Learning from the past to build the future governance of groundwater use in agriculture

Olivier Petit, Aurélien Dumont, Stéphanie Leyronas, Quentin Ballin, Sami Bouarfa, Nicolas Faysse, Marcel Kuper, François Molle, Charlotte Alcazar, Emmanuel Durand, et al.

Petit O., Dumont A., Leyronas S., Ballin Q., Bouarfa S., Faysse N., Kuper M., Alcazar C., Durand E., Ghoudi R., Hubert A., Le Visage S., Messaoudi I., Molle F., Montginoul M., Ndao S., Richard Ferroudji A., Rinaudo J.-D., Trottier J., Aubriot O., Elloumi M., Boisson M., Maurel F., Fofack-Garcia R., Rojat D., Romagny B., Ruck I., Salgues E. Learning from the past to build the future of groundwater governance and irrigation. *Water International*, 46:7-8, 1037-1059.
https://doi.org/10.1080/02508060.2021.2006948

Learning from the past to build the future governance of groundwater use in agriculture

Olivier Petit[a]*, Aurélien Dumont[b], Stéphanie Leyronas[c], Quentin Ballin[c], Sami Bouarfa[d], Nicolas Faysse[d,e], Marcel Kuper[d], François Molle[d], Charlotte Alcazar[f], Emmanuel Durand[g], Ridha Ghoudi[h], Aline Hubert[g], Selin Le Visage[i], Imane Messaoudi[j,k], Marielle Montginoul[d], Seyni Ndao[l], Audrey Richard Ferroudji[m], Jean-Daniel Rinaudo[d], Julie Trottier[n], Olivia Aubriot[o]; Mohamed Elloumi[p], Marc Boisson[q], Rhoda Fofack-Garcia[r], Frédéric Maurel[c], Dominique Rojat[c], Bruno Romagny[s], Emmanuelle Salgues[t]

[a]Univ. Lille, CNRS, UMR 8019 - CLERSE - Centre Lillois d'Études et de Recherches sociologiques et Économiques, F-59000 Lille, France ; [b]UNESCO, International hydrological programme, F-75000 Paris, France ; [c]Agence française de développement, F-75598 Paris, France ; [d]G-EAU, Cirad, INRAE, AgroParisTech, IRD, Montpellier Supagro, BRGM, Univ. Montpellier, F-34196 Montpellier, France ; [e]National Institute of Agronomy of Tunisia, Tunis, Tunisia; [f]SYMCRAU, F-13800 Istres, France ; [g]GRET, F-94736 Nogent-sur-Marne, France ; [h]CRDA de Gabès, Ministère de l'agriculture des ressources hydrauliques et de la pêche, Gabès, Tunisia ; [i]UMR TREE, CNRS, Université de Pau et des Pays de l'Adour, F-64000 Pau, France ; [j]Laboratoire Mosaïques Lavue, Université Paris Nanterre, F-92000 Nanterre, France ; [k]Laboratoire Géosciences, Université de Fribourg, 1700 Fribourg, Switzerland ; [l]OFOR, Dakar, Senegal ; [m]Independent Sociologist, F-34000 Montpellier, France ; [n]CNRS, UMR PRODIG, F- 93322 Aubervilliers, France ; [o]CNRS -CEH. F-93300 Aubervilliers, France; [p]Université de Carthage, INRAT, Laboratoire d'Economie Rurale, 2049 Ariana, Tunisie ; [q]Artelia, F- 38130 Echirolles, France ; [r]France Energies Marines, F-29280 Plouzané, France ; [s]Aix Marseille Univ, IRD, LPED, F-13000 Marseille, France ; [t]CACG, F-65004 Tarbes, France.

* Univ. Lille, CNRS, UMR 8019 - CLERSE - Bâtiment SH2 Cité Scientifique - 59655 Villeneuve d'Ascq, France. olivier.petit@univ-artois.fr

Abstract: The use of groundwater is increasing worldwide, particularly in agriculture. This leads to pumping races (from which the poorest farmers are often excluded), environmental disasters and the degradation of groundwater quality. Based on discussions between scientists and operational experts in two workshops held in 2018 and 2020, this paper, after taking stock of the dynamics and motivations of groundwater use in agriculture, reviews the solutions most commonly proposed, in particular by public authorities, to regulate the access to and use of this resource and to limit its overexploitation. These (often optimistic) solutions generally combine regulatory or economic instruments, or indirect measures linking water to other issues, and mechanisms based on the participation of all users. However, they rarely question the intensive agricultural systems driving groundwater demand and fail to recognise the multifunctional nature of groundwater. To overcome these hurdles we draw up possible ways forward for policy makers and resource users to develop negotiated solutions.

Key words: groundwater, governance, policy instruments, overexploitation, irrigation, agriculture, commons, common patrimony

Introduction

Groundwater use for agriculture, which soared in the second half of the twentieth century (Siebert et al., 2010), often competes with other uses. From an environmental viewpoint, groundwater feeds springs and rivers and helps to preserve wetlands, which are reservoirs of biodiversity. Furthermore, it is massively and increasingly used to supply agriculture, industry and drinking water for cities. Thus, its governance demands serious consideration to protect groundwater and establish pathways for its sustainable use.

This paper aims to contribute to the debate on the preservation of groundwater, focusing on agricultural use, since a growing proportion of the world's irrigated land area – currently at around 40% – relies on this resource (FAO, 2016). Furthermore, increased groundwater use is often linked to the intensification of agriculture, which explains how agriculture can account for around 70% of global groundwater abstraction (Siebert et al., 2010), making it a strategic resource.

The dynamics of agricultural groundwater use are driven by the economic return it provides along with comparatively easy and secure access to water resources. There is a trade-off between these benefits and the current and future consequences of depleting flows and reserves, with the added complexity of the invisibility of groundwater sources. This can result in the loss of groundwater-dependant ecosystems or farmers engaging in a pumping race that excludes the poorest among them, thereby deepening economic and social inequalities (Mukherji, 2006; Aubriot, 2013; Jouili et al., 2013; Hoogesteger & Wester, 2015; Ameur et al., 2017).

The classical solutions proposed to control and limit groundwater abstraction at the institutional level generally combine: (i) regulatory instruments (permits, bans, quotas, zoning, well closures), economic instruments (fees, subsidies) or indirect measures linking water to other issues (energy, food security) and (ii) participatory mechanisms involving all water users through community-based management schemes or other contractual arrangements (Villholth et al., 2018; Molle & Closas, 2020a; 2020b). Such solutions tend to face operational, financial, social, cultural and often political hurdles. More importantly, they rarely question the intensive agricultural systems that underlie the growing demand for groundwater or recognise the multifunctional nature of the resource. It would seem, therefore, that these solutions are mired in public policy contradictions by, on the one hand, aiming to reduce groundwater pumping to limit the environmental and social consequences of intensive use, while, on the other, maintaining the current level of withdrawal to 'buy' social peace, and even encouraging the development of new sources of water supply to strengthen the capitalistic and entrepreneurial modes of agriculture.

Academic work on groundwater governance is now well developed, and the topic has seen a revival of interest in the past few years with the publication of numerous studies and review articles (Megdal et al., 2015; Molle et al., 2018; Villholth et al., 2018; Closas & Villholth, 2020; Rinaudo et al., 2020; Rouillard et al., 2021). Groundwater governance is understood in this paper as 'the overarching framework of groundwater-use laws, regulations and customs, as well as the processes of engaging the public sector, the private sector, and civil society' (Megdal et al., 2015: 2). What is often missing from the academic literature, however, is a dialogue between scientists, stakeholders and decision-makers that would lead to credible options for future action and policy recommendations. The purpose of this paper is threefold: (i) to present the drivers of the current groundwater crisis, (ii) to review the solutions generally proposed and (iii) to discuss possible ways forward.

The analyses that follow build on discussions between scientists and operational experts working in the field of groundwater governance brought together by the French Development Agency[i] and the Scientific and Technical Committee for Water in Agriculture.[ii] Two workshops took place – in November 2018 and January 2020 – to evaluate the various experiences of groundwater governance in agriculture and find ways to improve them. The workshops were built on a sharing of experiences on the basis of case studies presented during the first workshop, followed by a comparison and discussion of the observable trends, the limitations of the current modes of governance and the challenges faced in overcoming them. The second workshop was more specifically spent designing potential ways forward, on the basis of thematic groups and multiple points of view, focusing on the collective dimension of groundwater governance and going beyond the specificities of each case study. They resulted in the publication of a Policy Paper on which this article is largely based (Dumont et al., 2021).

The researchers, practitioners and experts drew on their knowledge of context-specific arrangements during the workshops, and these points of reference are important in illustrating our argument. The findings of this working group were also discussed in a webinar in March 2021, which allowed us to run our diagnosis and progress paths by a much larger audience.

In this article we focus on the quantitative aspects of groundwater (over)abstraction and only address qualitative issues (e.g. pollution, salinisation) in terms of the former. Neither do we look at transboundary aquifers as these are more related to international relations. Selected case studies are based on the authors' fieldwork, meaning identified cases of overexploitation, as in North America, Australia and China, for example, are not discussed as such.

Following an overview of the use of groundwater for agriculture around the world we highlight several often-underemphasised issues to stress the actors' motivations in increasing pumping. These include a lack of knowledge of the hydrogeological dynamics and social aspects, and political inertia in the institutions responsible for groundwater governance. We then analyse some classical solutions that have been proposed and already largely implemented, particularly by public authorities, to regulate the access to and use of this resource, while highlighting their shortcomings. We then delineate some ways forward that deal with the collective aspects of groundwater governance while reconsidering the modalities of knowledge production and sharing in an attempt to grasp the socio-economic and environmental dimensions. The suggestions are intended to overcome the deadlock faced by policies focused on simply increasing the supply of water by advocating for a vision of groundwater that acknowledges and preserves its multifunctional nature.

The dynamics of groundwater use in agriculture: from economic motivations to institutional inertia

In this section, in addition to taking stock of the situation regarding groundwater use in agriculture, we also consider certain aspects sometimes underemphasised in the literature when looking at the inherent complexity of the dynamics of aquifers and their use in agriculture.

The social, economic and environmental consequences of intensive groundwater use

The pressure on groundwater is increasing constantly, both in quantitative (withdrawals) and in qualitative terms (pollution, salinisation), and there is a risk that this will increase with climate change, especially in semi-arid and arid areas (Taylor et al., 2013).

In many parts of the world, in the North and South, groundwater use has allowed farmers to secure and increase their income. Indeed, some regions owe the majority of their development to groundwater. For example, the 'green revolution' in India, which reduced famine, was largely enabled by the intensive use of groundwater combined with fertilisers (Aubriot, 2006). At the global scale, food security depends on international trade in agricultural produce, a significant proportion of which comes from groundwater-based irrigation, including crops that are also widely produced under rain-fed conditions, such as cereals (Dalin et al., 2017).

While many regions already use groundwater intensively, elsewhere (particularly in Sub-Saharan Africa) an inability to invest in the development potential of the resource, whether for economic, political or institutional reasons, means it is yet to be exhausted (Cobbing & Hiller, 2019).

The intensive use of groundwater has environmental consequences that are well identified but not always recognised or documented. The most obvious are the lowering of water tables, the degradation of the resource (pollution or marine intrusion into coastal aquifers) and land subsidence issues. Local groundwater withdrawals also have impacts at other scales on groundwater uses and resources: water that would have naturally discharged into springs, rivers or wetlands is instead captured, modifying the water exchanges between the surface and underground. This is particularly problematic in periods of drought, when groundwater naturally has a regulating effect by supporting rivers at low flow or wetlands connected to water tables. With the prospect of climate change, these issues are likely to become increasingly important and it is becoming urgent to prevent groundwater overexploitation where the dynamics of intensive use can still be reversed.

Aquifers can also be the host or vector of various water-quality problems. The natural quality of groundwater may be unsuitable for its various uses. Sometimes, exploiting groundwater which is itself of adequate quality can dislodge contaminants naturally present in a geological layer in contact with the aquifer, such as arsenic. The inadequate management of boreholes (in terms of their design or maintenance), linking water tables of different qualities, has also been widely documented (Santi et al., 2006). Furthermore, qualitative aspects are paramount when active aquifer management techniques are being considered, such as managed artificial recharge using treated wastewater or surface water. Finally, groundwater pollution should be taken into consideration, whether diffuse (nitrates, pesticides), accidental or due to spatially localised activities, and whether or not they depend on groundwater use. Irrigating with low-quality water, combined with poor drainage, can raise the level of the water table and thus its salt content, leading to soil salinisation.

All of these quantitative and qualitative phenomena generate cascades of consequences for which there is no known short-term remedy, even if, for example, the source of pollution is eliminated. They unfold across various spatial and temporal scales, affecting not only those using the aquifer but also downstream surface water users or the ecosystems.

Environmental impacts tend not to be adequately recognised in processes of water resource allocation. De Graaf et al. (2019) estimate that by 2050, in 42% to 79% of basins worldwide, excessive groundwater abstraction will disrupt ecological flows (defined as the quantity, seasonality and quality of watercourse flows required to sustain freshwater and estuarine ecosystems, as well as the needs and well-being of the people who depend on them). They point out that the alteration of surface flows may prove to be far more problematic than the loss of aquifer reserves and increased pumping costs.

Intensive abstraction also has economic and social impacts, particularly in terms of growing inequalities. Irrigators who cannot afford to invest in deeper wells, or pay the higher cost of water abstraction caused by lower groundwater levels, can become excluded from access to the resource (Mukherji, 2006; Ameur et al., 2017). In the southern Indian state of Tamil Nadu power relations have been observed between farmers considering themselves as ‘water masters’, who have the means to drill a borehole, and those who depend on the water made available to them by these ‘water masters’ in exchange for money or a portion of their own harvest (Aubriot, 2013). In Tunisia the implementation of a neoliberal policy in the mid-1990s favoured private investment, and the conditions of access to land and water resources profoundly changed, weakening those small-scale family farms that are unable to compete and become marginalised, as in the case of Sidi Bouzid (Jouili et al., 2013; Fautras, 2021).

Determinants and motivations of intensive groundwater use: from local actors to national policies

Groundwater exploitation for agriculture is driven by multiple factors at different levels that add up to dictate the intensity of abstraction. Here we discuss individual dynamics (in relation to networks of local actors), national agricultural and energy policies and, more broadly, macroeconomic factors (such as agricultural markets).

For farmers, groundwater abstraction provides a solution to restricted or insufficient access to surface water. It allows them to avoid the limitations of collectively managed surface water (community-based or public irrigation schemes), such as having to take turns in access or choose their crop based on the availability of water. It can arise from individual initiative or collective efforts to develop new territories, which, often promoted by the state, have fuelled agricultural intensification and expansion in arid or even desert areas, such as the Sahara in Algeria (Amichi et al., 2020).

The level of abstraction is closely tied to drilling techniques. In line with technological progress and according to their financial capability, farmers are gradually abandoning traditional wells that draw water from alluvial or shallow aquifers in favour of tapping deeper ones. This is facilitated by the availability of different sources of energy (electricity, diesel, gas). Easy access to deep aquifers prompts farmers to release themselves from collective surface irrigation systems, as observed in southern India (Aubriot, 2013) and Palestine (Trottier & Perrier, 2018), for instance. This shift in aquifer use, along with interactions between neighbouring wells and the lowering of the water table, causes traditional wells to fail, leading to their abandonment. Similarly, in the case of the Saïss aquifer system (Morocco), the number of farmers tapping the deep aquifer through tubewells significantly increased in the 2000s. This led to the gradual abandonment of traditional wells with limited access to water due to the geological characteristics of the aquifer and interactions between neighbouring wells, thus shifting the farmers from a world of water scarcity to one of apparent abundance (Fofack et al., 2018). The same was observed in Tunisia, where shallow wells are progressively transformed into boreholes to tap deeper aquifers (Elloumi, 2016). In the Niayes region (Senegal) we still observe the use of traditional wells (using pulley systems) alongside motor pumps.

Advanced drilling techniques aid farmers in accessing very deep aquifers. In extreme cases farmers can drill boreholes of several hundred metres to irrigate high added-value crops, such as the olive groves of the Loma de Úbeda aquifer (Spain). Their high cost means that several farms must join together to cultivate them, each gaining access to water in proportion to their investment, recalling the 'tubewell companies' of Gujarat in India (Shah & Bhattacharya, 1993). However, for those without hydrogeological knowledge there is a high risk of 'dry drilling', which, along with the high cost of drilling, may discourage farmers from undertaking such a project (Fofack et al., 2018).

Furthermore, public policies (particularly those concerning energy) directly or indirectly encourage this exploitation. Many farmers use engines, and these are powered either by subsidised fossil fuels (petrol, diesel or gas) connected to the power grid or by solar energy, which is developing rapidly. When the state subsidises energy, farmers have an indirect incentive to increase their abstraction. The consequences are worrying in some already vulnerable aquifers, as illustrated by a recent study carried out by Gupta (2019) in the state of Rajasthan in India.

In addition to energy subsidies, agricultural subsidies for certain crops can further encourage groundwater abstraction (Rouillard & Rinaudo, 2020). In Spain, European subsidies for the production of olive oil from La Loma, or wine from the Mancha Occidental aquifer, have greatly increased pressure on groundwater.

The intensive use of groundwater is often linked to the production of export crops and the role of international agro-industries. These could be cereals from the

Great Plains of the United States, fruits and vegetables from the Mediterranean region, asparagus from Peru, avocados from Chile, pistachios or almonds from California or wine, mangoes and other tropical fruits from Australia. The liberalisation of international trade and access to new markets (access to the European market for Spain in the 1980s, then for Morocco in the 2000s) play a decisive role in increasing abstraction. While these phenomena involving the exportation of 'virtual groundwater' (Dalin et al., 2017) generate local development, they are often accompanied by a monopolisation of resources by agribusiness and exacerbate water crises at the local level, leading to social and environmental crises, as observed for instance in Peru and Chile (Rinaudo & Donoso, 2019). This also raises questions about contemporary modes of consumption, whereby consumers increasingly rely on off-season, water-intensive and imported food. A clear example is the consumption of tomatoes all year round, implying their production in far-flung places.

Over-allocation of rights and widespread illegal use

Even when farmers are aware of the risk of the depletion of the resource on which their livelihood depends, they often remain in a pumping race comparable to the 'tragedy of open access' described by Garrett Hardin (1968), whereby the pursuit of individual interests in the exploitation of a common resource inevitably leads to its overexploitation if no control mechanism is set.

State regulation of abstraction through legal frameworks that integrate groundwater is increasingly common. However, overexploitation and its consequences have been tackled only belatedly, meaning that public authorities have allocated excessive rights to the resource. This can be partly explained by a lack of knowledge of the environmental consequences described above as well as by a lack of political will to take long-term issues into account.

It also results from an understanding of existing uses based on land ownership alone. In the valleys of northern Chile (Copiapo, La Ligua Petorca), for example, the total water rights allocated are four times higher than the available renewable resource, compounded by the promotion of water markets (see Box 1).

Box 1: Overallocation of groundwater in northern Chile

In the Copiapo Valley of northern Chile water rights have been over-allocated. Several factors can explain this situation of over-allocation. From a technical point of view, the available resource was evaluated following a relatively wet period, which resulted in its overestimation. The state was also under political pressure, which led to the continued allocation of temporary water rights (subsequently 'regularised') once the overexploitation was recognised. The existence of water markets exacerbated the situation by allowing users whose wells were dry to sell their rights to other users in better locations and facilitating the transfer of water rights from users with less intensive practices to those with more regular consumption (Rinaudo and Donoso, 2019). The model used to calculate the distribution of water rights (surface and groundwater) in Chile was based not only on a lack of data regarding the dynamics of the aquifer but also on a calculation that took the allocated water rights and not the amounts used as the quantity of water extracted. The model proved to be inappropriate and reinforced already existing inequalities in access to water (Budds, 2009).

The over-allocation of rights is almost systematically compounded by the problem of illegal abstraction. This can involve unauthorised well drilling, unauthorised irrigation of agricultural land or abstraction exceeding the allocated right. This has been described in Spain, where, according to a report released by WWF (2006), the Ministry of the Environment counted no fewer than 510,000 illegal boreholes in the early 2000s, each of which was abstracting more than 7,000 m3/year. This 'illegal' abstraction is motivated by the profitability of irrigated crops and is often indirectly encouraged by public subsidies, as described above, as well as crops that generate income and employment (Novo et al., 2015) for the local economy, or even as a means to preserve social order. The need to regulate illegal use and adjust rights where they have been over-allocated are therefore crucial in many contexts around the world, in developing and developed countries alike (Schulte & Cuadrado Quesada, 2020).

Lack of knowledge and status quo policy

The invisibility of aquifers makes the scarcity of the resource difficult to grasp – a central factor in overexploitation. General awareness is further hampered by a lack of hydrogeological surveys and, when they exist, meagre public availability of the data. As such, knowledge remains confined to expert circles.

The interactions of aquifers with ecosystems and surface water, and the interdependence of scales, while often insufficiently documented, are crucial in understanding how issues are embedded in territories. There is much debate around water withdrawals for gravity irrigation, which are considered as excessive, yet local actors and scientists emphasise that it is return flows to the aquifer that are crucial for domestic use as well as to sustain downstream wetlands, as illustrated by the case of the Crau plain in France (see Box 2).

Box 2: The multifunctional nature of aquifers: the example of the Crau plain in France[1]

In the Crau plain, located in the south of France (550 km²), the water table is located at highly variable depths (from 6 to 60 m, depending on the area), and traditional gravity irrigation has helped sculpt the landscape through the restitution of irrigation water to the shallow aquifer. It supplies a vast agricultural and market-gardening area (the Crau wetlands), as well as a nature reserve and a Natura 2000 site (in a more arid area comprised of steppes: the dry Crau). Apart from agriculture, diverse economic activities use the resource. Groundwater supplies drinking water not only to the inhabitants who live within its perimeter (approximately 100,000), but also to a great many users (170,000) who live nearby. This situation explains why considering the perimeter of the aquifer alone is insufficient to identify all relevant actors affected by its management. The problems of the different areas located within the hydrogeological perimeter of the aquifer (dry Crau and Crau wetlands), as well as those concerning the areas located beyond it, differ significantly. From the preservation of the environment to support for a quality agricultural sector and drinking-water supply, the challenges are all interlinked in different ways depending on the scales concerned and should be approached together with a view to preserving the common patrimony of the groundwater of the Crau region.

[1] Source: *Syndicat mixte de gestion de la nappe phréatique de la Crau* [Joint Association for the Management of the Crau aquifer] (https://www.symcrau.com/).

The lack of knowledge or uncertainty surrounding hydrogeological science is sometimes used as an excuse for inaction. For too long the claim that exhaustive knowledge must be acquired before anything can be done has justified the status quo and significantly delayed the adoption of measures to limit abstraction, or has extended consultation periods, as has been observed in the case of the Beauce aquifer in France (Petit, 2009).

Challenges in implementing solutions

When the sustainability of groundwater use is threatened, solutions are proposed alone or in combination: (i) schemes to increase the resource base or to save water, (ii) regulatory instruments implemented by the authorities, (iii) community initiatives.

Supply augmentation and water-saving schemes: ill-adapted and counterproductive solutions

A drop in the groundwater level can often prompt the exploitation of additional water resources, i.e. water transfers (sometimes over long distances) or unconventional sources, such as desalinated water or treated wastewater. Such supply augmentation options do not challenge the intensive agricultural systems at the origin of such a drop and tend to be costly both economically and environmentally. Transfers shift pressure onto the donor basin: wastewater often has already been used, and treating it does not 'add water' (however desirable this might be), while desalination comes with energy consumption and environmental impacts. In addition, while pressure may be relieved in the short term, boosting supply only encourages further shortages.

In the case of Morocco, substituting groundwater by surface water for urban supply is openly advocated so that farmers access more resources (Del Vecchio, 2020).

This move towards excluding non-agricultural users from groundwater resources can be also observed in Campo de Dalias, in southern Spain, where seawater desalination is a new source of supply to urban users, who bear its high cost (Dumont, 2015). In contrast, in Tunisia, groundwater is brought from inland plains to supply drinking water to urban areas on the coast. These transfers compete with local uses. In the plains of Sidi Bouzid or Kairouan, populations living near the aquifers request an increase of the allocation of these resources for local irrigation (Elloumi, 2016).

Supply augmentation solutions are often implemented alongside moves to save water based on technical innovations such as drip irrigation. Yet, while intended to save water, such innovations often result in agricultural intensification (introduction of crops with high added value but often higher water requirements) and an increase in the irrigated area, meaning a hike in water consumption (Ward & Pulido-Velazquez, 2008; Dumont et al., 2013; Birkenholtz, 2017; Trottier et al., 2020). In Morocco, for example, the arrival of drip irrigation on the Saïss plain was accompanied by a 50% increase in the irrigated area between 2005 and 2014 and the doubling of groundwater abstraction (Kuper et al., 2017).

Moreover, when areas irrigated with surface water undergo a change in irrigation technique it can lead to a drastic decrease in recharge due to irrigation 'losses', jeopardising the available recharge/abstraction balance in areas irrigated with both surface and groundwater. This has been observed in several Indian states and is also illustrated by the Chilean Copiapo valley and French Crau case studies mentioned in previous sections.

Among the technical solutions, managed aquifer recharge is in a category of its own by reinforcing the natural capacities of aquifers. This may include facilitating surface water infiltration during flood events or intercepting some subsurface flows through detention devices (Smith et al., 2016). The proper functioning of these devices may be the responsibility of local communities as illustrated by the flood spreading system in Ghardaïa in Algeria (Jadeja et al., 2018).

However, the risk associated with such solutions must also be recognised, particularly when they involve regular maintenance, such as the re-infiltration of treated wastewater or the use of infiltration wells. In India, for example, managed aquifer recharge is a consensual policy but its implementation is controversial (See Box 3).

Box 3: Managed aquifer recharge in India

In India groundwater accounts for more than half of the water used for irrigation and most domestic water. In the union territory of Puducherry and the state of Tamil Nadu, where groundwater is over-exploited and subject to pollution and sea-water intrusion in the coastal area, managed aquifer recharge structures are built or planned under national programmes with the support of international donors. Long-term monitoring appears to be necessary in both quantitative and qualitative terms (risk of pollution). There is a lack of user participation in their design and implementation and a lack of maintenance, and in some cases they are diverted from their initial purpose: from recharge to abstraction. Artificial recharge systems are often seen as a means to increase water supply without addressing demand. Thus, the purpose of recharge is not challenged while the means are. For example, farmers and NGOs actively defend traditional 'tanks' – seasonal lake-reservoirs that contribute to recharge – against artificial recharge wells, which they consider to be too expensive (Richard-Ferroudji et al., 2018).

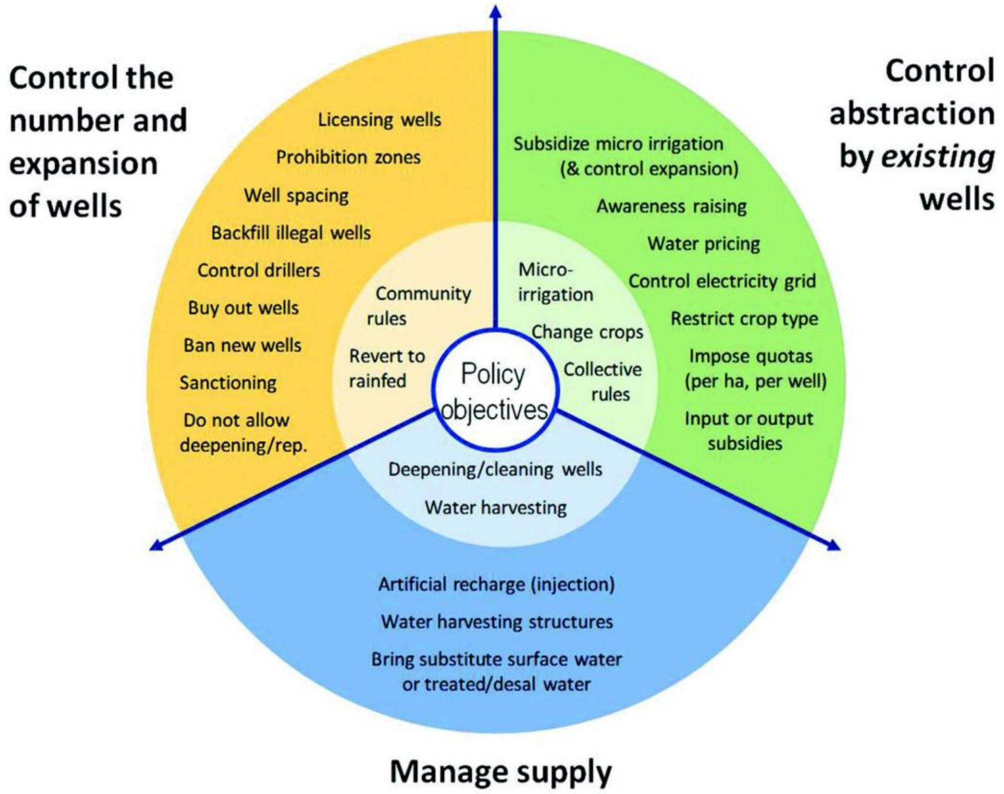
Long-term monitoring appears to be necessary to assess the quantitative and qualitative impacts of the recharge structures.

Regulatory actions taken by public authorities faced with their own dilemmas

Public authorities play a pivotal role in groundwater management. This is primarily due to the state's control of the management of land, the environment and natural resources, particularly water, which is often defined as being in the public domain. Formally, the state is also the guarantor of the general interest and of fair access to the resource for the various types of user. Moreover, public policy in domains such as agriculture, energy and public works may increase or reduce the demand for groundwater.

Faced with overexploitation, or simply to exercise their control of the resource, public authorities (central government, federal states, local authorities or even basin agencies) may implement a variety of regulatory and economic instruments (see Figure 1). These can include permits, bans, well closures, quotas, zoning by irrigated area or land use, etc. Public authorities may introduce economic measures, such as direct or indirect taxes and subsidies. These are designed to send a financial signal to farmers to limit their abstraction but are usually too small to have a significant effect. Some tools can appear contradictory or even encourage abstraction, whether directly (subsidised agriculture or electricity) or indirectly (subsidised water-saving technology).

Figure 1: Regulating groundwater access and use: the public authority's toolbox



[Source: Molle & Closas, 2020a]

Furthermore, the spatial extent of aquifers and the invisibility of the resource mean monitoring and controlling abstraction are difficult and expensive: abstraction can be carried out from any location, without its effect being directly noticed. The distribution of water volumes among the various users is complex, and the means of controlling abstraction are limited, especially in the absence of collective action and/or when the state faces legal constraints. Even if significant resources are allocated, public authorities are often helpless against the growth of (often illegal) boreholes (millions in India). They tend to respond with ill-adapted punitive systems, complicated and costly procedures to legalise illegal wells and unenforceable volumetric permit systems for groundwater abstraction. The common result is counterproductive behaviour, such as false declarations, meter tampering or even corruption (Molle & Closas, 2020a).

However, some experiments aim to counter the individualistic nature of groundwater exploitation (see Box 4).

Box 4: The role of irrigation cooperatives in the Izmir region (Turkey)

In the Izmir region of Turkey the size of the area irrigated with groundwater grew from 100,000 ha in 1978 to over 700,000 ha in 2014 (Le Visage & Kuper, 2019). Despite a failure (or lack of will) to 'combat illegal drillers' (Apaydın, 2011: 326), the water administration has sought to remain involved in monitoring this irrigation, particularly through the creation of irrigation cooperatives. Responsible for the management of collective boreholes at village level, these cooperatives irrigated almost 480,000 ha in 2014. Thus, the state (partially) supervises abstraction through collective boreholes authorised by the administration and equipped under its technical oversight. The cooperatives play a key role in local agricultural development by facilitating access to groundwater without the farmers having to individually invest in private boreholes. However, this model should not be idealised. Cooperatives often face difficulties, including the depth of the water table, poorly drilled boreholes, the incomplete or late collection of fees depending on fluctuations in agricultural income and high energy costs, and are financially unsustainable.

The obstacles to the effective public management of groundwater resources are often of a political nature. The political cost of restricting access to resources encourages public authorities to favour short-term economic development to the detriment of sustainable resource management. A certain 'social tolerance' of illegal use is thus commonly observed (López-Gunn & Martinez-Cortina, 2006). Any attempt to restrict access to the resource is opposed by those whose livelihoods depend on it (Loch et al., 2020). The political costs are closely related to the financial costs, both to irrigators and to the people depending on the resource at the local scale (Novo et al., 2015). The deadlock is compounded by the fact that the state is not a homogeneous entity but rather the vehicle of several visions, expressed through policies from different sectors at various levels, which sometimes prove to be contradictory. A national agricultural strategy favouring food self-sufficiency or production for export will result, as mentioned above, in greater extraction (see Box 5).

Box 5: When the state supports groundwater exploitation: the example of the Saïss plain (north-west Morocco)

Since the 1980s the Saïss plain has been strongly impacted by the dynamics of groundwater irrigation. Having 'one's well, borehole and water' had become a question of modernity and dignity – a sign of liberation from state control – and the pumping race turned into an identity race. Yet, state subsidies for the digging of boreholes, for drip irrigation equipment and for the planting of orchards, linked to facilitated access to land in the framework of the 'Green Morocco Plan', have benefited large farms to the detriment of small local farmers. Groundwater has come to be monopolised by a few major operators with financial means and political connections, who feel free to use the resource in an intensive (and uncontrolled) manner. Hence, there is a deliberate absence of state control and regulation in order to stifle growing political and social tensions in rural areas and ensure the coexistence of a mosaic of farms (Messaoudi, 2022).

Attempts by governments to reduce water rights have been documented throughout the world, revealing common difficulties. To address the short-term cost to the local economy and the loss of farmers' income caused by restricted water rights, 'gradual restrictions' can be proposed, either to balance dry and wet years, as in Beauce (France) (Petit, 2009), or to reduce abstraction in the long term, as in Spain (Sanchis-Ibor et al., 2017). The state may also buy back water rights, either temporarily or permanently. For example, the buyback included in the Spanish government's Plan Especial del Alto Guadiana aimed to allocate rights to vine irrigators who had none, as well as to restore natural outflows from the aquifer to the wetlands of the Tablas de Daimiel National Park, thereby justifying the cost of the measure to public finances. However, detailed accounting reveals that the anticipated results were overly optimistic, in particular because the water rights for vines (irrigated in summer) are fully used each year, unlike for cereals whose level of irrigation depends on rainfall in spring. A right is not equivalent to actual use (Dumont, 2015).

From community- to co-management: actors, legitimacy, limitations

While the role of public authorities is critical, their action alone is not sufficient. The difficulties in enforcement and the mixed results of regulatory and economic tools can be linked to a lack of user involvement in both their design and implementation. Users can be seen as responsible for the deterioration of the resource and as the direct beneficiaries of its preservation.

The problem of groundwater overexploitation is relatively recent, yet some local agricultural organisations have existed for a long time, sometimes focused on water management and sometimes on groundwater, as with the qanats of North Africa and the Near and Middle East. In some cases robust, age-old institutions for surface water management can inspire the design of specific institutions for groundwater, as in the Huerta de Valencia in Spain or in the oases of Algeria. These organisations are very rare, and, where they do exist, are not adapted to the scale of the problem caused by the intensive extraction made possible by boreholes. Therefore, it is not usually possible to rely on them to generate collective action for groundwater management. As stressed by Landy et al. (2021: 29), ‘there is nothing in the basic nature of water that makes it fundamentally prone to be a commons. It needs a social collective agreement for it to be managed “commonly” and in a sustainable way’.

Cases are reported, or even promoted, where aquifer users are deeply involved in management without it constituting ‘self-regulation’ per se (López-Gunn, 2003). The state often remains a key actor in regulating the use of water resources. Often it invites consultation with users by establishing rules or taking action. This can be illustrated by the confiscation of drills used for illegal wells in Morocco, by the Tunisian state's clampdown in Bsissi in the late 1990s, which led to a discussion that resulted in the creation of an Agricultural Development Group (ADG) for groundwater management (Molle & Closas, 2020b), or by Spain's official 'declaration of overexploitation' that made the creation of user associations compulsory. A similar process has taken place in France with the establishment of water user associations (Rouillard & Rinaudo, 2020). Collective dynamics to ensure that users adhere to allocation schemes or to create or strengthen joint practices are therefore generally co-management solutions in which public authorities remain fully involved (ibid.). However, the diversity of institutional arrangements is large, and the relative power of public authorities and groundwater users varies from one case to another, as stressed by a recent comparison between groundwater management institutions in France, Spain and the western US (Rouillard et al., 2021).

There are many drawbacks to the establishment and legitimacy of co-management groups (Molle & Closas, 2020b). These include a lack of precedent in cooperation, the prioritising of individual interests or a desire to maintain the social status linked to access to water, and a perception of the resource as a private object (due to its legal status in some countries) that precludes any collective action or intervention by the state. The cohesion of these groups is hampered by the diversity of profiles (from small farmers to agribusiness representatives) and the legitimacy of their leaders (sometimes self-appointed). Sometimes user groups fail to win the support of all their members; sometimes several user groups coexist; and in some cases these associations are not strongly supported by the state.

The co-management model, whether observed or promoted, can turn into a negotiation behind closed doors between the public authorities and the (representatives of powerful) direct users of the aquifer (Del Vecchio, 2020). There is often no real space for debate or decision-making that involves all stakeholders to address the diversity of issues, including environmental challenges and future generations, which are difficult to represent in the debate.

Possible ways forward

Turning to groundwater for agriculture is motivated by various factors and reflects a view of the resource as abundant and cheap to access. As exemplified by Kuper et al. (2017: 726) in the case of North Africa, ‘the availability of pumped groundwater 24 hours per day, 7 days a week provided a sense of abundance, at least in the short term’. This perception can lead to overexploitation – a trend that cannot be reversed by traditional solutions, such as the enforcement of regulatory tools by the state, often poorly equipped and with little legitimacy at the local level, or by increased supply (dams, reservoirs, water transfers with artificial recharge, etc.). The possible ways forward presented in this section are not intended to be a complete overview of all groundwater governance issues but are based on collective aspects relating to the necessity (i) to negotiate knowledges and visions, (ii) to broaden the debate beyond the volumetric dimension, and (iii) to balance the roles of user communities and public authorities – elements that are barely addressed in groundwater governance issues but are, we argue, decisive.

Negotiating knowledges and visions

Sharing knowledge on the functioning of aquifers is crucial. The effect of abstraction on the natural interactions of aquifers with surface water and ecosystems must be accurately assessed in order to quantify the available resource while taking into consideration all relevant variables. It is then necessary to have an estimate of effective abstraction. A clear distinction must be made between allocated water rights, effective abstraction and net consumption (considering the possible infiltration of drainage water). Moreover, the intricate interconnections of aquifers with ecosystems and surface water must be taken into account. For example, favouring pressurised irrigation to ‘save water’ where surface irrigation has helped, for many decades or centuries, to provide drinking water or sustain ecosystems reveals only a partial understanding of the water cycle. Finally, the resource/abstraction dynamic must be known and shared. The temporal response of aquifer systems in relation to qualitative and quantitative pressures and to their possible reductions must also be clearly established. Any action taken could take several decades to bear fruit, and efforts could be jeopardised if this dynamic is not adequately acknowledged. This is particularly the case for marine intrusion into coastal aquifers. Intermediate indicators can be formulated to reveal possible improvements.

When public authorities model aquifer function and abstraction estimates the results are often questioned by users who compare them to their daily experience of the scarcity of the resource. Hence, scientific knowledge should be open to resource users’ empirical knowledge, rather than creating a hierarchy, with ‘expert’ knowledge ranked above ‘local’ knowledge. A dialogue is needed between various forms of knowledge, the distinctions between which are often artificial (Agrawal, 1995). At the same time empirical evidence is not sufficient to understand the functioning of deep aquifers, and local knowledge related to this ‘new’ resource is often constructed by bore-owners and biased towards their own interests (Aubriot, 2013).

Having an institutional space for dialogue is crucial to confront and negotiate knowledge and visions based on tools and indicators that can be easily understood. Avenues worth exploring include tools derived from citizen science, the establishment of local observatories by managers (as illustrated in Box 6) and education, awareness and training programmes. An analysis of eleven case studies in France highlights the effectiveness of a variety of communication methods in making groundwater visible, from scientific reports to artistic representations, including maps, photography and digital media, and recruiting spokespeople to advocate for groundwater (Richard-Ferroudji et al., 2020).

This institutional space would allow the integration of new knowledge and adapt to changing conditions (climate issues for instance). Social learning will help to create and strengthen a collective approach to groundwater governance. One challenge in creating a functional space will be to identify the key actors (visible or invisible) and their interest in formalising their often-informal practices.

Box 6: Observatories: important forums for dialogue

Observatories generally focus on long-term monitoring requirements, and their scope depends on the actors concerned. In the case of groundwater they must enable boreholes to be located, monitor water levels and the main qualitative variables, maintain test sites, facilitate aquifer modelling work and so on. The Indo-French Centre for Groundwater Research based in Hyderabad, India, fits this model (Maréchal et al., 2018). Beyond strictly hydrological aspects, these systems provide detailed information on the various types of ecosystems that exist on the territory and their relations with groundwater, as well as on groundwater use and user profiles, particularly from a socioeconomic point of view. The range of tools includes indicators, mapped information and socio-anthropological and economic analyses. Observatories must also stimulate on-going reflection by users and support information-exchange and consultation mechanisms. This is rarely the case, however, and observatories often remain focused on the production of scientific knowledge.

A negotiated vision and collectively established regulations can also encourage compliance. In the Chaouïa region of Morocco, for example, decision-making was informed by the development of different reference scenarios shared among stakeholders (Faysse et al., 2014).

It is often difficult to establish a common vision, since stakeholders will each have their own legitimate viewpoint. More generally, as mentioned before, developing an institutional space for dialogue is a delicate process, as existing hierarchies and individual/collective interests in groundwater use will certainly be revealed, requiring specific negotiation approaches and tools. Also, dealing with overexploitation often demands challenging existing water use, and beyond that, some of the intensive agricultural systems put in place.

Nevertheless, achieving a meaningful dialogue requires the actors involved first to agree to step out of their various positions and engage in a real negotiation, and while such techniques are helpful, strong political support will be required to make this happen.

Broadening the debate beyond the volumetric dimension

A concerted decision-making process should find a context-specific solution rather than imposing an apparently universal strategy. The histories of the different users and uses of the resource must be taken into account, particularly those who have been deprived of access due to a drop in water table levels and find themselves marginalised (cf. interviews in Coste & Ploumpidis, 2007). The development of different baseline scenarios shared among actors helps to inform decision-making. In particular, it is important to understand the dynamics of entrepreneurial agriculture compared to those of traditional groundwater uses by developing alternative scenarios (Petit et al., 2018).

Shared diagnoses should be able to focus on the notions of ‘risk’ and ‘crisis’. Some overexploited aquifers have such a deficit that it seems improbable, even if pumping were discontinued, that they could return to their former water levels in the medium term. It is therefore advisable to intervene as quickly as possible, as soon as the early-warning signs of a future crisis are detected (Petit et al., 2017).

Broadening the debate beyond the establishment of an abstraction limit can generate change based on a set of socioeconomic factors. Indeed, when public authorities focus solely on the preservation of a common resource, such as groundwater, improvements are rarely seen. Diverging interests come into conflict, requiring negotiation processes that ensure the integration of all actors, including right-holder communities (see Box 7). Demonstrating the environmental and social impacts of groundwater exploitation in relation to the actors concerned can help define a negotiated pathway to reduce abstraction. It is therefore political, economic and social stakes, as much as environmental issues, that motivate the search for sustainable management.

Box 7: Local planning for integrated water resource management: the case of Niayes in Senegal[2]

In the Niayes region of Senegal, which forms a coastal strip between Dakar and Saint-Louis, the state, with support from the NGO Gret, is setting up local water platforms in municipalities to address the deterioration of groundwater. Following two years of consultation local actors have agreed a diagnosis and now share a vision for sustainable and equitable water resource management. They have also chosen their mode of governance and drawn up local plans for integrated water resource management. Memoranda of understanding for the plans have been signed by the platforms, ministerial management and the mayors of the relevant municipalities, and approved by the sub-prefects. This territorial and democratic approach stems from a political will to test local integrated water resource management through a process that connects the different levels rather than being top-down. However, the prerogatives of these platforms still need to be guaranteed through a reform of the legislative framework, currently underway, to assign the roles that are as yet only set out in their articles of association. Whether the platforms are truly representative of local actors and how power is balanced within them, warrants examination.

Balancing the roles of user communities and public authorities

The formation of user communities (self-organisation by irrigators or externally imposed) is generally a prerequisite to managing the resource. However, it is insufficient in itself and many groundwater-related issues are debated in discussion forums at other levels. Integrating citizens into these spaces, as well as users who are excluded from the resource, is also important. Thus the state should reform its approach and regulatory tools to open up these negotiation spaces, although this often goes

[2] https://www.gret.org/projet/recherche-action-sur-la-gestion-integree-des-ressources-en-eau-dans-les-niayes/

against deep-seated practices of non-transparency and centralised decision-making. It becomes crucial then to strengthen human resources (staff and skills) with, for example, the intervention of legitimate mediators with recognised skills.

Depending on the maturity of the user communities, they may be given certain responsibilities but also positive incentives in exchange for commitments (see the example of La Mancha Oriental, Spain, Box 8). If it is to be effective, this concerted management requires leadership which is seen to be legitimate, making it possible to put in place specific arrangements and economic incentives, as well as to take full advantage of the entire range of regulatory instruments and render them effective on the ground.

Box 8: Organisation and 'self-governance' of the irrigators of La Mancha Oriental (Spain)

The aquifer of La Mancha Oriental (Spain) is used to irrigate approximately 100,000 ha of cereals, vegetables and vines. Contributing naturally to the flow of the river Júcar, which crosses it, the volumes extracted have an adverse impact on the aquatic ecosystems and the sustainability of traditional irrigation downstream (the area surrounding Valencia).

It is noteworthy that the creation of a user association of irrigators to address the situation has reduced abstraction by approximately 25%. This is mainly due to cooperative regulation by the irrigators and a penalty system established in collaboration with the authorities. As the latter have a legitimate user representative to engage with they can more easily impose restrictive measures during droughts, such as financial compensation in exchange for reducing abstraction. This relative success (the adverse environmental impacts are still significant) can be explained by the existing social organisation of the irrigators and the local 'social capital', and by a change in certain agricultural practices, as well as by a number of 'external' factors that could call into question the 'spontaneous' aspect of this organisation, such as the additional supply of surface water (Molle & Closas, 2020b).

A responsibility that could be handed to users is deciding how the resource is allocated once the overall level of abstraction has been established, as has happened in France for instance (Rouillard & Rinaudo, 2020). It could also be the case that any request for a new abstraction right must receive the user group's approval before being submitted to the public authorities. This autonomy can strengthen adherence and compliance with the level of abstraction but is unlikely to be achieved if users do not receive some 'carrots' (e.g. additional supply from other sources, subsidies, etc.) in exchange for accepting the logic of the 'stick' (Molle & Closas, 2020b). More ‘flexible’ water distribution instruments, such as water markets or the allocation of a collective right to an irrigator community, can result in a higher rate of water right use: irrigators who would not have used their individual water right for a variety of reasons may transfer it to others. In addition, control may no longer be solely the responsibility of the public authorities and could thus involve users, or at least create a common sense of responsibility.

Finally, the inclusion of users in the sphere of decision-making and compromise can be based on a set of solutions integrating groundwater management and the mobilisation of additional resources (surface water, re-use or desalination) while supporting agricultural development. This comprehensive approach can make it possible both to restore the water balance in the short term and ensure that management mechanisms are in place for the long term.

Conclusion: strengthen the understanding of groundwater as a common patrimony and develop a territorial project

We conclude that it is imperative to move away from the dominant vision of groundwater as a natural capital to be exploited for the sole purpose of agricultural intensification and economic development. Rather, defining what constitutes a common patrimony (Calvo-Mendieta et al., 2017) among heterogeneous actors whose interests may sometimes clash is helpful in negotiating the sharing and management of groundwater. Technical and economic solutions must emerge from the agreements reached in social collective arenas at different levels.

Initiatives should derive from an approach in which groundwater is considered a common patrimony (for example prioritising the preservation of wetlands to take account of long-term issues). This way, problems are more likely to be discussed collectively and solutions found that depart from the conception of water as a commodity (Calvo-Mendieta et al., 2017). This also means being aware of the crucial aspect of access to groundwater for vulnerable groups as a means of livelihood and poverty alleviation. Indeed, the development of agribusiness, often with state support, denies certain users access to groundwater and neglects the environmental consequences of its intensive exploitation.

The rules and instruments arising from the consultation process must be legitimised and politically backed at the local level to improve the chances of sustainable groundwater management. According to Calvo-Mendieta et al. (2017: 127), ‘common patrimony becomes meaningful only in the identification of a community of holders who recognise themselves as being the guarantors for the preservation and transmission of the common resources in a given territory’. This means that local public actors and ‘indirect’ users should be involved in decisions concerning groundwater management. Hence, analysing the stakes of this management for the territory and the local economy is an effective way to achieve the adherence of local representatives and users, and, therefore, to widen the debate beyond the hydrogeological unit to address the multifunctional nature of groundwater. Communication and awareness-raising should be directed at the general public, especially when decisions by local representatives risk being misunderstood.

Finally, initiatives to promote groundwater preservation should ensure that its management is fully integrated into discussions on territorial development and basin management so that all local actors value it and consider it in future planning.

Territorial development refers here to the design of a socially constructed space where actors can project themselves and build activities and policies that allow this territory to reveal its specific resources (Caron, 2015). Appreciating the interconnectedness of surface and groundwater, and the various spaces delineated by overlapping aquifers, helps to identify which individual actors, and which formal and informal organisations, should be involved for each specific situation or issue. It is therefore important to renew development frameworks and models at a territorial scale, building on existing collectives. This is helpful in collectively determining which territorial project 'makes sense', particularly where the potential remains to increase groundwater exploitation, as in Sub-Saharan Africa.

Acknowledgements

This paper is the result of insights gained from the discussions of a joint working group of the French Development Agency (AFD) and the COSTEA project (www.comite-costea.fr).

Author contributions

OP, AD, SL, QB and SB: Organization of the workshops on which this paper is based; Conceptualization, Methodology, Writing- Original draft preparation.

NF, MK and FM : Facilitators of the working groups and rapporteurs in the workshop. Writing- Reviewing and Editing.

CA, ED, RG, AH, SLV, IM, MM, SN, ARF, JDR and JT : Presentation of detailed case studies in the workshop. Drafting of boxes. Writing- Reviewing and Editing.

OA and ME : Mobilised as discussants during the last workshop. Writing- Reviewing and Editing.

MB, RFG, FM, DR, BR and ES : Contributions in the forms of ideas during the workshop. Writing- Reviewing and Editing.

References

Agrawal, A. (1995). Dismantling the Divide between lndigenous and Scientific Knowledge. *Development and Change*, *26*(3), 413–439.

Ameur, F., Amichi, H., Kuper, M. & Hammani, A. (2017). Specifying the differentiated contribution of farmers to groundwater depletion in two irrigated areas in North Africa. *Hydrogeology Journal*, *25*, 1579–1591.

Amichi, F., Bouarfa, S., Kuper, M. & Caron, P. (2020). From Oasis Archipelago to Pioneering Eldorado in Algeria's Sahara. *Irrigation and Drainage*, *69*(Suppl. 1), 168–176.

Apaydın, A. (2011). Groundwater legislation in Turkey: problems of conception and application. *Water International*, *36*(3), 314–327.

Aubriot, O. (2006). Baisse des nappes d'eau souterraine en Inde du Sud : forte demande sociale et absence de gestion de la ressource. *Géocarrefour*, *81*(1), 83–90.

Aubriot, O. (Ed.) (2013). Tank and Well Irrigation Crisis: Spatial, Environmental and Social Issues. Cases in Puducherry and Villupuram Districts (South lndia). Delhi, Concept Publishing Company, 405 p.

Birkenholtz, T. (2017). Assessing India's drip-irrigation boom: efficiency, climate change and groundwater policy. Water International, 42(6), 663–677.

Budds, J. (2009). Contested H_2O: Science, policy and politics in water resources management in Chile. Geoforum, 40(3), 418–430.

Calvo-Mendieta, I., Petit, O. & Vivien, F-D. (2017). Common Patrimony: A Concept to Analyze Collective Natural Resource Management. The case of water management in France. Ecological Economics, 137, 126–132.

Caron, P. (2015) Territory: with government and market, a major institutional component to achieve resilience. Natures Sciences Sociétés, 23, 175-182.

Closas, A. & Villholth, K.G. (2020). Groundwater governance: Addressing core concepts and challenges. WIREs Water, 7(1), e1392.

Cobbing, J. & Hiller, B. (2019). Waking a sleeping giant: Realizing the potential of groundwater in Sub-Saharan Africa. *World Development*, *122*, 597–613.

Coste, N. & Ploumpidis, N. (with Anupama, K., Aubriot, O. & Gunnell, Y.). (2007). *Bittersweet waters: irrigation practices and modern challenges in South India*. Trilingual DVD (French, English, Tamil), Publications Hors Série 5, Pondicherry: French Institute of Pondicherry. https://vimeo.com/223447091

Dalin, C., Wada, Y., Kastner, T. & Puma M.J. (2017). Groundwater depletion embedded in international food trade. *Nature*, *543*, 700–704.

De Graaf, I.E.M., Gleeson, T., Van Beek, R., Sutanudjaja, E.H. & Bierkens, M.F.P. (2019). Environmental flow limits to global groundwater pumping. *Nature*, *574*, 90–94.

Del Vecchio, K. (2020). Gestion des eaux souterraines au Maroc : entre priorités du développement agricole et préoccupations environnementales. Les apports de la science politique. *Note COSTEA*, July, 7 p.

Dumont, A. (2015). *Flows, Footprints and Values: Visions and Decisions on Groundwater in Spain*, doctorado en Geología e Ingeniería Geológica, Universidad Complutense de Madrid, 311 p.

Dumont, A., Mayor, B. & López-Gunn, E. (2013). Is the rebound effect or Jevons paradox a useful concept for better management of water resources? Insights from the irrigation modernisation process in Spain. *Aquatic Procedia*, *1*, 64–76.

Dumont, A., Leyronas, S., Petit, O., Ballin, Q. (2021), Acting Together for the Sustainable Use of Water in Agriculture. Proposals to Prevent the Deterioration and Overexploitation of Groundwater. *AFD Policy paper*, n°8.

Elloumi, M. (2016). *La gouvernance des eaux souterraines en Tunisie*, IWMI Project Report, n°7, Groundwater governance in the Arab World, 121 p.

FAO (2016), *Global Diagnostic on Groundwater Governance*. Roma, FAO.

Fautras, M. (2021). *Paysans dans la révolution. Un défi tunisien*. Paris, Tunis, IRMC-Karthala, 494 p.

Faysse, N., Errahj M., Imache A., Kemmoun H., Labbaci T. (2014). Paving the way for social learning when governance is weak: Supporting dialogue between stakeholders to face a groundwater crisis in Morocco. *Society and Natural Resources*, *27*, 249–264.

Fofack, R., Billaud, J-P., Kuper, M. & Petit, O. (2018). Analyse du basculement des modes d’extraction des eaux souterraines dans le Saïss (Maroc). Vers une reconfiguration du monde des eaux cachées ? *Développement durable et territoires*, *9*(2).

Gupta, E. (2019). The impact of solar water pumps on energy-water-food nexus: Evidence from Rajasthan, India. *Energy Policy*, *129*, 598–609.

Hardin, G. (1968). The Tragedy of the Commons. *Science*, *162*(3859), 1243–1248.

Hoogesteger, J. & Wester, P. (2015). Intensive groundwater use and (in)equity: Processes and governance challenges. *Environmental Science and Policy*, *51*, 117–124.

Jadeja, Y., Maheshwari, B., Packham, R., Bohra, H., Purohit, R., Thaker, B., Dillon, P., Oza, S., Dave, S., Soni, P., Dashora, Y., Dashora, R., Shah, T., Gorsiya, J., Katara, P., Ward, J., Kookana, R., Singh, P.K., Chinnasamy, P., Goradiya, V., Prathapar, S., Varua, M. & Chew, M. (2018). Managing aquifer recharge and sustaining groundwater use: developing a capacity building program for creating local groundwater champions. *Sustainable Water Resources Management, 4*, 317–329.

Jouili, M., Kahouli, I. & Elloumi, M. (2013). Appropriation des ressources hydrauliques et processus d'exclusion dans la région de Sidi Bouzid (Tunisie centrale). *Études rurales*, 192, 117–134.

Kuper, M., Ameur, F. & Hammani, A. (2017). Unravelling the enduring paradox of increased pressure on groundwater through efficient drip irrigation. in: Venot J-P., M. Kuper and M. Zwarteveen (Eds), *Drip irrigation for agriculture: untold stories of efficiency, innovation and development*, Abingdon, Routledge.

Kuper, M., Amichi, H. & Mayaux, P.L. (2017). Groundwater use in North Africa as a cautionary tale for climate change adaptation. *Water International*, *42*, 725–740.

Landy, F., L. Ruiz, J. Jacquet, A. Richard-Ferroudji, M. Sekhar, H. Guétat-Bernard, M. Oger-Marengo, G. Venkatasubramanian & Noûs, C. (2021). Commons as Demanding Social Constructions: The Case of Aquifers in Rural Karnataka. *International Journal of Rural Management*, *17*(1), 27–54.

Le Visage, S. & Kuper, M. (2019). Sous les gölet, les forages. Infrastructures d'irrigation et trajectoires des territoires de l'eau dans la région d'Izmir (Turquie). *Développement durable et territoires*, *10*(3).

Loch, A., Perez-Blanco, C.D., Carmody, E., Felbab-Brown, V., Adamson, D. & Seidl, C. (2020). Grand theft water and the calculus of compliance. *Nature Sustainability*., *3*, 1012–1018.

López-Gunn, E. (2003). The role of collective action in water governance: a comparative study of groundwater user associations in La Mancha Aquifers in Spain. *Water International*, *28*, 367–378.

López-Gunn, E. & Martinez-Cortina, L. (2006). Is self-regulation a myth? Case study on Spanish groundwater user associations and the role of higher-level authorities. *Hydrogeology Journal*, *14*, 361–379.

Maréchal, J.-C., Selles, A., Dewan-Del, B., Boisson, A., Perrin, J. & Ahmed, S. (2018). An observatory of groundwater in crystalline rock aquifers exposed to a changing environment: Hyderabad, India. *Vadose Zone Journal*, 17:180076. doi:10.2136/vzj2018.04.0076

Megdal, S.B., Gerlak, A.K., Varady, R.G. & Huang, L.Y. (2015). Groundwater governance in the United States: Common priorities and challenges. *Groundwater*, *53*(6), 677–684.

Messaoudi, I. (2021). Quelle modernisation rurale pour quel développement ? Appropriations foncières, recompositions de l'espace et dualisme agraire au Maroc. *Annales de géographie*, forthcoming.

Molle, F. & Closas, A. (2020a). Why is state- centered groundwater governance largely ineffective? A review. *WIREs Water*, *7*(1).

Molle, F. & Closas, A. (2020b). Comanagement of groundwater: a review. *WIREs Water*, *7*(1).

Molle, F., López-Gunn, E. & van Steenbergen, F. (Eds.) (2018). The local and national politics of groundwater overexploitation. *Water Alternatives*, *11*(3).

Mukherji, A. (2006). Political ecology of groundwater: the contrasting case of water-abundant West Bengal and water-scarce Gujarat, India. *Hydrogeology Journal*, *14*(3), 392–406.

Novo, P., Dumont, A., Willaarts, B.A. & López-Gunn, E. (2015). More cash and jobs per illegal drop? The legal and illegal water footprint of the Western Mancha Aquifer (Spain). *Environmental Science and Policy*, *51*, 256-266.

Petit, O., (2009). Un regard rétrospectif sur l’évolution de la gouvernance de l’irrigation en Beauce (1993-2008). *Science et changements planétaires/Sécheresse, 20*(3), 262–270.

Petit, O., Kuper, M., López-Gunn, E., Rinaudo, J.D., Daoudi, A. & Lejars, C. (2017). Can Agricultural Groundwater Economies collapse? An Inquiry into the Pathways of four Groundwater Economies Under Threat. *Hydrogeology Journal*, *25*(6), 1549–1564.

Petit, O., Kuper, M. & Ameur, F. (2018). From Worker to Peasant and Then to Entrepreneur? Land Reform and Agrarian Change in the Saiss (Morocco). *World Development*, *105*, 119–131.

Richard-Ferroudji, A., Raghunath, T.P. & Venkatasubramanian, G. (2018). Managed aquifer recharge in India: Consensual policy but controversial implementation. *Water Alternatives*, *11*(3), 749–769.

Richard-Ferroudji, A. & Lassaube, G. (2020). The Challenge of Making Groundwater Visible: A Review of Communication Approaches and Tools in France. In: Rinaudo J-D., Holley C., Barnett S., Montginoul M. (eds) Sustainable Groundwater Management. Global Issues in Water Policy, vol 24. Springer, Cham.

Rinaudo, J-D. & Donoso, G. (2019). State, market or community failure? Untangling the determinants of groundwater depletion in Copiapó (Chile). *International Journal of Water Resources Development*, *35*(2), 283–304.

Rinaudo, J-D., Holley, C., Barnett, S. & Montginoul, M. (Eds) (2020). *Sustainable Groundwater Management. Global Issues in Water Policy*, vol 24. Springer, Cham.

Rouillard, J. (2020). Tracing the Impact of Agricultural Policies on Irrigation Water Demand and Groundwater Extraction in France. in: Rinaudo J.D.., C. Holley, S. Barnett, M. Montginoul (Eds) (2020). *Sustainable Groundwater Management. Global Issues in Water Policy*, vol 24. Springer, Cham.

Rouillard, J. & Rinaudo, J-D. (2020). From State to user-based water allocations: an empirical analysis of institutions developed by agricultural user associations in France. *Agricultural Water Management*. *239*, 106269.

Rouillard, J., Babbitt, C., Pulido- Velazquez, M. & Rinaudo, J-D. (2021). Transitioning out of Open Access: a closer look at Institutions for Management of

Groundwater Rights in France, California, and Spain. *Water Resources Research*, e2020WR028951.

Sanchis-Ibor, C., García-Mollá, M. & Avellà-Reus, L. (2017). Effects of drip irrigation promotion policies on water use and irrigation costs in Valencia, Spain. *Water Policy*, *19*(1), 165–180.

Santi, P.M., McCray, J.E. & Martens, J.L. (2006). Investigating cross-contamination of aquifers. *Hydrogeology Journal*, *14*, 51-68.

Schulte, S. & Cuadrado Quesada, G. (2020). Reducing Entitlements When Groundwater Has Been Over-Allocated: Policy Issues and Options. In: Rinaudo J.D.., C. Holley, S. Barnett, M. Montginoul (Eds) *Sustainable Groundwater Management. Global Issues in Water Policy*, vol 24. Springer, Cham.

Shah, T. & Bhattacharya, S. (1993). Farmer Organizations for Lift Irrigation: Irrigation Companies and Tubewell Cooperatives of Gujarat. Irrigation Management Network, Overseas Development Institute, London, Network paper, n°26.

Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Doll, P. & Portmann, F.T. (2010). Groundwater use for irrigation – a global inventory. *Hydrology and Earth System Sciences*, *14*, 1863–1880.

Smith, M., Cross, K., Paden, M. & Laban, P. (2016). *Spring – Managing groundwater sustainably*. IUCN, Gland, Switzerland, 133 p.

Taylor, R., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M. Bierkens, M.F.P., MacDonald, A., Fan, Y., Maxwell, R.M., Yechieli, Y., Gurdak, J.J., Allen, D.M., Shamsudduha, M., Hiscock, K., Yeh, P.J.-F., Holman, I. & Treidel, H. (2013). Ground water and climate change. *Nature Climate Change, 3*, 322–329.

Trottier, J., Leblond, N. & Garg, Y. (2020). The Political Role of Date Palm Trees in the Jordan Valley: The Transformation of Palestinian Land and Water Tenure in Agriculture Made Invisible by Epistemic Violence. *Environment and Planning E: Nature and Space*, *3*(1), 114–140.

Trottier, J. & Perrier, J. (2018). Water Driven Palestinian Agricultural Frontiers: The global ramifications of transforming local irrigation. *Journal of Political Ecology*, *25*(1), 292–311.

Villholth, K., López-Gunn, E., Conti, K., Garrido, A. & van der Gun, J. (Eds.) (2018). *Advances in Groundwater Governance*, Leiden, CRC Press/Balkema.

Ward, F.A. & Pulido-Velazquez, M. (2008). Water conservation in irrigation can increase water use. *PNAS*, *105*(47), 18215–18220.

WWF (2006). *Illegal water use in Spain. Causes, effects and solutions*, WWF/Adena, 20 p.

---

[i] Agence Française de Développement (AFD).

[ii] Comité scientifique et technique pour l'eau agricole (Costea).