruptive breakthroughs that make it possible to decouple development from environmental degradation (Target 8.4 -improve resource efficiency in consumption and production-). If this does not occur, the growing need for food will increase pressure on groundwater.

Ensure universal access to affordable, reliable, and modern energy services (Target 7.1 -universal access to modern energy-) may generate conflicts with groundwater as the extraction and processing of fossil fuels may present a risk of groundwater contamination. Also, the increase in biofuel cultivation means an increase in groundwater withdrawals. The use of renewable energies, such as solar energy, can reduce this problem, but it is also true that energy is necessary to extract, treat and distribute water from aquifers. There is no doubt that the water-energy-food nexus is a challenge in the field of groundwater.

The development of many cities has yet to be achieved with adequate urban planning, largely due to the rapid growth of an urban population with ever-increasing needs. This lack of planning causes, in addition to environmental degradation, a decrease in water infiltration (impermeabilization of land), subsidence phenomena (increased water withdrawals), groundwater contamination (untreated wastewater discharges, poor condition/inefficient drainage systems) and salinization of aquifers in the case of coastal cities. This problem is more severe in densely populated informal urban settlement areas, where infrastructure and urban services are inadequate (Guppy, Uyttendaele, Villholth, & Smakhtin, 2018). Achieving Targets 11.3 (inclusive and sustainable urbanization) and 11.6 (reduce the environmental impact of cities) will preserve groundwater resources in these areas.

Integrated water resources management makes it possible to balance water supply and demand. However, efficient, and sustainable management of water extraction and use must be promoted on both sides (Target 6.4 -increase water-use efficiency and ensure freshwater supplies- and 12.2 -sustainable management and use of natural resources-). Groundwater is used in all sectors, and in all of them, there is a wide range of improvements in the efficiency of the resource, such as hi-tech irrigation systems in agriculture, water reuse, etc.

Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters in all countries (Target 13.1) is related to groundwater from a double perspective. On the one hand, aquifers are a buffer during droughts, allowing water to be available during these periods. On the other hand, they can be positively and negatively affected by floods (increased recharge and greater probability of contamination).

Changes in land cover have a major influence on aquifer recharge and water quality. Variations in forest cover affect both the quantity (infiltration) and quality (increased acidification and nitrification) of groundwater. Therefore, promoting sustainable management of all types of forests, halting deforestation, restoring degraded forests, and substantially increasing afforestation and reforestation globally (Target 15.2) should consider groundwater. The spread of invasive species can also reduce aquifer recharge rates as these new species tend to have higher evapotranspiration rates than indigenous species (Guppy, Uyttendaele, Villholth, & Smakhtin, 2018). Measures must, therefore, also be taken to prevent the introduction of new species or reduce their impact (Target 15.8 – prevent invasive alien species on land and in water ecosystems).

As stated previously, water must be protected at its source, so the conservation of mountain ecosystems (Target 15.4 -ensure the conservation of mountain ecosystems-) is relevant to the preservation of springs.

As described in this chapter, groundwater is directly or indirectly interlinked to many of the sustainable development goals and meeting their targets cannot be achieved without adequate groundwater management. This management should consider surface water and non-conventional resources and be multi-sectoral, including soil and land. Given the importance of groundwater, it is surprising how poorly it is considered in sustainable development goals. Groundwater is invisible, as it is to the SDGs.

The World Federation of Engineering Organizations (WFEO) has various committees and working groups committed to the responsibility of action that engineers have, both personally and professionally, to achieve the Sustainable Development Goals. This commitment is reflected in the document "WFEO Engineering 2030. A Plan to advance the achievement of the UN Sustainable Development Goals through engineering” (World Federation of Engineering Organizations; Division of Science Policy and Capacity Building - Natural Sciences Sector, 2018).

On the occasion of the World Engineering Day for Sustainable Development 2021, WFEO participated in the UNESCO report "Engineering for Sustainable Development" (United Nations Educational, Scientific and Cultural Organization, and International Center for Engineering Education, 2021).

4 Groundwater and climate change

Ignacio González-Castelao

Climate is the set of atmospheric conditions that characterize a region, with the water cycle being an essential part of it and a climatic connector. Water is part of climate and, therefore, of its change; thus, there is an overlap between water and climate challenges. Groundwater is influenced by climate change since it is part of the water cycle, although its relationship differs from surface water systems.

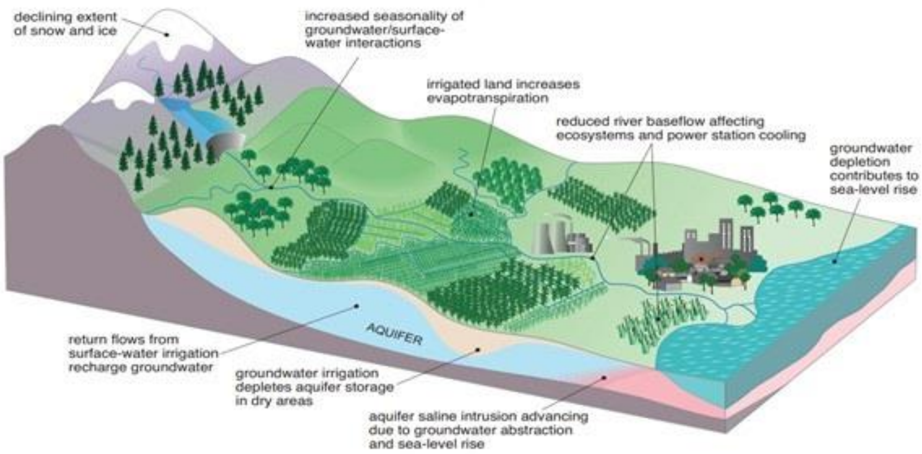

Figure 4-1: Conceptual representation of main interactions between climate change and groundwater. Illustration from International Association of Hydrogeologists (Foster & Tyson, 2016). For an enlarge version of this image click here or scan the QR code and refer to page 2.

Based on existing evidence, it is likely that human influence has impacted the global water cycle since 1960 (Stocker, et al., 2013). This has resulted in rates of natural climate change occurring faster (about ten times faster) than in the past (Foster & Tyson, Strategic Overview Series. Climate-Change Adaptation & Groundwater, 2019).

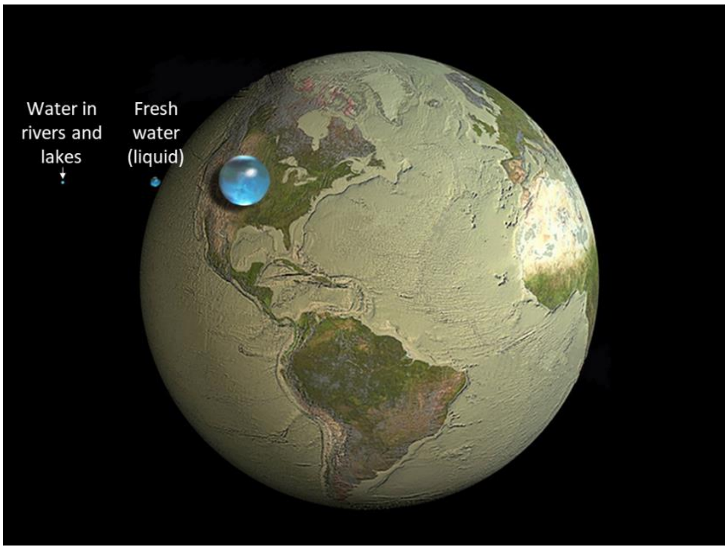

Figure 4-2: The blue spheres represent the relative amounts of terrestrial water compared to Earth's size. The largest sphere's volume represents the total water in, on, and above the Earth (1,385 km diameter). The freshwater (liquid) sphere represents groundwater, swamps, rivers, and lakes (272.8 km diameter). The smaller sphere represents water from rivers and lakes (56.2 km diameter). Image-based on an illustration from the U. S. Geological Survey (Perlman, Cook, Hole, Woods, & Nieman., 2016).

Although the total amount of water (the sum of solid, liquid, and gaseous states) has remained constant over millions of years, climate change will alter its current distribution in physical, qualitative, spatial, and temporal terms.

The earth has been warming due to an increased energy balance (incoming energy minus outgoing energy). The heat added to the planet has been absorbed by the oceans (93% considering the entire ocean depth and about 64% considering only the upper layer -0 to 700 m-), ice melting (3%), continental warming (3%) and atmospheric warming (1%).

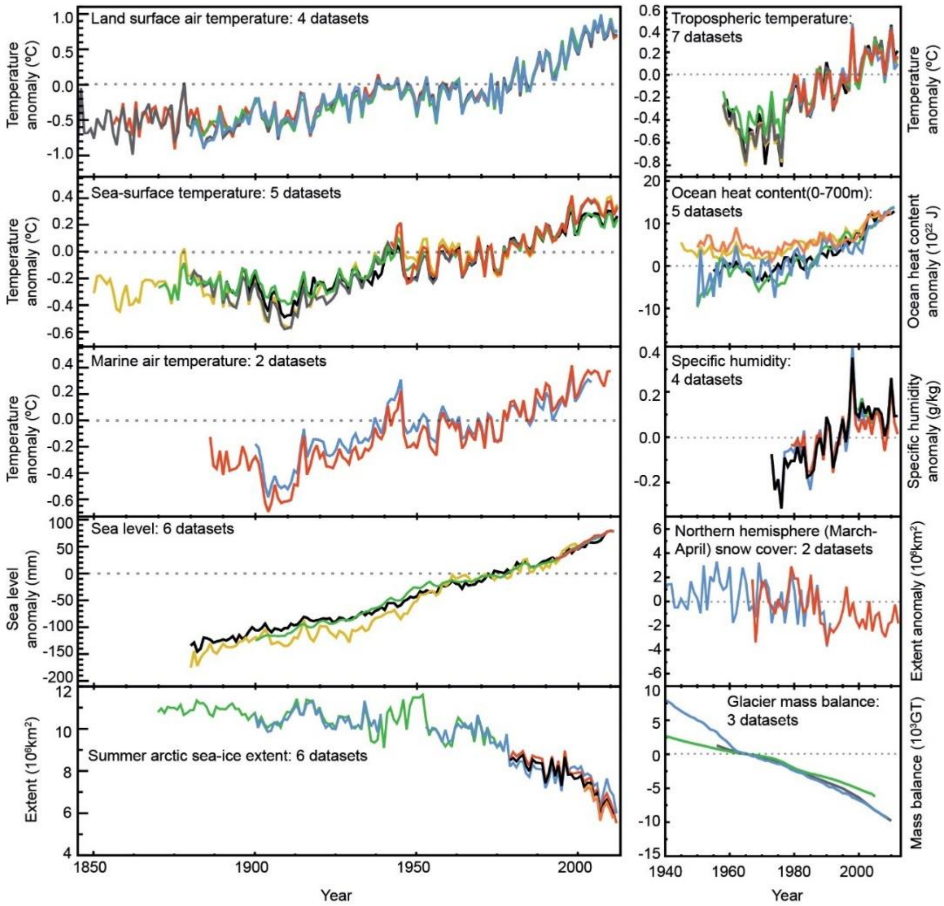

Figure 4-3: Indicators of a changing global climate. Illustration from IPCC 2013 report (Stocker, et al., 2013). For an enlarge version of this image click here or scan the QR code and refer to Figure TS.1.

This has caused the Earth's surface's global average temperature to increase since the end of the 19th century, 0.89 ^{o}C during the period 1901-2012. The area of the atmosphere where meteorological and climatic processes occur (troposphere) has also warmed, producing an increase in the water vapor in it. Specific humidity has increased both over land and over the oceans. The atmosphere can hold about 7% more water vapor with each additional degree of air temperature. Considering this, the predicted increase in the average amount of water vapor in the atmosphere is between 5% and 25% by the end of the 21st century (Stocker, et al., 2013).

Higher temperatures will raise atmospheric humidity and lead to an increase in global precipitation in the long term. This increase will be between 1 to 3% for every ^{o}C century (Stocker, et al., 2013).

Precipitations will generally be more intense and frequent, with significant spatial variation. Generating more floods in those areas where rainfall is expected to increase or where the average precipitation does not change but occurs in more concentrated episodes; however, there will be longer dry periods between rainfall events, leading to more droughts.

Figure 4-4: "Likely range" projections of global mean surface air temperature and global mean sea level rise for the mid (2046-2065) and late (2081-2100) 21st century, relative to the 1986-2005 reference period. Graph prepared by the author, based on data from the IPCC 2013 report (Stocker, et al., 2013).

As the main mechanism of aquifer recharge is precipitation, a priori, an increase in rainfall could increase the overall groundwater storage.

According to the results of several studies, recharge will increase by 2% on average globally by the 2050s. Less than the projected increases of 4% and 9% for annual precipitation and runoff (Clifton, et al., 2010).

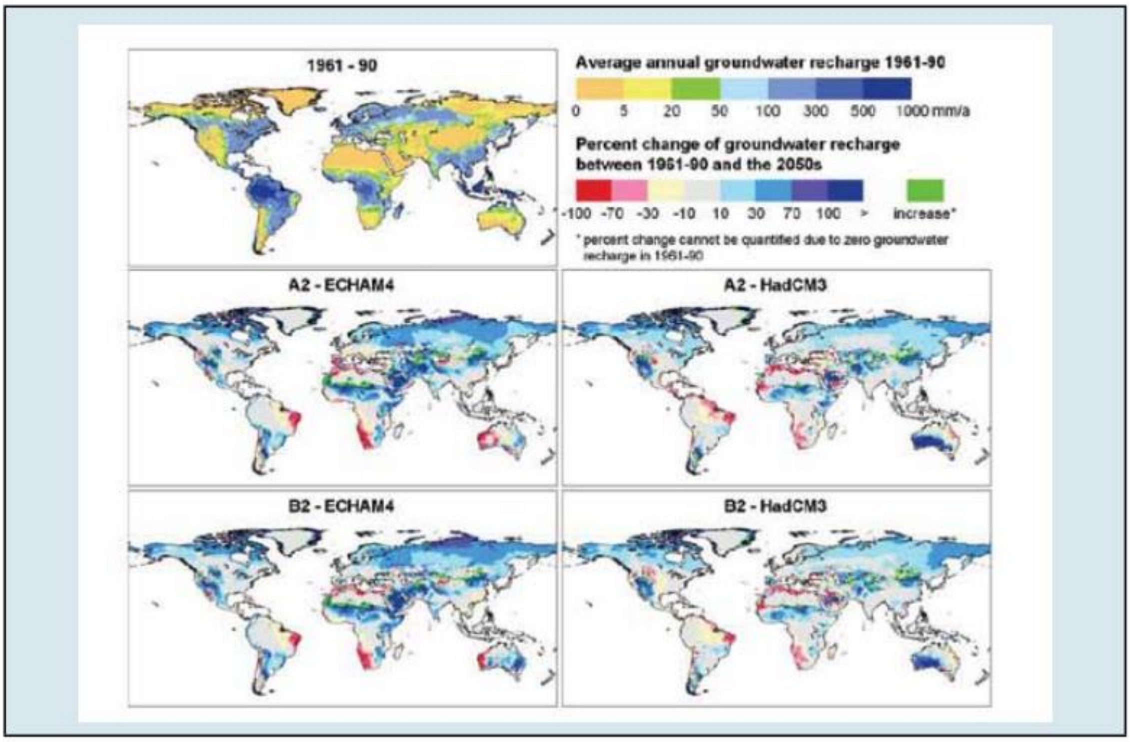

Figure 4-5: Global Estimates of Climate Change Impact on Groundwater Recharge. Impact of climate change on long-term average annual diffuse groundwater recharge. Percent changes of 30-year averages groundwater recharge between 1961–1990 and the 2050s (2041–2070), as computed by WaterGAP Global Hydrology Model (WGHM) applying four different climate change scenarios (climate scenarios computed by the climate models ECHAM4 and HadCM3, each interpreting the two IPCC greenhouse gas emissions. Illustration from Water Working Notes - World Bank Group (Clifton, et al., 2010).

Figure 4-5 shows regions most vulnerable to climate change, but existing uncertainties do not make it possible to scale up to a country or basin scale.

The global effects of climate change on aquifer recharge under different climatic conditions are indicated in Table 4-1.

High latitude regions	Temperate region	Arid and semi-arid regions
Recharge may occur earlier due to warmer winter temperatures, shifting the spring melt from spring toward winter. In areas where permafrost thaws due to increased temperatures, increased recharge is likely to occur.	Changes to annual recharge will vary depending on climate and other local conditions. In some cases, little change may be observed in annual recharge, however, the difference between summer and winter recharge may increase	In many already water-stressed arid and semi-arid areas, groundwater recharge is likely to decrease. However, where heavy rainfalls and floods are primary recharge sources, an increase in recharge may be expected. E.g., alluvial aquifers where recharge occurs via stream channels or bedrock aquifers where recharge occurs via direct infiltration of rainfall through fractures or dissolution channels.

Table 4-1: Summary of climate change impacts on recharge under different climatic conditions. Source: Water Working Notes - World Bank Group (Clifton, et al., 2010).

In mountainous areas, not only precipitation helps to recharge aquifers, but water infiltration from glaciers and snow melt plays an important role. The increase in temperature affects the melting of snow and ice, which decreases recharge in spring due to the shortening of the snowmelt season. Groundwater may provide some resilience to loss of meltwater from glacier and snow decline, but in the longer-term, groundwater recharge and contribution to streamflow is expected to decrease with ongoing climate change (medium confidence) (Somers & Mckenzie, 2020). However, the effects of climate change on aquifers in mountainous areas need to be more understood. (Working Group II - IPCC, 2022).

As previously mentioned, precipitation is the main climatic driver of groundwater recharge (diffuse recharge). Still, this recharge is influenced by the magnitude of precipitation and its intensity, seasonality, frequency, and type.

But there are other non-climatic factors affecting recharge that cause wetter climatic conditions to not systematically result in greater groundwater recharge in the same proportion or direction as changes in precipitation. These are geological environment, topographic relief, specific aquifer properties, size and type, land use and cover (vegetation), and soil type, among others. Some of these non-climatic factors or characteristics are intrinsic to the location. Still, others can be subject to human-made changes (growth in the global population, food demand -which drives irrigated agriculture-, land use change, and socio-economic factors). These factors are responsible for the difference between the effects of climate change on groundwater and surface water systems. All this adds additional complexity to assessing the effects of climate change on groundwater, thus increasing the degree of uncertainty in predictions.

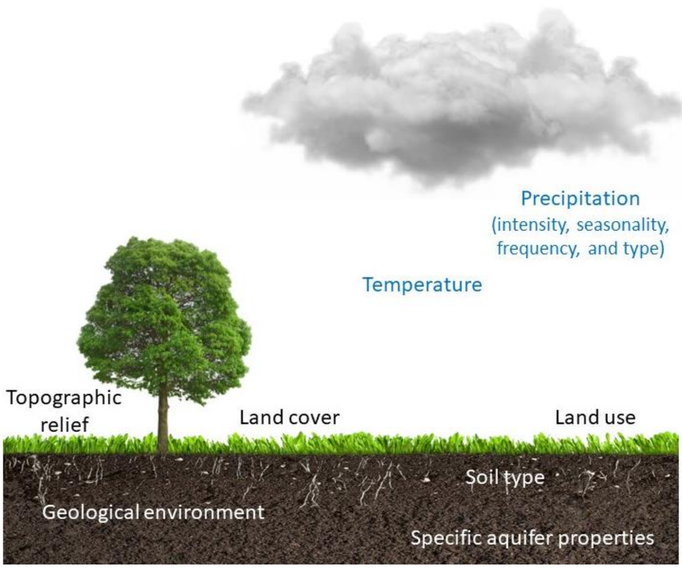

Figure 4-6: Main climatic (in blue) and non-climatic factors affecting aquifer recharge. Non-climatic factors cause wetter climatic conditions to not systematically result in increased groundwater recharge in the same proportion or direction as changes in precipitation. Some non-climatic factors can be subject to human-made change. In coastal areas, rising sea levels should also be considered a factor. Illustration prepared by the author.

All this means that the ratio between groundwater change and precipitation is not 1:1. According to some local studies (Figure 4-7), these ratios can vary between -0.8 and +0.6 or between 0 and +0.87 (Clifton, et al., 2010).

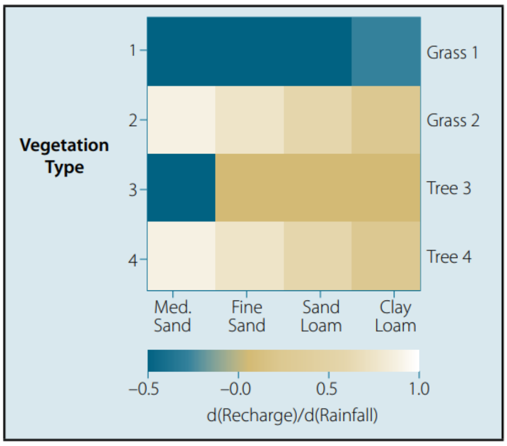

Figure 4-7: Simulated Change in Recharge per Unit Change in Rainfall under a Double-CO2 climate change Scenario in Western Australia. Grasses 1 and 2 represent perennial grasses, and Trees 1 and 2 represent pine and eucalypt canopies. Illustration from Water and Climate Change: Impacts on groundwater resources and adaptation options (Clifton, et al., 2010)

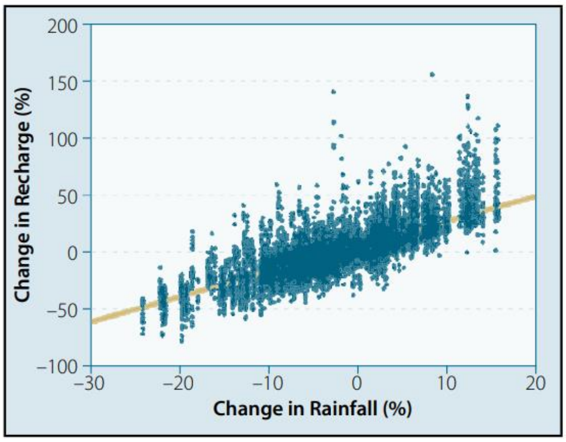

Figure 4-8: Change in Rainfall Versus Change in Recharge for Murray Darling Basin, Australia. Illustration from Water and Climate Change: Impacts on groundwater resources and adaptation options (Clifton, et al., 2010).

Studies of a semi-arid basin in Africa concluded that a 15% reduction in rainfall could lead to a 45% reduction in groundwater recharge (Sandstorm, 1995). In the Murray Darling Basin (Figure 4-8), Australia, studies also concluded that the percentage change in groundwater recharge was greater than the percentage change in rainfall by a factor of approximately 2.2 (Green, Charles, Bates, & Fleming, 1997). In addition, even when there is no change in rainfall, the increase in temperature causes an increase in the vapor pressure deficit, which results in an increase in evapotranspiration and hence a decrease in recharge (Crosbie, McCallum, Walker, & Chiew, 2010). The decline in recharge manifests as a reduction in stream discharge and, therefore, in streamflow.

Fewer but more intense rainfall events can decrease soil moisture. They can lead to soil erosion and gullying or compaction of soils, decreasing infiltration capacity and groundwater recharge, thus increasing runoff and surface flow. Also, floods or intense and prolonged rainfall can reduce the quality of infiltrated water into aquifers by carrying a greater pollutant load.

Increased soil moisture deficit caused by droughts can lead to soil crusting and the generation of hydrophobic soils, which increases surface flows (overland flows) and decreases aquifer recharge in future precipitation events (Clifton, et al., 2010). Also, more extended dry periods between rainfall events result in shorter recharge periods.

Climate change also indirectly affects aquifers as human populations depend on groundwater systems for their livelihoods under unfavorable climatic conditions. If there is no alternative to groundwater, droughts' increased duration and frequency will intensify the search for new or deeper aquifers. These increase the security of the water supply by providing a "natural buffer" against surface water variability, thus making groundwater an adaptation measure to climate change. In addition, droughts increase the risks of disease, effects nutrition, and cause inadequate sanitation that will impact groundwater. This situation will be more pronounced in areas of high-water demand, such as rapidly growing cities, due to high urbanization ratios or high population increases or to maintain current development (food production during drought, etc.).

Rising temperatures affect groundwater due to the increase in global average precipitation and lead to evapotranspiration changes. The evapotranspiration increase affects aquifer recharge, especially in arid and semi-arid areas where it can also lead to groundwater salinization. Land cover loss leads to reduced rainfall interception and infiltration and increased runoff (Clifton, et al., 2010).

Forests influence the water cycle at local, regional, and global scales reducing surface runoff, increasing infiltration to groundwater, and improving water quality (Working Group II - IPCC, 2022).

The land cover change affects evapotranspiration and precipitation, rainfall interception by vegetation canopies, infiltration, and runoff. Land cover impacts on the hydrological cycle are similar to human water use (Working Group II - IPCC, 2022). Land uses strongly influence groundwater quality.

Sea level rise due to climate change is mainly due to seawater's expansion and ice melting. But, to a lesser extent, groundwater withdrawals indirectly contribute to global sea level rise as water transfers from long-term terrestrial storage to circulation in the surface hydrosphere. Recent estimates range up to 0.6 mm/a, with a value of 0.3 mm/a (equivalent to 106 km^3/a water transfer or 18% of current sea-level rise) most likely during 2000-08 (Foster & Tyson, 2016).

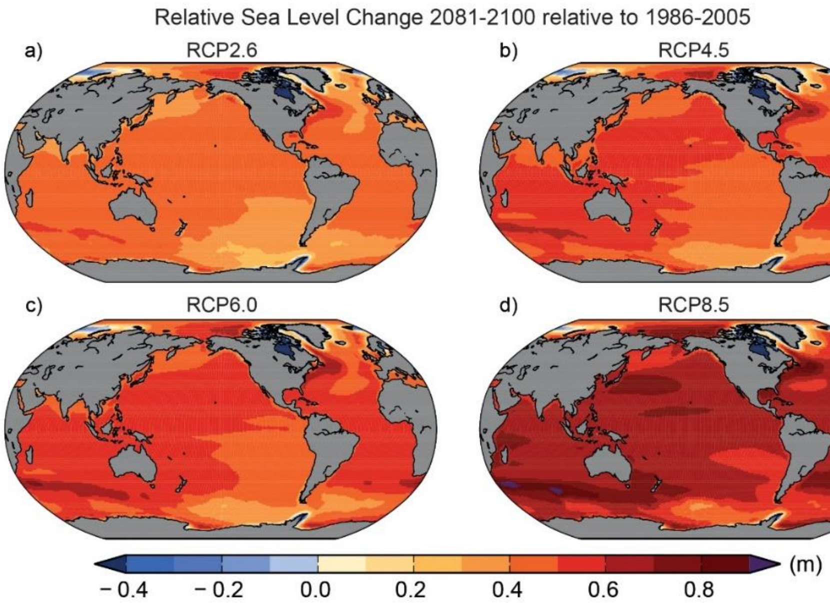

Figure 4-9: Ensemble mean net regional relative sea level change (metres) evaluated from 21 CMIP5 models for the RCP scenarios (a) 2.6, (b) 4.5, (c) 6.0 and (d) 8.5 between 1986–2005 and 2081–2100. Illustration from IPCC report, 2013. Illustration from IPCC report, 2013 (Stocker, et al., 2013). For an enlarge version of this image click here or scan the QR code and refer to Figure TS.23.

In coastal aquifers, sea level rise primarily affects groundwater quality (marine intrusion, storm flooding, etc.) and aquifer water table height. Storm surges and higher sea levels are likely to lead to seawater intrusion and salinization of groundwater resources, affecting drinking water supply (Working Group II - IPCC, 2022).

All this leads to the degradation of coastal groundwater, and changes in recharge and discharge are likely to change the vulnerability of aquifers to diffuse pollution (Clifton, et al., 2010).

In low-lying coastal areas of most regions, future increases in mean sea levels will amplify the impacts of coastal hazards on settlements and eventually lead to the inundation of very low-lying coastal settlements (Working Group II - IPCC, 2022).

Groundwater in islands is particularly vulnerable to these dynamic climate impacts and human-induced perturbations. The quality of groundwater is often as critically important as its quantity regarding groundwater sustainability (Treidel, Martin-Bordes, & Gurdak, 2012).

Rising sea levels coupled with droughts pose a significant risk to groundwater, especially on islands and atolls where groundwater is the primary source of freshwater.

Projections indicate that atolls may be unable to provide domestic freshwater resources due to the lack of potable groundwater shortly (by 2030 under RCP8.5+ice -sheet collapse- scenario, by 2040 under RCP8.5, or 2060s in scenario RCP4.5). For example, an 11-36% reduction is estimated in the volume of fresh groundwater lens of the Maldives's small atoll islands (area < 0.6 km²) due to sea-level rise (Working Group II - IPCC, 2022). In this regard, the Institution of Engineers Mauritius has recently published several articles on engineering and the pathway to building resilience to climate change in SIDS (The Institution of Engineers of Mauritius, 2022).

Together with population growth, changes in rainfall patterns and agricultural demand, these projections are expected to increase water stress in small islands. (Working Group II - IPCC, 2022).

All this makes small island freshwater systems some of the most threatened on the planet.

Climate change is expected to increase reliance on groundwater withdrawals as an adaptation strategy to increased variability in precipitation and surface water resources. This role is critical, so it is essential to protect groundwater from progressive overexploitation, pollution, and salinization. Integrated management of this resource is necessary to avoid anthropogenic pressures that threaten groundwater quality and are likely to increase in the future.

One of the measures to adapt to the expected increases in heavy rainfall events is managed aquifer recharge (MAR).

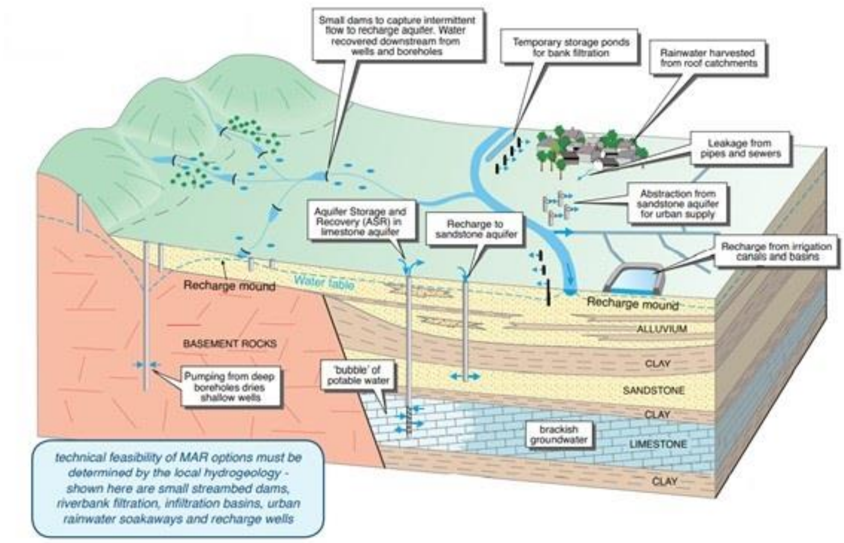

Figure 4-10: Range of managed aquifer recharge (MAR) options adapted to local settings. Illustration from International Association of Hydrogeologists (Foster & Tyson, 2019). For an enlarge version of this image click here or scan the QR code and refer to page 3.

Groundwater is the most important reserve of freshwater on the planet. The storage times of groundwater, from decades to centuries or millennia, explain the comparative resistance of aquifer systems, compared to surface water, to climate variability and change, thus constituting a buffering element.

Deeper aquifers react with delay to large-scale climate change but not short-term climate variability. Shallow groundwater systems (especially unconsolidated sediment or fractured bedrock aquifers) are more responsive to smaller-scale climate variability (Clifton, et al., 2010).

The overall effects of climate change on groundwater quantity and quality have been addressed throughout this section. Still, these effects will be dwarfed in many areas by non-climatic factors that strongly influence the capacity to manage groundwater resources adequately (Clifton, et al., 2010). The nexus between climatic and non-climatic factors is what will, in the end, determine future groundwater scenarios. For this reason, it is essential to carry out integrated management not only of all water resources but also of the soil and land, a multisectoral management.

In this context, the UNESCO-IHP project GRAPHIC (Groundwater Resources Assessment under the Pressures of Humanity and Climate Change) is a very important tool to improve the understanding of how groundwater interacts in the global water cycle, how it supports ecosystems and humanity and responds to the complex and coupled pressures of human activity and climate change.

All these interactions, climatic and non-climatic, lead the Sixth Assessment Report of the Intergovernmental Panel on Climate Change report to make the following statements regarding groundwater:

"AR5 concluded that the extent to which groundwater abstractions are affected by climate change is not well known due to the lack of long-term observational data (Jiménez Cisneros, et al., 2014). AR 6 (Douville, Raghavan, & Renwick, 2021) confirmed that, despite considerable progress since AR5, limitations in the spatio-temporal coverage of groundwater monitoring networks, abstraction data, and numerical representations of groundwater recharge processes continue to constrain understanding of climate change impacts on groundwater" (Working Group II - IPCC, 2022).

"AR5 concluded that the range of projected future changes in groundwater storage was large, from statistically significant declines to increases due to several uncertainties in existing models (Jiménez Cisneros, et al., 2014). AR6 (Douville, Raghavan, & Renwick, 2021) concluded with high confidence that projected increases in precipitation alone cannot ensure an increase in groundwater storage under a warming climate unless unsustainable trends in groundwater extraction are also reversed" (Working Group II - IPCC, 2022).

5 Groundwater and integrated water resource management

Emilio Custodio

5.1 Introduction and definitions

Groundwater is an essential phase of the terrestrial (continental and island) water cycle. Its importance relative to surface water depends on multiple geological, geographical, climate, soil and vegetation factors that cover a wide spectrum of possibilities that result in hydrological and hydrogeological processes responding to a wide spectrum of parameters. Human activity has been added to those related to these natural factors, directly on the water cycle or indirectly through land-related actions. Figure 5-1, which the US Geological Survey has elaborated to include the human effects, shows surface and groundwater flow through the territory and the relationships between them.

Groundwater is the water in the geological formations below the land surface and, specifically, fills the pores, voids, and fractures in them, referred to as the saturated zone. The zone of the ground where voids coexist with water and air is the non-saturated zone, where capillary forces act. Figure 5-1 refers to water quantity but does not show in detail water quality aspects, which are as important as quantity ones and will still be more important in the future.

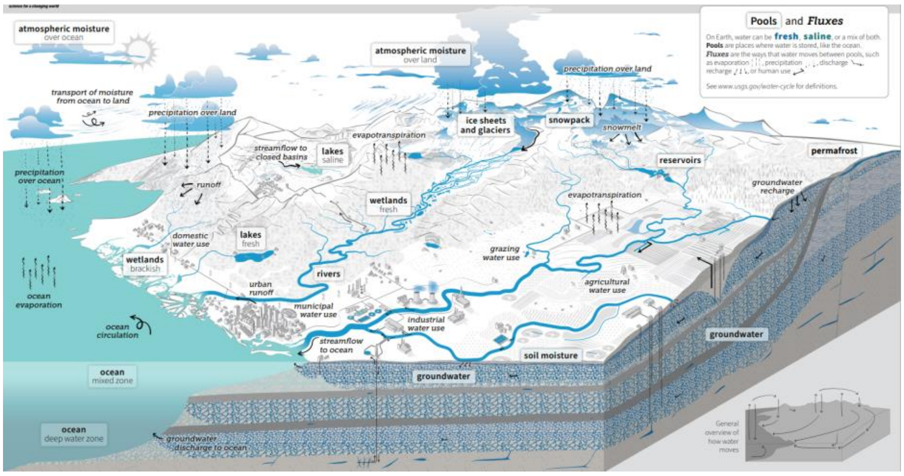

Figure 5-1: The terrestrial hydrological cycle, taking into account human effects. The water cycle describes where water is on Earth and how it moves. It shows how human water use affects where water is stored, its movement, and the quality. Illustration from United States Geological Survey (Corson-Dosch, et al., 2022). For an enlarge version of this image click here or scan the QR code.

Aquifers are saturated formations that contain, transmit and allow mobilizing significant quantities of groundwater below the land surface, while aquitards have but only transmit groundwater sluggishly. Aquifers and aquitards combine to form aquifer systems. Groundwater flows according to the hydraulic head, generally measured by the piezometric level, and the hydraulic permeability of the formations. A given aquifer system receives recharge from the surface in both diffuse and in concentrated form, originating in precipitation (rain and snowmelt), in infiltrating surface water generated in the same place or coming from other areas (allochtonous), and as inflow from other aquifers superposed and at the sides. Return flow or irrigation excess adds to diffuse recharge in irrigated agriculture areas. Diffuse recharge percolates through the non-saturated (vadose) zone. Groundwater in a given aquifer system outflows (discharge) in springs, feeds the base flow of rivers, and maintains lakes and wetlands – the visible part of groundwater – or is transferred to other aquifers superposed and at the sides. The water held in aquifers and aquitards is the storage or stock, defined in the next section as reserves. The aquifer systems have a storage that is at least, in common circumstances, one or two orders of magnitude higher than the yearly flow, while the contrary holds for surface water.

This chapter presents first the basic characteristics of groundwater and aquifer systems, followed by the concept and practice of integrated water resources management (IWRM) and comments on aquifer management practices and the way to water and groundwater governance. The point of view is dominantly that of a hydrologist and groundwater engineer.

What is presented and discussed thereinafter derives from reports produced by diverse United Nations organizations (FAO, GEF, GWP, UNESCO) and books on groundwater in the World (Margat & Van der Gun, 2013) and Integrated Water Resources Management and Governance (Jakeman, Barreteau, Hunt, Rinaudo, & Ross, 2016); (Martínez-Santos, Aldaya, & Llamas, 2014); (Technical Advisory Committee. Global Water Partnership, 2000); (Villholth, López-Gunn, Conto, Garrido, & Van der Gun, 2018). Besides, free access books dealing with general aspects and presenting paradigmatic situations in Spain (Custodio, 2015; 2022) are considered.

5.2 Basic groundwater characteristics that define its role in the hydrological cycle

Groundwater plays a vital role in nature, covering essential ecological functions and maintaining ecological services to humankind. Besides, groundwater is an essential source of water resources to humans, not only to try to honor, jointly with surface water, the right to water, but also what is needed for a comfortable life, the production of food and fiber, and the different industrial and economic activities.

Getting groundwater in large quantities for social needs has required significant technological development in wells, pumping machinery, energy and transportation and distribution means, and in some cases, treatment to correct quality. This has been achieved recently, during the first half of the 20th century and in many areas at a later stage.

Hydrogeological and groundwater hydrologic principles, science and technology are well advanced nowadays, with the handicap of being groundwater invisible to the people but also to trained people. Depending on the site, studies may be complex and costly and should be at the appropriate scale and with boundaries that may differ from that of the surface basin or subbasin. Monitoring is expensive and needs dedicated networks to avoid non-representative results. Non representative results are misleading and may feed data series leading to erroneous interpretations. Surface water monitoring generally relies on a few points with a high frequency of observations. Groundwater needs many points – often with more than one observation facility – distributed on the territory, with low frequency of measurements and the direct or indirect monitoring of many discharge points.

As water and groundwater are socially and ecologically important, their consideration needs adequate scientific knowledge and monitoring, but not excessive due to the cost. This knowledge is the support of economic, social, legal, administrative, political and ecological considerations, and policies, which dominate management and decision-making. In this management and decision-making, population support and political acceptance are often carried out by non-hydrologists, who should rely on and trust experts. This is the background of integrated water resources management (IWRM).

Scientific and technical documents and reports on groundwater resources often use terms that are not precisely defined or whose meaning is different when used in distinct social environments. This situation may lead to inaccurate water and mass balances and uncertainty in decision-making, especially in areas under water-stressed conditions. Comparisons are even more complicated when surface and groundwater resources are considered together and when other water sources are involved (Custodio, 2021).

The concepts of reserve and resource are well defined in mining for non–renewable minerals, including oil and gas. Defining groundwater reserves is more difficult as groundwater is generally renewable considering decades or some human generations.

These concepts have different meanings from that of mining and do not fully correspond to that of surface water. A natural resource can be defined as something found in nature and necessary or useful to humans. This definition is an anthropocentric concept as the existence of a natural resource is linked to its use. Besides, different people may value resources differently, depending on cultural background, view of nature, social situation, resource scarcity, and technological and economic factors.

Total groundwater resources refer to the total inflow into the aquifer or aquifer system. A careful definition is needed to avoid double accounting of water flow to some extent. Available groundwater resources are the total resources minus those required to maintain the flow of rivers and springs, lakes, wetlands and shallow water tables, and sea outflow in coastal areas to limit seawater intrusion and avoid an excessive increase in water salinity. The given definition of available groundwater resources is not universal and depends on local legislation and norms according to the priority assigned to ecological preservation.

Regarding water resources, it is important not to confuse water resources accessibility with how to withdraw water, nor the source of water supply with water resources. The techniques to exploit surface water are quite different from those for groundwater: diversions and dams versus wells and boreholes.

For a defined area, to avoid double accounting, the renewable surface water and groundwater resources should not be estimated according to the assumed origin of the mobile water: runoff or infiltration. The total water resources should be the point of departure for assessing surface and groundwater resource components. How to split the total water resources into shares of surface and groundwater depends on whether it is preferred to obtain the required water by surface water diversions or by pumping from aquifers. Such preferences depend on practical, administrative, economic criteria and the need to control user competition and conflicts.

Surface water and groundwater interact and exchange water during their downward flow. In humid areas, where only a minor share of groundwater flows directly into the sea, groundwater and the groundwater-fed stream base flow form a single resource. In arid regions, the opposite is true: short-term surface runoff events or surface water inflows from wetter regions are the main sources of aquifer recharge, and part of their flows evaporate in closed depressions. Here again, surface water and groundwater are the same resource, although they are sometimes reused, and this must be considered in water budgets. The larger the territory, the greater the portion of the water flowing alternately between surface water and groundwater.

Due to surface and groundwater exchange and the dependence of shallow aquifer evaporation and evapotranspiration on depth to the water table, recharge, discharge, and resources are not aquifer or aquifer system properties. They depend on location, flows and timing of exploitation.

Groundwater reserve is the total quantity of water in the aquifer or aquifer system, down to some depth or up to a maximum salinity. Groundwater reserves depend on formation volume and total porosity. A large part of the groundwater reserve cannot be abstracted as it is held in place by capillary forces in the non-saturated zone or it is too slowly drained from aquitards. Exploitable or drainable groundwater reserves are the part of total reserves that could be abstracted down to a given depth, with a maximum salinity and in a reasonable time.

Renewable groundwater is the water in an aquifer system with a short average residence time, commonly years or decades. Renewable groundwater often coincides with groundwater resources.

There is intensive groundwater exploitation when the abstraction rate under current exploitation conditions produces significant changes in the aquifer system functioning and pattern, including the relationships with surface and seawater and the associated piezometric and water table drawdown. The designation of intensive groundwater exploitation (development) is used to avoid the lack of accuracy and negative tilt of the term overexploitation (Custodio, 2009).

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5.3 Groundwater resources in the context of human needs and the environment

A sufficient and adequate understanding of the role of groundwater in the global water cycle and estimating its fluxes at different scales is necessary. Still, the relevant technical, economic, administrative, water quality and environmental constraints also have to be considered. This introduces some subjectivity and may reflect how groundwater competes with surface water resources and the social preferences of the moment. The quantification of surface and groundwater resources cannot be done independently due to the physical continuity between them.

Groundwater provides primarily renewable resources (fluxes that can be captured) and, in more exceptional cases, non-renewable and slowly renovating resources (reserves that can be exploited and depleted – mined). The buffering effect of groundwater reserves provides a certain degree of freedom to the exploitation regime of the renewable resources, making it less dependent on the natural variation of recharge.

A drawdown of piezometric levels accompanies groundwater exploitation to get the needed water in the wells, leading to a decrease in natural discharges. Figure 5-2 shows how the flow pattern changes in a simplified aquifer recharged locally by diffuse infiltration of precipitation. The consequences are that the river gains less water, exploitation cost increases due to lower water levels, and the wetlands and riverine forest shrink.

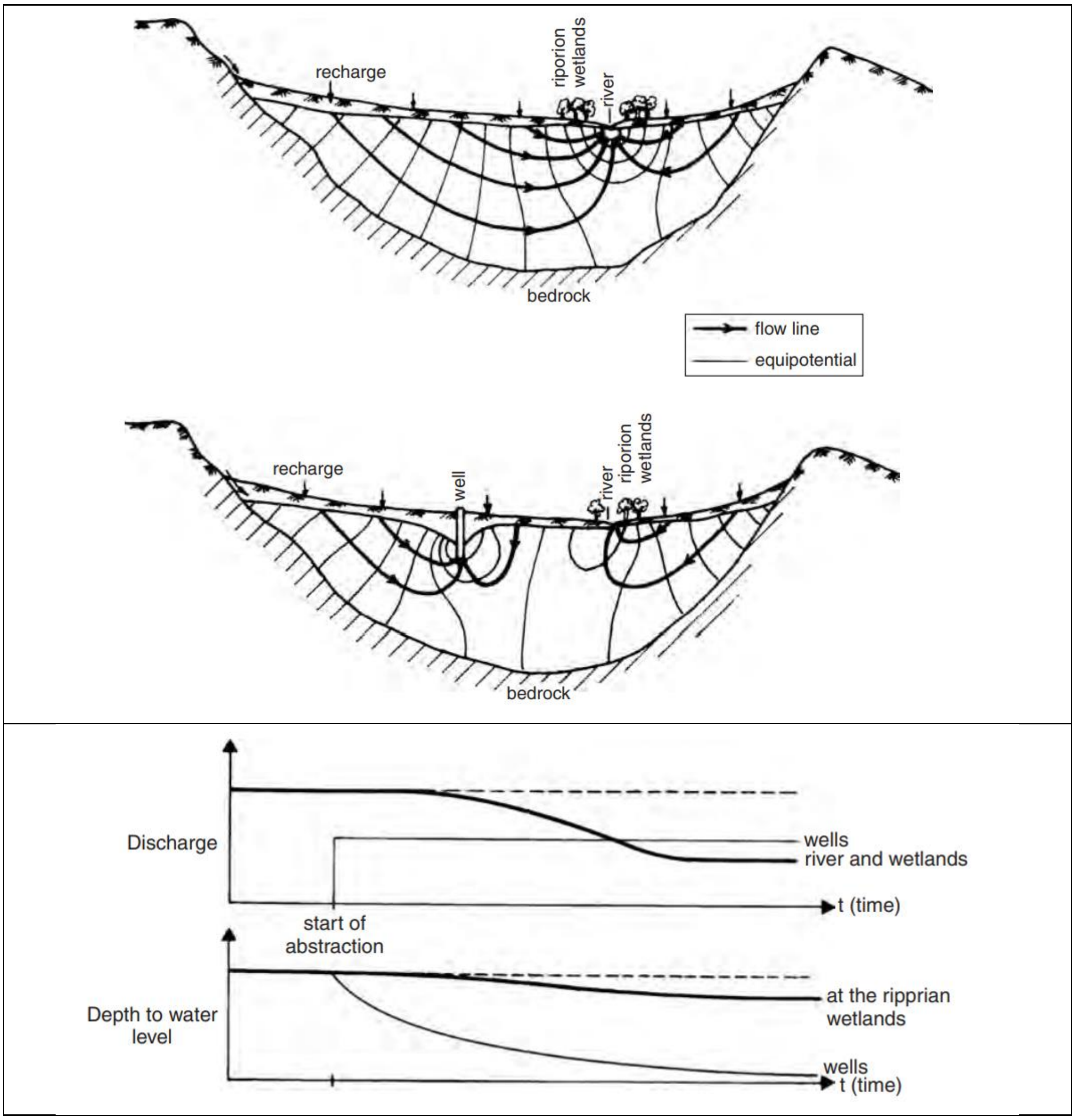

Figure 5-2: Changes in the flow pattern in a simplified alluvial or basin aquifer recharged locally by diffuse infiltration of precipitation, containing a hydraulically connected river from other areas. The boxes show the slow evolution of the water table level and the flows, until stabilization, for exploitation that is less than half the local recharge. The consequences are that the river gains less water as it goes through the area, groundwater exploitation cost increases due to water level lowering, and the wetlands and riverine forest shrink. (Custodio, 2009) .

The fact that groundwater abstraction reduces spring flow and the water flow increase of rivers going through the aquifer area is quite well known. A gaining (effluent) river commonly becomes a losing (influent) stream. This connection must be considered carefully in water resources evaluation and management. Figure 5-3 shows two examples of this.

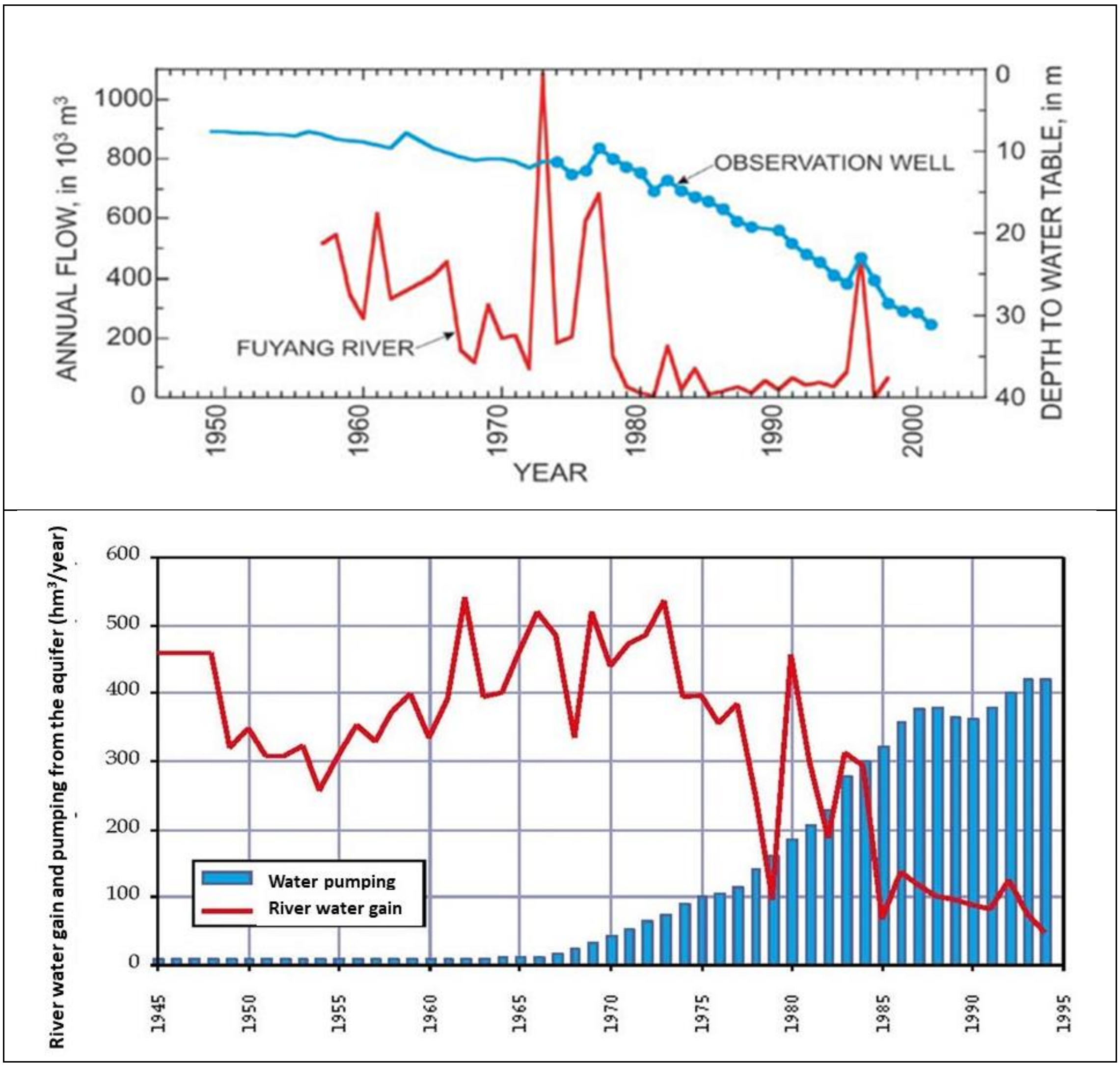

Figure 5-3: Stream flow and well hydrographs show the direct relationship between aquifer development and river flow, with some delay due to the evolution of reserves in the aquifer and depending on aquifer hydraulic properties and well emplacement. Upper figure: Fuyang River in North China Plain (Konikow & Kendy, 2005). Lower figure; Júcar (Xúquer) River in the La Mancha Oriental highlands, in northeastern Spain (MIMAM, 2000).

Many important wetlands and shallow water table areas depend on groundwater discharge, especially in arid and semiarid regions. Different forms of dependence are possible, as discussed in (Custodio, 2000).

5.4 Groundwater resources management

Unlike surface water, groundwater is freely accessible to numerous people scattered over an area, who may exploit it and influence its quality. Groundwater is a natural, generally renewable, common pool resource. Individuals abstracting groundwater have their objectives at a scale different from the larger scale of an aquifer. They generally have no knowledge of the aquifer's properties, resources, or characteristics.

Groundwater management involves adapting individual actions to the objectives and constraints shared by society, defined for each physical management unit, usually a given aquifer system or part of it. The aim is to consider the specific advantages of groundwater resources by allocating groundwater to what is considered, at that moment, the most essential and beneficial uses, as well as taking advantage of the buffering and purification capacity of the aquifers. Management includes the protection and conservation of groundwater resources while maintaining the positive role and functions they have in the water cycle and the environment.

For centuries, groundwater has been exploited and used, but without previous scientific knowledge of groundwater resources and attempts to manage these resources rationally. However, gradually, access to groundwater has become easier, and its exploitation has strongly increased, with the result that wells started interfering with each other and aggregated pumping rates became large enough to modify the groundwater regimes significantly. Secondary effects (negative externalities) of individual withdrawals (lowering of water levels, reduction of spring flows and river base flows, degradation of wetlands, etc.) are automatically transferred to third parties, not only to other groundwater operators but to the entire local community and environment. Additionally, many non-related groundwater activities of individuals and local communities can significantly impact groundwater systems and groundwater users. One of the main effects is groundwater contamination and pollution.

The state of groundwater systems is continuously changing, they are dynamically interacting with other physical and socio-economic systems, and many actors are pursuing their goals more or less independently. Observed or expected changes in groundwater status often diverge from what is most desirable, but it is far beyond the reach of single individuals to control these changes. Furthermore, groundwater is a common pool resource accessible to many, and there may be significant discrepancies between the interests and preferences of individuals and those of the local community as a whole. All these reasons motivate and justify groundwater resource management actions.

Evolving from a stage where the focus is predominantly on groundwater exploitation to the scenario of groundwater resources management is a logical response to increases in complexity and better-perceived problems. This shift creates opportunities to address emerging problems through actions such as (Margat & Van der Gun, 2013):

- Resolving water use conflicts between groundwater users.
- Slowing down or stopping non-sustainable abstraction.
- Mediating conflicts between those who benefit from groundwater development and those who suffer the adverse consequences of extraction, especially the ones who do not participate in the benefits.
- Identifying, reducing, and eliminating threats to groundwater resources.

However, groundwater resource management is more than simply reacting to observed or anticipated problems. It should ensure that the potential of groundwater as a resource is not overlooked or underestimated and that the significant opportunities offered by groundwater are fully realized. Groundwater management should be guided by a strategic vision of this resource's role in the country or area concerned regarding water supply, economy, and natural environment. This implies that a balance has to be established between exploiting and conserving groundwater in conformity with political preferences regarding water, socioeconomic development, employment, and the environment.

Groundwater and surface water cannot be generally managed independently from each other. According to how and how intensely both are interconnected and interrelated, considering quantity and quality, groundwater management should be integrated into overall water resources management. River basins are the most appropriate spatial units for water management in many circumstances. However, aquifers boundaries may greatly differ from river basin boundaries. Highly transmissive and regional deep aquifers may extend over more than a river basin. This makes groundwater management complex, especially in arid zones. The distribution of the groundwater resources of an extensive aquifer system with hydraulic continuity to the corresponding river basin may vary seasonally and even more due to the exploitation.

Groundwater resources management implies establishing appropriate institutions for each management unit, including creating an authority with adequate mandate, powers, and resources. It also requires the definition of how users participate in establishing objectives, selecting management instruments, and effectively controlling management actions. This is the foundation of good groundwater governance (Custodio, 2002).

5.5 The concept of Integrated Water Resources Management

Some United Nations Agencies have promoted the concept of Integrated Water Resources Management (IWRM) at the international level. This aims to optimize the results of economic resources transferred by donor countries and organizations to developing countries, going beyond investments in facilities and works, to consider the economic and social context and the environment. Therefore, integrated refers to the management and is mostly the point of view of politicians and high-level policymakers. The integration of water sources for the possible best water use is a different point of view, mostly by engineers and hydrologists, as explained in the next Section.

The Technical Committee of the Global Water Partnership (GEF, 2016) (SGV, 2016) has defined IWRM as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems". Many authors have adopted this definition (Martínez-Santos, Aldaya, & Llamas, 2014) (Nelson & Quevauviller, 2016) (Savenije & Van der Zaag, 2008) (White, 2013). It is a solid definition, but more potential than practical, a goal to reach, with few present and future practical results regarding actual water management, leaving many questions unanswered (Van Rijswick, Edelenbos, Hellegers, Kok, & Kuks, 2014).

IWRM is a framework designed to improve the management of water resources based on four fundamental principles adopted at the 1992 UN Dublin Conference on Water (ICWE, 1992) and the Rio de Janeiro Summit on Sustainable Development:

- Fresh water is a finite and vulnerable resource essential to sustain life, development, and the environment.
- Water development and management should be based on a participatory approach, involving users, planners, and policymakers at all levels.
- Women play a central part in water provision, management, and safeguarding.
- Water has an economic value in all its uses and should be recognized as an economic good. A balance must be achieved between economic efficiency, ecosystem sustainability, and social equity.

IWRM is a cross-sectoral policy approach designed to replace the traditional, fragmented sectoral approach to water resources and their management, which has often led to poor services and unsustainable resource use. IWRM is based on the understanding that water resources are an integral component of the ecosystem, a natural resource, and a social and economic good and that the multiple uses of limited water resources are interdependent. IWRM tries to answer questions related to how decision/action affects fundamental aspects:

- Social equity: effect on other water users or the benefits from its use.
- Economic efficiency: effect on the available financial and water resources. The economic value should consider the current and future social and environmental costs and benefits.
- Environmental sustainability: effect on the functioning of natural systems, avoiding or limiting land uses and developments that negatively affect these systems.

Therefore, IWRM is not a guide on how water should be managed, but a broad framework in which decision-makers can jointly establish water management objectives and coordinate the use of different instruments to achieve them.

IWRM approaches involve applying knowledge from various disciplines and the insights from diverse stakeholders to devise and implement efficient, equitable, and sustainable solutions to water and development problems, considering the different uses of demands through coordinated action. Therefore, an IWRM approach is an open and flexible process to bring together decision-makers from different sectors affecting water resources and all stakeholders to establish policies and make solid and balanced decisions in response to specific water challenges.

After the UN World Water Development Report 3 (White, 2013), some important conditions for implementing IWRM are:

- Political will and commitment.
- Basin management plan and clear vision.
- Participation and coordination mechanisms, fostering information sharing and exchange.
- Capacity development.
- Well-defined flexible and enforceable legal frameworks and regulations.
- Water allocation plans.
- Adequate investment, financial stability, and sustainable cost recovery.
- Good knowledge of the natural resources in the basin.
- Comprehensive monitoring and evaluation.

As each country and region differ in history, socioeconomic conditions, cultural and political context, and environmental characteristics, there is no single blueprint for IWRM. The framework has to be adapted to solve the actual local problems (Pahl-Wostl, Jeffrey, & Sendzimir, 2011), giving different values to the importance of economic, environmental, and social impacts. While the differences in implementation across countries can make IWRM difficult to define, it can be broadly characterized by several key trends (Biswas, 2008) (Lenton & Muller, 2009):

- Move away from command-and-control instruments, which focus on supply-side water management, such as large-scale water infrastructures, towards incorporating demand-side management through economic mechanisms.
- Increased awareness of the importance of sustainable development and the incorporation of social and environmental considerations in water management.
- Shift from top-down and centralized water security approaches to more flexible and decentralized ones that include a variety of diversified governance structures at appropriate scales.
- Increasing emphasis on stakeholder collaboration and the involvement of local communities in decision-making, which include:
  - Incorporating specialized knowledge.
  - Encouraging more innovative solutions to problems due to greater diversity of viewpoints.
  - Encouraging cooperation and reducing the risk of conflicts over water resources.
  - Developing more open, inclusive, and democratic solutions to generate greater support leading to more sustainable results.

However, the IWRM concept has some handicaps: it is difficult to implement, the schemes can yield very different results, it is time-consuming and needs intensive collaboration, it requires a level of coordination too complex for large-scale projects, and it is difficult to evaluate the performance of IWRM itself.

Therefore, IWRM may not be a good option in many cases, and less complex solutions should be promoted. (Giordano & Shah, 2014).

5.6 Water resources and groundwater in integrated water resources management

The engineering and technical approach to IWRM refers to the combined use of water resources and how to manage the results directed to water supply and water security as a primary step towards more socially oriented goals. This is different from the vision of international organizations, as explained in the previous section. The subject is not water resources as an abstract concept but each one of the available water sources. Each water source has its characteristics, which must be considered to improve the integration. Management is coordinated, as the different sources often have a clear dependence on each other in hydrological terms, as well as in quality, time, place, cost, preferences of persons and society, and environmental considerations-

Only exploitable water resources should be considered in IWRM.

Many different water sources are possible and vary in significance and type depending on the situation under consideration. These sources generally include surface and groundwater in almost any case, except in arid areas where surface water may be absent. To surface and groundwater sources, depending on local circumstances, it may be added:

- Groundwater recharged by irrigation return flows and water transport losses, which can be significant and even dominant in valleys and agricultural lowlands when irrigation is carried out with imported water. Generally, this varies according to the season of the year.

- Water reuse to supply some water demands, depending on the treatment applied and quality. Reuse can be done directly by mixing with other water sources, through treatments, or as groundwater after artificial recharge.
- Seawater desalination near the coast and up to a certain altitude. It is more expensive than other water resources but can be similar to other sources in arid areas. Desalination plants can produce in continuous operation or remain on standby until their production is needed, even if the produced water costs increase.
- Rainwater harvesting in small basins or runoff from roofs and urban works. It can be stored locally on the surface or aquifers through artificial recharge.

Desalinated and reused water is sometimes called industrial water and is considered a new water source (unconventional water resources). Brackish groundwater and recycled water are generally not considered new water sources but an additional treatment of a previous water source.

The use of each of the available water sources could be better optimized. Optimization is for all integrated resources. The optimal solution varies over time, seeking economy, the guarantee of supply, adequate quality, and preservation of ecological values and services. Some water sources may remain unused for a given period, while others are intensively used.

In an integrated system of water sources, groundwater generally plays a regulation role (buffering) through its large storage capacity. Available surface water is preferentially used, as, when there is not enough surface storage volume, it will leave the area while most groundwater remains. Groundwater storage is used through pumping wells when available surface water is insufficient. Therefore, besides competing, they play a complementary role. However, this is not a general rule, as the location of wells in relation to the river introduces time lags that can be exploited to increase complementarity at times of high seasonal demand by adding extraction from groundwater reserves to river water before losses from the river become significant. This is a well-known practice, as in the Tames River, England, the Plains of the central United States, and La Mancha Oriental, Spain (Custodio, Sahuquillo, & Albiac, 2017b). The preservation of wetlands, maintaining a river flow downstream, reducing energy costs, and existing regulations introduce limitations and constraints that must be considered.

The conceptual evolution of IWRM began after the initial period of uncontrolled or poorly controlled groundwater development in different regions. This happened in the 1930s-1940s, in central and western United States and later in Mexico, Israel, and the Mediterranean areas of Spain and France, then in Brazil, North Africa, India, and Australia, and more recently in China and many other countries. The objective was to determine the sustainability of groundwater developments and, specifically, the associated water demands, mainly regarding quantity and quality in some cases. The central concept was safe yield, later modified to include some externalities and environmental restrictions.

The concepts of joint and complementary use, without or with added infrastructures, were developed for engineering considerations. As economic, social, administrative, and ecological issues gained importance, the shift to include them led to the development of the IWRM concept, as explained before. This happened in the 1990s and fully developed in the 2000s to extend the scope and to be able to approach the real situations in certain aquifer systems. Since the 2010s, the evolution has been moving towards the water and groundwater governance (Custodio, 2023), with a similar development in different countries but with temporal variations (Llamas, Martinez-Santos, & de la Hera, 2007).

Decision-making needs tools to assess it, although those deciding are generally different from assessors and often are neither water nor groundwater specialists. The tools may be elementary in many cases, but in complex situations, modeling is needed. Most models to support decisions on water management, such as AQUATOOL and associated codes (Andreu, Capilla, & Sanchis, 1996), consider the water sources, storage, and demands as points connected by lines. A point is often a too poor representation of extensive aquifers and widely distributed groundwater abstractions. In this case, a groundwater flow – even a groundwater transport and water quality – model has to be considered, which significantly complicates – but does not hind – finding a solution. The available groundwater models can be used, although numerical solutions based on the eigenvalue calculation method help, as the parameter matrix remains constant in problems that can be assumed linear.

5.7 Instruments for groundwater management

A variety of instruments (tools) can be used in groundwater resources management to help approach the technical and wide-ranging objectives of IWRM (GWP, 2022). Some are direct, others are indirect and aim to influence people's behavior. Tools are also needed to develop strategies and plans and to monitor their effects.

The most common technical (engineering) tools consist of subsurface dams to intercept or retain groundwater, artificial recharge, soil, and terrain changes to promote stormwater infiltration, rainwater harvesting, well drilling to stimulate beneficial use of underexploited aquifers, and remediation techniques for polluted sites. The artificial increase of groundwater reserves and resources is considered in the next section.

Collective works or facilities play an important role in surface water management but are less common and have secondary importance in groundwater resources management. Groundwater resources management generally depends on implementing indirect management tools to meet social management objectives. These indirect management tools are of regulatory, economic, and informative nature.

Legal instruments consist of regulations that comply with specific rules, especially concerning the construction of new wells and bores and groundwater abstraction. Additional studies may be needed to assess the potential side effects of groundwater abstraction proposals. The implementation of regulations or the supervision of their compliance may come under the authority of a water police or a mandated water management institution. The management of shared resources by two or more water administrations must follow the rules agreed upon on a case-by-case basis, which often include the obligation to cooperate and exchange information, apply the no-harm principle, and protect, preserve, and management of the aquifer resources.

Economic and financial instruments influence the behavior. The ability of individuals, societies, and organizations to exploit or affect groundwater can be aligned in the direction desired by the groundwater management authority through legally embedded financial instruments. At least in theory, as practical experience is still small. These instruments can be incentives, such as the stimulation of exploitation by investment loans, subsidies, free or low-cost insurance for exploration or drilling risks, tax-free energy supply for pumping, and supporting efforts for mitigating pollution. However, such incentives must be supported and in line with the knowledge of the status of the resources to avoid wicked results. These tools can also work in the opposite direction (disincentives). This occurs when taxes are applied to restrict or disincentivize groundwater extraction through taxes on withdrawals or on activities that cause pollution.

Linked to the economic and financial instruments, surface and especially groundwater markets exist in several parts of the world. They are often informal and have little or no regulation. A certain degree of regulation of water markets can be useful to address adverse side effects, such as the emergence of monopolies. The water markets in Southern Asia improve the access of small farmers to irrigation water. In the western states of the USA, the water markets and Water Bank in California direct water to activities with high economic returns. Privately managed water markets, mostly for groundwater and small reservoirs, have been successfully working for decades in Gran Canaria and Tenerife, Canary Islands, Spain (Custodio, 2015). Informal groundwater markets have operated and still operate in southeastern Spain, taking advantage of rights acquired before groundwater became a public domain.

Educational, informational, and awareness-raising instruments can motivate cooperative action and adapt the behavior. The institutional setting, available funds, and professional capacity of staff in charge of water resources management activities strongly influence the success of these instruments. For effectiveness, the mandates for technical interventions, regulating, use of financial instruments, and sharing information with stakeholders should concentrate on single groundwater management authorities. Each with jurisdiction over complete aquifer systems, regardless of their size and their possible spread over several administrative or political districts. Their responsibility must be clearly defined. There is a need for coordination with other institutions and authorities whose activity may affect groundwater (land planning, agriculture, livestock, tourism, mining, forestry, etc.). This should be regulated at a higher administrative level, but still aware of the problems and goals to be achieved.

More decentralized and more community-oriented management is a present-day trend, entrusting the management responsibility to the community of those who exploit and use groundwater resources. This is important in IWRM. There are different degrees of entrustment, but in any case, responsibilities have to be clearly stated. Their development could be faster as it is difficult to convince stakeholders and groundwater users that they depend on a common pool resource, as well as to overcome the resistance of the water authorities that this is not a loss of power and capacity, but a win-win venture. Examples are the successful Communities of Groundwater Users (CGU) existing in Spain. The first and more successful one operates since 1975, and is involved in the management of various water sources and the regulation provided by an alluvial and delta aquifer (Queralt, Bernat, & Custodio, 2020) (Custodio, 2023). In the Astien Sands aquifer, southern France, there are organizations similar to the CGU since 1997. The Groundwater Technical Committees (GTC) in Mexico have existed since 1993 (Hidalgo & Pena, 2009). They were established primarily top-down by the Mexican water authority, which retains high power. Other groundwater users’ organizations exist in India and China. The dominantly arid climate of a large part of Australia needs careful management under realistic approaches (Cook, et al., 2022).

Efforts in Spain to create top-down groundwater users' organizations according to the rules established in the water law were unsuccessful. However, the CGU originated primarily bottom-up to solve a known and recognized problem, taking advantage of becoming public-law organizations. The important difference between the CGU and the traditional and numerous Irrigation Communities in Spain is that these last are mostly for the maintenance and operation of a water concession and private investments, but not the water resource itself.

5.8 Increase in groundwater reserves and resources in IWRM

Groundwater flow and storage can be increased through artificial recharge and, more recently, MAR (managed artificial recharge). This is a technique of aquifer management often linked to engineering aspects associated with IWRM (Dillon & Arshad, 2016). Artificial recharge has many possible purposes besides increasing groundwater flow and storage, as shown in Figure 5-4, and varies from a side effect of other human activity (generation of return irrigation flows, increased river infiltration induced by pumping in nearby wells) to actions devised specifically to introduce water into the ground, including enhancement of infiltration.

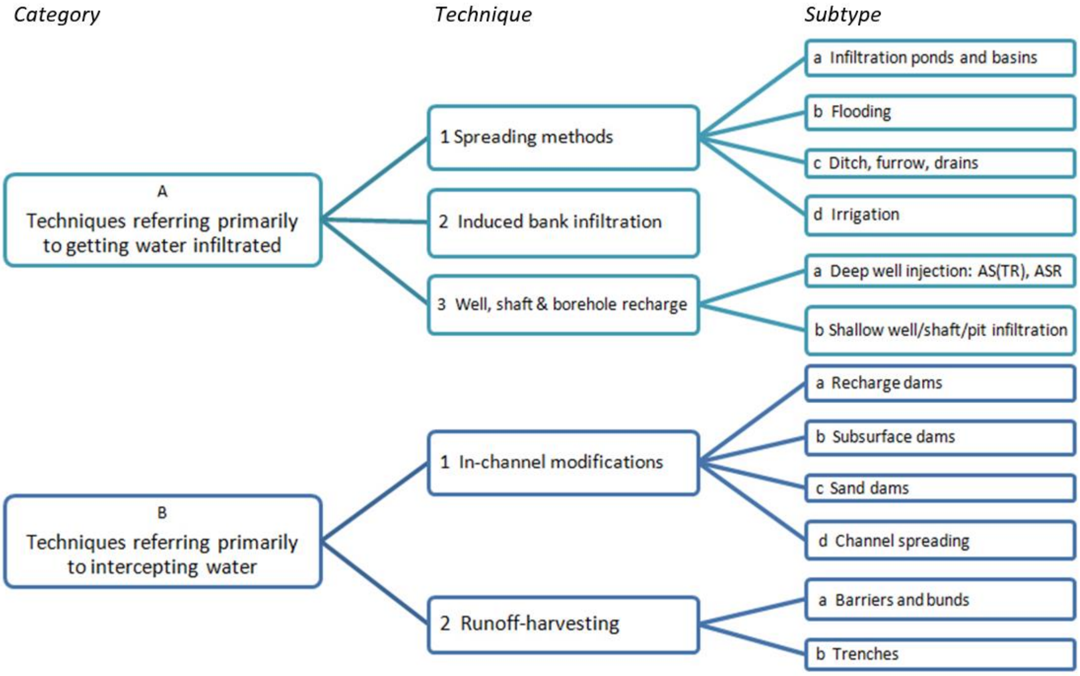

Figure 5-4: Overview of managed artificial recharge (MAR) techniques and subtypes. Illustration from Groundwater around the World: A Geographic Synopsis -Chap.4 (Margat & Van der Gun, 2013).

The overview of managed artificial recharge (MAR) techniques is complex. Technically, it has to solve and control the timing of recharge water availability, its quality, clogging, and prevent the introduction of contaminants into the aquifer. In addition, it is costly and needs sustained maintenance, the more the smaller is the infiltration surface and the higher is the turbidity of recharge water. Therefore, the practical implementation of an activity considered in a groundwater management scheme often presents serious problems to be carried out as a permanent solution, either continuous over time or to be operated intermittently. There have been numerous experiences since the late 19th century, but only a few have developed beyond the pilot stage or first attempts to become permanent, with well-defined goals. Artificial recharge is an often-considered topic in hydrogeological meetings and water planning commissions, but more rarely with well-defined goals and implementation of supporting administrative and social structures.

There are well-organized periodic meetings on MAR (managed artificial recharge) and international organizations support projects on the subject, such as MARSOL. The European Union's MARSOL project aim is to demonstrate that MAR is a viable approach to address expected long-term water shortages, combat seawater intrusion in coastal areas, and give pre-treated wastewater a final clean-up (MARSOL, 2022). Two of the eight field sites selected for the project are Algarve-Alentejo (Portugal) and Llobregat River infiltration basins (Spain). Figure 5-5 shows an experimental site. Portugal.

Figure 5-5: Rio Seco riverbed infiltration ponds (left image) and MAR clogging and infiltration experiments developed in Rio Seco (right image) (Campina de Faro, Algarve, Portugal). Illustrations from MARSOL. For more details on this MARSOL project click here or scan the QR code.

Currently, two main topics are the most frequently considered. One is to mitigate a possible reduction in aquifer recharge in some areas due to climatic change by enhancing and implementing artificial recharge, often reactivating and improving traditional knowledge in arid and semiarid areas. The other is to help in treated urban wastewater reclamation through infiltration in the soil of recharge ponds by developing pond layers that help in reducing contaminants remaining in the water, and especially those of emerging interest for public health.

There are operational artificial recharge facilities in many European countries, the United States, India, Australia, the Maghreb, the Middle East, and Africa.

Many of the artificial recharge facilities are located near a well field. Many others intend primarily to increase the resources of an entire aquifer system, such as the recharge facilities in the Santa Clara Valley in California and the numerous recharge systems across rural India. In Los Angeles, California, one of the goals of artificial recharge is to maintain the water distribution role of the aquifer to a widely dispersed population. In the Baix Llobregat, Barcelona, Spain, artificial recharge is to maintain enough groundwater storage to solve seasonal water scarcity for urban supply when surface water is unavailable (see Figure 5.6), and currently, marine intrusion is controlled by a barrier of reclaimed water injection along part of the coast (Queralt, Bernat, & Custodio, 2020).

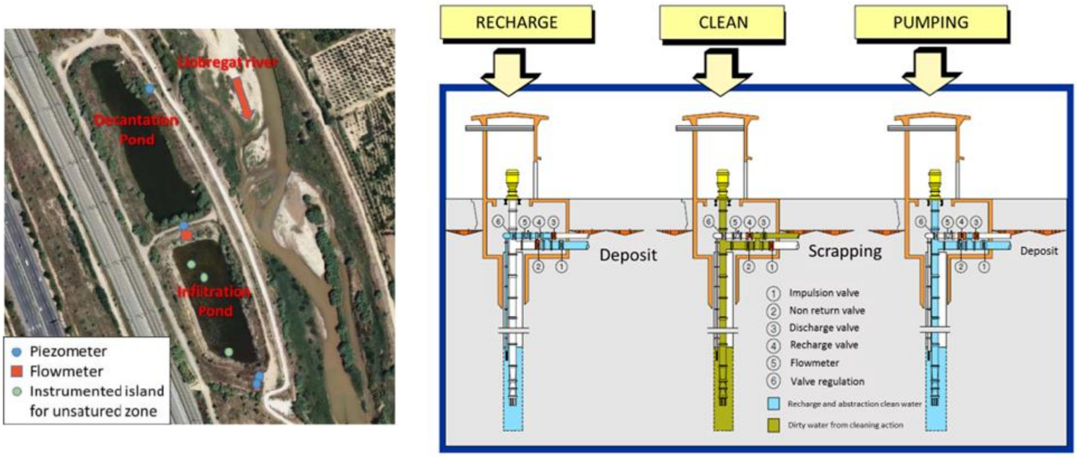

Figure 5-6: Aerial view of Sant Vicenç dels Horts (Barcelona, Spain) ponds where the monitoring system is shown (left image) and operation of the dual-purpose injection and pumping wells (right image). Illustrations from the Journal of Environmental Science and Engineering (Queralt, Bernat, & Custodio, 2020).

In arid or semi-arid regions, dams or dikes have been built to increase aquifer recharge through highly irregular and ephemeral surface water flows under natural conditions, as in the Arabian Peninsula. In the Sierra Nevada Mountain range in southeastern Spain and on the Pacific slope of the Andes in Peru, ancient canal systems are maintained to recharge meltwater and mitigate summer water shortages artificially (Jódar, et al., 2022). These examples and many others are technological actions that help to meet IWRM objectives under real conditions.

As mentioned above, artificial recharge may only be an unplanned result, as in aquifers underlying plains that are intensively irrigated with surface water. Infiltrated excess irrigation water may contribute much more to recharge than rainfall, especially in arid or semi-arid zones. This is especially important in the Indus Valley in Pakistan, the Nile Delta and Nile Valley in Egypt, several plains of Northern China, and even Mediterranean alluvial plains in Europe, especially in the plain of Crau near the Rhone delta in France and many coastal plains along the Spanish Mediterranean coast and Gran Canaria Island. The same is true for many floodwater-irrigated oases in the foothill areas of the northern Sahara or Central Asia. As pointed out by Margat and van der Gun (2013), additional recharge by irrigation returns flows have beneficial impacts by facilitating intensive exploitation of aquifers, but also may have negative impacts due to groundwater level rise that results in waterlogging and soil salinization in arid zones.

The implementation of IWRM concept has been successful in the Lerma-Chapala River basin in central Mexico, which is highly water-stressed, with intensive use of surface and groundwater resources. Increasingly frequent conflicts over water allocation and considerable water pollution and soil degradation levels (Hidalgo & Pena, 2009). The situation is improving with the recent move towards IWRM and subsequent improvements in water governance. The improvement in water governance is due to reforms beginning in the 1970s to move away from centralized governance towards IWRM. Six regional water resources offices were set up by the early 1980s, introduced in Section 5.7 as GTC, including the Lerma-Chapala River Basin Regional Management agency. Basin Councils have formal authority to implement the proposed water reallocation policies. The move towards IWRM in the Lerma-Chapala Basin has been a long (30 years) and complex process, but the benefits are starting to be realized.

The mentioned case studies highlight the fact that IWRM can lead to economically, socially, and environmentally sustainable solutions to complex water issues. However, as already said, this is not the common case. Critical evaluation of the successes and failures of such schemes is crucial to understanding how water management can be improved. While people may want a set of predetermined solutions to solve water problems, the fact is that complex problems require complex solutions, and one of the main reasons for adopting IWRM may be that its flexibility embraces and accounts for the challenges of complexity. Figure 5-7 shows the results of engineering IWRM to the Low Llobregat Area, to supply water to the corresponding zone of Barcelona's Metropolitan Area.

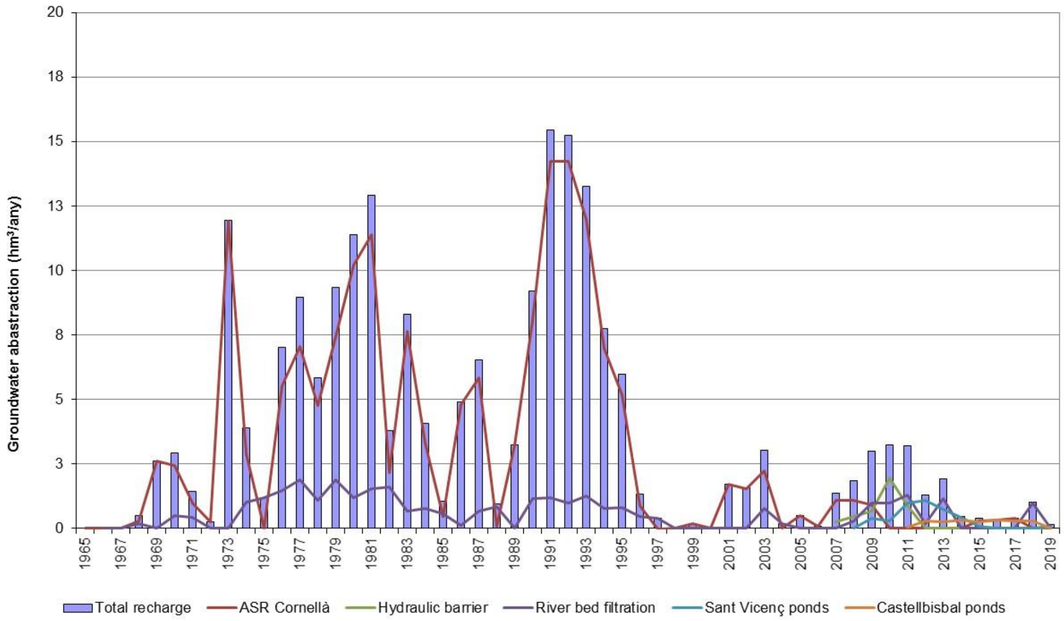

Figure 5-7: Evolution of yearly recharge water volumes for the several artificial recharge technologies applied in the Lower Llobregat aquifers (Barcelona, Spain). In the case of Castellbisbal pond, there was also recharge between 1980 and 1998, but detailed data are not available (ASR = aquifer storage and recovery). Illustrations from the Journal of Environmental Science and Engineering (Queralt, Bernat, & Custodio, 2020).

Climatic conditions, such as rain, temperature, and atmospheric humidity, can affect the volumes of water used by plants in evapotranspiration and those transferred to recharge aquifers. Expected climate change scenarios will tend to modify hydrological and hydrogeological parameters, directly impacting evapotranspiration (which increases) and recharge (which decreases).

The European Union Watershed Management Plans have shown, for Southern Europe aquifers, that the relationship between current and expected annual average recharge for 2071-2100 is expected to be less than 50% of today´s natural recharge values. For example, as evaluated for the Portuguese Torres Vedras aquifer system (Lobo Ferreira, Leitão, & Oliveira, 2014). This lack of water, provided that the model uses the correct functions and realistic parameters, will result in drought and crop losses. Managed Aquifer Recharge (MAR) techniques can secure 'excess' water and store it in the soil through engineered systems for temporal storage or influence gradients.

5.9 Groundwater governance in the context of IWRM

Groundwater resources management emerges only after people have become aware of opportunities or problems related to their groundwater resources and after developing ideas on how to address them. Consequently, there is often a considerable delay between the beginning of intensive groundwater exploitation in an area, the development of groundwater management, and the need for the integration of groundwater resources. In general, a certain degree of deterioration is unavoidable to initiate the action. The turning point depends on shared knowledge and information and rising costs. The initial interventions are often based largely on technical tools, as they are relatively easy to accept or even supported by the stakeholders.

In many countries, groundwater resource management consists of isolated measures implemented in selected areas or even nationwide, in some cases with significant effects and others without. In other countries, more comprehensive groundwater resources management approaches have emerged, tending to evolve towards an ever-increasing scope, consistent with increasing awareness, institutional capacity, socioeconomic conditions, and political environment. Typical initial steps are integrating groundwater and surface water, water quantity and quality, as well as all uses and functions of water into one water resources management plan. In the next step, the socioeconomic dimensions are included, and later ecosystems as a component of equal importance to the socioeconomic ones. This evolution leads to improved coordination between government levels that used to be separate (water resources, environment, nature conservation, spatial planning, energy, employment, etc.) or even to their integration.

Regardless of available knowledge and information, decisions must be made whatever approach followed. The degree of success and adequacy of these decisions needs to be supported when making them based on sufficient and accurate information on the groundwater systems under consideration. In addition, the opinions and priorities of the main categories of stakeholders must be known and considered to identify and analyze possible strategies and measures to be adopted.

Groundwater resources management faces many additional difficulties during the assessment and planning phase as well as during the subsequent implementation of measures, compared to surface water management, as commented before:

- The delineation of aquifer boundaries is much more difficult, as they are hidden. But mostly because of their three-dimensional geometry and the complexity and high cost of exploring boundaries. Besides, the boundaries may change over time due to the characteristics of the natural regime or in response to groundwater abstraction (shared aquifers or aquifers with hydrological continuity), a not uncommon circumstance, especially for deep and regional aquifers. Interbasin aquifer boundaries or boundaries involving political borders among counties and inside the countries are specially hard to address.
- Surface water management depends much on a physical hydraulic infrastructure that can be operated with reasonably predictable results. Groundwater management relies primarily on changing people's behavior, either by regulations or through incentives and disincentives, with results often much more uncertain.
- Numerical models are commonly used to explore the advantages of alternative strategies as a decision-support tool and thus to support the groundwater management strategies and measures finally adopted. However, groundwater systems often suffer from insufficient knowledge and limited data. The simulation models used tend to focus on hydrodynamic and/or water quality processes. They may sometimes include economic evaluation of measures, but human behavior is not considered in current modeling practice.

- Monitoring the achievement of groundwater objectives is more complex and, in most cases, needs to be improved. It relies on piezometric monitoring networks, water quality sampling campaigns, and well inventories. Monitoring levels, observation or sampling frequencies, and other performance indicators vary considerably. Many countries have made significant progress in groundwater monitoring, but methods and practices are heterogeneous and insufficient for a good land covering. In several cases, monitoring is declining.

Considering what has been said about the technical and social points of view of IWRM, it is necessary to take into account the particular characteristics of groundwater resources, especially the large proportion of water volume relative to the annual flow (average time of renewal) and the delayed and buffered response associated with external action. This is just the opposite of surface water, except if there is a large storage associated with natural or artificial lakes (reservoirs), which changes the competition for a water resource into complementarity. Besides, water quality considerations differ between surface and groundwater. In both cases, the rate of use must be balanced with the ecological values and services they provide, which is an essential pillar of IWRM. All this leads to the currently developed concept of water governance (Villholth, López-Gunn, Conto, Garrido, & Van der Gun, 2018), which has an aspect related to groundwater governance (Custodio, 2023).

6 Mining and groundwater

Rafael Fernández-Rubio

6.1 Introduction

Water is an indispensable resource in mining activity (in a broad sense). On the other hand, the mining operation as a whole very often requires groundwater drainage since the deposit is located, fully or partially, in the saturated substrate.

Under these conditions, the implementation of adequate in advance preventive drainage systems can turn the drained groundwater into valuable resources, taking advantage of its presence and considering its storage conditions. This is how this drainage (in addition to fulfilling its specific missions from the hydrological, mining, and environmental perspectives) can not only meet the project's needs but also satisfy other environmental demands during the life of the mining operation and after it.

In this context, mining is practically the only industrial activity that can become a water producer for itself and to meet other needs, in direct use or after physical or chemical treatments that make it suitable. The equipment of drainage infrastructures can allow, a posteriori, to meet the external water demands (post-mining closure stage) in the implementation of adequate hydrological-environmental rehabilitation and management, thus valuing the water resource.

There are many options and examples of this good practice in mining projects developed in different countries and environments in response to the unavoidable requirements of today's society and the context of sustainable development. This approach should ideally be planned and implemented as early as possible to facilitate the optimization of integrated water-mining management.

6.2 Mining-hydrological framework

With the simplifications imposed by the limited extension of this paper, we can say that the emplacement of a mineral mass in the subsoil often responds to the laws governing the movement of mineralizing fluids. This movement is fundamentally similar to that of groundwater in the subsoil. But it must also be recognized that the presence and/or circulation of these waters, throughout the geological evolution, can impact the evolution of the mineral deposit itself, especially in those of pneumatolytic, hydrothermal, and exhalative origin (Vázquez Guzmán, 2012). Thus, we have often experienced the synergies involved in the teamwork of metallogeneticists and hydrogeologists, allowing valuable mutual enrichment.

Also important, for example, is the role of groundwater in the oxidation of sulfide mineral deposits, with its oxidation-leaching processes and transport of certain ions (solutes). This is a context in which hydrogeology controls the evolution of the oxidation of the deposit (gossan cuprock) and the transport of noble metals and their concentration in deposition processes in the transition belt from oxides to sulfides. The same could be said of the role of groundwater in transporting uranium in sandstones and other permeable materials, among others.

But there is also an important factor to consider in the water-mineral interrelationship: when a deposit with sulfides is drained, its oxidation occurs, along with the dissolution of the minerals, which physically and chemically affects the quality of the groundwater, with a drastic decrease in pH and the release of metal ions. These changes can affect sub-surface and surface runoff. This water will have to be treated before its use, a task in which great achievements have been made with bioremediation (passive treatments).

6.3 Water presence in mines

For groundwater specialists (hydrogeologists), their sources of information are mainly surface observations, especially geology and hydrology. The contributions from the subsoil that can be provided by geophysical prospecting techniques (of various kinds) are also particularly relevant, as well as the information that can be obtained using investigation and withdrawal boreholes. To this background, the mining hydrogeologist adds a unique and incomparable possibility of documentation by being able to physically access the often-complex hydrogeological systems through the mining excavations, thus observing their behavior to the water recharge due to precipitation and the anthropic actions of drainage of the system, with reactions such as water inrush, or the modifications of hydraulic load or drainage, among others.

In any case, in mining activity, groundwater in the subsurface is frequent, given the depths that are usually reached in these exploitations and the extension in size that they acquire, either with underground or with open pit mining. In this context, it should be noted that the need for dewatering not only arises when there are aquifers of high storage capacity and permeability in the area of influence of the excavation, but also with low permeability materials, in which the presence of water leads to problems of geotechnical behavior (instability and creep, mainly), requiring depressurization measures.

But, in addition, the interconnection of surface and groundwater is common, making drainage and drain unavoidable in many mining operations. This entails the obligation to carry out detailed and precise hydrogeological studies, often supported by large investments in research, equipment, and control. Hence the large volume of information acquired must be processed with modern computer tools. In this way, it can be asserted that mining areas usually present themselves as the most studied regarding groundwater and the best equipped with drainage and monitoring devices. It would be suicidal not to do so.

6.4 Mine drainage water

Many mines extract more tons of water than ore. This is the case of mines located below the water table, in contact with aquifers, and even where the orebody is the aquifer itself. It should also be noted that mining requires lowering the water level, which implies extracting not only water resources but also reserves and, as the depth and extent of mining increases, the greater the extension of the conoid of piezometric depression. This entails capturing more and more water, an operation that must be maintained for the duration of the extractive activity, in a true groundwater mining.

For example, at the Belchatów open-pit lignite mine (Poland), where I worked as a drainage consultant, 62,500 m^3/h were pumped in the 1980s by dozens of catchment boreholes located in a peripheral ring and the interior of the pit. These waters were subjected to a simple decanting process in ponds, with dense phreatophyte vegetation, to obtain a clean effluent suitable for any use.

To meet this requirement of drainage with the best quality water, it is necessary to implement appropriate actions to reduce as much as possible the access of water (surface or groundwater) to the mine, by redirecting surface runoff, use of geological barriers, impermeability works from the surface or underground, sealing of boreholes, etc. In general, the operation is carried out with techniques that we call in advance preventive drainage which, from the hydrodynamic point of view, consist of generating a depression effect in the hydrogeological system, to which the groundwater flows. In this way, it is possible to obtain quality water, adequate to meet the demands, which is integrated into the rational management of water resources.

6.5 Mine drainage flow

In many mines, it is necessary to implement very important drainages, whose flows and volumes depend fundamentally on the characteristics of the aquifers involved (hydraulic lowering, the permeability of the medium, the thickness of the protection barriers, etc.), on the surface water input and the rainfall infiltration rate. We extract the following specific information from a gathering publication that we published a few years ago (Fernández Rubio, Water Resources Management and Mining: An International Perspective, 2006).

In general, the mines with the highest water inflows are in areas with the highest precipitation rates, as Pei (Pei, 1998) demonstrated when he studied water inflows in 15,750 mining operations in China. In any case, the flows and volumes drained by many mines may be surprising for those far from the mining world. Thus, we can cite, for example, the Kursk iron ore mine in the former Soviet Union, with 50,000 m^3/h; the Belchatów open-pit lignite mine (Poland), with 62,500 m^3/h; or the 226,800 m^3/h flow of a group of coal mines in the former Soviet Union (Fernández Rubio, 1986).

Another example is the Neyveli lignite mine (India), where 40 submerged pumps had to be installed in pumping wells to lower the hydrostatic pressure of the underlying aquifer to 1.5 m below the exploitation level, extracting 9,600 m^3/h. This meant pumping 24 tons of water for every ton of coal extracted, to which had to be added, in the heavy rainy season, another 16 tons of water infiltration (Banerjee & Shylienger, 1978).

The relationship between infiltration water flows and coal/mineral tonnages extracted in some mines in the world shows variations ranging from 1:1 to more than 100:1 -Armstrong, 1988, in (Mulenga, 1991)- (Figure 6-1). For coal mines in Spain, an average of 2.5 m^3/t of washed coal has been estimated, with values ranging from 1.2 to 4.0 m^3/t (Fernández Aller, 1981).

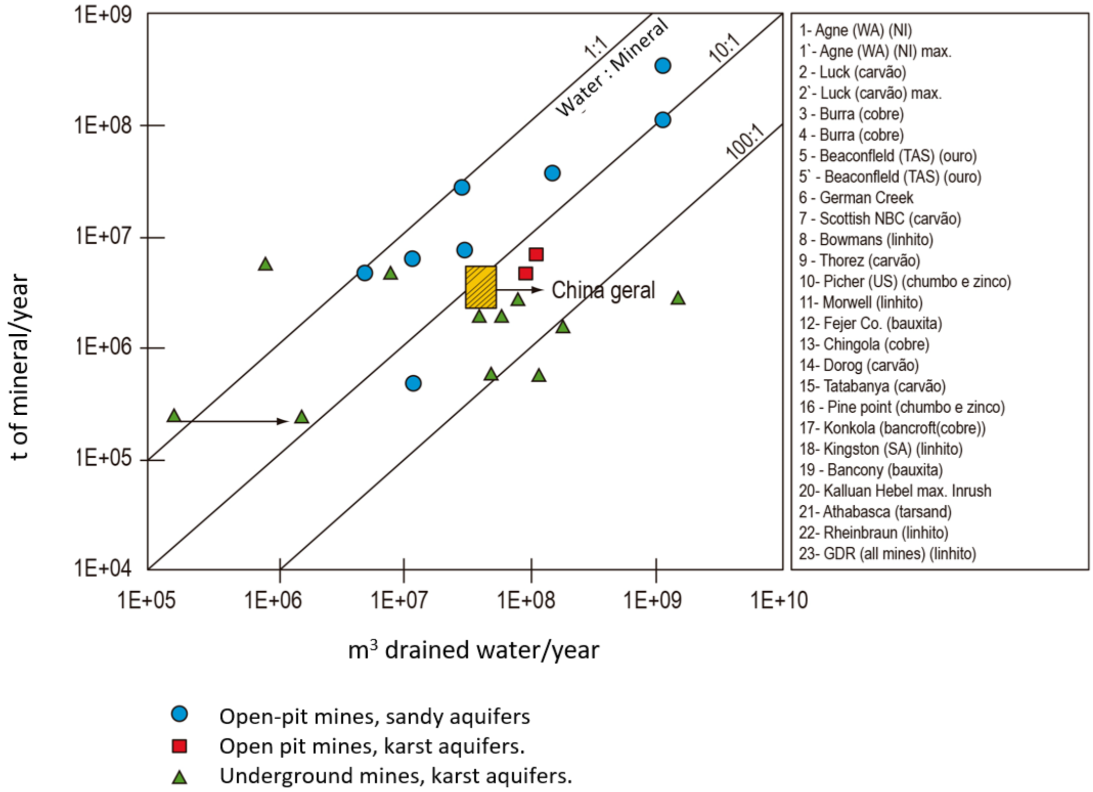

Figure 6-1: Ratio of mine drainage to ore mined in the world's major mines -Armstrong, 1988, in (Mulenga, 1991)-, 1991).

At the Mufulira mine (Zambia), the ratio is 5 m^3 of water per ton of ore mined (Wightman, 1978), while at Konkola (Zambia) the ratio has increased over time, from 30 to 90 m^3 per ton of ore (Mulenga, 1991) (Figure 6-2).

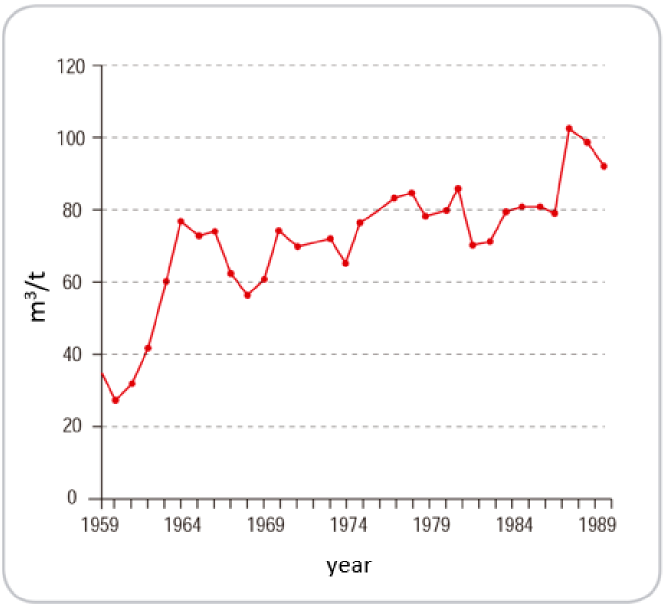

Figure 6-2: The ratio between the volume of water pumped from the mine and the tons of ore extracted at the Konkola mine (Zambia) (Mulenga, 1991).

In the same coalfield, energy consumption for pumping has a major impact in the context of mining operations. At the Pootkee mine (Jharia Coalfield, India), out of a total installed power of 4,100 kW, 55% corresponds to pumping, with a specific consumption of 25 kWh/t of coal extracted (Banerjee & Shylienger, 1978). At the Reocín mine (Cantabria, Spain), the cost of drainage was estimated at one-quarter of the technical costs of the operation (Trilla, López, & Peón, 1978), with a pumping rate, in 1979, of 35x106 m^3 (Fernández Rubio, 1980).

At the Nchanga open pit mine (Zambia), the subsurface pumping system had an installed capacity of 7,200 m^3/h (Stalker & Schiannini, 1978) and 41x10^6 m^3 had to be pumped over four years to lower the piezometric level by an average of 30 m/year (Stalker & Schiannini, 1978). At the Fengfeng coal mine (China), about 7,200 m^3/h of water was pumped (Chich-Kuei & Chang-Lin, 1978).

Water inputs are very large in the Far West Rand gold mines (South Africa), with mining down to depths of about 3 km in a karst domain. Thus, Wolmarans and Guise-Brown, in citing the pumping of the Oberholzar compartment refer to a maximum of 7,080 m^3/hour (Wolmarans & Guise-Brown, 1978).

In the coal mines of northern China, an inrush of 123,120 m^3/h is cited at the Fanggezhuang mine in the Kailuan coal basin (Hebei province), with a production of 3 million tons, related to the collapse of a cavity 60 m in diameter and 313 m high (Pei, 1998) (Baiying, Hongtian, & Hang, 1988). Another catastrophic irruption, 90,000 m^3/h, occurred in August 1966 at the Jiangbei mine (Pei, 1998) (Zhongling, 1988).

The data presented here show the large water output that, on many occasions, need to be drained in mining operations. In any case, the largest water contributions that we know of are related to karst environments.

6.6 Evolution of drainage flow rates according to the Gaussian curve

In many mining sites, it is common to have large water inrushes, with a strong initial increase in the flow and a gradual reduction until it reaches a relative stabilization. This behavior is frequent when the water comes from:

- Interception of preferential water conduits in a heterogeneous medium.
- Access to more or less confined watertight hydrogeological compartments.
- Roof collapses affecting overlying aquifers.
- Bed uplift pressures due to the pressure of underlying confined aquifers, whose waters break out through the protective layer.

These turbulent flows can carry large amounts of suspended solid matter. Suppose the inrushes occur in mines where the protective layer has not been affected. In that case, the evolution of the flows usually shows slower increases than when the protective layer has been adversely affected. A typical example occurred in the Far West Rand gold mines (South Africa), with an overlying karst aquifer in dolomites 1,200 m thick and an estimated groundwater storage volume of 2,200x10^6 m^3 -Schwartz & Midgle, 1975 *in* (Wolmarans & Guise-Brown, 1978)-. The interception of the syenite dikes (distant between five and sixteen kilometers), which compartmentalize this aquifer, has led to frequent water inrushes with peaks of high flows. Such as the one that occurred in the Driefontein mine, at 874 m depth, which reached 4,500 m^3/hour, in a sector previously defined as free of water in fissures because it contributed almost no water in the previous investigation boreholes. Driefontein West and East mine drainage exceeded 14,000 m^3/hour and stabilized at 3,500 m^3/hour after seven years (Figure 6-3).

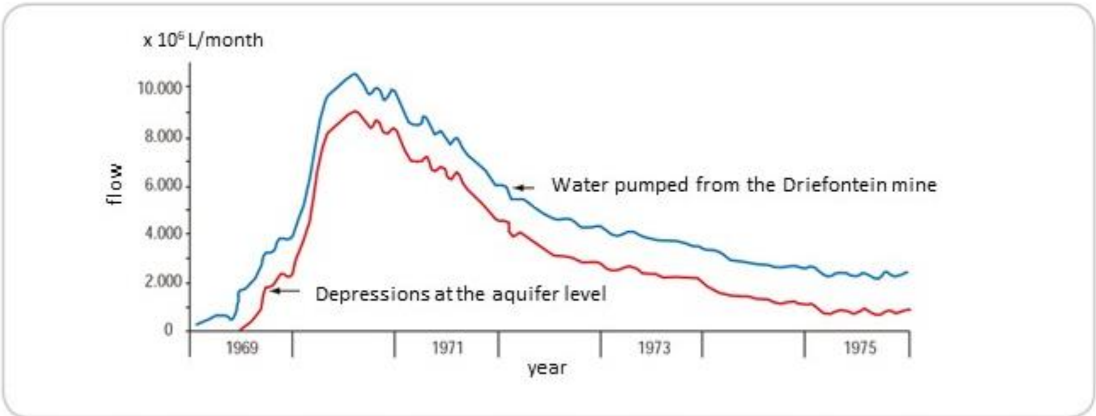

Figure 6-3: Driefontein West and East mine drainage (Wolmarans & Guise-Brown, 1978).

In four mines in this area, with an average of 25 years of activity, a total of 1997x10^6 m^3 had been pumped by 1976. Under these conditions, it is logical that attempts to drill mine shafts were unsuccessful between 1898 and 1930, until cementation was introduced, which allowed the first shaft to be completed in 1934 (since then, more than a dozen mines have drilled shafts) (Wolmarans & Guise-Brown, 1978).

Another case to cite is that of the deepest exploitation of the underground coal mine in Berga (Barcelona, Spain), where the uplift pressure of the underlying karst aquifer caused the eruption of the confined water, with the rupture and uplift of the ground, with significant water inflows, challenging to reduce.

At the same mine, other significant rapid inrushes have been related to heavy rainfall and infiltration from the surface through abandoned underground mine faces. In two sections of the Juktan tunnel (Sweden), there was also a rapid inflow of water immediately after blasting, which reached initial flows of 648 and 306 m^3/h, stabilizing within a short time at 126 m^3/h in each case (Figure 6-4). Both irruptions were linked to 20 and 35-m-long sections, with intense subvertical fracturing (Carlsson A. & Olsson T., 1978).

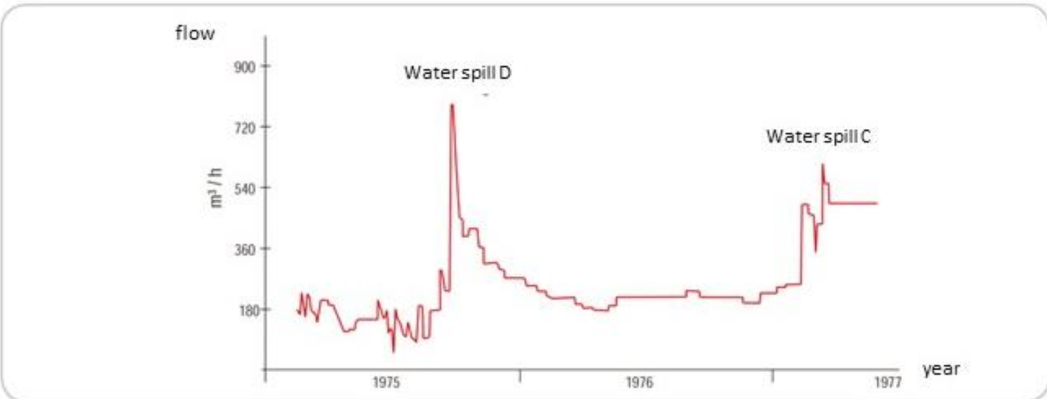

Figure 6-4: Water inflows during construction of the Juktan tunnel.

We could also include the case of the La Oportuna underground coal mine (Andorra, Teruel, Spain), in which a series of irruptions occurred due to roof collapses and the consequent intercommunication with the overlying multilayer aquifer system. The drainage water brought large quantities of sands and plastic clays, with kaolin, which eventually filled the collapsed zone, until the water supply was restored to the pre-irruption situation.

In coal mining in India, as in other regions seasonally affected by heavy tropical rains (monsoons), flow increases during these hydroclimatic episodes are typical. Such is the case of torrential rains, which bring rainfall of up to 800 mm in 24 hours in northern Bihar (Banerjee & Shylienger, 1978), where during the heavy rains of 1975, many deep mines were flooded. At the Vazante mine (Gerais Mines, Brazil), we found that drainage, despite its intensity, hardly decreased piezometric levels in years of heavy rainfall.

At the Domokos chromite mine (Greece), water inflows of 500 m^3/h have been recorded immediately after the rains to pass to normal flows of 320 m^3/h during the dry period. The mine site is mainly located in peridotites, with subvertical fracturing reaching the surface through which these water inflows occur, mainly in the excavations located in the upper parts of the mine. For an annual pumping of $3.5x10^6$ m^3, 75% came from depths less than 80 m (Marinos, Economopoulos, & Nicolau, 1978). In 1973, an extraordinary drainage pumping had to be carried out due to very heavy rains in the Marquesado iron mine (Granada, Spain), when a catastrophic rainfall caused the failure of the dikes that maintained the rainwater course and prevented the entry of water into the open pit mine, flooding the bottom of the pit.

In addition, in many cases of underground mining with collapse processes, which cause subsidence in large areas, there are rapid water inflows during rainy periods, which cause significant peaks in the extracted flows. In these cases, the inputs may correspond to direct precipitation in the collapse zones and the watershed. This occurs, for example, in the Konkola mine, where collapse affects the Lubenguele and Kakosa rivers (Frasa Consulting Engineers, 1993).

Due to the subsidence effect, the flow variations recorded in the Pennsylvania mines are perfectly related to the flow variations in the surrounding rivers (Figure 6-5) (Growitz, 1978).

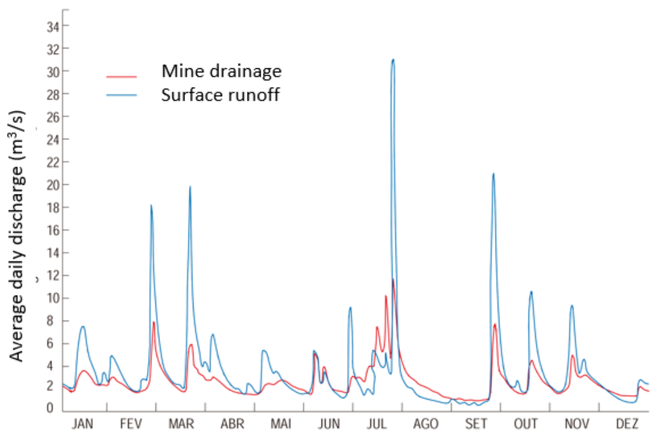

Figure 6-5: Mine drainage and runoff hydrograms for the year 1975 in the Pennsylvania coal mines (Growitz, 1978).

In this sense, mine dewatering, with its corresponding lowering of the piezometric level, can cause rivers to lose flow when crossing the drained area. When these strong temporary increases in flow occur, or there is a risk of them arising, the construction of underground reservoirs in the mines is recommended to accumulate and regulate the maximum flows. Thus, in the Jharia coalfield (India), pumping variations between maximum and minimum periods are of the order of 4 to 1. This can be evidenced in the correlation of monthly precipitation records with energy consumption (Figures 6-6), with a lag of the order of one month between the two peaks, as pumping is prolonged longer due to the time required for infiltration of precipitation (Banerjee & Shylienger, 1978).

Figure 6-6: Monthly energy consumption and rainfall B.C.C.L. Jharia Coaldfield, India (Banerjee & Shylienger, 1978).

In this context of energy costs, in the Reocín mine (Cantabria, Spain), the convenience of pumping at night, with cheaper electricity prices, justified the construction of underground reservoirs for water accumulation during the day (Fernández Rubio, 1980).

6.7 Evolution of increasing drainage flow rates over time

Drained water flows may increase gradually over time, mainly due to the extension in size and depths of the mining operations (open pit or underground excavation). This implies an increase in the cone of depression and induced recharge from other aquifers.

A typical example of this behavior occurs in the Reocín underground mine (Cantabria, Spain), where over many years, there has been an average annual increase in drainage flow of 126 m^3/h. Indeed, this water inflow is subject to significant variations depending on rainfall (infiltration through a highly developed karst system) or the interception of draining faults.

In contrast, at the Nchanga copper mine, with $870x10^6$ m^3 pumping flow rate (period 1953 to 1978), there is an average increase of only 25 m^3/h, despite the expansion of the drainage both horizontally and at depth. This can be interpreted because of having reached the maximum potential input of the hydrogeological system. In this mine, the drainage boreholes show rapid increases in flow immediately after the beginning of the rainy season, suggesting an easy recharge from the surface (Stalker & Schiannini, 1978).

At the Mufulira copper mine (Zambia), the twenty-year record shows some increase with oscillations in the range of 3,000 to 4,250 m^3/h (Wightman, 1978).

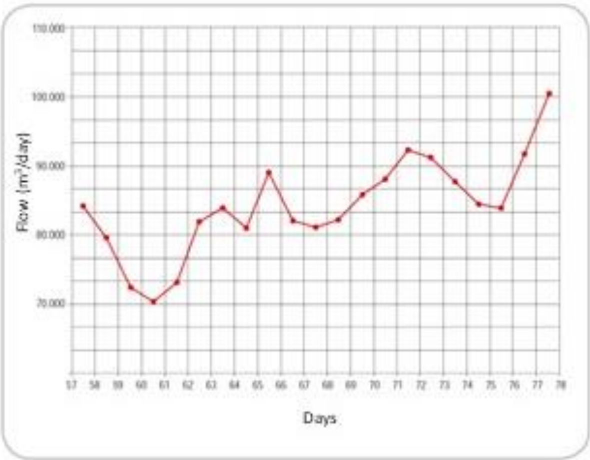

Figure 6-7: Average water pumping per day at Mufulira mine, Zambia (Wightman, 1978).

In the Aliveri underground lignite mine (Greece), a sudden inrush occurred in a transverse gallery of the -38 m sublevel. The initial 120 m^3/h of water doubled within two hours and reached 900 m^3/h two days later (Figure 6-8). It was necessary to close the gallery with a concrete dike, inject its downstream faces and, finally, inject cement through the drainage pipes of the dike, to isolate the water and to be able to continue extraction 27 days later (Marinos, Economopoulos, & Nicolau, 1978).

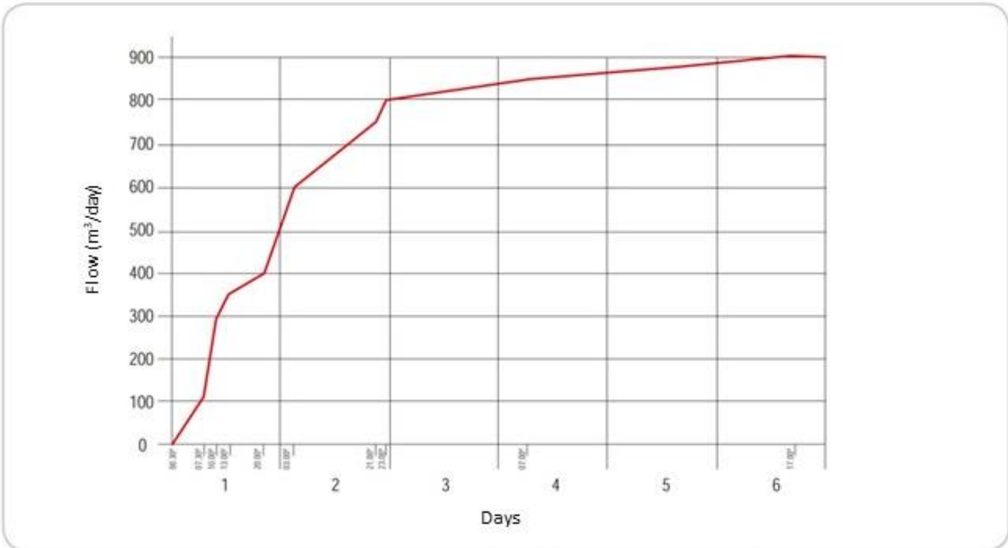

Figure 6-8: Evolution of a water irruption at the Alivieri Mine (Greece) (Marinos, Economopoulos, & Nicolau, 1978).

Pumping increase over time is also evident when analyzing the flows drained by the Pennsylvania coal mines, which increased from 68,220 m^3/h in 1941 to 93,960 m^3/h in 1975 (Growitz, 1978), as an effect of the increase in the area affected by open-pit mining. An improvement in the water pumped' s quality has accompanied this flow increase.

6.8 Evolution of constant drainage flow rate over time

There are frequent cases of mine drainage with a flow rate that remains relatively constant over long periods. This can occur due to several circumstances:

- By regulating the drainage through pumping wells, with their corresponding shut-off valves, to adjust the input to the installed pumping capacity.
- By the sum of the reduction in aquifer reserves, corresponding to a given drainage depth, and the increase due to the lateral extension of the mining operation.
- By a base input from the drainage of a multi-layered aquifer system, with drip inputs through an intermediate aquitard.
- Due to the decrease in drained aquifer reserves compensated by the increase in water supplied for mining works.

In this regard, the frequent decrease of permeability with depth significantly reduces water inflow as the mining depth increases. Schmieder provides a very instructive example for permeability variation in a set of Hungarian mines in various hydrogeological contexts (Schmieder, 1978). For our part, we observe the same behavior in mines operating in relatively homogeneous hydrogeological environments. Typical examples of this behavior are the pumping of the Konkola mine (Zambia), where the total pumping flow rate is regulated by controlling the opening or closing of valves systematically installed in the underground drainage boreholes (controlled water) (Mulenga, 1991). The Neves Corvo mine (Portugal) also shows a roughly constant flow evolution as a result of a situation of equilibrium between the reduction of flows due to the drainage of stored reserves and the increase caused by the continuity of deeper mining operations and by the extension by accessing new lateral ore bodies (Frasa Consulting Engineers, 1987).

At the Marquesado iron mine (Granada, Spain), due to induced recharge from subsurface aquifers partially isolated by aquitards, semi-constant flows were pumped for each drainage depth (Medina Salcedo, Fernández Rubio, & Gordillo Martín, 1977).

6.9 Drainage flow rate evolution decreasing over time

This behavior is normal when drainage or water inrush occurs under the following circumstances:

- Non-permanent regime drainage, by pumping with submerged pumps installed at a fixed depth, where the water column (and hence transmissivity) decreases as the conoid of depression decreases; and
- Drainage following a sudden water intrusion in the mine, for whatever cause.

The first case may occur throughout the mine's life or at different moments of staged drainage when new pumping levels are imposed. This behavior was observed in the Castilla iron mine (Guadalajara, Spain). An open pit mine drained by vertical pumping wells located on the periphery and inside the pit, each time it was necessary to reduce the water table to lower the bottom of the pit to a new floor (Fernández Rubio, 1974). We can also include the case of the Marquesado open-pit iron mine (Granada, Spain) whenever it was necessary to lower the dynamic level to deepen the pit.

6.10 Mixed flow evolution

In many cases, the evolution of the drained flow over time follows behaviors that combine those described above. This can occur due to controlled modification of the pumping flow or because the mining operation affects hydrogeological bodies with different characteristics.

7 Transboundary aquifers

Ramiro Martínez, Ariadna Callea, Daniel Chico

7.1 Definition

Groundwater is the most abundant source of freshwater on earth, accounting for approximately 97% of non-frozen freshwater. It is an essential natural resource that significantly contributes to human development. About 50% of the world's population drinks groundwater daily. It is often crucial to maintain rural populations that are far from surface water or infrastructure supply. Regarding food production, groundwater is estimated to contribute to over 40 percent of the world's irrigated crop production. Groundwater sustains ecosystems, maintains the base flow of rivers, and stabilizes land in areas with easily compressible soils. Aquifers can also buffer impacts resulting from seasonal variability and climate change. However, groundwater does not stop flowing at political borders, and large resources are stored in transboundary aquifers. Therefore, identifying, mapping, assessing, and developing governance mechanisms for transboundary aquifers are important tasks for ensuring the sustainability of these resources and peaceful cooperation between countries. 40% of the world's available water is transboundary (United Nations, 2022).

The United Nations International Law Commission's Draft Articles on the Law of Transboundary Aquifers (Draft Articles) define an aquifer as "a permeable water-bearing geological formation underlain by a less permeable layer and the water contained in the saturated zone of the formation". The Draft Articles further define a transboundary aquifer or a transboundary aquifer system as an aquifer or aquifer system with parts located in different States.

Therefore, several international bodies, institutions, and commissions between countries have been established worldwide to develop governance tools such as agreements, plans, and declarations to ensure water management.

Global groundwater resources assessment is one of the International Groundwater Resources Assessment Center's (IGRAC) main activities. In addition, IGRAC -as UNESCO/WMO (United Nations Educational, Scientific and Cultural Organization/World Meteorological Organization)- provides and promotes the global sharing of information and knowledge. In both activities, transboundary aquifers play a central role.

In 2000, UNESCO's Intergovernmental Hydrological Programme implemented the Internationally Shared Aquifer Resource Management initiative (ISARM), aimed at establishing a global inventory of transboundary aquifers and developing and supporting cooperation between countries through improving knowledge of transboundary aquifers. This initiative carried out regional studies to delimit aquifers, as well as to assess and analyze hydrogeological, legal, socio-economical, institutional, and environmental aspects.

There are now 468 identified transboundary aquifers and aquifer systems underlying almost every nation, an increase from 366 in 2015. The exact boundaries of a large number of transboundary aquifers are still incomplete, particularly at the local level, where transboundary aquifers may be small but vital for communities' livelihoods (United Nations, 2022).

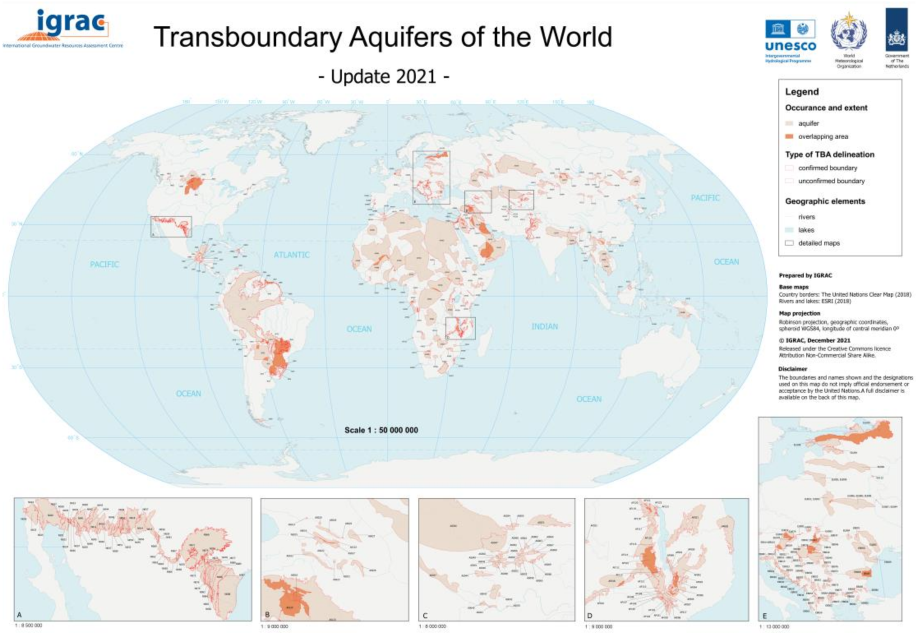

Figure 7-1: Transboundary Aquifers of the World. Illustration from IGRAC (IGRAC, 2021). For an enlarge version of this image click here or scan the QR code.

7.2 Water managements particularities

Rapid population growth and industrial and agricultural development place increasing demands on groundwater resources worldwide. From North Africa to Northern Europe, to Asia, to North and South America, cities have become critically dependent on groundwater, and water use for irrigation is also increasing. Potentially challenging conditions around international groundwater are intensifying in places as far afield as India and Bangladesh, across the Middle East, Mexico and the United States, and Libya and Egypt. Treaty provisions and international institutions with jurisdiction over groundwater, where they exist, have a very limited scope.

In many areas, surface water scarcity or quality, especially in arid or semi-arid regions, has encouraged farmers and municipalities to increase groundwater use. The result has often been overpumping of aquifers with consequent deterioration of water quality or even well depletion. This overexploitation can lead to severe conflicts in international aquifers beyond the transboundary zones. For example, rivalries over water resources in the region encompassing Israel, Jordan, and Syria (Hayton & Utton, 1992).

Groundwater, like surface water, often ignores political boundaries, and different countries share many large aquifers. For example, the Northeast African aquifer extends below Libya, Egypt, Chad, and Sudan; a critical European aquifer beneath the Rhine or an important aquifer underlying the Amazon River basin in South America. On the Arabic Peninsula, there are aquifers shared by Saudi Arabia, Bahrain, and perhaps Qatar and the United Arab Emirates, and Jordan. In most of these groundwater bodies there is a significant lack of data on the aquifers as a whole. Many of them are indispensable for agricultural and industrial companies. In addition, all these groundwater basins and their division by international boundaries may be in areas subject to intense current or future development processes. Unfortunately, only recently, the international community has turned its attention to the issue of international law and which institutions are appropriate for managing resources peacefully.

Generally, drivers of water stress are the same for domestic and transboundary aquifers. Political boundaries add specific challenges. Actions on the aquifer in one country can significantly impact the other side of the border. Large groundwater withdrawals in one territory can cause a lowering of the water table in a neighboring country. Sometimes, it can even cause groundwater flows to reverse across the boundary or impact systems that are hydraulically connected to the transboundary aquifer, for example, by reducing river flows or affecting groundwater-dependent ecosystems. In addition, aquifer pollution can cross political boundaries, causing potentially severe impacts on neighboring states and complicating any remediation efforts (United Nations, 2022).

The distribution of groundwater use-derived benefits is a relevant aspect of hydro diplomacy (Grech-Madin, Döring, Kim, & Swain, 2018), a process that can be applied at different stages of stakeholder interactions (from preventing to contributing to effective conflict resolution) and levels of intervention (from local to international authority) (Vij, Warner, & Barua, 2020) (Bréthaut, Gallagher, Dalton, & Allouche, 2019).

As a key policy tool, water diplomacy offers a stronger political commitment to co-management of shared waters. However, water diplomacy actors must also address water governance at the sub-state level. As a political, multilevel, and normative field, peace and conflict studies offer multiple approaches designed to bring together actors at all levels (Grech-Madin, Döring, Kim, & Swain, 2018). In addition, exploring both hidden and manifest interactions is fundamental to understanding cross-border negotiations.

7.3 Facing difficulties. Coordination

According to UN-Water, coordination at the regional level is crucial to address the specific water-related challenges faced by countries in each of these areas:

- Transboundary cooperation is lacking in most countries. Most countries do not have all their transboundary basin areas covered by operational agreements.
- Actions in one country have consequences in another.
- Overexploitation and pollution of lakes, rivers, and aquifers can threaten ecosystem services across borders.
- Upstream activities can negatively impact coastal resources. Depleted aquifers can allow saltwater intrusion in coastal areas and increase the concentration of arsenic and fluoride, and other toxic substances.
- Governments must cooperate on transboundary water resources management. More cooperation is essential, especially in areas vulnerable to the impacts of climate change and where water is already scarce. Transboundary basins and aquifers create a hydrological, economic, and social nexus between communities living in border areas and beyond.

Water management is, by definition, conflict management. Its management is usually divided and often subject to unclear and/or contradictory legal principles. There is no single objective water management: all water management is multi-objective.

There is a widespread thought that in shared waters, countries tend to manage them unilaterally to avoid problems and potential conflicts affecting their neighbors. Still, this would happen at some point, even without cooperation. Although the potential for endless disputes is exceptionally high in shared basins, history shows that water can catalyze dialogue and cooperation.

Improved water cooperation is achieved by focusing more attention on water management, water capacity development, or hydro-education of officials, and overall improving water governance. When the problem crosses borders, politicians get involved and the international community begins to focus on the transboundary basin and the potential conflict.

Another problem-multiplying factor in transboundary aquifers is climate change. When water agreements are reached, specific hydrology is assumed. But hydrology changes. For example, in the case of the U.S. and Mexico on the Colorado River, the scenario adopted had more water than average, but much more water than there is now due to its multi-decade drought (Wolf, 2022).

According to Aaron Wolf, “this could be an opportunity because the stress forces people to pay attention. There was a certain danger when water was ‘easy’; you used it once, you polluted it and you sent it downstream. We can now monitor dams and groundwater across borders from satellites, we have access to understanding what is happening in ungauged basins. Moreover, tools and approaches are getting better and better precisely to deal with the growing threats that we are facing” (Wolf, 2022).

Referring Francesco Sindico’s words, there are two key factors regarding international law and transboundary aquifers. The first one is what are the rules, if any, that two countries willing to manage a transboundary aquifer can consider. Most of these can be found in the United Nations International Law Commission Draft Articles on the Law of Transboundary Aquifers. Still, the legal mosaic is much more complex and includes the United Nations Watercourses Convention, the UN Economic Commission for Europe Water Convention, and its Model Provisions on Transboundary Groundwaters.

Once the regulations are known, the second question for the two countries is how to apply them to the real scenario.

A great example of cooperation is the Albufeira Convention. Signed between Spain and Portugal, it represents the continuity of the tradition of treaties that the two countries have reached since the 19th century for the management of transboundary rivers (Escuder, 2022).

The agreement's official name is "Agreement on cooperation for the protection and sustainable use of the waters of the Spanish-Portuguese hydrographic basins”. It includes the provisions of the European Union's Water Framework Directive, which establishes that each country may prepare the part of the hydrological plan referring to its territory in the case of international river basin districts.

The agreement requires Spain to provide Portugal with minimum volumes of water every year, quarter, week, and, in some cases, every day. The requirement is established for each river and in locations close to the border to guarantee minimum flows at certain times and specific points (control stations).

7.4 Specific cases

There are very few cases worldwide of international agreements regarding transboundary aquifers in force. Some examples are: the Genevese aquifer (France, Switzerland), the Northwestern Sahara Aquifer System (Algeria, Libya, Tunisia), the Nubian Sandstone Aquifer System (Chad, Egypt, Libya, Sudan), the Guarani Aquifer (Argentina, Brazil, Paraguay, Uruguay), the Saq-Disi Aquifer (Jordan, Saudi Arabia), and the Calcaires Carbonifères (Belgium, France) (United Nations, 2022).

Genevese aquifer

The Genevese aquifer extends over 19 km between the Lake of Geneva and the Rhône River on the western side of the canton of Geneva. Its width varies between 1 and 3,5 km, and the aquifer lies partly across the French border. Waterlogged gravel may reach up to 50 m. Depending on topographic conditions, the average water level may range between 15 m and 80 m deep (De los Cobos, 2018).

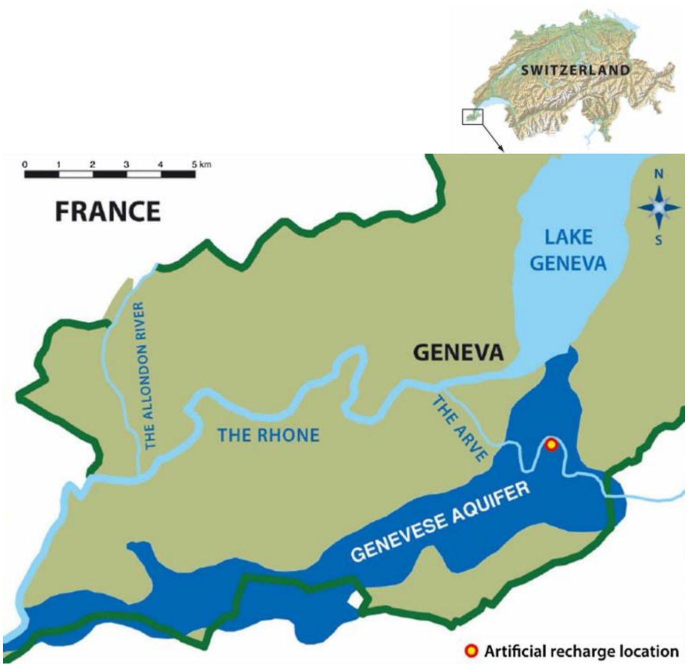

Figure 7-2: The Genevese aquifer (De los Cobos, 2018)

Lake Geneva and Genevese groundwater provide drinking water to nearly 700.000 inhabitants of Geneva and the neighboring French region. The groundwater, shared by the municipality of Geneva, Switzerland, and the department of Haute-Savoie (Upper Savoy), France, is exploited on both sides of the border thanks to ten water catchment wells in Switzerland and four in France. In the 1960s and 1970s, groundwater levels dropped drastically due to the large quantity of uncoordinated pumping carried out by the distribution entities and users in Geneva and across the border in France. Wells that had dried up had to be closed. At that moment, the first technical discussions took place both in France and in the canton of Geneva to find solutions to stop the overexploitation of the aquifer. Political leaders began to consider artificial groundwater recharge to preserve this shared resource.

Finally, the State Council of the Republic and the canton of Geneva, and the Prefecture of Haute Savoie (Upper Savoy) signed an agreement on June 19, 1978. The main reason for the agreement was "the need to establish a system for joint use of Genevese groundwater so as to protect that natural resource and preserve its water quality" − a rationale that proved to be justified from the very start. The agreement allows the Canton of Geneva to build and operate the groundwater recharge facility, of which it remains the sole owner. The State of Geneva may delegate the plant operation to a third party (water rights).

The agreement is for 30 years and is tacitly renewable for 5-year periods unless terminated by either party one year in advance.

Due to the radical change in demographics and the economic attractiveness of the Genevese region, there is an ever-greater trend toward establishing a cross-border approach. A committee on a "transboundary water community" was formed in 2007. This water community is included in the Franco-Valdo-Genevan regional project. It creates a joint strategic environmental vision for the entire territory and covers the heritage, social and economic aspects.

The successful management of Genevese groundwater was the basis for establishing this transboundary water community which was made official with the signing of a memorandum of understanding for cross-border water cooperation on December 12, 2012. This demonstrates the recognition given to the commission's almost 40 years of work. Despite the difficulties and the efforts needed to make it even more effective, the commission aims to create effective, beneficial, and dynamic cross-border relations (De los Cobos, 2018).

The Genevese groundwater memorandum is an unusual example of a transboundary agreement on aquifer management between communities belonging to the European Union and a Swiss canton. It is the result of what could be considered the legal validation of a pragmatic approach.

Amazon basin

The Amazon basin occupies the entire central and eastern area of South America, extending from the Andes Mountains to the Guyana Plateau in the north and the Brazilian Plateau in the south. The basin covers approximately 44% of the land area of South America, covering parts of Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, and Venezuela. It is characterized by a wide climatic and topographic variety, with elevations ranging from sea level at the mouth of the Amazon River up to 6,500 meters above sea level in The Andes (United Nations, 2022).

Initially it was defined as an Aquifer System since it is formed by several interconnected aquifers. This area also has smaller aquifers; some are being studied, and others lack basic knowledge.

Thus, coordinated actions between countries are required to delimit the boundaries of the Amazon Aquifer System.

For example, the aquifer systems of Leticia (Colombia) and Tabatinga (Brazil) make up a single transboundary aquifer, which in turn represents a subsystem of the great hydrogeological basin of the Amazon Aquifer System, as it was preliminarily called. According to the Strategic Actions Program - Regional Strategy for the Management Integrated Water Resources of the Amazon Basin within the watershed are (United Nations, 2022):

- The Boa Vista Aquifer System is located in Roraima and partially in Venezuela and Guyana, covering about 14,900 km².
- The Solimões Aquifer System has a recharge area of about 457,600 km² (Gomes, 2008) and is mainly located in the state of Acre, partially in Bolivia and Peru, and in the west of the state of Amazonas.

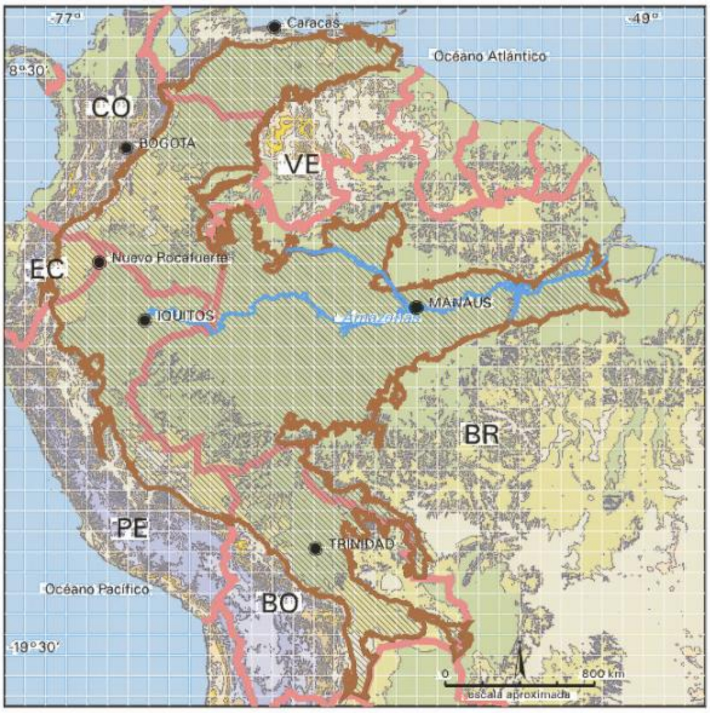

Figure 7-3: Amazonas aquifer system. Illustration from "Transboundary aquifer systems in the Americas. Preliminary assessment" (UNESCO-IHP/OEA/IGRAC, 2007). For an enlarge version of this image click here or scan the QR code and refer to page 125.

The Amazon aquifer system covers the hydrogeological provinces of South America called Amazonas and Orinoco, where several types of aquifers are made up of unconsolidated and consolidated sediments. In Brazil, it presents a large extension and a thickness of up to 2,200 m as a free aquifer, also found in confined conditions and great thickness. In Venezuela, it corresponds to the Orinoco Province and physiographically corresponds to the Venezuelan plains, with an approximate area of 200,000 km². It is characterized by well-performing aquifers and by the quality of the waters (UNESCO-IHP/OEA/IGRAC, 2007).

Considering that it is in a low-inhabited region and difficult to access, the aquifer is still little known. A more profound knowledge of the part of the countries where it is located is necessary for a better characterization, knowing its limits, geometry, potential, and hydraulic characteristics. In Brazil, it is known that the chemical quality of the water is good. However, in microbiological terms, there are limitations for human consumption in urban areas due to the high natural vulnerability (the aquifer has a high-water table, close to the surface) and the high potential for contamination due to poorly constructed wells, absence or poor sanitary protection, and lack of basic sanitation, mainly in the urban areas.

Most of the Amazon aquifer system corresponds to the vast Amazonian plain in the central and eastern parts. Despite the abundance of surface water, groundwater is widely used by the six countries.

The population is located in riverside cities, indigenous communities, and the plains on the left bank of the Orinoco. The primary use is for local human supply, mainly in the capitals. The Amazon aquifer is vital for many riverside communities as it is the only alternative resource due to natural and anthropic contamination of surface water.

Nowadays, ACTO (Amazon Cooperation Treaty Organization), in its regional action framework for water resources management, is implementing four surface water projects and one groundwater initiative. This framework includes the fundamental pillars necessary for water security in the region. The Multisectoral Nexus model for the Amazon Region, jointly with the Inter-American Development Bank, and technical cooperation, aim to increase regional knowledge to better address actions on drinking water supply, basic sanitation, and solid waste management services (ACTO, 2021).

In addition, the project for the Implementation of the Strategic Actions Program (SAP) between ACTO and the United Nations Environment Program (UNEP) will implement thirteen national projects to strengthen government and local community capacities to respond to extreme hydro-climatic events and the impacts of climate change in the region.

The Regional Action in the Area of Water Resources initiative between ACTO and Brazil's National Water and Basic Sanitation Agency (ANA) enables the development and implementation of shared networks for hydrometeorological water quality monitoring in the Amazon Basin. In addition, it is helping to provide a regional database on water resources and climate change and the development of protocols for regional information exchange for the different monitoring networks, enabling regional monitoring of SDGs 6 and 13 (ACTO, 2021).

Guarani aquifer

One of the most important aquifers in South America is the Guaraní Aquifer, located in the Río de la Plata basin system in Brazil, Paraguay, Argentina, and Uruguay. It covers over 1.2 million km² and has an average annual discharge of 40 to 60 km³. There are already more than 2,600 wells in the region, providing water for more than 500 urban centres. In Brazil, it covers an area of approximately 850,000 km² (9.9% of the territory); in Argentina 225,000 km² (7.8%); in Paraguay 70,000 km² (17.2%) and Uruguay 45,000 km² (25.5%) (Hispagua, 2022).

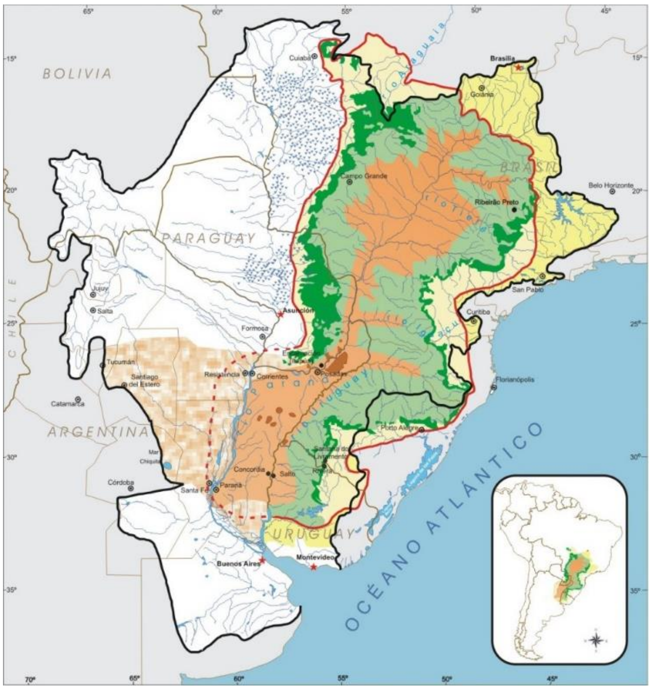

Figure 7-4: Guarani aquifer system. Illustration from ICAA (Instituto Correntino del Agua y del Ambiente, 2022). For an enlarge version of this image click [here] or scan the QR code.

Brazil is the country that withdraws the most groundwater, totally or partially supplying between 300 and 500 cities; Uruguay has 135 public water supply wells, some of which are used for thermal exploitation. There are about 200 wells in Paraguay, mainly for human use. In the east of Argentina (Entre Ríos province), there are five freshwater thermal springs and one saltwater spring. In contrast, in the west there is only one thermal saltwater spring, which causes specific problems due to the salty effluent.

Due to the large water abstraction and its impact on the sustainability of the aquifer, in 2005, the countries initiated joint activities through the General Secretariat of the Guarani Aquifer System Project to consider the aquifer's future. This initiative succeeds in reducing the hydro-political vulnerability of the aquifer while the countries work together to mitigate conflicts, sustainably manage groundwater and share groundwater-related information (Hispagua, 2022).

The agreement on the Guarani Aquifer, ratified by Argentina, Brazil, Paraguay, and Uruguay, entered into force on November 26, 2020. This agreement on the management, conservation, monitoring, and sustainable use of the Guarani Aquifer's transboundary water resources represents a benchmark in the actions to be adopted regarding the management of the aquifer's water resources and urges these four countries to promote the conservation and protection of the environment, to ensure "the multiple, rational, sustainable and equitable use of its water resources". It was also agreed to establish a Commission made up of the four States, which will coordinate cooperation among them to achieve the principles and objectives of the agreement.

CAF (Development Bank of Latin America), in its role as implementing agency of the Global Environment Facility (GEF), received since November 2019, the confirmation that the Project "Implementation of the Guarani Aquifer Strategic Action Program: enabling regional actions" was approved by the GEF Secretariat as a medium size project with a grant amount of USD 2 MM (in millions of US dollars). This initiative results from the cross-border coordination effort between Argentina, Brazil, Paraguay, and Uruguay, which have been working together since 2009 due to the Strategic Action Program (SAP) development (CAF, 2021).

Nubian Sandstone Aquifer System

The Nubian Sandstone Aquifer System (NSAS), shared by four countries in northeast Africa (Chad, Egypt, Libya, and Sudan), is the world's largest "fossil" groundwater aquifer, covering some two million square kilometers. Its large freshwater reserves have the potential to meet the countries' growing demand for water. However, if not carefully managed, the aquifer faces overexploitation and eventual depletion, as its water is ancient and non-renewable. The four Nubian countries have agreed on a framework to jointly manage the Nubian aquifer to optimize the equitable use of the shared groundwater resource and its sustainability (IAEA, 2013).

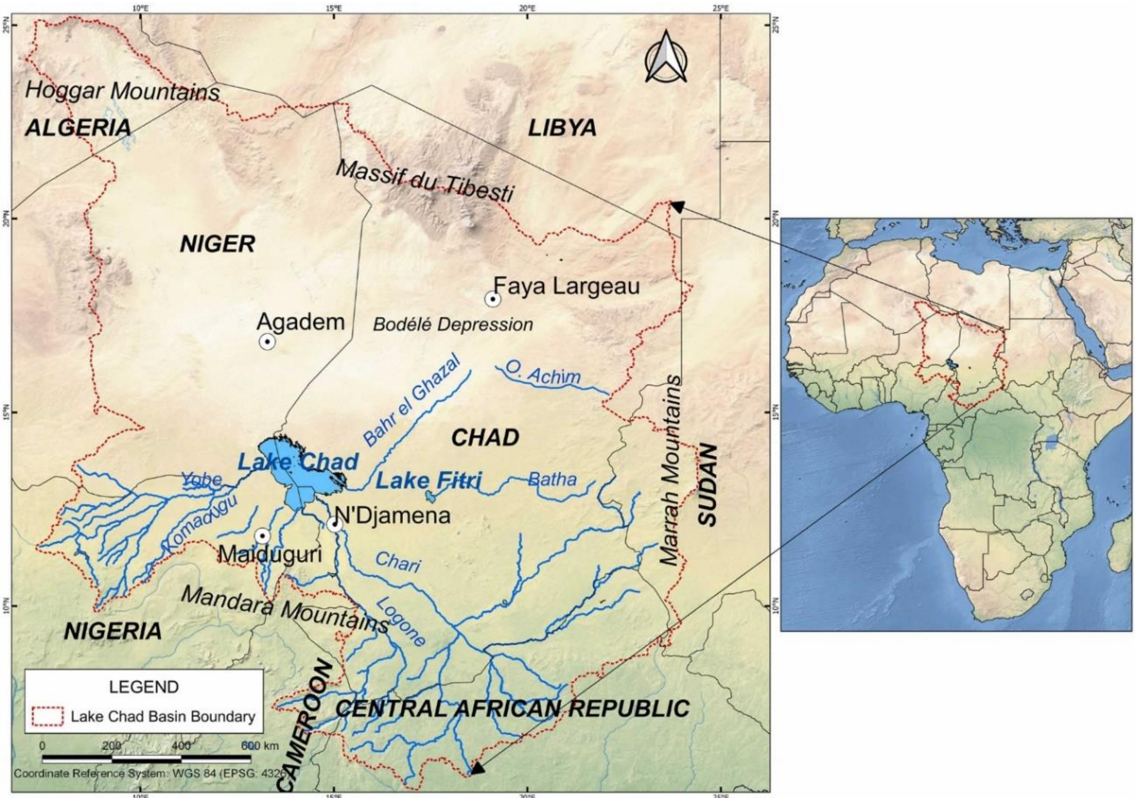

Figure 7-5: The Lake Chad Hydrologic Basin. Illustration from "The Lake Chad transboundary aquifer. Estimation of groundwater fluxes through international borders from regional numerical modeling" (Vaquero, et al., 2021).

In recent decades, the water surface area of Lake Chad has reduced from approximately 25000 km² in 1963 to less than 2000 km² in the 1990s, heavily impacting the basin's economic activities and food security. In the Sahelian area, direct infiltration from rainfall through the unsaturated zone is usually extremely low. For the Lake Chad drainage basin, recharge of the phreatic aquifer is mainly due to infiltration from watercourses, floodplains, and the edges of Lake Chad.

The Lake and its basin resources provide livelihoods for some 47 million people (IAEA, 2013), mostly farmers, fishermen, and livestock owners. But today, the resources are rapidly decreasing due to several decades of droughts and desertification caused by reduced rainfall, strong winds, and rising temperatures in the Sahel region. Some population sectors, along with their herds, have migrated south.

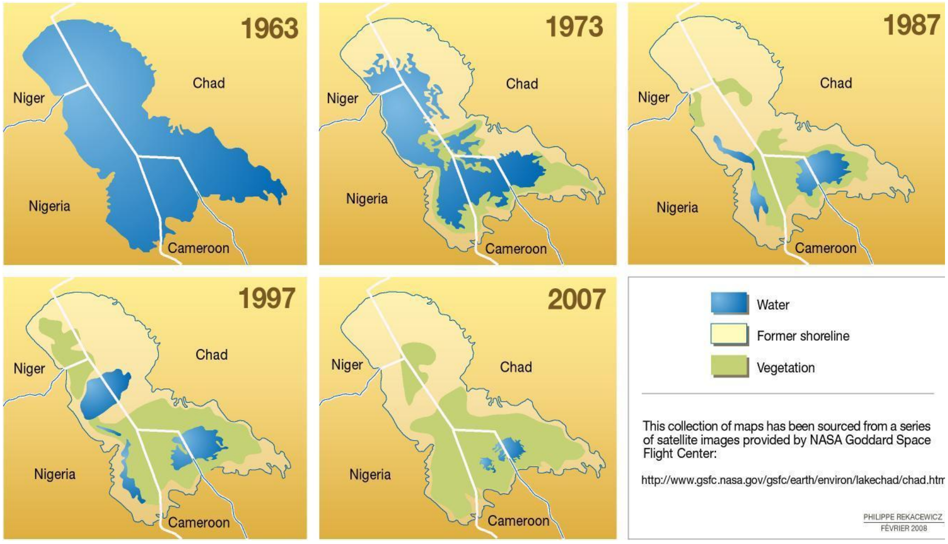

Figure 7-6: Lake Chad resource changes between 1963 and 2007. Illustration from GRID-Arendal (GRID-Arendal, Philippe Rekacewicz, 2006). For an enlarge version of this image click here or scan the QR code.

On 18 September 2013, the Governments of Chad, Egypt, Libya, and Sudan formalized an agreement for joint management of the shared aquifer (Strategic Action Programme -SAP). This program provides a framework for agreed collective actions to manage the aquifer. Specifically, it outlines the legal, policy, and institutional reforms needed to address the major transboundary problems affecting the aquifer and their causes at the regional and national levels (IAEA, 2013).

The agreement results from a joint project of the IAEA and the United Nations Development Programme-Global Environment Facility (UNDP-GEF) in cooperation with the United Nations Educational, Scientific and Cultural Organization (UNESCO). The project aimed to assist the four African countries in establishing a regional program framework by improving scientific data by preparing a Shared Aquifer Diagnostic Analysis (SADA). It also aimed to improve cooperation between the countries sharing the aquifer.

The current situation of more than 90% reduction of Lake Chad has been described by the Food and Agriculture Organization (FAO) as an ecological catastrophe. As noted by a former Nigerian President, Olusegun Obasanjo in 2015, "Lake Chad may no longer exist in 30 years' time. Hence, we must ensure that the 47 million people who depend on this lake for survival are prepared for the worst possible scenario. There is an indication that the Nubian Sandstone Aquifer (NSA), which extends to Chad, could be the sustenance of the lake. It is realistic to face the fact that regardless of whether the lake level rises, is maintained or completely dries out, the basin is foreseen to experiencing increasing desertification, which in turn will result in increased food insecurity in the region" (Amali, Bala, & Adeniji, 2016).

Since 2018, a project has been in progress to enable the implementation of the SAP of the Nubian Sandstone Aquifer System. The project addresses the key objectives identified in the agreed SAP on reforming/updating legal, policy, and institutional arrangements, strengthening capacity, and implementing collective actions within the four countries and at a regional level to protect Nubian aquifer resources and associated ecosystems. The objective of the project is to begin implementing the regional SAP through legislation, policy, and support for: rational and equitable integrated management, socioeconomic development, and protection of the ecosystem and aquifer resources in the four riparian countries. Since the development of SADA (the process by which cross-border threats are identified and prioritized) and SAP, valuable information and data have been generated through the activities of national organizations (UNESCO-IHP, 2022).

Through strengthening national institutions and regional Joint Authority, this project contributes to supporting the effective operation of the Joint Authority to coordinate the management of the NSAS.

7.5 International initiatives. UNECE

International water law was initially developed for surface waters. Concern for groundwater began progressively with the growing awareness of the importance of transboundary aquifers.

An example is the Convention on the Protection and Use of Transboundary Watercourses and International Lakes, UNECE (Economic Commission for Europe) Water Convention, which entered into force in 1996 and was extended to non-UNECE member states in 2003 (UNECE, 2022). The Convention is a unique legally binding instrument that promotes the sustainable management of shared water resources, the implementation of Sustainable Development Goals, conflict prevention, and the promotion of peace and regional integration.

The Water Convention requires parties to prevent, control and reduce transboundary impact, use transboundary waters reasonably and equitably, and ensure their sustainable management. Parties bordering the same transboundary waters are required to cooperate by signing specific agreements and establishing joint agencies. As a framework agreement, the Convention does not replace bilateral and multilateral agreements for particular basins or aquifers. Its objectives are quite limited to existing agreements (e.g., Albufeira), but it encourages their establishment, implementation, and further development.

The Convention was originally negotiated as a regional framework for the pan-European region. Following an amendment procedure, since March 2016, all UN member states have been able to accede to it. Chad and Senegal became the first African Parties in 2018. Ghana then acceded in 2020 and was followed by Guinea-Bissau and Togo in 2021. The accession of these countries offers new opportunities for enhanced cross-border cooperation in sub-Saharan Africa, conflict prevention, and regional stability (UNECE, 2022).

The world is far from achieving Sustainable Development Goal 6 on water and sanitation. To achieve this critical goal, the UN system, the international community, and national governments must work significantly faster and smarter, maximizing synergies and providing countries with more effective support. For that reason, UN-Water's work focuses on enabling data-driven acceleration and coordination to achieve SDG 6 and other international water-related commitments (United Nations, 2022).

SDG Target 6.5 emphasizes the importance of transboundary cooperation "By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate." But why should we monitor transboundary cooperation? This monitoring allows countries to assess the current status of cooperation with neighboring countries and set targets for improved coordination.

Indicator 6.5.2 tracks the percentage of transboundary basin area within a country that has an operational agreement for water cooperation. This is understood as a treaty, convention, or other formal bilateral or multilateral agreement between riparian countries that provides a framework for cooperation.

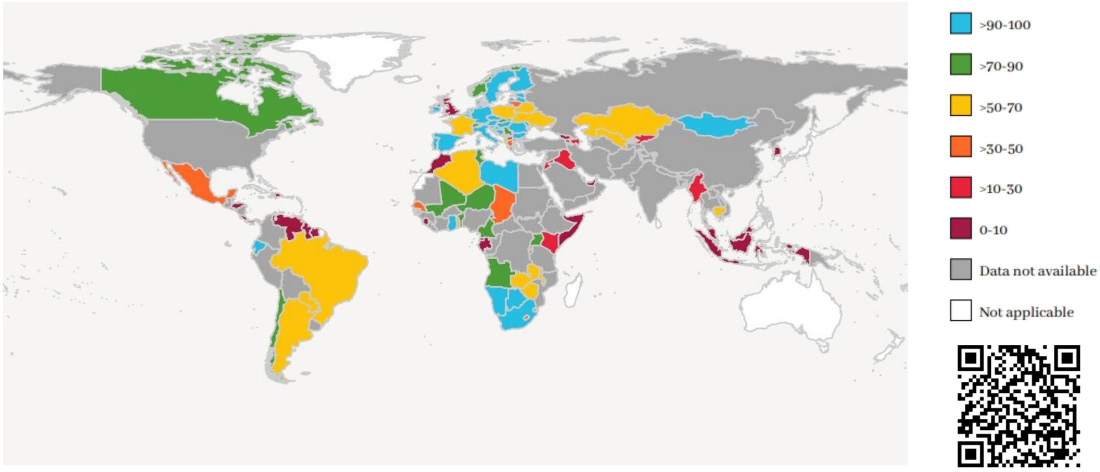

Figure 7-7: Proportion of total surface area of transboundary basins (river, lake, or aquifer) within a country with an operational arrangement for water cooperation in force. Image from UN-Water, Progress on Transboundary Water Cooperation (SDG target 6.5) (UN-Water, 2022). For an enlarge version of this image click here or scan the QR code.

Bilateral agreements are the primary source of international law because they can create obligations for the two signatory countries. They represent an international legislative function. Therefore, treaties can be considered the first instance for neighboring countries to establish boundary issues and, consequently, the sovereignty of their territories and natural resources, such as transboundary aquifers.

7.6 The role of engineering

Engineers can play a key role in most issues related to transboundary aquifers. Technicians should support some tasks, especially in transboundary planning and management agreements. Among others, some examples of these tasks are:

- The characterization of the aquifers and include, in these agreements, sufficient criteria to evaluate and distribute the benefits (economic productivity of the water) and the costs (investment needs for exploitation and monitoring). Among other reasons, this provides the opportunity to obtain direct funding from international institutions or mixed funding schemes.
- The need to have appropriate aquifer simulation models agreed upon by the parties involved to propose equitable and/or proportional formulas for sharing water resources. These studies represent a very valuable basis for future integrated management of surface and water resources in the countries concerned.
- Sufficient and adequate control and monitoring networks to provide the necessary data for the calibration and exploitation of these models. There is an inherent difficulty in building models if data quality is inadequate.
- Procedures to ensure transparency in the information exchange between the parties: definition of protocols, periodicity, formats, and resolution of discrepancies. A key factor is the role of an agent to monitor the agreements and the plans that are implemented, as well as control the fulfillment of the agreed objectives and deadlines.

All of the above requires highly qualified and skilled professionals who can provide the necessary expertise and support to the institutional arrangements. In addition, it is necessary to have a solid background to give the appropriate support for policy decisions based on these key elements.

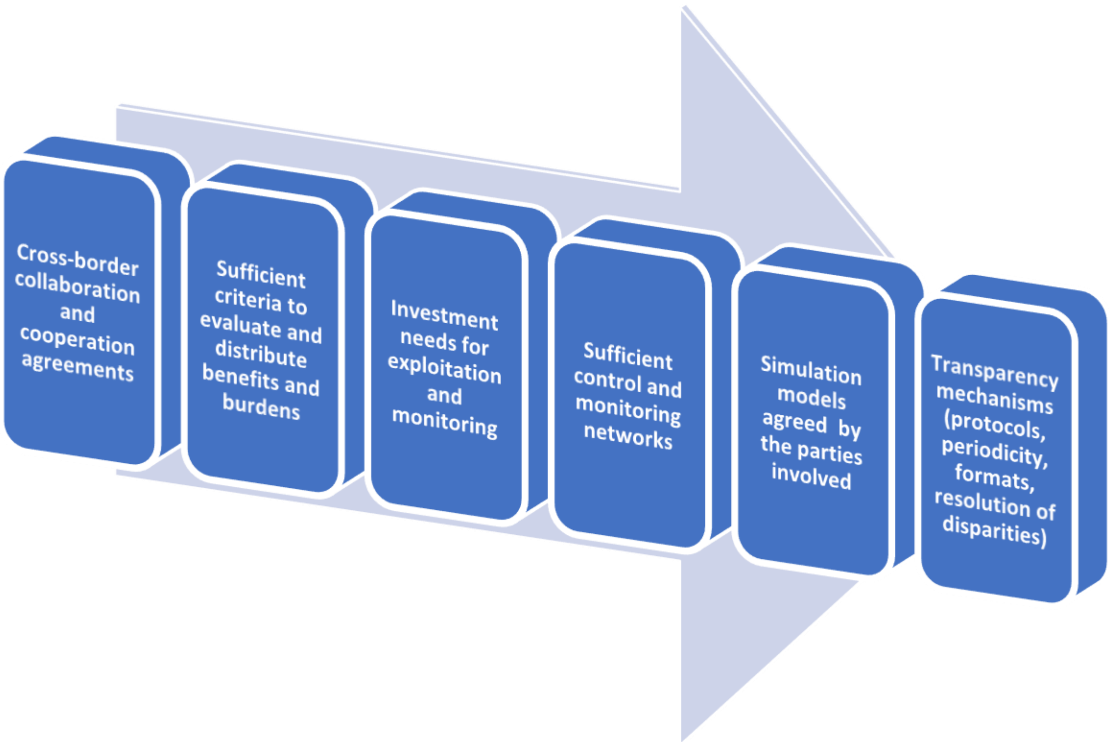

Figure 7-8: The role of engineering in supporting the implementation of transboundary agreements (planning and management). Illustration prepared by the author.

7.7 Conclusions, remarks, and observations

Transboundary aquifer cooperation has the potential to generate significant benefits, especially in areas vulnerable to the impacts of climate change and where water is already scarce. Transboundary basins and aquifers create a hydrological, economic, and social nexus between communities living in border areas and beyond. The resilience of local communities is strengthened by improved capacity and mutual learning to solve common challenges related to natural resource scarcity and security, food security, and climate change, as well as the preservation of sensitive ecosystems (United Nations, 2022).

Bilateral cooperation and management are required to achieve sustainable use of water resources and provide security to States and the people that share transboundary aquifers. Knowledge of the exact amount of water that can be withdrawn is crucial to ensure development and protect the environment. The key questions to answer are how much, when, how, and by whom. For this purpose, it is essential to have reliable data, science-based information, and well-developed monitoring networks to determine the part or proportion of the aquifer that a State has the right to use; and, on this basis, to reach agreements or operational memorandums. Bilateral agreements are the main source of international law; this national and international link is key in managing a transboundary aquifer. Moreover, in the absence of treaties, conventions, or any international agreement, the International Court of Justice plays a key role in the deliberation of international disputes.

Regarding the future, the central concern is adaptation efforts against climate change. This requires a governance effort based on solid and robust data, models, and monitoring networks that can provide the basis for decision-making. In addition, the transboundary basin countries must receive funds to prepare national adaptation action plans for sustainable development to address the expected impacts of climate change. Moreover, the international community could assist in providing insurance against climate risks. Initiatives towards this purpose could spread risk, ensure the continuity of government operations after a significant loss and, most importantly, help ensure appropriate adaptation measures.

Engineers can play a crucial role in transboundary issues, especially in their support for the operation of cross-border planning and management agreements. Highly qualified professionals are required to provide the necessary technical expertise and support to the institutional agreements but also to the control and monitoring networks that provide the required data to the calibration, operation, and monitoring of the simulation models.

8 Vulnerable groups and groundwater: leaving no one behind

Natalia Gullón

8.1 Why raise the issue of groundwater and vulnerable populations?

Globally, groundwater resources account for about 99% of the Earth's total liquid freshwater (United Nations, 2022) and already constitute half of the water withdrawn for domestic use. Therefore, they are an essential resource for ensuring the human right to water for people, especially for the most vulnerable populations, who depend on them to a greater extent to ensure their drinking water supply for water consumption, hygiene, and food preparation. However, the current context of population growth, overexploitation, and increasing pollution of groundwater, together with the variation in available quantities due to climate change, means that available groundwater is decreasing, strongly impacting the populations that depend on it. In other words, not only the water security of these populations is at stake, but also their food security and health. However, according to the United Nations (United Nations, 2022), one-third of groundwater facilities in rural areas are persistently polluted by pathogens. It is necessary to place the issue of groundwater-vulnerable populations on the agenda if we want to ensure water availability, sustainable management, and sanitation for all by 2030, as set out in Sustainable Development Goal 6. This is also key to post-pandemic recovery and preventing future easily transmissible diseases. This chapter focuses on human consumption as a priority use aimed at satisfying the human rights to water and sanitation, not addressing other uses such as agricultural or industrial.

Figure 8-1: Family at the well, Bolivia. Peri urban Water and Sanitation Program, PHASE I (BOL-001-M) of the Cooperation Fund for Water and Sanitation, Spanish Agency for International Development Cooperation (AECID).

8.2 Who are the vulnerable groups?

People in vulnerable situations can be defined as those who, "because of their age, gender, physical or mental health, or because of social, economic, ethnic or cultural circumstances, find it particularly difficult to fully exercise their rights", as established by the Violence Observatory of Peru. It is, therefore, a heterogeneous category that sometimes responds to historical reasons and others to contingent situations and may be motivated by different forms of discrimination.

There are, unfortunately, many causes of discrimination related to water and sanitation, among which poverty generally ranks high, according to the United Nations World Water Development Report 2019 (WWAP -UNESCO World Water Assessment Programme-, 2019). It is common to identify ethnic, religious or linguistic minorities, indigenous peoples, refugees and migrants, people of certain descent (e.g. castes) and in general rural populations as vulnerable groups, as it is found that there is a substantial gap in access to water and sanitation in these communities. Furthermore, in many places, women and girls often suffer inequalities and discrimination in exercising their human rights to safe drinking water and sanitation.

Indigenous peoples have been historically marginalized and have seen their values, knowledge, and lifestyles systematically ignored and poorly recognized, which has led to their exclusion from decision-making processes and public policies. However, indigenous communities have a special relationship with springs and wetlands, as they consider that these have an intrinsic value that goes beyond the services they provide to people (United Nations, 2021). And this is indeed the case, as stated in the report Groundwater: Making the invisible visible.

Subterranean ecosystems also provide important ecosystem services, such as storing and providing water resources, attenuating contaminants, and controlling disease (Griebler & Avramov, 2015). "Indigenous peoples can be key actors in sustainable development. In many cases, indigenous peoples' knowledge systems and traditions have maintained a sustainable balance with their living environment, including its water, for thousands of years" (WWAP-United Nations World Water Assessment Programme-, 2017). "Their value expands well beyond the cultural sphere that brought them to life" (UNESCO, 2018).

Women and girls are also the main water and solid fuel collectors in households without access to an improved water source and clean energy in their homes, with adverse implications for their health and safety (UN Women, 2018), in three out of four households without access to drinking water in their homes, the responsibility for providing water is assigned to women and girls. Their informed participation in water management decisions is therefore essential, not only for the realization of the human rights to water and sanitation but also to ensure that services are sustainable over time. In this regard, to guarantee their participation, it is necessary that they can express their opinions and assert their needs because they "play a central role in the provision, management, and safeguarding of water", as already stated in the Dublin Principles, established three decades ago, during the International Conference on Water and the Environment held in the Irish capital in 1992 (ICWE, 1992)-

Rural populations are closely linked to the territory, ecosystems, rivers, springs, and wells on which they depend, as they are mainly supplied by rainwater storage tanks, surface water sources, springs, and wells. This is mainly due to the lack of other types of infrastructure, as they are generally located in remote areas -sometimes almost isolated- and sometimes suffer from a lack of attention by the administrations regarding the enjoyment of public policies. Similarly, rural areas generally receive fewer investments in water and sanitation initiatives.

Figure 8-2: Housewife in the community of San Francisco in the Department of Alto Paraná, Paraguay. © Miguel Lizana/AECID.

Furthermore, disability, health status, or age can also be determining factors. People with intellectual, physical, or sensory disabilities are disproportionately represented among those without access to safe drinking water and sanitation. Differences in ownership -of land or residence- and social and economic status can also lead to discrimination (WWAP -UNESCO World Water Assessment Programme-, 2019).

Displacement settlements, both temporary and permanent, and prisons deserve special attention, as they tend to be densely populated and need to be provided with adequate drinking water and sanitation services.

This is not intended to be an exhaustive list of vulnerable groups, and it is also important to keep in mind that some people may experience multiple forms of discrimination or inequality at the same time. The key is to ask ourselves: Who is being left behind? Unfortunately, various causes of discrimination, marginalization, exclusion, and inequalities hinder progress toward the human rights to safe drinking water and sanitation and the 2030 agenda.

Therefore, the situation of people regarding groundwater must be approached from a human rights-based perspective. Water, like sanitation, is a human right explicitly recognized by the United Nations General Assembly in July 2010. The role of the State as duty bearer is fundamental, so it is necessary to promote public policies that promote the efficient use of financial resources and adequate management of water resources (sustainable, participatory, and transparent), that promote universal access and explicitly address exclusion and inequality to leave no one behind, following the spirit of the 2030 agenda.

Human rights commitments oblige States to work towards universal access to water and sanitation in an accessible, sustainable, safe, and culturally acceptable manner, without discrimination and giving the most vulnerable people the opportunity. The human rights to water and sanitation are indispensable to human dignity. They are closely linked to other rights, such as the right to life and health, the right to a healthy environment, the right to food, to work, and to freedom of movement. Therefore, good water resources management and water governance are essential. According to the United Nations (UN WWDR 2019), the human rights-based approach can provide a very useful perspective for understanding and implementing integrated water resources management, emphasizing accountability, participation, and non-discrimination principles (WWAP -UNESCO World Water Assessment Programme-, 2019).

The water governance principles established by the OECD focus on the importance of promoting "stakeholder engagement for informed and outcome-oriented contributions to water policy design and implementation". It highlights that special attention should be paid to underrepresented categories (youth, poor, women, indigenous people, and domestic users) (OECD, 2015).

Figure 8-3: Carrying water from the old community well in Cañales de Bijagual to their homes. Source: Plan Triple A (Portoviejo, Ecuador).

8.3 World situation

Millions of people in the world depend on groundwater resources. It is estimated that almost 50% of the world's urban population is currently supplied by groundwater. This means that a large number of cities depend on groundwater resources, and this dependence is increasing. Also, private wells are built to extract water from aquifers through manual drilling or excavation in peri-urban areas and informal (unplanned) settlements where public water services are unavailable. The same applies to rural areas. But these people do not have the certainty that this water source will last over time because of additional water withdrawals, groundwater contamination, and saline intrusion in the aquifers, among others. In addition, some people who depend on groundwater lack basic decision-making skills: information on the impact of climate change, the water cycle, etc.

Currently, water scarcity due to drought affects almost 40% of the world's population (United Nations, 2022). This situation may be exacerbated in some regions by population growth and the effects of climate change (UN 2019). According to experts, 500 million more people will suffer from such shortages for every degree Celsius rise in global temperature. Groundwater resources are the hidden treasure that can help increase basic access to safe drinking water sustainably and affordably, especially for undersupplied rural populations in most parts of the world, particularly in scattered rural populations or in the aridest areas of the planet. Its use is crucial not only for direct consumption but also for sanitation systems, industry, agriculture, and ecosystems.

Box 8.1: **The Spanish Agency for International Development Cooperation (AECID).**

The Spanish Agency for International Development Cooperation (AECID) is the main management body of the Spanish Cooperation, oriented to the fight against poverty and sustainable human development. AECID depends on the Ministry of Foreign Affairs, European Union, and Cooperation through the Secretary of State for International Cooperation and Ibero-America and the Caribbean. AECID, together with its partners, works in more than 30 countries through its network of Technical Cooperation Offices, Cultural Centers, and Capacity-building Centers.

AECID carries out many initiatives to guarantee access to water and sanitation systems and water availability for agriculture: projects in the Philippines or the Palestinian Territories, a new Masar-Water component in North Africa, and initiatives in Senegal or Cape Verde, among others. But undoubtedly, AECID's most ambitious commitment to the Sustainable Development Goal 6 is the Cooperation Fund for Water and Sanitation in Latin America and the Caribbean.

This Fund aims to contribute to the realization of the human rights to water and sanitation and to support Latin American countries' progress towards the Sustainable Development Goals for the sector. Created in 2008, it is the Spanish Cooperation's main commitment and financial instrument in the WASH sector.

To date, this Fund has disbursed nearly 800 million € in donations, which have attracted almost 801 M€ in local counterpart funds for implementing programs and 118 M€ in European Union delegated funds. The Fund has a portfolio of 81 programs in 18 Latin America and the Caribbean countries, with a particular emphasis on peri-urban and rural areas, mainstreaming the gender approach and with special attention to cultural diversity.

Figure 8-4: Countries where the Cooperation Fund for Water and Sanitation programs are established.

The Cooperation Fund for Water and Sanitation essentially focuses on programs to provide sustainable services through infrastructure that guarantees access to water and sanitation; through strengthening public management systems that are efficient, transparent, and participatory; and through capacity-building in the public institutions and organizations of recipient countries.

Besides, the Fund has redoubled its efforts regarding Integrated Water Resources Management, strengthening water institutions and supporting the development of comprehensive public policies in the sector. These interventions have the ultimate purpose of guaranteeing the human right to water and sanitation, and contributing to achieving the 2030 Agenda

At the end of 2021, the Fund has directly benefited more than 4.1 million people, and more than 100,000 people have received water service management training. Moreover, awareness-raising campaigns on hygiene and the use of water resources have reached at least 1.6 million people.

Source: Spanish Agency for International Development Cooperation (AECID).

Groundwater resources play an increasingly relevant role in climate change adaptation (UN 2022), as groundwater is a finite resource that is more resistant to droughts, maintains it's quality more easily, and can be regenerated. There are technologies used since ancient times to recharge aquifers to use them as water storage intentionally. Groundwater can complement surface water availability, especially during water scarcity seasons, either through wells or by increasing the availability of surface water resources through lateral groundwater flows in rivers. Aquifer recharge can even serve as a flood risk management measure and protection against aquifers' salinization.

In addition, groundwater itself has several significant advantages for ensuring availability and affordability for the most vulnerable populations. Its flow and quality are more stable over time, which allows these waters to be used almost directly on most occasions. Also, it offers an important feature that can be crucial in times of drought since it can be "overused" during these dry periods, provided that the aquifer levels are then allowed to recover for the necessary time. This would entail a high level of control over the volume of water available and the possibility of stopping using it when it is not strictly necessary. However, as already mentioned, the fact is that more than 30% of all groundwater facilities in rural areas are polluted. This generally affects vulnerable groups the most since relying on a water source that is not safe or sustainable over time can pose a risk. In this context, knowing how to manage water in households is necessary. For this purpose, for example, the Pan American Health Organization promotes Water Safety Plans, which many institutions and countries have adopted. This is a methodology for identifying and assessing the risks associated with water management from catchment to consumer, promoting the implementation of good practices in water management.

Figure 8-5: Water well on the farm of a rural family. Paraguay. © Miguel Lizana / AECID.

8.4 The sanitation crisis and its impact on groundwater

2.2 billion people still lack access to safely managed drinking water services, and more than half of the population - 3.6 billion people - do not have access to safely managed sanitation services (WWAP -UNESCO World Water Assessment Programme-, 2019). This severe sanitation crisis means that wastewater is often discharged directly into watercourses or the ground with the consequent risk of polluting groundwater resources. UNESCO estimates that 80% of wastewater returns to the ecosystem without being treated or reused (WWAP -United Nations World Water Assessment Programme-, 2017).

As a result, at least 2 billion people worldwide use a drinking water source contaminated with fecal matter. Microbial contamination of water due to fecal pollution poses the greatest risk regarding sanitation and transmission of diseases such as diarrhea, cholera, dysentery, typhoid fever, and poliomyelitis.

It is also estimated that 368 million people are supplied with water from wells and springs that are not adequately protected. This can have important consequences for health, since the presence of microorganisms and chemicals in water (such as arsenic, fluoride or nitrate, and new contaminants such as pharmaceuticals, pesticides, perfluoroalkyl and polyfluoroalkyl substances or microplastics) are the main causes of many diseases.

The consequences of polluted water are particularly serious in the case of health facilities, where patients and professionals are exposed to greater risks of infection and disease when water supply, sanitation, and hygiene services are unavailable. Even today, nearly 2 billion people depend on health facilities that lack basic water services (WHO/UNICEF, 2020).

In addition to the environmental damage caused by this contamination, according to WHO and UNICEF, 297,000 children under the age of five die each year due to diarrheal diseases caused by poor sanitation or unsafe water (WHO/UNICEF, 2019).

Figure 8-6: Fetching water in the San Francisco settlement, Alto Paraná Department, Paraguay. © Miguel Lizana/AECID.

Poor water quality and inadequate sanitation lead to disease and death, hindering economic growth and undermining households' efforts to pull themselves out of poverty (UNPD, 2006). Groundwater pollution affects the quality of water abstracted for human consumption and the ecosystems that depend on groundwater resources. These are essential to fight against poverty and water and food security, but also for socio-economic development and the creation of decent jobs, as well as for the resilience of societies and economies to climate change. In addition, it is estimated that groundwater dependence will increase in the coming years due to the growing demand for water in all sectors and to changing rainfall patterns due to climate change. However, as the United Nations denounces in its latest report of 2022, entitled

"Groundwater: Making the invisible visible", the big problem is that this reality becomes invisible to the eyes of the populations and authorities: "Invisible because it happens underground. Invisible because it happens in the poorest and most marginalized communities". It is, therefore, necessary to protect, control and understand groundwater. The lack of such controls gives way “to its intensive exploitation and/or contamination, ultimately endangering its sustainability as well as its accessibility to the most vulnerable populations, who depend on these groundwater sources for their drinking water supply ", as stated in the report (United Nations, 2022).

The United Nations Special Rapporteur on the human rights to safe drinking water and sanitation, Mr. Pedro Arrojo, points out in a recent report on rural populations that "increasingly, the quality of surface or groundwater is affected by the impacts of climate change, by economic developments external to the communities or by the lack of adequate sanitation systems in the communities themselves" (Arrojo, 2022).

To help ensure access to water for these populations, it is necessary to work in several areas, starting with the availability of reliable data on the status of groundwater, establishing regulations for its protection, and working with a human rights approach and an Integrated Water Resource Management perspective.

8.5 Water governance. The need for reliable and up-to-date data and an appropriate regulatory framework

One of the main difficulties is the lack of reliable data on the status of groundwater bodies (qualitative and quantitative), such as accurate aquifer dimensions, geological characteristics, estimated water resources, and current exploitation rate. Only if this information is available will it be possible to adequately map groundwater quantity, quality, and availability.

Furthermore, the United Nations report "Groundwater. Making the Invisible Resource Visible", highlights that, due to the importance of aquifers for ecosystems, social development and economic activities, it is necessary to move towards political processes that harmonize decision-making, monitoring and management of groundwater at both national and international levels.

For this purpose, appropriate regulatory frameworks are needed to ensure groundwater resources' protection, proper and joint management with other water sources (surface and non-conventional), territorial planning, etc. It is also essential to consider that in many cases, management is carried out by communities themselves and that they are, at the same time, as users, also responsible for the conservation and management of water. Therefore, it is necessary to highlight the importance of valuing and resuming some traditional practices that have allowed water protection for centuries.

Finally, considering the strong linkage between water management and the environment, it is necessary to provide a vision of Integrated Water Resource Management (IWRM). As discussed in Chapter 5, this implies the conservation and coordinated use of water resources at all levels, taking into account also the impacts on land and the environment, different water uses (human, industrial, agricultural, etc.) and also all people' s needs in water planning and management. The objective is to improve the use of the resource without compromising the sustainability of ecosystems and ensure its equitable distribution, prioritizing human consumption and focusing on the populations with fewer resources. This is established in General Comment 15 of the Committee on Economic, Social and Cultural Rights on the right to water, which determines that “priority in the allocation of water must be given to the right to water for personal and domestic uses” (CESCR/OHCHR, 2003).

Proper aquifer management requires attention to land use, replenishment, protection, and implementation of measures to preserve the multiple services and functions of the groundwater system. To this end, planning is essential, preferably at the basin level, and considering the joint management of all water resources. It is necessary to establish regulations on waste discharge, management, and maintenance of the resource and aquifer recharge, through actions that improve rainwater harvesting and soil infiltration.

Within the framework of IWRM, it is worth highlighting the importance of Nature-Based Solutions (NBS), which, in the case of groundwater, could help to recharge aquifers more efficiently. This can be achieved, for example, through improved land management and urban green infrastructure (e.g.: permeable pavements or Sustainable Urban Drainage Systems), as pointed out in ONGAWA’s report "Nature-based Solutions for Water in Development Cooperation" (Vela & Del Busto, 2022). The combination of nature-based solutions could alleviate drought, buffering periods of extreme scarcity. However, "The potential of natural water storage (particularly subsurface, in aquifers) for disaster risk reduction is far from being realized” (WWAP (United Nations World Water Assessment Programme)/UN-Water, 2018).

Another aspect of particular relevance for IWRM is the informed participation of the stakeholders. It is, therefore, essential to work on capacity building and public awareness of the sustainable use of the resource.

Figure 8-7: The well installed at home. Water and Sanitation Program in dispersed rural communities in the Canton of Portoviejo, Province of Manabí, Ecuador.

8.6 Conclusions and future challenges

The proper management of groundwater resources plays a crucial role in defending human rights to water and sanitation, especially concerning the most vulnerable populations.

Groundwater is basic for half of the world's population, it has an essential impact on people's health, and it is closely related to the environment. Due to its characteristics, it is particularly important in the current situation of climate change. It is also key to post-pandemic recovery and countries' economic growth and development.

For all these reasons, it is necessary to pay special attention to groundwater. Promote in-depth studies to determine the status of aquifers -in terms of quantity and quality- and seek solutions to the main problems they currently face: overexploitation and contamination, generally caused by untreated wastewater. It is also necessary to work from an IWRM perspective, where groundwater and surface water are interrelated with non-conventional resources, and to establish protection regulations. All of this must be achieved from a human rights approach, which allows for solutions and initiatives that benefit all people without leaving behind the most vulnerable groups suffering the most from groundwater contamination and depletion. Therefore, to give a voice to these vulnerable groups, participatory processes in IWRM are particularly relevant.

9 Conclusions

Ignacio González-Castelao

Water is one of the most important natural resources for life, the formation of different types of landscapes and ecosystems, and for the development. It is a cross-cutting resource that affects sustainable development's three dimensions: social, environmental, and economic.

Our water resources are threatened by climate change, but mainly by human activities. Population growth and current lifestyles are depleting the resources provided by the earth, ecosystems, and biodiversity. The Living Planet Index shows an average rate of decline in species population size of 68% between 1970 and 2016. Thanks to technological changes, land management practices, etc., global biocapacity has increased by approximately 28% in the last 60 years. However, to live, we still need 1.56 times more land than we have (WWF, 2020).

Protecting water sources at origin by maintaining natural infrastructure is essential for better water quality and quantity. Two-thirds of humanity depend on renewable water resources from forests and mountains, where 57% and 28% of the planet's surface water is generated. Healthy rivers, lakes, wetlands, and aquifers provide many benefits to people worldwide: for agriculture, industry, drinking, and much more.

Most of the planet's freshwater is groundwater, which makes it an essential resource for achieving the Sustainable Development Goals (SDG). Targets that do not explicitly consider the real value of this underground resource. Groundwater is invisible, as it is to the SDG.

Large-scale groundwater extraction is relatively recent and has significantly boosted irrigated food production and rural and urban development, especially in rapidly growing cities.

Nowadays, access to groundwater is easier than ever, so its use has spread rapidly. Many regions worldwide are mainly supplied by groundwater, especially in arid and semi-arid areas. The global groundwater abstraction rate has tripled over the past 50 years and continues to increase at an annual rate of 1–2%. Two-thirds of the total amount is abstracted in Asia (Siebert, et al., 2010).

All this has led to a rapid decrease in the quantity and quality of water in aquifers. It should not be forgotten that many individual and local community activities unrelated to groundwater can impact aquifer systems, causing their contamination and pollution.

The different projected climate change scenarios indicate an increase in global average precipitation, but as has already been described in other chapters of this document, there are other non-climatic factors affecting recharge that cause wetter climatic conditions to not systematically result in greater groundwater recharge in the same proportion or direction as changes in precipitation. These non-climate factors include geological environment, topographic relief, specific aquifer properties, size and type, land use and cover (vegetation), and soil type. Some of these non-climatic factors or characteristics are intrinsic to the location. Still, others can be subject to human-made changes (growth in the global population, food demand -which drives irrigated agriculture-, land use change, and socioeconomic factors). These factors are also responsible for the difference between the effects of climate change on groundwater and surface water systems.

Significant concerns are groundwater depletion (losing the buffer against rainfall variability) and changes in soil moisture (and runoff) due to changing land surfaces for urban settlements or agriculture.

Climate change also indirectly affects aquifers as human populations depend on groundwater systems for their livelihoods under unfavorable climatic conditions. If there is no alternative to groundwater, droughts' increased duration and frequency will intensify the search for new or deeper aquifers.

In addition, sea level rise is expected to be another threat to groundwater quality in coastal areas, being a real concern the future scenarios projected for small islands and atolls.

All this adds additional complexity to assessing the effects of climate change on groundwater. The Sixth Assessment Report on Climate Change report concluded that there is high confidence that projected increases in precipitation alone cannot ensure an increase in groundwater storage under a warming climate unless unsustainable trends in groundwater extraction are also reversed (Douville, Raghavan, & Renwick, 2021).

Climate change and anthropogenic pressure (needs arising from world population growth and the current development model -consumption model-) will put more stress on groundwater, both from the point of view of abstraction and pollution.

All this makes the human right to water (indispensable for human dignity) challenging in low-income regions, where groundwater is considered an essential source of drinking water, causing more poverty among already vulnerable groups.

Integrated water resources management is necessary to address all these scenarios and to achieve SDG 6 (clean water and sanitation) targets. In an integrated system of water sources, groundwater generally plays a regulation role (buffering changes) through its large storage capacity.

The conceptual evolution of IWRM began after the initial period of uncontrolled or poorly controlled groundwater development in different regions (the 1930s-1960s).

Groundwater resource management only arises after the population has become aware of the opportunities or problems related to its resources. Hence, a certain degree of deterioration is inevitable to initiate action. It should not be forgotten that water management is, by definition, conflict management. All these challenges intensify when aquifer management is shared between countries (transboundary aquifers).

IWRM is a cross-sectoral policy concept designed to replace the traditional, fragmented sectoral approach to water resources and their management, which has often led to poor services and unsustainable resource use. IWRM is based on the understanding that water resources are an integral component of the ecosystem, a natural resource, and a social and economic good and that the multiple uses of limited water resources are interdependent. IWRM tries to answer questions about how decisions/actions affect fundamental aspects.

Groundwater management must go beyond mere combined management with surface water. Integrated management of all water resources must be carried out by incorporating non-conventional resources. But going further into integrated management, it should also be multisectoral, including soil and land management.

As each country and region differ in history, socioeconomic conditions, cultural and political context, and environmental characteristics, there is no single blueprint for IWRM. The framework has to be adapted to solve the actual local problems (Pahl-Wostl, Jeffrey, & Sendzimir, 2011), giving different values to the importance of economic, environmental, and social impacts.

IWRM implies the conservation and coordinated use of water resources at all levels, taking into account the impacts on land and the environment, different water uses (human, industrial, agricultural, etc.), and also all people's needs in water planning and management. The objective is to improve the use of the resource without compromising the sustainability of ecosystems and ensure its equitable distribution, prioritizing human consumption and focusing on the populations with fewer resources. Public participation in IWRM is essential to give voice to local knowledge and vulnerable groups, ensuring that no one is left behind.

Within the framework of IWRM, it is worth highlighting the importance of nature-based solutions and managed aquifer recharge (MAR).

Since 60% of the world's freshwater flows cross national borders and there are approximately 468 transboundary aquifers, the governance of integrated management of these water resources becomes more complex, making it essential for cooperation between countries and between political and administrative regions.

Unfortunately, only recently, the international community has turned its attention to the issue of international law and which institutions are appropriate for managing resources peacefully.

Elements of groundwater management are also used in mining activity, where water not only influences the rock cycle but is also present in the extraction of minerals, where it can cause geotechnical behavior problems.

However, IWRM is also subject to knowledge, governance, and funding.

IWRM approaches involve applying knowledge from various disciplines and the insights from diverse stakeholders to devise and implement efficient, equitable, and sustainable solutions to water and development problems, considering the different uses of demands through coordinated action. Therefore, an IWRM approach is an open and flexible process to bring together decision-makers from different sectors affecting water resources and all stakeholders to establish policies and make solid and balanced decisions in response to specific water challenges.

Governance must facilitate the establishment of management and government structures and a regulatory framework for groundwater management, together with the existence of adequate funding. Such funding is essential to improve aquifer knowledge, among others.

Also, economic and financial instruments influence behavior. The ability of individuals, societies, and organizations to exploit or affect groundwater can be aligned in the direction desired by the groundwater management authority through legally embedded financial instruments (incentives and disincentives).

These two pillars, governance and financing, are also essential, and engineers must be present, or at least represented, in both.

Engineering has played an important role in groundwater development. Providing groundwater in large quantities for social needs has required significant technological development in wells, pumping machinery, energy and transportation and distribution means, and in some cases, treatment to correct quality. This has been achieved recently, during the first half of the 20th century and in many areas at a later stage.

Engineering contribution has not only been technological but also in terms of knowledge (aquifers characterization, aquifer simulation models, control and monitoring networks, procedures to ensure transparency in the information, among others), providing information for correct decision-making and conflict resolution. Also, greater technical and scientific knowledge of natural behaviors has allowed a better understanding of ecosystems and the functions they perform. Thus, when the environmental conditions are appropriate for a given ecosystem, new environmentally advantageous solutions with a higher degree of certainty about their effectiveness and efficiency are provided. These are Nature-Based Solutions and MAR, among others.

Challenges related to groundwater and its management are not the same in all regions of the world, nor do all countries have the same needs or development levels. Facing these challenges, engineering has been able to adapt scientific knowledge to the needs of society and the environment providing the appropriate solution to each specific case. Thus, contributing to a sustainable, intelligent, and inclusive development, trying to leave no one behind.

References

Douville, H., Raghavan, K., & Renwick, J. (2021). Water Cycle Changes. In V. P. [Masson-Delmotte, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 156). Cambridge and New York: Cambridge University Press. doi:10.1017/9781009157896

ACTO. (24 de February de 2021). *Amazon Cooperation Treaty Organization.* Obtenido de Los avances de la cooperación en la gestión de aguas transfronterizas del ODS 6.5.2 es discutido en seminario internacional: http://otca.org/los-avances-de-la-cooperacion-en-la-gestion-de-aguas-transfronterizas-del-ods-6-5-2-es-discutido-en-seminario-internacional/

Amali, A., Bala, M., & Adeniji, F. (2016, November). Dying Lake Chad: Adaptive strategies to climate change and water scarcity of the Lake Chad basin. *Conference: Water management in a changing World: Role of Irrigation for Sustainable Food Production*. Chiang-Mai, Thailand.

American Geoscience Institute. (2022, November 13). Retrieved from Map of groundwater depletion in the United States: https://www.americangeosciences.org/critical-issues/maps/groundwater-depletion-map-united-states

Andreu, J., Capilla, J., & Sanchis, E. (1996). AQUATOOL, A generalized decision–support system for water–resources planning and operational management. *Journal of Hydrology*, 177: 269–291.

Arrojo, P. (2022). *A/77/167: Human rights to safe drinking water and sanitation of people in impoverished rural areas. Report of the Special Rapporteur on the human rights to safe drinking water and sanitation.* UN.

Baiying, L., Hongtian, X., & Hang, G. (1988). Research on the harnessing of Ordovician limestone confined water in Northern China Coalfields. *International Mine Water Congress. Melbourne. Proceedings. 3*, (pp. 31-33). Melbourne.

Banerjee, S., & Shylienger, R. (1978). Mine Drainage Problems in Indian Coalfields, with Special Reference to the Problems in Jharia Coalfield. *Symposium on Water in Mining and Underground Works SIAMOS*, 27-44.

BGR & UNESCO. (2022, November 12). Retrieved from World-wide Hydrogeological Mapping and Assessment Programme: https://www.whymap.org/whymap/EN/Maps_Data/Gwr/Gwr_statistics/gwr_statistics_node_en.html

BGR-UNESCO. (2022, November 13). Retrieved from World-wide Hydrogeological Mapping and Assessment Programme: https://www.whymap.org/whymap/EN/Maps_Data/Additional_maps/addimaps_node_en.html

Biswas, A. (2008). Integrated Water Resource Management: Is it working? *International Journal of Water Resources Development*, 24(1): 5-22. Retrieved from https://www.tandfonline.com/doi/full/10.1080/07900620701871718?scroll=top&needAccess=true

Bréthaut, C., Gallagher, L., Dalton, J., & Allouche, J. (2019). Power dynamics and integration in the water-energy-food nexus: Learning lessons for transdisciplinary research in Cambodia. *Environmental Science & Policy, Vol. 94*, 153-162. doi:10.1016/j.envsci.2019.01.010

BRGM. (13 de November de 2022). *BRGM, the French geological survey*. Obtenido de BRGM, the French geological survey: https://www.brgm.fr/en/reference-completed-project/hydrogeological-map-africa

Brodaric, B., Booth, N., Boisvert, E., & Lucido, J. (2016). Groundwater data network interoperability. *ournal of Hydroinformatics 18 (2)*, 210–225. Retrieved from https://doi.org/10.2166/hydro.2015.242

Bruinsma, J. (2009). *The resources outlook to 2050. FAO Expert Meeting on How to Feed the World in 2050.*

CAF. (7 de June de 2021). *Banco de desarrollo de América Latina/Development Bank of Latin America*. Obtenido de Acuífero Guaraní, un importante recurso hídrico transfronterizo.: https://www.caf.com/es/conocimiento/visiones/2021/06/acuifero-guarani-un-importante-recurso-hdrico-transfronterizo/

Carlsson A., & Olsson T. (1978). Hydrogeological aspects of groundwater inflow in the Juktan tunnels, Sweden. *Proc. Int. Symp. on Water in Min. and Underground Works*, 373–390.

Carrard, N., Foster, T., & Willetts, J. (2019). Groundwater as a Source of Drinking Water in Southeast Asia and the Pacific: A Multi-Country Review of Current Reliance and Resource Concerns. *Water*, 11, 1605. Retrieved from https://doi.org/10.3390/w11081605

CESCR/OHCHR. (2003, January 20). General Comment No. 15: The Right to Water -Arts. 11 and 12 of the Covenant-. Geneva: Office the High Commissioner for Human RightsUN / Committee on Economic, Social and Cultural Rights. Retrieved from https://www.refworld.org/pdfid/4538838d11.pdf

Chich-Kuei, C., & Chang-Lin, C. (1978). The Exploitation and control of karst water in coal measures. *Symposium on Water in Mining and Underground Works SIAMOS 78. I*, 111-124.

Clifton, C., Evans, R., Hayes, S., Hirji, R., Puz, G., & Pizarro, C. (2010). *Water working notes No. 25: Water and Climate Change: Impacts on groundwater resoures and adaptation options.* Water Sector Board of the Sustainable Development Network of the World Bank Group. Retrieved from https://issuu.com/christinadianparmionova/docs/water_and_climate_change_-_impacts_on_groundwater_

Conti, K. (2015). *Groundwater in the sustainable development goals. Position paper No. 1. Including Groundwater in the Draft Goals.* IGRAC.

Cook, P., Anderson, M., Bourke, S., Cartwright, I., Cleverly, J., Currell, M., . . . Werner, A. (2022). Sustainable management of groundwater extraction: an Australian perspective on current challenges. *Journal of Hydrology: Regional Studies. Volume 24, December 2022, 10206*.

Corson-Dosch, H., Nell, C., Volentine, R., Archer, A., Bechtel, E., Bruce, J., . . . Read, E. (2022). United States Geological Survey. Retrieved from https://www.usgs.gov/media/files/water-cycle-poster-pdf

Crosbie, R., McCallum, J., Walker, G., & Chiew, F. (2010). Modelling the climate change impact on groundwater recharge in the Murray-Darling Basin. *Hydrogeology Journal*. doi:18:1639-1656

Custodio, E. (2000). Groundwater–dependent wetlands. *Acta Geologica Hungarica*, 43(2): 173–202. Retrieved from https://rac.es/ficheros/doc/00531.pdf

Custodio, E. (2002). Aquifer overexploitation, what does it mean? *Hydrogeology Journal*, 10(2): 254–277. Retrieved from https://static1.squarespace.com/static/5eb18d627d53aa0e85b60c65/t/5ef49172749a523e4d235bc9/1593086323951/Custodio-Emilio-2002.pdf

Custodio, E. (2009). Intensive groundwater development: A water cycle transformation, a social revolution, a management challenge. In *L. Martínez–Cortina, A. Garrido, E. López–Gunn (eds). Rethinking Water and Food Security* (pp. 259–298.). Botín Foundation/CRC Press. Retrieved from https://fundacionbotin.org/89dguuytdfr276ed_uploads/Observatorio%20Tendencias/PUBLICACIONES/LIBROS%20SEM%20INTERN/Rethinking%20water/14-capitulo14.pdf

Custodio, E. (2015). *Aspectos hidrológicos, ambientales, económicos, sociales y éticos del consumo de reservas de agua subterránea en España. (Hydrogeological, environmental, economic, social and ethical aspects of groundwater reserves consumption in Spain).* UPC-SUEZ-CETAQUA. Publication Services of the Universitat Politècnica. Retrieved from https://upcommons.upc.edu/handle/2117/111272

Custodio, E. (2021). Concepts on groundwater resources. *Concepts on groundwater resources*, 132 (1-2): 141-146. Retrieved from https://www.igme.es/boletin/2021/132_1-2/BGM_132--1-2_Art-14.pdf

Custodio, E. (2023). *Evaluación de la gestión y gobernanza del agua subterránea. Aplicación a áreas seleccionadas españolas. [Groundwater management and governance. Application to selected Spanish areas].* Barcelona: CETAQUA. Publication Services of the Universitat Politècnica de Catalunya.

Custodio, E., Albiac, J., Cermerón, M., Hernández, M., Llamas, M., & Sahuquillo, A. (2017a). Groundwater mining: benefits, problems and consequences in Spain. *Sustainable Water Resources Management*. doi:10.1007/s40899-017-0099-2

Custodio, E., Sahuquillo, A., & Albiac, J. (2017b). Sustainability of intensive groundwater development: experience in Spain. *Sustainable water resources management* . doi:10.1007/s40899–017–0105–8

De los Cobos, G. (2018). The Genevese transboundary aquifer (Switzerland-France): The secret of 40 years of successful management. *Journal of Hydrology: Regional Studies. Volume 20*, 116-127. doi:https://doi.org/10.1016/j.ejrh.2018.02.003.

Deep Resources. (2015, Jun 18). *Deepresource*. Retrieved from Deepresource: https://deepresource.wordpress.com/2015/06/18/groundwater-depletion-worldwide/

Dillon, P., & Arshad,, M. (2016). Managed Aquifer Recharge in Integrated Water Resource Management. In A. Jakeman, O. Barreteau, R. Hunt, J.-D. Rinaudo, & A. Ross, *Integrated groundwater management. Concepts, approaches and challenges* (pp. 435-452). Springer Open.

EEA. (2010, December 3). Retrieved from https://www.eea.europa.eu/data-and-maps/figures

ESCAP United Nations. (2018). *Environment and Development Series 2018: Harnessing environmental action for sustainable development in Asia and the Pacific.* Bangkok: United Nations publication.

Escuder, I. (16 de July de 2022). ¿De quién es el agua de los ríos que pasan por dos países? *La Razón*. Obtenido de https://www.larazon.es/sociedad/20220717/ymki3sergjdy3nh2mpsjrkrsle.html

European Commission. (2022, November 18). *KnowSDGs Platform*. Retrieved from https://knowsdgs.jrc.ec.europa.eu/

Fernández Aller, R. (1981). Water pollution in the coal mining industry in Spain. *Industria Química. I*, 135-141.

Fernández Rubio, R. (1974). Hydrogeology of the Castilla mine (Sierra Menera, Guadalajara). *Doc. Invest. Hidrológica. 16*, 139-173.

Fernández Rubio, R. (1980). *Hydrogeological study of the Reocín mine (Santander).* Granada: Real Compañía Asturiana (Internal Report).

Fernández Rubio, R. (1980). *Hydrogeological study of the Reocín mine (Santander).* Granada: Real Compañía Asturiana (Internal Report).

Fernández Rubio, R. (1986). *Impact of mining on hydrological systems.* Madrid: E.T.S. Ingenieros de Minas.

Fernández Rubio, R. (2006). *Water Resources Management and Mining: An International Perspective.* IBRAM/ANA.

Ferreira, J., & Rodrigues, J. (1988). BALSEQ — A Model for the Estimation of Water Balances, Including Aquifer Recharges, Requiring Scarce Hydrologic Data. In v. 2. NATO ASI Series, *Estimation of Natural Groundwater Recharge* (pp. 978-94). Springer Dordrecht. doi:https://doi.org/10.1007/978-94-015-7780-9

Foster, S., & Loucks, D. (2006). *Non-renewable groundwater resources : a guidebook on socially-sustainable management for water-policy makers.* Paris: UNESCO. Retrieved from https://www.ircwash.org/resources/non-renewable-groundwater-resources-guidebook-socially-sustainable-management-water-policy

Foster, S., & Tyson, G. (2016). *Strategic Overview Series. Global Change & Groundwater.* International Association of Hydrogeologists. Retrieved from https://iah.org/wp-content/uploads/2016/07/IAH-Global-Change-Groundwater-14-June-2016.pdf

Foster, S., & Tyson, G. (2019). *Strategic Overview Series. Climate-Change Adaptation & Groundwater.* International Association of Hydrogeologists .

Frasa Consulting Engineers. (1987). *Neves-Corvo mine: first hydrogeological follow-up report (Somincor Internal Report).* Madrid.

Frasa Consulting Engineers. (1993). *Quantification of Konkola Mine Water Inflow by Source (ZCCM Internal Report).* Madrid.

GEF. (2016). *Global Diagnostic on Groundwater Governance / Global Framework for Action to achieve the Vision on Groundwater Governance. Groundwater Governance – a Global Framework for Action (2011-2016). The World Bank-FAO-UNESCO-GEF.* Rome: FAO. Retrieved from https://www.fao.org/3/i5706e/i5706e.pdf

Giordano, M., & Shah, T. (2014). Non-integrated water resources management. In P. Martínez Santos, M. Aldaya, & M. Llamas, *Integrated Water Resources Management in the 21th Century: Revisiting the Paradigm* (pp. Chap 3: 37-43). Botín Foundation-CRC Press.

Girman, J., Van der Gun, J., Haie, N., Hirata, R., Lipponen, A., Lopez - Gunn, E., . . . Wallin, B. (2007). *Groundwater Resources Sustainability Indicators.* Paris: United Nations Educational, Scientific and Cultural Organization.

Global Groundwater Statement. (2022, November 14). *Global Groundwater Sustainability: A Call to Action*. Retrieved from https://www.groundwaterstatement.org/

Gomes, J. (2008). Panorama da Qualidade das Águas Subterrâneas no Brasil. *XV Congresso Brasileiro de Águas Subterrâneas.* Retrieved from file:///C:/Users/burqu/Downloads/23802-Texto%20do%20artigo-86331-1-10-20110915.pdf

Grech-Madin, C., Döring, S., Kim, K., & Swain, A. (2018). Negotiating water across levels: A peace and conflict "Toolbox" for water diplomacy. *Journal of Hydrology Volume 559*, 100-109. Retrieved from https://doi.org/10.1016/j.jhydrol.2018.02.008

Green, T., Charles, S., Bates, B., & Fleming, P. (1997). Simulated effects of climate change on groundwater recharge: Gnangara Mound, Western Australia. *24th Hydrology and Water Resources Symp.*, (pp. 149–154). Auckland.

GRID-Arendal, Philippe Rekacewicz. (2006, February). *GRID-Arendal*. Retrieved from https://www.grida.no/resources/5593

Griebler, C., & Avramov, M. (2015). Groundwater ecosystem services: A review. *Freshwater Science, Vol. 34, No. 1,*, 355–367.

Groundwater Asia. (2022, November 12). *Groundwater Asia. Mapping Groundwater Resilience to Climate Change and Human Development in Asian Cities*. Retrieved from https://groundwaterasia.org/

Growitz, D. (1978). Hydrogeologic factors that may affect mine drainage in the anthracite region of Pennsylvania, Eastern United States. *Symposium on Water in Mining and Underground Works SIAMOS-78. I*, 153-172.

Growitz, D. (1978). Hydrogeologic factors that may affect mine drainage in the anthracite region of Pennsylvania, Eastern United States. *Symposium on Water in Mining and Underground Works SIAMOS 78. I*, (pp. 153-172). Granada.

Guppy, L., Uyttendaele, P., Villholth, K., & Smakhtin, V. (2018). *Groundwater and Sustainable Development Goals: Analysis Of Interlinkages. UNU-INWEH Report Series, Issue 04.* Hamilton, Canada: United Nations University Institute for Water, Environment and Health.

GWP. (2022). Retrieved from Integrated water resources management toolbox. Global Water Partnership: http://www.gwptoolbox.org

Harrington, N., & Cook, P. (2014). *Groundwater in Australia.* Adelaide: The National Centre for Groundwater Research and Training.

Hayton, R., & Utton, A. (1992). Aguas Subterraneas Transfronterizas: Anteproyecto de Tratado Bellagio, 32 Nat. Resources J. 345. Retrieved from https://digitalrepository.unm.edu/nrj/vol32/iss2/5

Hidalgo, J., & Pena, H. (2009). Turning water stress into water management success: Experiences in the Lerma-Chapala River Basin. In R. Lenton, & M. Muller, *Integrated Water Resources Management in Practice: Better Water Management for Development,.* London: Earthscan.

Hispagua. (20 de November de 2022). *Cuencas transfronterizas de América. Acuífero Guaraní.* Obtenido de file:///C:/Users/burqu/OneDrive%20-%20Ignacio%20Glez.-Castelao%20Mtnez.-Pe%C3%B1uela/Documentos/STCoW/2022%20Engineering,%20ground%20water%20and%20IWRM/Cap%C3%ADtulo%207%20-%20Acu%C3%ADferos%20Transfronterizos/221525%20Nueva%20versi%C3%B3n%20documento%20R

IAEA. (2013, September 20). *Chad, Egypt, Libya and Sudan agree on framework for joint management of the Nubian Sandstone Aquifer System.* Retrieved from https://www.iaea.org/newscenter/news/chad-egypt-libya-and-sudan-agree-on-framework-for-joint-management-of-the-nubian-sandstone-aquifer-system

ICWE. (1992, January 26-31). International Conference of Water and the Environment, The Dublin Statement on Water and Sustainable Development. Dublin, Ireland. doi:https://www.ircwash.org/sites/default/files/71-ICWE92-9739.pdf

IGRAC. (2021). Transboundary Aquifers of the World [map]. Delft, Netherlands: International Groundwater Resources Assessment Centre. Retrieved from https://www.un-igrac.org/sites/default/files/resources/files/2021TBAMap_UNESCO%20Version.pdf

IGRAC. (2022, November 14). *IGRAC*. Retrieved from https://www.un-igrac.org/agenda/groundwater-key-sdgs

Instituto Correntino del Agua y del Ambiente. (21 de Novembre de 2022). *ICAA*. Obtenido de https://icaa.gov.ar/sistema-acuifero-guarani

Jacobson, G., & Lau, J. (2022, November 13). *Australian Goverment. Geoscience Australia*. Retrieved from https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/15629

Jakeman, A., Barreteau, O., Hunt, R., Rinaudo, J.-D., & Ross, A. (2016). *Integrated groundwater management. Concepts, approaches and challenges.* Springer Open. Retrieved from https://www.un-igrac.org/sites/default/files/resources/files/Integrated%20groundwater%20management%20-%20Concepts%2C%20approaches%20and%20challenges.pdf

Jiménez Cisneros, B., Oki, T., Arnell, N., Benito, G., Cogley, J., Döll, P., . . . Mwakalila, S. (2014). Freshwater resources. In C. V. Field, *Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 42). Cambridge and New York: Cambridge University Press.

Jódar, J., Martos-Rosillo, S., Custodio, E., Mateos, L., Cabello, J., Casas, J., . . . Lambán, L. (2022). The recharge channels of the Sierra Nevada range (Spain) and the Peruvian Andes as ancient nature-based solutions for the ecological transition. *Water*. Retrieved from file:///C:/Users/burqu/Downloads/water-14-03130-v2.pdf

Kingdom, B., Liemberger, R., & Marin, P. (2006). *The Challenge of Reducing Non-Revenue Water (NRW) in Developing Countries. How the Private Sector Can Help: A Look at Performance-Based Service Contracting.* Washington, DC: The International Bank for Reconstruction and Development/The World Bank.

Konikow, L., & Kendy, E. (2005). Groundwater depletion: A global problem. *Hydrogeology Journal*, 13: 317-320.

Lenton, R., & Muller, M. (2009). *Integrated Water Resources Management in Practice : Better Water Management for Development.* London: Earthscan Publications.

Llamas, M., & Martínez-Santos, P. (2005). Intensive Groundwater use: a silent revolution that cannot be ignored OK. In IWA, *Water Science and Technology Series, Vol. 51, No. 8,* (pp. 167-74). London: IWA Publishing.

Llamas, M., Martinez-Santos, P., & de la Hera, A. (2007). Dimensions of sustainability in regard to groundwater resources development: an overview. In S. Ragone, A. de la Hera, N. Hernandez-Mora, G. Bergkamp, & J. McKay, *Global Importance of Groundwater in the 21st Century International Symposium in Groundwater Sustainability, Alicante, 24–27 Jan 2006.* Westerville.: National Groundwater Association Press,.

Lobo Ferreira, J., & Oliveira, M. (2004). Groundwater vulnerability assessment in Portugal. *Geofísica Internacional, Vol. 43, Num. 4*, 541-550.

Lobo Ferreira, J., Leitão, T., & Oliveira, M. (2014). Portugal's river basin management plans: groundwater innovative methodologies, diagnosis, and objectives. *Environ Earth Sci*. Retrieved from http://repositorio.lnec.pt:8080/xmlui/handle/123456789/1006457

Margat, J., & Van der Gun, J. (2013). *Groundwater around the World. A Geographic Synopsis.* Boca Ratón: Taylor & Francis Group, LLC.

Marinos, G., Economopoulos, J., & Nicolau, N. (1978). Problems of water inrush into Greek underground mines with special emphasis to sea water inrush through karstic limestones or impermeable formations. *Symposium on Water in Mining and Underground Works SIAMOS 78. I*, (pp. 463-475). Granada.

Marsol. (2022, November 13). Retrieved from Marsol: http://www.marsol.eu/

MARSOL. (2022, December 10). *MARSOL Managed aquifer recharge solutions*. Retrieved from http://www.marsol.eu/6-0-Home.html

Martínez-Santos, P., Aldaya, M., & Llamas, M. (2014). Integrated Water Resources Management: State of the art and the way forward. London: Botín Foundation-CRC Press. doi:https://doi.org/10.1201/b16591

Matos de Abreu, F., Cavalcante, I., & Silva Matta, M. (2013). *O sistema aquífero grande Amazônia – SAGA: um imenso potencial de água subterrânea no Brasil.*

Medina Salcedo, F., Fernández Rubio, R., & Gordillo Martín, A. (1977). Hydrogéologie de plaine du Marquesado et influence de son drainage meridional (Guadix-Baza basin, Spain). *Hydrog. Grands Basins Sédimentaires*.

MIMAM. (2000). *Libro blanco del agua en España (White Paper on Water in Spain).* Madrid: Dirección General de Obras Hidráulicas y Calidad de las Aguas, Ministerio de Medio Ambiente. Retrieved from http://www.cedex.es/CEDEX/LANG_CASTELLANO/ORGANISMO/CENTYLAB/CEH/Documentos_Descargas/LB_LibroBlancoAgua.htm

Mulenga, S. (1991). Groundwater flow through Konkola (Bancroft) Copper Mine – Zambia. *Thesis London Imp. College*.

Nelson, R., & Quevauviller, P. (2016). Groundwater law. In A. Jakeman, O. Barreteau, R. Hunt, J. Rinaudo, & A. Ross, *Integrated Groundwater Management. Concepts, Approaches and Challenges* (pp. 173-196). Springer Open. Retrieved from file:///C:/Users/igcas/Downloads/IGMbook2016.pdf

OECD. (2015). *OECD Principles on Water Governance.*

Open Geospatial Consortium. (2022, December 12). *OGC WaterML*. Retrieved from https://www.ogc.org/standards/waterml

Pahl-Wostl, C., Jeffrey, P., & Sendzimir, J. (2011). Adaptive and Integrated Management of Water Resources. In R. Grafton, & K. Hussey, *Water Resources Planning and Management.* Cambridge: Cambridge University Press.

Pei, E. (1998). The main hydrogeological characteristics of mineral deposits in China. *International Mine Water Congress. 3*, (pp. 93-101). Retrieved from https://www.imwa.info/docs/imwa_1988/IMWA1988_Pei_093.pdf

Perlman, H., Cook, J., Hole, Woods, & Nieman., A. (2016, July 16). *usgs.gov*. Retrieved from https://www.usgs.gov/special-topic/water-science-school/science/how-much-water-there-earth?qt-science_center_objects=0#qt-science_center_objects

Queralt, E., Bernat, X., & Custodio, E. (2020). Improving water quantity and quality supply security by managed artificial recharge technologies in the Lower Llobregat aquifers integrated into a conjunctive surface and groundwater management scheme for Barcelona, Spain. *Journal of Environmental Science and Engineering*, A9: 119-139. doi:10.17265/2162-5298/2020.04.001

Rebouças, A. (1999). Groundwater resources in South America. 232-237. Retrieved from https://repositorio.usp.br/directbitstream/25319911-6bf2-4bcb-b1de-bdc495052dfa/

Sandstorm, K. (1995). Modelling the effects of rainfall variabilty on groundwater recharge in Semi-arid Tanzania. *Nordic Hydrology 26*, 313–330.

Savenije, H., & Van der Zaag, P. (2008). Integrated water resources management: Concepts and issues. *Physics and Chemistry of the Earth*, 33: 290–297. doi:10.1016/j.pce.2008.02.003

Schmieder, A. (1978). Forecasting the rates of water inflowing into mines. *Symposium on Water in Mining and Underground Works SIAMOS-78. I*, (pp. 511-534). Granada.

SGV. (2016). *A Shared Global Vision for 2030. Project Global Framework for Action (2011-2016). The World Bank-FAO-UNESCO-GEF.* Rome: FAO. Retrieved from https://www.fao.org/3/i5508e/i5508e.pdf

Shiklomanov, I., & Rodda, J. (2004). *World Water Resources at the Beginning of the Twenty-First Century.* UNIVERSITY OF CAMBRIDGE.

Siebert, S., Burke, J., Faures, J., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. (2010). Groundwater use for irrigation – a global inventory. *Hydrol. Earth Syst. Sci., 14*, 1863–1880. Retrieved from https://doi.org/10.5194/hess-14-1863-2010

Somers, L., & Mckenzie, J. (2020). A review on groundwater in high mountainenvironments. *Wiley Interdisciplinary Reviews: Water*. doi:10.1002/wat2.1475

Stalker, W., & Schiannini, P. (1978). Mine open pit dewatering at Chingola, Zambia. *Symposium on Water in Mining and Underground Works SIAMOS*, 251-272.

Stocker, T., Qin, D., Plattne, G.-K., M. T., Allen, S., Boschung, J., . . . (eds.), P. M. (2013). *IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Stocker, T.F., Qin, D., Plattner, G.-K., Alexander, L., Allen, S., . . . P. (2013). *Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

Sweeney, M. (1988). Water inflow patterns in Zambian mines. *International Mine Water Congress. 3*, (pp. 65-75). Melbourne.

Technical Advisory Committee. Global Water Partnership. (2000). *Integrated Water Resources Management.* Stockholm: Global Water Partnership. Retrieved from https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/04-integrated-water-resources-management-2000-english.pdf

The Institution of Engineers of Mauritius. (2022). Engineering: The pathway to building resilience to climate change in SIDS. *Journal of The Institution of Engineers of Mauritius*.

Treidel, H., Martin-Bordes, J., & Gurdak, J. (2012). *Climate Change Effects on Groundwater Resources. A Global Synthesis of Findings and Recommendations.* London: Taylor & Francis Group.

Trilla, J., López, C., & Peón, A. (1978). On the origin and dynamics of the water flowing into the Reocín mining operations (Santander, Spain). *Symposium on Water in Mining and Underground Works SIAMOS-78*, 293-307.

UN Women. (2018). *Turning promises into action: gender equality in the 2030 agenda for sustainable development.* UN Women. Retrieved from https://www.unwomen.org/sites/default/files/Headquarters/Attachments/Sections/Library/Publications/2018/SDG-report-Summary-Gender-equality-in-the-2030-Agenda-for-Sustainable-Development-2018-en.pdf

UNECE. (2022, November 20). *Economic Commission for Europe*. Retrieved from https://unece.org/environment-policy/water/about-the-convention/introduction

UNESCO. (2018). *Culture for the 2030 Agenda.* Paris: UNESCO. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000264687

UNESCO-IAHP ISARM Programme. (2009). *Atlas of Transboundary Aquifers. Global maps, regional cooperation and local inventories.* Paris: UNESCO.

UNESCO-IHP. (2022, November 20). *UNESCO-IHP Groundwater Portal.* Retrieved from Nubian Aquifer: https://groundwaterportal.net/project/nubian-aquifer

UNESCO-IHP/OEA/IGRAC. (2007). *Sistemas acuíferos transfronterizos en las Américas. Evaluación preliminar / Transboundary aquifer systems in the Americas. Preliminary assessment.* Montevideo/ Washington DC. Obtenido de http://www.oas.org/dsd/water/Documentos/Sistemas%20Acu%C3%ADferos%20Transfronterizos%20en%20las%20Am%C3%A9ricas.pdf

UNICEF and World Health Organization. (2011). *Drinking Water Equity, Safety and Sustainability: Thematic Report on Drinking Water.* WHO/UNICEF.

United Nations. (2021). *The United Nations World Water Development Report 2021: Valuing Water. .* Paris: UNESCO.

United Nations. (2022). *The United Nations World Water Development Report 2022: Groundwater: Making the invisible visible.* Paris: UNESCO.

United Nations Educational, Scientific and Cultural Organization, and International Center for Engineering Education. (2021). *Engineering for Sustainable Development.* Paris: UNESCO.

UNPD. (2006). *Human Development Report, 2006. Beyond scarcity: power, poverty and the global water crisis.* New York: United Nations Development Programme. Retrieved from https://hdr.undp.org/content/human-development-report-2006

UN-Water. (2016). *Water and Sanitation Interlinkages across the 2030 Agenda for Sustainable Development.* Geneva.

UN-Water. (2022, November 26). *Progress on Transboundary Water Cooperation (SDG target 6.5)*. Retrieved from https://www.sdg6data.org/en/indicator/6.5.2

UN-Water. (2022, November 14). *UN-Water SDG 6 Data Portal*. Retrieved from https://www.sdg6data.org/en

UN-Water. (n.d.). *Transboundary Waters*. Retrieved from UN-Water: https://www.unwater.org/water-facts/transboundary-waters/

Van Rijswick, M., Edelenbos, J., Hellegers, P., Kok, M., & Kuks, S. (2014). Ten building blocks for sustainable water governance: an integrated method to assess the governance of water. *Water International*. doi:10.1080/02508060.2014.951828

Vaquero, G., Siavashani, N., García-Martínez, D., Elorza, F., Bila, M., Candela, L., & Serrat-Capdevila, A. (2021). The Lake Chad transboundary aquifer. Estimation of groundwater fluxes through international borders from regional numerical modeling. *ournal of Hydrology: Regional Studies, 38*, 21.

Vázquez Guzmán, F. (2012). *Mine Deposits Handbooks.* Unidad de Proyectos. E.T.S.I. Minas, Madrid Polytechnic University.

Vela, C., & Del Busto, E. (2022). *Soluciones basadas en la naturaleza para el Agua en Cooperación al Desarrollo. Claves de su aplicación en cooperación al desarrollo.* ONGAWA Ingeniería para el Desarrollo Humano. Obtenido de https://ongawa.org/soluciones-basadas-en-la-naturaleza-claves-de-su-aplicacion-en-cooperacion-al-desarrollo/

Vij, S., Warner, J., & Barua, A. (2020). Power in water diplomacy. *Water International, 45:4*, 249-253. doi:10.1080/02508060.2020.1778833

Villholth, K., López-Gunn, E., Conto, K., Garrido, A., & Van der Gun, J. (2018). *Advances in groundwater governance.* London: CRC Press/Balkema, Taylor & Francis Group. Retrieved from http://bnfwv4fm4l13stiajd7sf413.wpengine.netdna-cdn.com/wp-content/uploads/sites/2/2019/01/advances-in-groundwater-governance.pdf

White, C. (2013, June 10). *Integrated Water Resources Management: What is it and why is it used?* Retrieved from Global Water Forum (GWF): https://globalwaterforum.org/2013/06/10/integrated-water-resources-management-what-is-it-and-why-is-it-used/

WHO/UNICEF. (2019, June 18). 1 in 3 people globally do not have access to safe drinking water. *News release*. Retrieved from https://www.who.int/news/item/18-06-2019-1-in-3-people-globally-do-not-have-access-to-safe-drinking-water-unicef-who

WHO/UNICEF. (2020, December 14). Almost 2 billion people depend on health care facilities without basic water services. *UNICEF Press Release*. Retrieved from https://www.unicef.org/press-releases/almost-2-billion-people-depend-health-care-facilities-without-basic-water-services

Wightman, D. (1978). Nanginwall dewatering at Mufulira Division of Roan Consolidated Mines Limited, Zâmbia. *Symposium on Water in Mining and Underground Works SIAMOS-78. I*, 559-571.

Wolf, A. (2022, January 5). Boiling Point: Water, Borders and Conflict with Aaron Wolf. *What aboit water?* Retrieved from https://www.whataboutwater.org/s03e06/

Wolmarans, J., & Guise-Brown, F. (1978). The water hazard in deep gold mining of the Far West Witwatersrand. *Symposium on Water in Mining and Underground Works SIAMOS-78. I*, 329-346.

Working Group II - IPCC. (2022). *Climate Change 2022. Impacts, Adaptation and Vulnerability. Working Group II contribution to th Sixth Assessment report of the IPCC.* IPCC.

World Bank Group. (2021). *Understanding poverty: water*. Retrieved from Understanding poverty: water: https://www.bancomundial.org/es/topic/water/overview

World Federation of Engineering Organizations; Division of Science Policy and Capacity Building - Natural Sciences Sector. (2018). *WFEO Engineering 2030. A Plan to advance the achievement of the UN Sustainable Development Goals through engineering.* Paris.

WWAP (United Nations World Water Assessment Programme)/UN-Water. (2018). *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water.* Paris: UNESCO. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000261424

WWAP -UNESCO World Water Assessment Programme-. (2019). *The United NationsWorld Water Development Report 2019: Leaving No One Behind.* Paris: UNESCO. Retrieved from https://en.unesco.org/themes/water-security/wwap/wwdr/2019

WWAP -United Nations World Water Assessment Programme-. (2017). *The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource.* Paris: UNESCO. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000247153

WWAP-United Nations World Water Assessment Programme-. (2017). *The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource.* Paris: UNESCO.

WWF. (2020). *LIVING PLANETREPORT 2020 - Bending the curve of biodiversity loss.* Gland, Switzerland: WWF.

Zaisheng, H., & Hao, W. (2012, 8 14). *China Geological Survey. Groundwater resourcesin Asia - Problem and Challenge.* Retrieved from https://en.cgs.gov.cn/achievements/201601/t20160112_35416.html

Zhongling, M. (1988). Karst water gushing in mines. *International Mine Water Congress. 3*, (pp. 87-101). Melbourne.

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