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PAPER

Groundwater licensing and its challenges

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Abstract

The registering and/or licensing of groundwater abstraction is held as a "best practice" in the control of groundwater use and a necessary step toward volumetric management of resources. Yet, groundwater licensing and legalization processes in areas with many scattered (often agricultural) users tend to face severe difficulties and are rarely successful. Based on a global survey on groundwater governance, this article revisits the reasons for the users' lack of interest, the failure of most legalization/licensing processes, and the frequent lack of both capacity and the political will of government agencies in conducting such processes. It identifies a groundwater licensing dilemma that explains why governments deploy too little effort too late, and finally proposes a few steps and principles to be considered when deciding whether licensing is achievable and how to increase the likelihood of success.

Keywords Groundwater management · Over-abstraction · Socio-economic aspects · Licensing · Wells

Introduction

The overexploitation of groundwater, however contested its definition (Custodio 2002; Molle et al. 2018), is recognized by a dropping water table and undesirable effects that can no longer be glossed over and have come to be considered greater than the benefits of groundwater use (Famigletti 2014; Wada et al. 2012). These effects include drying springs and desiccated wetlands, reduced river base-flow, land subsidence, dried-up wells, declining groundwater quality, and saline water intrusion (Foster and Chilton 2003; Konikow and Kendy 2005; Richey et al. 2015). Addressing excessive use readily triggers two key questions: how much is too much? and how could abstraction be reduced (Molle et al. 2018)? Discussions about what should be done generally hinge on identifying who is pumping, how much, and where. As the oft-repeated mantra goes, "you cannot manage what you do not know" (see Alley and Alley 2017; García et al. 2018; Grönwall and Oduro-Kwarteng 2018; OECD 2015; Wijnen et al. 2012; World Bank 2010). Quantification is therefore seen as a prerequisite to informed decision-making and is defined here as *the procedures by which well characteristics (e.g. location, capacity, type of use) are known, registered, and possibly made lawful, and through which actual groundwater use is monitored, measured, or estimated*. While these two elements—the identification of wells and their actual abstraction—seem to be linked and complementary, it must be noted that use can also be estimated (such as through remote sensing) without full knowledge of existing wells. Likewise, actual use cannot be easily derived from the characteristics of existing wells such as their abstraction capacity, since it can vary according to factors that include the weather, water depth, crop type, the availability/cost of energy for pumping, and whether the farmer has fallowed the land.

While "administrative permit-based water rights systems are becoming a norm" (Mechlem 2016, p. 12) and "permitting or licensing used by governments to administer rights to extract groundwater" is seen as "cornerstones of law on groundwater" (Smith et al. 2016, p. 8), groundwater licensing and allocation are now taught as best practice (e.g. Cap-Net 2010). In sub-Saharan Africa, "high-income donor countries have promoted permit systems and water use metering as global best practices and as critical ingredients of integrated water resources management" (van Koppen and Schreiner 2019, p. 148). In India, the latest (2011) Groundwater Model Bill proposed by the federal government extends the requirement for permits to all uses. Half of India's states have passed laws largely inspired by the 2005 Model Bill, with common features that include the prohibition of drilling in 'notified' areas,

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licensing, regulation of the depth and spacing of wells, and the blanket regularization of existing wells/uses (Water Governance Facility 2013).

Whether groundwater rights emanate from colonial systems, Roman law, civil law, or communist or Islamic traditions, the great majority of policy and legal reforms since World War II, and particularly since the 1980s, have worked to constrain individual water rights and strengthen and formalize usufruct rights systems through state regulation (Burchi and Nanni 2003). The progression from customary rights, open access/rights of capture, or even property rights to state-centered regulation is not at all unique to groundwater and can be witnessed for all renewable resources (Scott 2008). While such formalization is allegedly intended to strengthen the security of water rights and facilitate allocation by the state to different uses (Mechlem 2016), some analysts consider that such state-mediated formalization and quantification of groundwater rights is an implicit way to ease its transfer to cities or uses with high water productivity, sometimes allowing water grabbing (see Birkenholtz 2015; Boelens and Seemann 2014).

In most cases the permits/entitlements/licenses granted by the state are not rights per se (with the exception of Chile and some parts of the US), but usufruct rights. As will be shown later, the state can qualify the right to use the water by fixing quantitative parameters (e.g. maximum well discharge, maximum monthly or annual abstraction volumes), restrict the validity of the license (typically between 5 and 50 years), the quality of the right (e.g. limit use to certain purposes, decrease the entitlement according to the hydrologic situation, determine rules for well maintenance operation), or transferability (allowing groundwater markets, or impeding a plot of land with an illegal well to be sold). In what follows, licenses and permits will be used interchangeably, but (private) 'rights' will be used when it applies and 'authorizations' when a simple notification of use is required—see Theesfeld (2010) for a discussion on groundwater rights and Scott (2008) for a wider perspective on the evolution of natural resources property rights.

While the need to inventory and/or register wells is largely taken for granted, and groundwater-use metering is frequently adopted as standard policy by governments, especially when facing groundwater depletion, there is scant literature examining in detail how such management tools, arguably sound on paper, perform in practice, or what the real implications are on the ground and for users—see for example Al Naber and Molle (2017) on Jordan and Reis (2014) on Mexico). Indeed, quantification appears to be beset by obstacles that reflect the spatially diffuse nature of groundwater use and the often high number of abstractors of this invisible resource, as well as social and political realities at the local and national level. Although illegal use remains a key feature of groundwater economies that undermines management, it is often treated as an inconvenient truth or side-effect deemed to be gradually and naturally eliminated through the simple application and expected enforcement of groundwater management rules. These issues have received limited attention with some notable exceptions such as Dworak et al. (2010) or De Stefano and López-Gunn's (2012) paper on Spain and industrialized countries, aiming to expand the standard warning found in groundwater policy literature that licensing and metering require adequate institutional capacity or political will to be effective.

This paper sets out to revisit the empirical evidence regarding how quantification is achieved in practice, with an emphasis on large, agriculture-based groundwater economies in developing countries. The analysis is drawn from a wider global stock-taking exercise of groundwater governance that considered ~1,200 documents, complemented by communications via email with 40 knowledgeable scientists in various key countries and further insight from field and policy research conducted in the Middle East and North Africa (MENA)—see IWMI 2011; in several instances this paper indicates relevant countries or cases without providing a full reference due to space limitations (readers can refer to Molle and Closas 2017 for greater detail).

Because fully fledged attempts at registering wells never start from a blank slate, one first needs to examine the specific challenges posed by the legalization of existing wells. This is somehow a prerequisite because it will be difficult to establish and run a well licensing program if a large number of wells remain both unregistered and unaffected by the law. The paper then reviews the difficulties inherent in licensing processes, with illustrations from selected countries in which these issues are prominent. The ensuing section emphasizes how both the legalizing and regular licensing processes must not be seen as rational bureaucratic procedures to be established but, rather, as loci of power and political interests. Hydrogeological, logistical, and political difficulties combine to generate a policy inertia that leads us to identifying a 'licensing policy dilemma'. The final section draws again on the global survey to discuss and outline the context in which these well-licensing policies are more likely to succeed and finally propose a few general principles that should inform such policies. While this article focuses on the question of groundwater licensing, the issue of metering will be addressed elsewhere (Molle and Closas forthcoming). These parallel reviews aim to contribute to an assessment of the use, expectations, effectiveness, and limits of groundwater quantification policies in order to inform and improve existing and future groundwater management and regulatory approaches.

Identifying and legalizing existing users

Inventorying and registering *existing* wells are the first steps toward quantification. From the 1980s onwards, many countries either established new systems of water permits (based on existing historical groundwater rights or licenses) or reactivated regulations that mandated the registration of wells but had largely been ignored. Where no system of declaration existed, it was all but impossible to deny legalization or “regularization” to those who had already invested in their wells. Likewise, where a system was already in place, the overwhelming proportion and number of already-dug unregistered wells meant that denying these historical uses legal recognition would be politically unfeasible. In both cases, existing users were generally allowed to be legalized and licensed over a period of time, subject to conditions such as reasonable or productive use, and proof of former use. These points will be addressed and developed in this section.

Identifying existing groundwater uses

The difficulties in legalizing wells begin with identifying who was using the water, and how much, prior to the inventory and/or the new legislation. It is obviously tempting for users to declare and register above actual use in order to protect their access to groundwater against any future limitations, or even to declare nonexistent use if there is no control (e.g. in Tunisia; S. Massuel, IRD, personal communication, 2015) for fear of a ban on well drilling.

In Chile, the 2005 reform of the Water Law sought to address the partial irregularity of groundwater use. The General Water Directorate (DGA) granted permanent abstraction rights to any abstraction of less than 2 L/s that had been established prior to June 2004 as attested by the user before the end of 2005. This led to the overallocation of groundwater volumes in aquifers across the country and the drop in water levels in particular regions with high groundwater use for agriculture and/or mining (Rinaudo and Donoso 2019). In Spain, groundwater users had to prove that they had been abstracting water prior to the enactment of the 1985 law, which led to administrative chaos, since neither the law nor subsequent regulation specified which documents could be used as proof (Closas et al. 2017).

In 1992, a new National Water Law in Mexico declared both surface and groundwater to be in the public domain and required groundwater users to register all abstraction points in the Public Registry of Water Rights. A multitude of “irregular” or provisional extraction authorizations required regulation and additions to the registry, with users being granted an entitlement (or “concession”) to abstract a certain amount of groundwater at each well (CONAGUA 2009). Due to insufficient institutional and human resources, however, the water administration could not verify the authenticity of the permits or confirm the legitimate use of groundwater (World Bank 2009). In Toluca Valley, for example (Reis 2014), to establish volumetric concessions officers used information such as the characteristics of the wells’ construction and operation and the number of hectares irrigated (e.g. 6,000 m^3/ha/year). However, it also surfaced that agricultural users could state any volume in their application and the concession would be granted unchecked; as a result, most are “over-concessioned”, i.e. hold entitlements to higher volumes than they actually use.

In South Africa, attempts to determine the legality of existing users through the “validation and verification” process proved to be complicated and time-consuming (Movik and de Jong 2011). The Department of Water Affairs had “very limited capacity to evaluate and judge each application on its own merits, check on-site, or enforce the licensing process. Administrative pressure, and the proven threat that vested applicants can report any delays to the Water Tribunal, pushes officials towards allocating whatever is being asked for” (Funke and Jacobs 2011, p. 90).

Shifting deadlines

Regularization procedures generally give well owners (whether legal or illegal) a specific timeframe (typically ranging from 6 months to 2 years) within which to register their wells. However, the expectation that people will be ready to comply and happy to legalize their wells is (almost) always proven wrong. Consequently, registration procedures are lengthy and unconcluded, with their deadlines regularly extended:

- In Morocco, a legalization period for wells dug before 1995 was opened in 1998; in 2009, wells dug before 2009 could be registered within a 3-year period, later extended by a further 3 years to 2015 (BRLI and Agro Concept 2012).
- In Jordan, the 2002 bylaw gave the owners of illegal wells 6 months to register (if they fit a certain socioeconomic criterion); an amendment in 2003 gave another year, and in 2007, registration was restricted to wells drilled before 2005 and awaiting a land settlement. In 2014, all wells dug before 2005 were considered illegal and liable to be backfilled (Al-Naber and Molle 2017).
- In Guanajuato, Mexico, a first-time limit was issued in 1995, then 1996, and yet one more on February 2002 with a time limit of up to September 2002 (Shah 2005).
- Despite making existing well registration mandatory, as well as the application for permits for new wells after December 2012, the Bangalore Water Supply and Sewerage Board had only recorded 135 bore wells 3 months later. The deadline to register existing wells was extended three times (Water Governance Facility 2013).
- In Iran, the 1983 water law legalized unlicensed deep wells dug since 1979. In 2006, regional water authorities tried to stop the unabated growth of illegal wells, but social resistance led the parliament to terminate the program

and issue a new law in 2010, which, again, legalized illegal wells dug before 2005 (Nabavi 2018).

Logistical nightmare

Legalization processes are fraught with high costs, false declarations, litigation, corruption cases, and what almost invariably turn out to be a logistical nightmare. In Spain, on the last day of the registration period in 1988, 12,000 applications for groundwater abstraction permits overwhelmed and crippled the Guadiana River Basin Authority (Fornés Azcoiti et al. 2005). Subsequent governmental programs to regularize groundwater abstraction also proved to be insufficient and costly: between €150 and €300 million for the 500,000 wells to be registered in Spain (some estimate their number at 1 or even 2 million) at a unit cost per well of €300 to €600 (Fornés Azcoiti et al. 2005).

In South Africa, the regulation of groundwater abstraction through licensing hit problems, with the administrative burden of a large number of licenses requested by small-scale users, as well as delays caused by the difficulty of obtaining the necessary information from applicants (Seward 2010). The runtime to process licenses took years rather that the target of 5 months, resulting in heavy backlog (Pietersen et al. 2011). Licensing "is often regarded as a tedious piece of bureaucracy rather than a powerful tool for ensuring sustainability, especially when license applicants usually expect the process to be completed in a few months" (Seward 2010, p. 242). There is a lack of human resources, socioeconomic data related to groundwater resources, and technical and professional expertise (Knuppe 2011; Seward et al. 2015).

In Tanzania, only 3,680 water-use permits (and effluent-discharge and drilling permits) had been allocated across the entire country by 2014. This prompted van Koppen et al. (2016, p. 601) to observe that, "even if the hundreds of thousands of smallholder irrigators had been informed about the law and had applied for a permit, state capacity would have been too limited to process even a fraction of their applications". In five other African countries—Kenya, Malawi, South Africa, Uganda, and Zimbabwe—the number of water-use permits (combining surface and groundwater) ranged from 1,320 to 10,799, while estimates of the number of water users requiring a permit came to several hundreds of thousands (van Koppen and Schreiner 2019). Kenya has granted 4,000 permits (80% for groundwater use) after a century of obligation to register, while 45,000 boreholes were identified in 2012. The available means pale with regard to the huge number of abstractors remaining in juridical limbo.

Legal complexities

A particular problem arises when the consolidation of water entitlements comes with a shift from a private right system to a public one with concessions. In Spain, the 1985 law declared water to be in the "public domain" and that the state would regulate and control groundwater abstraction via concessions issued by River Basin Authorities for all users of wells over 7,000 m^3/year (Closas et al. 2017). This allowed well owners to register their historical rights with the Registry of *Public* Waters within 3 years of the law's passing, or in the Catalogue of *Private* Waters and remain in the private property regime indefinitely. The maintaining of the Catalogue of *Private* Waters was to avoid the risk of having to compensate users financially for the loss of their private right (Fornés Azcoiti et al. 2005). This risk, and the confusing alternative offered, worked against a smooth transition towards an administration of public entitlements. In 3 years, only 10–20% of the total private groundwater abstraction rights had been entered into the registry, and only 8% in the catalogue (Fornés Azcoiti et al. 2005).

In South Africa, several types of entitlement were created to bridge the gap between the old water legislation and the new National Water Act. The Existing Lawful Water Use category was "intended as an interim measure to allow water use to continue until converted to a license" (Department of Water and Sanitation, 2015). The idea was to avoid the high cost of revoking all preexisting rights, which would have caused "a barrage of cases to be brought against the state" (Movik and de Jong 2011, p. 72). The 1996 law allotted a "reserve" to the environment and to poor people, implying a possible legal challenge to, and reconsideration of, the rights formerly ascribed to white farmers. This legal and political complexities associated with such a move against powerful entrenched interests, together with the hydrologic uncertainties over how much water is to be allocated, are still a large part of the current deadlock (Movik and de Jong 2011).

Litigation is common in the US, for example in Texas, where the Edwards Aquifer Authority Act (1993) created a new permit system that specified the quantity of water that could be used, leading to extensive challenges in court. Groundwater districts face difficulties in enforcing the law and simply concede to permit requests, as they lack the financial capacity for legal battles and risk bankruptcy (Closas and Molle 2018).

Incomplete inventories and illegal wells

Inventories and registration processes are almost always found to be partial and patchy. This is due to: (1) a lack of capacity on the part of the administration to process applications, as illustrated above; (2) well owners often preferring not to declare their wells (see the following); and more crucially (3) the continuous drilling of illegal wells. The commonplace incapacity and/or unwillingness of states to control illegal drilling make registration seem a Sisyphean task.

In 2005, Spain's former Ministry for the Environment estimated that there were around 510,000 illegal wells in the country (WWF 2006), while the Water White Book put the figure at a million (MMA 2000) and Llamas et al. (2001) at around 2 million. To take an example, nearly 40,000 wells existed in the Western Mancha Aquifer in 2008, of which only 17,000 had been registered with the River Basin Authority (Martinez-Santos et al. 2008).

In 2009, the Mexican National Water Commission (CONAGUA 2009) estimated that there were around 140,000 wells in the country, only 42,600 of which were officially registered, while a further 10,000 had some form of license. Official statistics for the state of Guanajuato show that 250,000 ha are irrigated with wells; however, aerial photography and on-site visits by the Secretariat for Agriculture found the irrigated area to be around 326,000 ha (CONAGUA 2009). In the Ica Valley, Peru, 79% of all wells inventoried in 2014 had no license (Aldoradín 2015). Wang et al. (2007, p. 66), who surveyed 448 villages and 126 townships in China, found that "few regulations have had any effect inside China s villages", with only 10% of well owners having applied for a drilling permit.

In Algeria, the Mitidja Plain Management Plan (2013) notes that, for the Wilaya of Blida, 2,000 illegal wells can be found alongside 1,200 legal wells. A UNDP-funded project in Lebanon in 2014 estimated there to be 59,124 unregistered private wells in the country when only 20,537 had been registered (MoEW and UNDP 2014). In Iran, the estimate number of illegal wells varies between 170,000 and 400,000. In the Kairouan Plain, Tunisia, between 2,000 and 3,000 wells were licensed before the revolution, but a study provided an estimate of between 8,000 and 9,000 (S, Massuel, IRD, personal communication, 2015). In 2011, however, the ministry gave farmers the option of being connected to the grid. In a matter of two months 12,000 applications were made, in addition to those wells already connected (MoEW and UNDP 2014). In Syria, a decree in 2001 required all illegal wells to be licensed, yet it was estimated in 2010 that 57% remained unlicensed, while more wells continued to be drilled without permits (de Châtel 2014). In the Salamieh region, 80% of the 6,356 wells inventoried in 2005 lacked a permit (Saadé-Sbeih 2011). In Yemen, the National Water Resource Authority received around 2,000 license applications between 2003 and 2007, which can be contrasted with the close to 100,000 wells existing across the country at that time (Redecker 2007).

In 2010, a European Commission conference on unauthorized water usage in agriculture provided estimates suggesting that such use could be larger than authorized use in several regions of the EU, particularly in the more arid southern member states (Dworak et al. 2010). Italy is believed to host 1.5 million illegal wells; and by the late 2000s in the Roussillon Aquifer, south of France, only 10–20% of wells had been officially registered (Montginoul and Rinaudo 2009). This situation was confirmed by a report by the European Academies Science Advisory Council, which concluded that, in Southern European Union Member States, "a common concern is the rapid growth in the number of users of groundwater […]; in some parts, these unregulated users are in number equal to the regulated sector" (EASAC 2010. p. 1).

Lastly, it must be noted that even when an inventory has been carried out successfully, the number of wells provides only limited information on groundwater. For example, studies carried out in North Africa (Massuel et al. 2017) have shown that some wells are drilled for social status purposes or when the family land is divided and individuals prefer to drill their own well so as to be independent. In such circumstances, the number of wells increases but overall abstraction does not.

(Dis)incentives to legalize or register wells

At face value, legalization would seem to be attractive to users, particularly since it is often seen to secure use and facilitate transfer by inheritance or transaction. Yet a reluctance to register is widespread for various reasons, including: (1) the fear of groundwater being taxed or restricted in the future; (2) a burdensome administrative process; (3) registration fees to be paid; (4) the possible imposition of a water meter and monitoring of actual use; and (5) disputing the state's ownership and/or intrusion in private or local affairs (Burchi and Nanni 2003; Molle and Closas 2017).

The short-term benefits derived from illegal groundwater abstraction are often preferred to possible restrictions, due to whether farmers think these would be imposed by the state or arise naturally from dropping aquifers, or because they do not believe that the situation of open-access system could be reversed (De Stefano and López-Gunn 2012). In South Africa, for example, those users who have obtained licenses perceive no advantage, as "they observe that their fellow water users continue to draw water as before, whereas they, who now possess licenses, have to pay fees and comply with the conditions of the license in order to be able to continue with their use" (Movik and de Jong 2011, p. 73). Social norms and local customs also often encourage tolerance to illegal use, as in Spain (De Stefano and López-Gunn 2012) and Iran (Mirnezami et al. 2018).

Therefore, authorities often seek compliance through 'sticks' (i.e. disincentives) and threats embedded in the legislation (e.g. not allowing the sale of land with an illegal well). Another option is to force drilling companies to be officially registered (e.g. Turkey, Oman, Jordan, several Indian states, Nebraska in the USA) or even to restrict drilling to one private company controlled by the government, as in Abu Dhabi

(Fragaszy and McDonnell 2016). However, in many countries, bribing, poor law enforcement, minimal fines (e.g. Turkey, see Apayadin 2011) and limited state resolve have let illegal drilling (and therefore illegal unlicensed wells) flourish.

When farmers have been willing to declare their wells, it is usually because the state has extended attractive 'carrots'. Incentives include:

- Credit or subsidies: a neat example is provided by the Plan Maroc Vert in Morocco, which subsidizes investment into micro-irrigation at 80–100%. Mexico encourages regularization with a subsidy on electricity (Mukherji and Shah 2005)
- (Legal) connection to the electricity grid (3-phase and/or higher voltage; e.g. Tunisia)
- The allocation of EU subsidies (e.g. the Western Mancha Aquifer, Spain; see Closas et al. 2017)
- The possibility to hire foreign workers (Jordan)
- The possibility (increasingly seen in France) for a farmer (or cooperative) with irrigated production to pass a contract with a supermarket, receive subsidies, or take out a private insurance—the well needs to be legal and this engages the responsibility of the contracting party as well (M. Montginoul, INRAE, personal communication, 2019)

However, when the cost of drilling is high and the perceived threat of penalties is sufficient, as in Mafraq, Jordan, where a 300 m deep well equipped for a 50-ha farm involves an investment of US $60,000 (Al-Naber and Molle 2017), farmers opt for the legal process to secure their investment. High investment and/or transaction costs for formal applications deter poorer smallholders, confining them to illegality to the benefit of large commercial users such as industry and agribusiness. This has been observed in Lebanon and Tanzania, where a deep borehole of 80–150 m can be unofficially drilled for around US $2000, while legal drilling, with permits, geological surveys, a pump, and drilling and pumping tests, costs US $7,000–25,000 (Komakech and de Bont 2018).

Inequities are also involved in the administrative complexity of registration processes. Large commercial farmers or investors have the means to employ lawyers to carry out the paperwork, as in Ica, Peru (Cardenas Panduro 2012), and Chile (Budds 2009). In South Africa, complying with the law and regulation regarding groundwater permits is difficult for illiterate users, who must also shoulder the administrative burden and expense (van Koppen and Schreiner 2014).

Licensing and water-use entitlements

There are official procedures for prospective groundwater users to obtain permits, except where licensing does not apply (e.g. in areas not declared as overexploited). Much of what has been previously said about legalization also applies here—in particular, the reluctance to follow administrative procedures, the state's lack of capacity to deal with the number of applications, political pressures, and the ability of influential people to circumvent the rules to obtain permits. This section examines and illustrates in more detail the challenges faced by licensing in general.

Exemptions

In most countries, certain wells are either exempt from groundwater licensing, in recognition of the need to alleviate the administrative burden, or must only be declared, for example to the municipality (Varady et al. 2016). Thresholds are defined with regard to the well's depth, the diameter of the bore, the type of use, the area irrigated, the pump capacity, the volume abstracted (per day or per year), etc., as illustrated in the following:

- In South Africa, groundwater entitlements used for reasonable domestic purposes, small garden plots, and livestock are termed 'schedule 1' and do not need to be registered.
- In the Orange County Water District, California, wells with an outlet diameter of less than 1 in. (2.54 cm) do not have to be declared.
- In Australia, despite all irrigation use in groundwater management units being subject to licensing, mining leases benefit from both license and metering exemptions.
- In Perth, Western Australia, garden bores watering an area of less than 0.2 ha, water for firefighting, watering cattle or other livestock, and short-term dewatering are exempt.
- In Sweden, irrigation does not require authorization as long as it does not harm public or private interests.
- In Yemen, since the Water Law of 2002, wells with a depth under 60 m do not need a permit to drill. The limit is 150 m in Lebanon, 40 m in Morocco, and 10 m in France and Turkey.
- In Poland, Bulgaria, and the UK, only extraction over 5, 10, and 20 m^3/day, respectively, requires authorization or a license; in Flanders (Belgium), the limit is 500 m^3/year and in Spain 7,000 m^3/year.
- In Saudi Arabia, farmers whose land exceeds 2.5 ha need permits for well drilling.
- Limits can be based on the horsepower of the pump, as in Portugal (5 hp) and West Bengal (5 hp. discharging less than 30 m^3/h).

These examples largely reflect the degree of water scarcity, the respective shares of irrigation and other uses, and hydrologic factors. However, exempting certain categories of wells from licensing may prove to be problematic in time, as in

Prescott, Arizona, for example, where the combined abstraction of exempted wells is the third largest water use (Trout Unlimited 2007) and the Perth metropolitan area, where an estimated 167,000 garden bores (in 2009) accounted for approximately 15% of total groundwater abstraction (Sinclair Knight Merz 2012).

The application process

Administrative procedures may include a drilling (or "exploration") permit followed by a license to use groundwater (as in Turkey), although the two may also be combined into a single procedure. State regulations can be demanding and complex, with applications often passing through several departments and/or ministries and requiring technical reports, field visits and checks. Sometimes they can even allow for contestation by neighbors or the general public (e.g. Morocco). In Kenya, those digging wells or drilling boreholes must keep records, including geological logs, water levels, pumping test data, and borehole yield, to be submitted upon completion of drilling. An assessment of the impact on neighboring wells is required on occasion. Physical, chemical, and bacteriological analyses must be carried out on water samples from wells/boreholes, and meters and piezometers must be installed on boreholes (Water Act 2012).

In the plain of Marrakech, Morocco, groundwater abstraction permits are only required for wells deeper than 40 m. Applications must include a study of the project's impact on water resources, cultivable land, and aquatic ecosystems. They then go through a public inquiry conducted by various administrations and are gazetted and displayed at the local administration office. If a concession is granted, the well owner has 60 days to submit a report, with pumping tests, the static level of groundwater, the results of chemical and bacteriological analyses (a requirement dropped in 2009), and soil samples taken at each meter of excavation. Unsurprisingly, farmers prefer to continue drilling wells illegally rather than following such a costly and exacting procedure (Tanouti 2017).

In Lebanon, well permit applications are evaluated by the Water Rights and Hydrogeological Services and signed off by the minister himself (for wells deeper than 150 m). A second permit for the exploitation of the well is then needed. Due to a lack of personnel (the ministry has no hydrogeologist and the Hydrogeological Service operates with nine staff against 49 official positions), applications are outsourced to authorized private companies, which examine the well, its yield, etc. and issue a report (Nassif 2019). Applicants pay US $935 for this service. As a result, the number of fully licensed wells barely reaches 3,000 (Nassif 2019).

In South Africa, applicants must produce information such as the land title deed, application forms, technique used to capture the water, a risk assessment and reserve determination, and pay for the application before it is filed and then reviewed by both the regional and national offices (Movik and de Jong 2011). It is a highly complex process, due to the postapartheid redistribution of water entitlements, and is mired in all sorts of technical, legal, and ground-level monitoring difficulties, as described earlier.

In India, the number of wells is so overwhelming (2.6 million deep tube wells of a total of 20 million wells – GoI 2017) that both legalization and issuing permits seem to be farfetched goals given the regulatory and logistical burden. Nonetheless, half of the states have introduced such measures. Although procedures are often limited to overexploited aquifers declared as "prohibition zones", if they are to be meaningful, however, they must fix a number of conditions (well spacing, maximum capacity, abstraction quota, etc.), all of which require costly field checks.

Hydrologic challenges

The criteria used to establish whether a drilling or abstraction application can be accepted are varied. Most groundwater authorities set a maximum level of abstraction considered "sustainable", "safe", or "acceptable". This is often (mistakenly) taken as the estimated recharge rate (Custodio 2002), and since its determination requires substantial monitoring and scientific study, the granting of licenses frequently begins before the limits are established, as in Tanzania, where the 2005 law dictates that basin masterplans set up such limits despite licensing having long been in place (van Koppen et al. 2016). In the early days of groundwater development, licenses or permits were generally given without due consideration to resource availability, as part of an administrative procedure and often without much scientific understanding of aquifer characteristics. This situation can endure even after overuse has become evident. In Peru's Ica Valley, for example, the granting of licenses for agriculture was launched, with numerous pending applications, without serious oversight of the volumes abstracted and no assessment of groundwater availability or the maximum annual volume to be abstracted, despite numerous studies (Ministerio de Agricultura 2018). In Copiapó, Chile, water rights were granted "without knowledge of the capacity of the aquifer; laws, decrees and resolutions did not have hydrological basis or tried to obscure mistakes without solving them" (No a la Mina 2015). Furthermore, since "studies are contracted out to private companies and since information is generated by consultants nobody is in a position to assess whether it is correct or not" (No a la Mina 2015).

Uncertainty surrounding groundwater resources hampers the determination of safe yields. This firstly has to do with the heterogeneity of aquifers, the complexity of groundwater flows, and the difficulty of estimating how much water percolates in different ways into the subsoil (Bredehoeft 1997). In the Altar-Pitiquito area of Mexico, for example, recharge (natural and induced) was estimated at around 300 Mm^3 in the 1970s, then at 213 Mm^3, and more recently at only 118 Mm^3, while others estimate it at only 70 Mm^3 (Wilder and Lankao 2006). Another key area of uncertainty relates to groundwater/surface-water interactions. Although long identified by hydrogeologists, this issue has only been seriously incorporated into management in the past 20 years, even in countries such as Denmark, the US, and Australia, where scientific capacity is high (Molle and Closas 2017). Furthermore, licensing based on the availability of the resource not only requires an accurate assessment of the resource, it must also determine actual use. This is even more challenging and is addressed in the companion paper on metering.

Determining and enforcing a "safe yield" is a thorny and often contested issue. Establishing the percentage of recharge available for pumping becomes a political question involving value-laden judgments on the value of groundwater uses and functions and the degree of externalities that is deemed "acceptable" (Molle et al. 2018). There is ample global evidence that the availability of groundwater resources (and also of surface-water allocations, see Molle and Wester 2009) is almost invariably assessed in an optimistic manner (Molle et al. 2018), or reassessed to serve specific interests—Tetreault and McCulligh (2018), for example, report that in northern Zacatecas, Mexico, "official numbers for the natural recharge of the Cedros aquifer multiplied manifold in the run up to the installation of Canadian-based Goldcorp's open-pit silver mine". This suggests that both the assessment of the available resource and the delay in carrying it out are influenced by a political interest in minimizing the problem. This is understandable, as the establishment of quantitative quotas theoretically puts an end to the otherwise comfortable fuzziness that allows abstraction to increase and tough decisions to be delayed. Political reluctance to set quantitative limits is evident in countries such as Morocco, Egypt, Turkey, and Mexico (Molle and Closas 2020a). It was telling that in the Murray Darling Basin in Australia, the 1994 cap on surface-water abstraction was not accompanied by a similar cap on groundwater—a politically acceptable if not scientifically or environmentally sound solution (Nevill 2009).

Licenses for altering wells

Licensing wells generally means that procedures must also be established for applications to deepen, clean, or replace wells (if clogged or dried up) to prevent users from referring to these categories to camouflage the drilling of new wells. In Oman, for example, permits are required to dig new wells, but also to deepen or to change the purpose, the pumping equipment, or the use of formerly disused wells, and prior to any transaction (Oman 2009). An application for well deepening cannot be justified by improving water quality or yield, and the irrigated area cannot be enlarged. Jordan places the same conditions and requires similar permits for all well maintenance operations (deepening, cleaning, replacing). In Turkey, groundwater users must apply for a "license for reclamation and alteration" if they want to deepen or otherwise alter their wells. In Yemen, no permit is required to deepen a well for the first time, but only if the additional depth does not exceed 20 m.

Water license holders in Spain must notify the water authority of any modifications to a well (deepening, widening) or face operating beyond the protection of the administrative system. Where well deepening is necessary, the authorities typically use it to force users into a process whereby a private water right is converted into a public concession for groundwater use (De Stefano and López-Gunn 2012). Likewise, in Jordan, the need to alter a well is used to change the category of the right or even to reduce the entitlement (Al-Naber and Molle 2017).

However, this is not always the case. In the Ica Valley, Peru, the drilling ban was extended and reinstated in June 2011, yet the national water agency allowed wells that had become disused in the past 6 months (due to a technical problem or having dried up, for example) to be replaced by a new well. However, this is difficult to ascertain on the ground, and many old, non-functional wells have been replaced by new ones, increasing overexploitation (Cardenas Panduro 2012). Likewise, the regulation has been circumvented in Jordan, where some farmers apply for a well-cleaning license but instead deepen the well to get more water. Field observations appeared to show that farmers can even fill a well with soil or obstruct it superficially so that a replacement license is approved upon inspection. Once the new well is drilled, they remove the obstacles and reopen the original well (Al-Naber and Molle 2017).

There is a further noteworthy constraint to well alteration permitting. Emergency interventions can be required on malfunctioning wells in the course of an irrigation campaign in order to save the crops, which is incompatible with the slow pace of administrative procedures. This pushes farmers to circumvent or obviate legislation in order to continue abstracting groundwater (De Stefano and López-Gunn 2012).

The politics of well licensing

Intersecting political and bureaucratic interests

As fraught as the legalization and licensing processes described in the preceding two sections can be, they are also gateways to rights/entitlements and, as such, a locus of power and subject to be manipulated by influential users (see Molle and Closas 2020a for a full illustration of this point). This means that in addition to the difficulties inherent in their scale and costs, these processes will also be deeply affected by bureaucratic and political power struggles.

First, the licensing system can be captured by local elites, influential investors, local administrations, ministry officials, or politicians, depending on the case. In Yemen, local elites could strengthen their clientele (but were also made dependent) through preferential access to irrigation, public investment in new wells, and diesel subsidies distributed by the state (Al-Weshali et al. 2015). In West Bengal, the issuing of new permits for electricity connections (for submersible pumps) is mediated by local elites such as village council heads, who refuse to forward new applications if the applicant is not an adherent of their party or if the permit would harm the interests of party supporters. Villages with stronger representatives also obtained disproportionately high numbers of permits (Mukherji 2006). When the Groundwater Act of 2005 required permits for wells, 64% of applications had to be rejected, with evidence of likely rent-seeking behavior on the part of the administration (Buisson 2015). In Maharashtra, local village councils are reluctant to implement laws restricting the digging or drilling of new wells for fear of not being re-elected (Phansalkar and Kher 2006). In Lebanon, too, cases are reported of local political leaders from the Bekaa Valley petitioning the ministry to issue permits to their constituents (Nassif 2019).

Powerful groundwater users, such as large-scale producers and investors producing for export markets, often have close political connections and the power to obtain groundwater licenses, as in Guanajuato state in Mexico (Hoogesteger 2018). In the state of Jalisco, politically connected well owners can obtain new concessions despite a general ban on drilling (World Bank 2009). In the Ica Valley, Peru, investors quickly obtain permission to link their wells to the power grid, which small farmers often struggle to do (James 2015). In Abu Dhabi, one agriculture official explained that, “here there is no such thing as ‘illegal’ for a local who has good connections” (Fragaszy and McDonnell 2016, p. 42). Investors close to power in countries such as Morocco, Algeria, Egypt, or Jordan have no difficulty in obtaining land or groundwater licenses (Molle and Closas 2017).

While investors are often able to elicit favors or leniency from the administration, social and political conditions may also stymy the state’s action and undermine well licensing. In Gujarat, in 2013, the proposal of a bill to make compulsory the licensing of groundwater abstraction beyond a certain depth, with penalties for noncompliance, provoked strong reactions, and the bill was shelved in 2014 “for fear of irking farmers” and as a message of “good governance to the people” (The India Express 2014). Political sensitivity also explains how overexploited aquifers are not, or only belatedly, declared as such in order not to limit access (e.g. Mexico and Morocco). In Jordan, initial groundwater tariff reforms in 1994 were met with opposition, leading to the occupation of the parliament floor and the king’s intervention in the matter (Venot and Molle 2008). In the Souss Massa River Basin, Morocco, and in Bsissi, Tunisia, the decision by the local water management agencies to close some illegal wells generated mass protests and forced the state to negotiate and soften its approach. Generally speaking, but most notably in Egypt, Tunisia, and Morocco, the Arab Spring substantially weakened the states’ authority and capacity to act.

Licensing can also be undermined by antagonistic sectoral state policies, where agricultural administrations subsidize and incentivize groundwater-based irrigation where aquifers are already dropping dramatically (World Bank 2007). A clear illustration is provided by Morocco s Plan Maroc Vert, which supports subsidies, massive investment in agriculture, and provisions for the bypassing of groundwater restrictions to subsidize well drilling and drip irrigation (Tanouti 2017). In many countries, private and political interests in the promotion and expansion of agriculture have the upper hand over resource and environmental conservation (Tanentzap et al. 2015).

Policy inertia, or the “licensing dilemma”

Regulating the use of groundwater means constraining users access to this resource. Enforcing sustainable use in situations of overexploitation and/or quick groundwater development means curtailing the stream of benefits generated by the groundwater economy. All the logistical, financial, social and political difficulties in the legalizing and licensing processes highlighted in the preceding, explain and outline a “groundwater licensing dilemma”. The dilemma underlines the early day logic of inaction (slack or no licensing) that feeds on a combination of poor understanding of hydrogeology, differing and often conflicting state development priorities, an absence of uncontroversial induced externalities, and the high cost of maintaining an accurate and robust administration of wells.

These are significant hindrances and it generally takes many years for the state to detect, acknowledge, and react to signals of overexploitation, and many more to increase technical capacity, enhance bureaucratic capacity, constrain development logic, and oppose the entrenched vested interests that have developed with the groundwater economies over the years. By the time this tall order has been achieved (if ever), aquifers have dropped dramatically, use has grown far beyond any measure of “safe yield”, and the number of wells (notably illegal ones) has become overwhelming. There are hardly any examples of profitable large-scale groundwater economies, particularly agriculture-based, that have managed to prevent or reverse overexploitation by bureaucratic control or otherwise.

This would suggest that robust licensing *and* a sound knowledge of the resource, not to mention the tricky political process through which a "desirable" or "safe" level of abstraction could be established, should *precede* any groundwater development phase. However, this is difficult because the financial, bureaucratic, and political costs of such early moves cannot be justified by the actual status of the resource. Hydrogeological, societal, and political forms of inertia inhibit the timely recognition of the problem: the impact of groundwater abstraction is divided between reduction of stocks and outflows, and it takes time to be recognized, and even more so to be acted upon through policy and legal reform. Since there is no tabula rasa for regulatory regimes, as vested interests and livelihoods have naturally developed with decades of groundwater use, it is very difficult to impose a new system of regulation from scratch. In practice, states "wait until more intensive exploitation occurs before undertaking the technical work necessary to nominate extraction limits", as Nelson and Quevauviller (2016, p. 181) note with regard to the Australian case. Kemper's (2007, p. 160) recommendation that "well-defined groundwater use rights can become a key method to control over-abstraction […] *once* the resource becomes scarce" (emphasis added) overlooks the inertia and costs already described. In other words, decision-makers face an uneasy choice between an uphill and a doomed strategy: starting licensing early, without the justification for deploying the corresponding human and financial means to "get the data right" and support the administrative process; or waiting until over-abstraction has materialized and is recognized by all—by which time, bureaucratic and political inertia will compound a process already beset by a lack of hydrological knowledge, a large number of illegal wells, and low administrative capacity.

Lessons drawn and principles for groundwater licensing

Groundwater regulations establish the conditions on which drilling rigs can be owned and used, and wells dug or drilled, as well as the volume of water that can be abstracted. While these approaches are generally sound and straightforward on paper, the three preceding sections have shown that, in practice, they are beset by a number of practical, logistical, financial, social, and political difficulties.

In summary, well legalization processes take much longer than intended, with deadlines continuously extended, and are rarely completed. Many users choose to remain illegal for a variety of reasons (costly or burdensome process, fear of taxation and metering, etc.), and insufficiently enforced drilling bans fuel new illegal wells. Data gathered on numbers of wells is frequently incomplete or plainly wrong, as users have no real incentive to report accurate data, and agencies face a number of constraints and disincentives. The effectiveness of licensing measures is often undermined by various external and internal factors such as local political pressure or a lack of continuity in registration programs. The financial cost to the administration (and the user) of a legalization process and of licensing in general is frequently overlooked, especially when litigation is a common response and the acquisition of field data is involved (verifying the existence and status of wells, etc.). The examples of Spain and Jordan suggest that it could take more than 20 years to achieve registers that include at least 80% of existing wells.

Are these overall observations overly pessimistic? Are there cases where well licensing is not a problem and/or illegal wells are under control, and what can be learned from such cases? In this final section, the results from the global survey are mobilized again and some general lessons are drawn from cases where licensing is by and large effective, concluding with proposals for some steps and principles that have the potential to increase the likelihood of a sound licensing process.

Some lessons learned from experience

A limited number of aquifers have been identified as having relatively credible or successful quantitative management, involving not only the recording of all users but also the monitoring of actual use (see Molle and Closas 2020a, b for a detailed review of such cases). These have been found where a public agency has the capacity to enforce regulations as well as where users co-manage the resource (Molle and Closas 2020a, b). Since the physical, political, and regulatory circumstances can vary widely within a single country (not only federal countries such as India, the USA, and Australia but also others such as Spain and France), lessons are largely aquifer-specific. Yet, the review showed that the registration of existing wells (or at least knowledge of existing use) is facilitated by particular factors:

- Groundwater is (by far) the main resource available (e.g. 100% of supply in Denmark), and its control is vital.
- Groundwater resources are fully or over exploited.
- Wells are limited in number, easily accessible (e.g. 1,200 working wells in Bahrain), and/or managed by a handful of bulk users, industries or municipalities (e.g. coastal California or Japan); the extent of the aquifer, or the designated management area, correlates with the number of wells, and is also limited. Most identified cases have fewer than 1,000 users, but some above—Eastern La Mancha, Spain (~1,000), the Beauce, France (2,000+ wells), and the San Luis Valley, US (,3000+ wells).
- The identification of farms and irrigated areas is facilitated by their size and layout (e.g. central pivots in Texas, Nebraska, and the Saudi Arabian desert), or by a dry environment that facilitates the use of remote-sensing technology to identify irrigated areas (Spain, MENA, and the Gulf region).

- There is substantial social homogeneity among farmers (e.g. Nebraska). (Well-registration is much harder in areas with socioeconomic inequalities—a combination of small farmers and large, well-connected investors—as in Mexico, Peru and much of the MENA region.).
- The state and/or groundwater user association has adequate authority and legitimacy to take action against illegal wells and to control drilling processes.
- In all cases, the identification of existing wells and the control of further illegal drilling require either strong state agency/supervision (e.g. the adjudicated basins in California; the Edwards Aquifer in Texas; Australia) or co-management, where users are instrumental in controlling wells (e.g. Bsissi, Tunisia; Eastern La Mancha, Spain; Nebraska, USA; New Zealand).

The licensing/registration of wells appears as a *necessary* condition, since there is, to the authors' knowledge, no example of sustainable aquifer management that does not include the registration of wells. However, it is clearly not *sufficient*, although governance structures that succeed in controlling wells are more likely to be able to successfully manage groundwater altogether.

Proposed steps and principles

The insights presented in this paper on both what makes well licensing problematic and what facilitates it, allow the identification of a few useful steps and principles, keeping in mind that neither is necessary or sufficient, in the sense that the diversity of both hydrological and sociopolitical processes does not allow generalization or prescriptive recipes.

Assess the current situation. Launching legalization processes in large aquifers (typically alluvial plains or deltas) with tens or hundreds of thousands of wells, the appropriateness and effectiveness of the licensing approach should be questioned (even more so where the state has proven to be weak and open to political influence). A groundwater law with licensing "has no meaning unless it is underpinned at meso and local levels by institutional structures to implement these", as Shah reflects pondering on India, where groundwater development is massive, atomistic, and anarchical: he recommends avoiding the licensing of bore wells and withdrawal permits, advocating instead "a tool kit of indirect instruments" (centered on the pricing of electricity) to regulate groundwater abstraction (Shah 2007, p. 32). If the aquifer is too large, it can be split into hydrologically sound smaller parts (as in Nebraska and Australia).

Define exemptions. An important issue is that of the definition of exemptions. Thresholds must be carefully crafted to strike a balance between reducing the bureaucratic workload for regulatory agencies and not undermining the quantitative management of the aquifer. Monitoring and zoning of areas with low to over-abstraction should be developed as early as possible, so that hydrological knowledge carries adequate legitimacy (in terms of both scientific robustness and co-construction with users) to dictate caps and drilling bans before they are overdue.

Allocate adequate means. There is still little recognition that managing water resources demands very substantial funding (at a level consistent with their vital role in life, the environment, and the economy). Open-access regimes and limited pollution require little administration, but these days are long gone and the stakes have risen dramatically: the monitoring of quantity and quality, modeling, enforcement, multi-stakeholder participation, etc. have huge implications in terms of the funding, trained personnel, and organizations that must be put in place to deliver effective and sustainable groundwater management (see Shah 2005, for a comparison between India and China). All these requirements are sorely underfunded. Implementing policies with inadequate means leads to "misallocated resources, wasted political capital, and frustration" (Thomas and Grindle 1990, p. 1178).

Make registration simple. Rather than making a long list of demands (as in Kenya or Morocco), well registration/legalization should be made easy and cheap, if not free, as in Texas, where abstractors of the Edwards Aquifer can register online for a US $10 fee. Of course, this shifts more of the burden to the administration, which must be adequately resourced and funded (see the preceding point). The alternative is outsourcing registration to private companies, as in Lebanon (which has 3,000 fully registered wells, of a total of 80,000), but this shifts high costs onto users and is self-defeating.

Balance incentives (carrots vs. *sticks)*. The failure to register a well should entail a loss of benefits (e.g. use of the grid or subsidies for investments) and credible threats (e.g. denial of user entitlements when the aquifer is declared fully allocated; not being able to sell a plot of land with an illegal well). While legalizing/registering a well should on the contrary be rewarded (e.g. allowing connection to the grid or access to subsidies).

Build legitimacy. A recent global assessment of groundwater governance (FAO 2016, p. 13) found that "legal and regulatory frameworks for groundwater have often been inadequate and their application has proved problematic […]. In many countries, non-compliance is pervasive, and in all regions, pollution continues largely unchecked. The problems are weak regulatory capacity and widespread lack of adherence to the objectives and practices of regulation". Building authority and legitimacy is the crux of governance, whether it is state-centered or come under the co-management category (Molle and Closas 2020b).

Credibility and legitimacy can arise from the co-construction of the modeling of the aquifer, as indicated previously, or from transparency in terms of well ownership and abstraction (and the quantities involved): the Edwards Aquifer agency publishes all the relevant data on its website, so does the New South Wales government in Australia. The Jordanian Ministry of Water published in newspapers the names of well owners who had not paid their fees. In the Eastern La Mancha Aquifer, Spain, joint walk-through surveys by the user association and the administration allowed wells to be better identified. In parts of the US such as Nebraska and Kansas, licenses are granted by the groundwater districts themselves. Such transparency makes it harder for people to exploit regulatory loopholes and bypass the regulations to drill wells or abstract water illegally.

Eventually, the analysis comes back to questioning the state's *ability* to deploy regulatory power on the ground and its *willingness* to do so. Low budgets, poor hydrological knowledge, deferred declaration of over-abstracted aquifers as prohibition zones, weak monitoring and sanctioning, and unresolved competition between ministerial objectives are, at the same time, political assets for politicians and decision-makers who tend to prioritize short term private benefits (attending to clients and avoiding social unrest) over longer-term sustainability considerations (Molle and Closas 2020a). The feasibility and meaningfulness of implementing licensing registration therefore depend on the wider political context that shapes state–citizen relationships and what can possibly be achieved through a co-management framework based on legitimacy, transparency, and well-defined regulatory and management roles.

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References

Alley WM, Alley R (2017) High and dry: meeting the challenges of the world's growing dependence on groundwater. Yale University Press, New Haven, NJ

Al-Naber M, Molle F (2017) Controlling groundwater overabstraction: policies vs. local practices in Jordan Highlands. Water Pol 19(4): 692–708

Al-Weshali A, Bamaga O, Borgia C, van Steenbergen F, Al-Aulaqi N, Babaqi A (2015) Diesel subsidies and Yemen politics: post-2011 crises and their impact on groundwater use and agriculture. Water Altern 8(2):215–236

Aldoradín H (2015) A formalizar el uso de aguas subterráneas, Diario Correo [To formalize the use of groundwater]. http://diariocorreo.pe/edicion/ica/a-formalizar-el-uso-de-aguas-subterraneas-593731/. Accessed 10 April 2020

Apaydin A (2011) Groundwater legislation in Turkey: problems of conception and application. Water Int 36(3):314–327

Birkenholtz TL (2015) Recentralizing groundwater governmentality: rendering groundwater and its users visible and governable. WIREs Water 2:21–30

Boelens R, Seemann M (2014) Forced engagements: water security and local rights formalization in Yanque, Colca Valley, Peru. Hum Organ 73(1):1–12

Bredehoeft JD (1997) Safe yield and the water budget myth. Ground Water 1997(35):929

BRLI, Agro Concept (2012) Gestion de la demande en eau dans les pays méditerranéens: gestion de la demande en eau—étude de cas du Maroc [Water demand management in mediterranean countries: water demand management—Morocco study case]. BRLI, Elmwood Park, NJ

Budds J (2009) Contested H2O: science, policy and politics in water resources management in Chile. Geoforum 40:418–430

Buisson MC (2015) What does pump sets electrification change? Impacts on cropping patterns, productivity and incomes in West Bengal. 26th European Regional Conference, International Commission on Irrigation and Drainage ICID, 12–15 October 2015, Montpellier, France

Burchi M, Nanni M (2003) How groundwater ownership and rights influence groundwater intensive use management. In: Llamas R, Custodio E (eds) Intensive use of groundwater: challenges and opportunities. Balkema, Dordrecht, The Netherlands, pp 227–240

Cap-Net (2010) Groundwater management in IWRM: training manual. Cap-Net UNDP, Pretoria, South Africa

Cardenas Panduro AI (2012) La carrera hacia el fondo: acumulacion de agua subterranea por empresas agro- exportadoras en el Valle del Ica, Peru [The race to the bottom: accumulation of groundwater by agro-exporting companies in the Ica Valley]. Msc Thesis, Wageningen University, Wageningen, The Netherlands

Closas A, Molle F (2018) Chronicle of a demise foretold: state vs. local groundwater management in Texas and the High Plains aquifer system. Water Altern 11(3):511–532

Closas A, Molle F, Hernández-Mora N (2017) Sticks and carrots to manage groundwater over-abstraction in La Mancha. Spain Agr Water Manage 194:113–124

CONAGUA (2009) Actualizacion de la disponibilidad media anual de agua subterránea, Acuifero (0523) Principal- Region Lagunera, Estado de Coahuila [Update on the annual average availability of groundwater, aquifer (0523) Principal – Lagunera region. State of Coahuila]. Comision Nacional del Agua. https://es.slideshare.net/encuentrociudadanolag/conagua-disponible. Accessed 10 April 2020

Custodio E (2002) Aquifer overexploitation: what does it mean? Hydrogeol J 10(2):254–277

de Châtel F (2014) The role of drought and climate change in the Syrian uprising: untangling the triggers of the revolution. Middle Eastern Stud 50(4):521–535

De Stefano L, López-Gunn E (2012) Unauthorized groundwater use: institutional, social and ethical considerations. Water Policy 14: 147–160

Department of Water and Sanitation (2015) Water is life, sanitation is dignity. DWS, Republic of South Africa. www.dwa.gov.za/WAR/determine.aspx. Accessed 18 August 2015

Dworak T, Schmidt G, De Stefano L, Palacios E, Berglund M (2010) Background Paper to the conference Application of EU Water-related Policies at Farm Level. Report for the European Commission - DG Environment, Louvain-la-Neuve, Belgium

EASAC (2010) Groundwater in the southern member states of the European Union, EASAC policy report 12. German Academy of Sciences Leopoldina, Halle, Germany

Famigletti J (2014) The global groundwater crisis. Nat Clim Chang 4: 945–948

FAO (2016) Global diagnostic on groundwater governance (Special edn. for World Water Forum 7). Groundwater Governance: A Global Framework for Action, GEF Groundwater Governance Project. www.groundwatergovernance.org. Accessed 29 March 2019

Fornés Azcoiti JM, de la Hera PA, Llamas Madurga R (2005) La propiedad de las aguas subterráneas en España: la situación del Registro/catálogo [The property of groundwater in Spain: the situation of the registry/catalogue]. Ingen Agua 12(2):125–185

Foster SSD, Chilton PJ (2003) Groundwater: the processes and global significance of aquifer degradation. Philos T R Soc B 358:1440. https://doi.org/10.1098/rstb.2003.1380

Fragaszy S, McDonnell R (2016) Oasis at a crossroads: agriculture and groundwater in Liwa, United Arab Emirates, IWMI/USAID Project Report no. 15. Groundwater Governance in the Arab World, IWMI/USAID, Cairo

Funke N, Jacobs I (2011) Integration challenges of water and land reform: a critical review of South Africa. In: Uhlig U (ed) Current issues of water management. InTech, London, pp 81–106

García M, Smidt E, de Vries JJ (2018) Emergence and evolution of groundwater management and governance. In: Villholth K, López-Gunn E, Conti KI, Garrido A, van der Gun J (eds) Advances in groundwater governance. CRC Press/Balkema, Leiden, The Netherlands, pp 33–54

Grönwall J, Oduro-Kwarteng S (2018) Groundwater as a strategic resource for improved resilience: a case study from peri-urban Accra. Environ Earth Sci 77(6)

Hoogesteger J (2018) The ostrich politics of groundwater development and neoliberal regulation in Mexico. Water Altern 11(3):552–571

IWMI (2011) Groundwater Governance in the Arab World. International Water Management Institute. http://gw-mena.iwmi.org/outputs/. Accessed 10 April 2020

James I (2015) The costs of Peru s farming boom: thriving agribusiness, declining aquifers and conflicts over water. www.desertsun.com/story/news/environment/2015/12/10/costs-perus-farming-boom/76605530/. Accessed 29 March 2019

Kemper K (2007) Instruments and institutions for groundwater management. In: Giordano M (ed) Agricultural groundwater revolution: opportunities and threats to development. CABI, Cambridge, pp 153–172

Knuppe K (2011) The challenges facing sustainable and adaptive groundwater management in South Africa. Water SA 37(1):67–79

Komakech HC, de Bont C (2018) Differentiated access: challenges of equitable and sustainable groundwater exploitation in Tanzania. Water Altern 11(3):623–637

Konikow L, Kendy E (2005) Groundwater depletion: a global problem. Hydrogeol J 13(1):317–320

Llamas MR, Fornés JM, Hernández-Mora N, Martínez Cortina L (2001) Aguas subterráneas: retos y oportunidades [Groundwater: challenges and opportunities]. Fundación Marcelino Botín, Madrid

Martínez-Santos P, De Stefano L, Llamas MR, Martínez-Alfaro PE (2008) Wetland restoration in the Mancha occidental aquifer, Spain: a critical perspective on water, agricultural and environmental policies. Restor Ecol 16(3):511–521

Massuel S, Amichi F, Ameur F, Calvez R, Jenhaoui Z, Bouarfa S, Kuper M, Habaieb H, Hartani T, Hammani A (2017) Considering groundwater use to improve the assessment of groundwater pumping for irrigation in North Africa. Hydrogeol J 25:1565–1577

Mechlem K (2016) Groundwater governance: the role of legal frameworks at the local and national level—established practice and emerging trends. Water 2016 8(8):347

Ministerio de Agricultura (2018) Plan de gestion del acuifero del valle de Ica y pampas de Villacuri y Lanchas [Management plan for the Ica Valley aquier and plains of Villacuri and Lanchas]. Autoridad Nacional del Agua, Ministerio de Agricultura, Peru. https://www.yumpu.com/es/document/read/14493693/plan-de-gestion-del-acuifero-del-valle-de-ica-y-pampas-de-villacuri-y-. Accessed 10 April 2020

Mirnezami SJ, Bagheri A, Maleki A (2018) Inaction of society on the drawdown of groundwater resources: a case study of Rafsanjan plain in Iran. Water Altern 11(3):725–748

MMA (2000) Libro blanco del agua en España. Ministerio de Medio Ambiente, Madrid

MoEW, UNDP (Ministry of Energy and Water and the United Nations Development Programme) (2014) Assessment of groundwater resources of Lebanon. Groundwater Assessment and Database Project, Final output, Ministry of Energy and Water/Lebanese Center for Water Management and Conservation, Beirut

Molle F, Closas A (2017) Groundwater governance: a synthesis. IWMI/USAID Project Report no. 6. Groundwater Governance in the Arab World, IWMI, Cairo

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

Molle F, Closas A (2020b) Co-management of groundwater: a review. WIREs Water 7(1)

Molle F, Wester P (2009) River basin trajectories: an inquiry into changing waterscapes. In: Molle F, Wester P (eds) River basins trajectories: societies, environments and development. CABI, Wallingford, UK, pp 1–19

Molle F, López-Gunn E, van Steenbergen F (2018) The local and national politics of groundwater overexploitation. Water Altern 11(3):445–457

Montginoul M, Rinaudo JD (2009) Quels instruments pour gérer les prélèvements individuels en eau souterraine? Le cas du Rousillon [What instruments to manage individual groundwater abstraction? The case of the Rousillon]. Economie Rurale 310:40–56

Movik S, de Jong F (2011) License to control: implications of introducing administrative water use rights in South Africa. Law Environ Dev 7(2):68–78

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

Mukherji A, Shah T (2005) Groundwater socio-ecology and governance: a review of institutions and policies in selected countries. Hydrogeol J 13(1):328–345

Nabavi E (2018) Failed policies, falling aquifers: unpacking groundwater overabstraction in Iran. Water Altern 11(3):699–724

Nassif MH (2019) Analyse multi-scalaire des politiques et de la gouvernance de l'eau dans le bassin du Litani, Liban [Multi-scalar analysis of water policies and governance in the Litani Basin, Lebanon]. PhD Thesis, University of Montpellier, France

Nelson R, Quevauviller P (2016) Groundwater law. In: Jakeman AJ, Barreteau O, Hunt RJ, Rinaudo JD, Ross A (eds) Integrated groundwater management: concepts, approaches and challenges. Springer, Heidelberg, Germany, pp 173–196

Nevill CJ (2009) Managing cumulative impacts: groundwater reform in the Murray-Darling basin, Australia. Water Resour Manag 23:2605–2631

No a la Mina (2015) La batalla del agua de Copiapó [The battle for water of Copiapo]. https://noalamina.org/latinoamerica/chile/item/7451-la-batalla-del-agua-de-copiapo. Accessed May 2020

OECD (2015) Drying wells, rising stakes: towards sustainable agricultural groundwater use. OECD, Paris

Oman (2009) Ministerial decision no. 2009/3. Ministry of Municipalities and Water Resources, Oman

Phansalkar S, Kher V (2006) A decade of the Maharashtra groundwater legislation: analysis of the implementation process. Law Environ Dev 2(1):67–83

Pietersen K, Beekman HE, Holland M (2011) South African groundwater governance case study. WRC Report no. KV 273/11, The World Bank, South African Department of Water Affairs, Water Research Commission, Waterford, MI

Redecker G (2007) NWSSIP 2005–2009 Two years of achievements and an outlook: a donor s perspective. KfW Office Sana'a, Yemen

Reis N (2014) Coyotes, concessions and construction companies: illegal water markets and legally constructed water scarcity in central Mexico. Water Altern 7(3):542–560

Richey AS, Thomas BF, Lo MH, Reager JT, Famigletti JS, Voss K, Swenson S, Rodell M (2015) Quantifying renewable groundwater stress with GRACE. Water Resour Res 51(7):5217–5238

Rinaudo JD, Donoso G (2019) State, market or community failure? Untangling the determinants of groundwater depletion in Copiapó (Chile). Int J Water Resour D 35(2)

Saadé-Sbeih M (2011) L'exploitation des eaux souterraines en Syrie centrale: construction de diagnostics et politiques d'intervention [The exploitation of groundwater in Central Syria: construction of diagnostics and intervention policies]. PhD Thesis, Université de Lausanne, Switzerland

Seward P (2010) Challenges facing environmentally sustainable ground water use in South Africa. Ground Water 48(2):239–245

Seward P, Xu Y, Turton A (2015) Using backcasting to explore ways to improve the national water department's contribution to good groundwater governance in South Africa. Water Int 40(3):446–462

Scott A (2008) The evolution of resource property rights. Oxford University Press, New York

Shah T (2005) Governing the groundwater economy: comparative analysis of national institutions and policies in South Asia, China and Mexico. In: Sahuquillo A, Capilla J, Martinez-Cortina L, Sanchez-Vila X (eds) Groundwater intensive use. Balkema, Dordrecht, The Netherlands, pp 23–51

Shah T (2007) The groundwater economy of South Asia: an assessment of size, significance and socio-ecological impacts. In: Giordano M, Villholth KG (eds) The agricultural groundwater revolution: opportunities and threats to development, vol 3. CABI, Cambridge, pp 7–36

Sinclair Knight Merz (2012) Assessment of groundwater licensing, metering and extraction estimation arrangements and techniques in Australia. Waterlines Report no. 83, National Water Commission, Canberra

Smith M, Cross K, Paden M, Laban P (2016) Spring: managing groundwater sustainably. IUCN, Gland, Switzerland

Tanouti O (2017) La gestion intégrée des ressources en eau à l épreuve du bassin versant: le cas du bassin du Tensift au Maroc [Integrated water resources management in a watershed: the case of the Tensift Basin in Morocco]. PhD Thesis, Université de Paris Nanterre, France

Tanentzap AJ, Lamb A, Walker S, Farmer A (2015) Resolving conflicts between agriculture and the natural environment. PLoS Biol 13(9): e1002242

Tetreault D, McCulligh C (2018) Water grabbing via institutionalised corruption in Zacatecas, Mexico. Water Altern 11(3):572–591

The India Express (2014) 'Non-populist' irrigation bill shelved for fear of irking farmers, February 5, 2014. http://indianexpress.com/article/cities/ahmedabad/non-populist-irrigation-bill-shelved-for-fear-of-irking-farmers/. Accessed 17 August 2014

Theesfeld I (2010) Institutional challenges for national groundwater governance: policies and issues. Ground Water 48(1):131–142

Thomas JW, Grindle MS (1990) After the decision: Implementing policy reforms in developing countries. World Dev 18(1):1163–1181

Trout Unlimited (2017) Gone to the well once too often: the importance of groundwater to rivers in the West. A Report by Trout Unlimited s Western Water Project, February 2007, Trout Unlimited. https://www.tu.org/. Accessed May 2020

Van Koppen B, Schreiner B (2014) Moving beyond integrated water resource management: developmental water management in South Africa. Int J Water Resour Dev 30(3):543–558

Van Koppen B, Schreiner B (2019) A hybrid approach to statutory water law to support smallholder farmer-led irrigation development (FLID) in sub-Saharan Africa. Water Altern 12(1):146–155

Van Koppen B, Tarimo AKPR, van Eeden A, Manzungu E, Sumuni PM (2016) Winners and losers in IWRM in Tanzania. Water Altern 9(3): 588–607

Venot JP, Molle F (2008) Groundwater depletion in Jordan highlands: can pricing policies regulate irrigation water use? Water Resour Manage 22(12):1925–1941

Varady et al (2016) Modes and approaches of groundwater governance: a survey of lessons learned from selected cases across the globe. Water 2016(8):417

Wada Y, van Beek LPH, Bierkens MFP (2012) Nonsustainable groundwater sustaining irrigation: a global assessment. Water Resour Res 48(6). https://doi.org/10.1029/2011WR010562

Wang J, Huang J, Rozelle S, Huang Q, Blanke A (2007) Agriculture and groundwater development in northern China: trends, institutional responses, and policy options. Water Policy 9(S1):61–74

Water Act (2012) Water Act, chap 372. The Republic of Kenya. http://kenyalaw.org/kl/fileadmin/pdfdownloads/RepealedStatutes/WaterAct_Cap372_.pdf. Accessed 15 February 2020

Water Governance Facility (2013) Groundwater governance in India: stumbling blocks for law and compliance. SIWI, Stockholm

Wijnen M, Augeard B, Hiller B, Ward C, Huntjens P (2012) Managing the invisible: understanding and improving groundwater governance. The World Bank Water Papers, The World Bank, Washington, DC

Wilder M, Lankao PR (2006) Paradoxes of decentralization: water reform and social implications in Mexico. World Dev 34(11):1977–1995

World Bank (2007) Making the most of scarcity: accountability for better water management in the Middle East and North Africa. The World Bank, Washington, DC

World Bank (2009) Poverty and social impact analysis of groundwater over-exploitation in Mexico, Latin America and Caribbean region. The World Bank, Washington, DC

World Bank (2010) Deep wells and prudence: towards pragmatic action for addressing groundwater overexploitation in India. The World Bank, Washington, DC

WWF (2006) Illegal use of water in Spain. Causes, effects and solutions. WWF Adena, Madrid