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PAPER

Can agricultural groundwater economies collapse? An inquiry into the pathways of four groundwater economies under threat

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Abstract The aim of this paper is to investigate the notion of collapse of agricultural groundwater economies using the adaptive-cycle analytical framework. This framework was applied to four case studies in southern Europe and North Africa to question and discuss the dynamics of agricultural groundwater economies. In two case studies (Saiss in Morocco and Clain basin in France), the imminent physical or socio-economic collapse was a major concern for stakeholders and the early signs of collapse led to re-organization of the groundwater economy. In the other two cases (Biskra in Algeria and Almeria in Spain), collapse was either not yet a concern or had been temporarily resolved through increased efficiency and access to additional water resources. This comparative analysis shows the importance of taking the early signs of collapse into account. These signs can be either related to resource depletion or to environmental and socio-economic impacts. Beyond these four case studies, the large number of groundwater economies under threat in (semi-)arid areas should present a warning regarding their possible collapse. Collapse can have severe and irreversible consequences in some cases, but it can also mean new opportunities and changes.

Keywords Socio-economic aspects · Groundwater economy · Arid regions · Agriculture · Over-abstraction

Introduction

Groundwater has long been considered an emblematic example of common pool resources, subject to overexploitation in the absence of a governance system to regulate water use. Starting in the 1960s, an agricultural groundwater-based boom was triggered in many (semi-)arid regions by a combination of easily accessible pumping and irrigation technologies, promoted by public policies through both direct and indirect subsidies. This enabled the extraction of large amounts of groundwater for high numbers of farmers, mainly through private tube-wells. Powerful agricultural lobbies captured a large part of the rents distributed through subsidies, which then strengthened the process of agricultural intensification with ecological and social consequences. These general trends vary in time and space under the influence of contextual factors like property rights, social organization, the role and weight of the state, the type of aquifer system, and the dominant agricultural model (Mukherji 2006). Nevertheless, it can be said that at the global scale, groundwater political economies have become visible, due to the increasing importance of groundwater in, e.g. food trade, food prices, and food security (Shah 2009). This has been documented in many (semi-)arid regions, for example in Mexico, China, India, Spain, Australia, USA, Morocco, Algeria, and Tunisia, where the irregular nature of surface-water availability makes groundwater a strategic source for irrigation (Changming et al. 2001; Scott and Shah 2004; Konikow and Kendy 2005;

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Llamas and Martínez-Santos 2005a; Shah 2009; Ross and Martinez-Santos 2010; Kuper et al. 2016). Increased groundwater use is currently anticipated in other parts of the world, particularly in sub-Saharan Africa due to increased food insecurity, easier access to technology and the existence of adequate groundwater resources for small-scale farming (Altchenko and Villholth 2015).

Several authors, including some in this journal, have warned that intensive agricultural water use will lead to *serious problems* in the mid- to long term, while insisting on the fact that there are already a multitude of indicators announcing coming problems, such as "water-table depletion, groundwater quality degradation, land subsidence, or ecological impacts on the aquatic ecosystems" (Llamas and Martínez-Santos 2005a). Beyond these indicators, linked to the state and dynamics of the water resource, there are other additional early warnings which also announce on the one hand the degradation of the biodiversity of groundwater-dependent ecosystems (Murray et al. 2003), and on the other the social inequity or even a social crisis (Llamas and Martínez-Santos 2005a) and economic consequences for farmers heavily engaged and dependent on the groundwater economy (Mukherji 2006). Some authors even warned about social and economic "collapse" of societies dependent on an eroded resource base such as groundwater, preceded by a period of environmental decline (Brown 2012).

Are we facing a global groundwater crisis? Certainly not, since groundwater remains available in many agricultural regions. Mukherji and Shah (2005) thus warned against adopting a "doomsday prophesy" on a total collapse of groundwater economies (hereafter GWEs), ignoring the benefits these economies have brought or can bring about, even more in the absence of reliable data. However, the social, economic and environmental sustainability of a GWE model based on agricultural intensification, high value-added all-year crops, affordable and easy to use technologies often led by entrepreneurial farmers, can be questioned. Thus, the aim of this paper is to analyze the main factors influencing the pathways of GWEs potentially heading for social, economic and/or physical collapse. What are the early signs of collapse and what are the strategies of actors dealing with these early signs? How long will these GWEs be able to cope with a series of compounding social, economic and environmental factors, whose convergence could prevent sustainable development? In this paper, GWEs are understood as social ecological systems (hereafter SESs), which can be defined as complex systems composed of interdependent human and biophysical variables with inherent properties like diversity, resilience, redundancy, non-linear feedbacks and modularity (Levin et al. 2013). In this context, what are the implications of a possible collapse of GWEs, in particular what are the possibilities for a re-organization and a new SES to emerge after the collapse? The combined effect of declining water tables, soil erosion and soil fertility loss, salinization, increased inequity, price volatility in agricultural markets, and the increased price of inputs (energy, for instance) particularly in a context of climate change, can severely impact these systems in the medium to long term, and could eventually lead to the collapse of GWEs.

The article first focuses on past and current trends in the development of GWEs using the analytical framework of the adaptive cycle of SESs to examine the life cycle of GWEs. In so doing, the importance of collapse in SESs is emphasized as a point of departure in the discussion about the pathways of GWEs. Second, four selected GWEs under threat in North Africa and southern Europe are analyzed. The last section discusses the consequences of the development of GWEs under threat, in terms of resilience and collapse.

From the life-cycle of GWEs to the adaptive cycle of SESs: collapse as an emerging issue?

The aim of this section is to confront two analytical frameworks dealing with the collapse of GWEs. The first one, derived from the works of Llamas and Martínez-Santos 2005a and Shah et al. (2003), aims at understanding the life-cycle of GWEs. The central focus of this analytical framework is on groundwater resources and has been already largely referred to in order to stress the governance issues related to groundwater exploitation in the world. The second analytical framework is built on the adaptive cycle of SESs. GWEs have never been specifically studied with this framework and the new insights derived from this approach are the central focus of this paper. However, in order to better understand the specificities of this second analytical framework, it is useful to start by summarizing the insights derived from the life cycle of GWEs and the way this framework addresses the notion of collapse.

The life-cycle of GWEs: collapse as a foreseeable outcome?

In the groundwater governance literature, the life-cycle of GWEs has been analyzed from two converging perspectives. According to Llamas and Martinez-Santos 2005a, in the 20th century, groundwater-related development in (semi-)arid regions went through five historical stages (Tables 1 and 2).

During the first stage (*hydroschizophrenia*), the state's attention is mainly focused on developing surface-water resources, while paying little attention to groundwater development. Groundwater starts to gain prominence through the action of individual agents (the *silent* revolution) and was recognized as an important resource by the state much later. The second stage begins when groundwater use becomes increasingly important from a socio-economic viewpoint. The third

Table 1 Life-cycle of groundwater economies: rough (ground)water policy trends in (semi-)arid countries (Llamas and Martínez-Santos 2005a)

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Hydroschizophrenia	Silent Revolution	Farmers' lobbies	Conservation lobbies	Social conflict

stage is characterized by powerful farmer lobbies that emerge to protect their collective interests. Farmers' lobbies typically negotiate subsidized electricity rates or put pressure to halt attempts by the state to regulate and control. In the fourth stage, conservation lobbies voice their opposition to the continued expansion of the GWEs on the basis of documented environmental impacts. The fifth stage is marked by social conflicts between the farming and environmental lobbies over the costs and benefits of the groundwater development model.

For the Indian subcontinent, Shah et al. (2003) proposed a similar model with a four stage development (Table 2) leading to a "decline of the groundwater socio-ecology with immiserating impacts". This means that those most dependent on a GWE could eventually be worse off than before entering it, thus questioning the long-term sustainability of groundwater's supposed benefits in terms of social justice and of lifting people out of poverty.

Even if such a description of the life-cycle of GWEs seems pessimistic, Shah et al. insist on the need to develop sustainable strategies to prevent a dramatic outcome. Llamas and Martínez-Santos 2005b even warned against those who use *hydromyths* to limit groundwater development:

> "The benefits of this silent revolution have been quite significant, even if some groundwater-related problems have also arisen in certain places. Precisely these have caused certain scholars to spread a series of *hydromyths*, which have led some to consider groundwater development a pillar of sand prone to *collapse*, or as a *bubble* likely to burst (Postel 1999). However, while these problems are sometimes real, it can be shown that they are many times pretended or exaggerated, or due to poor land use planning, rather than to intensive groundwater development" (Llamas and Martínez-Santos 2005b, p. 164).

Table 2 Life-cycle of groundwater economies: rise and fall of groundwater SESs in South Asia (Shah et al. 2003)

Stage 1	Stage 2	Stage 3	Stage 4
The rise of the green revolution and tube-well technologies	Groundwater-based agrarian boom	Early symptoms of groundwater overdraft and degradation	Decline of the groundwater socio-ecology with immiserating impacts

Shah (2006) is less optimistic when asking: "What might be done to sustain groundwater socio-ecologies and keep them from falling over the edge of the precipice?". This attitude is probably due to the fact that Shah, in addition to a resource perspective, explicitly assumed a user-perspective and an institutional perspective to groundwater use, accounting for what happens to groundwater users during the life cycle of GWEs (Mukherji and Shah 2005).

Thus, the frameworks developed by Shah et al. (2003) and Llamas and Martinez-Santos (Llamas and Martínez-Santos 2005a, b) are much more focused on the ways to prevent a collapse of GWEs, rather than an invitation to study specifically the collapse of SESs as a possible outcome and to question the consequences and future phases following a collapse. In this respect, one could ask whether a linear or a cyclical model is more appropriate to address the collapse of GWEs. The interesting feature of the adaptive cycle of SESs is that it allows this issue to be addressed: it proposes to identify conditions under which a new cycle could start after a collapse.

The adaptive cycle of SESs: collapse as a turning point

The notion of collapse is a central element discussed in the literature on the adaptive cycle of SESs. The adaptive cycle was developed in the works of the resilience alliance, reflecting an ecological view of collapse (Holling and Gunderson 2002). This cycle does not intend to explain particular cases but can be used to reflect on the dynamics of SESs: the adaptive cycle is often presented as a metaphor (Walker et al. 2004).

The adaptive cycle consists of four phases (see Fig. 1): exploitation (r), conservation (K), release (or collapse) (Ω) and re-organization (α).In the exploitation phase (r), growth is rapid, competition is high and resilience to disturbance is high. The r phase shifts slowly to the conservation phase (K), when the consumption of available resources continues to expand. In the K phase, networks of actors collectively decide to limit the exploitation of resources and at the same time to increase the efficiency of exploitation. The r and K phases are generally considered as the fore-loop of the adaptive cycle and can last for decades. The rigidity caused by the K phase (definition of new norms, new laws, limiting the capacity of users to exploit natural resources) renders the SES vulnerable to collapse and, when collapse occurs, the release phase (Ω)

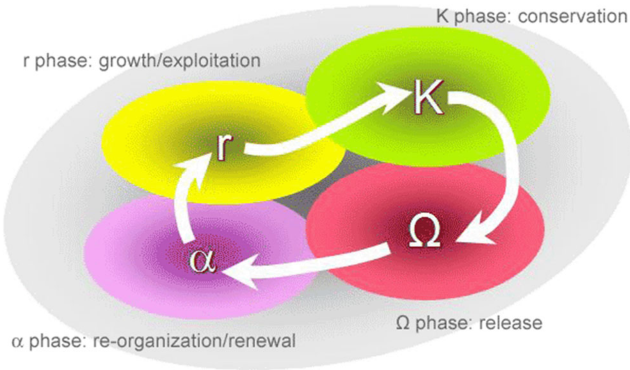

Fig. 1 Adaptive cycle (source: Resilience Alliance 2015)

begins. A restructuring of the SES starts and results in the re-organization phase (α), which lays the foundations for a new cycle. According to Walker et al. (2004):

> "The dynamics of SESs can be usefully described and analyzed in terms of a cycle, known as an adaptive cycle, that passes through four phases. Two of them— a growth and exploitation phase (r) merging into a conservation phase (K)—comprise a slow, cumulative forward loop of the cycle, during which the dynamics of the system are reasonably predictable. As the K phase continues, resources become increasingly locked up and the system becomes progressively less flexible and responsive to external shocks. It is eventually, inevitably, followed by a chaotic collapse and release phase (Ω) that rapidly gives way to a phase of reorganization (α), which may be rapid or slow, and during which, innovation and new opportunities are possible. The Ω and α phases together comprise an unpredictable back loop. The α phase leads into a subsequent r phase, which may resemble the previous r phase or be significantly different."

When applying the adaptive cycle to GWEs, the cycle would probably be: (1) GWEs develop in an institutional set up that puts few constraints on groundwater use (*exploitation phase r*); (2) negative externalities appear, political lobbying emerges to protect vested interests and there may be political measures or collective action to reduce the volume of water legally available to farmers (*conservation phase K*); (3) a (partial) destruction of the GWE, either in its resource component (stock depletion or deterioration of water quality), in the economic performance of the agricultural sector (reduction in production, bankruptcy of farms), in the social dimension (conflicts, migration), or in related environmental issues (deterioration of dependent ecosystems) (*release phase* Ω); (4) adaptation and re-organization through, for instance, changes in cropping patterns and the development of alternative surface-water resources or even migration of the rural population (*re-organization phase* α). In this framework, the capacity to cope with a situation of collapse is understood as the resilience of SESs.

Taking the notion of collapse seriously

The notion of collapse can be understood as important in both frameworks presented in the preceding. Even if Shah et al. (2003) and Llamas and Martínez-Santos 2005a do not explicitly refer to this notion, their interpretation of the life cycle of GWEs suggests that the end of the cycle can be dramatic, due to the dependence of actors on intensive groundwater use and associated problems. Preventing such a drama is their central focus. However, because the last stage in both frameworks can be characterized by the collapse of GWEs, they offer the invitation to reflect on the collapse as a possible outcome but do not really question or indeed analyze the possible steps after this collapse. In contrast, the adaptive cycle framework explicitly acknowledges the possibility of a collapse in SESs, which can also be seen as an opportunity for a new cycle (*release*). The importance of this sequence (exploitation-conservation-collapse), which is more or less explicitly referred to in both frameworks, necessarily passes through looking more closely at the notion of collapse.

In social sciences, Tainter (1990) was one of the first to develop a modern view of the collapse of complex societies. According to Tainter: "collapse (…) is a political process. It may, and often does, have consequences in such areas as economics, arts and literature, but it is fundamentally a matter of the sociopolitical sphere. A society has collapsed when it displays a rapid, significant loss of an established level of sociopolitical complexity. (…). The collapse (…) must be rapid—taking no more than a few decades—and must entail a substantial loss of sociopolitical structure. Losses that are less severe, or take longer to occur, are to be considered cases of weakness and decline." (Tainter 1990, p. 4).

This notion was used more recently to deal with the history of environment-society relationships. Diamond (2005) defines collapse as "a drastic decrease in human population size and/or political/economic/social complexity, over a considerable area, for an extended time". He identified 12 environmental problems leading to the collapse of historical societies, among which 8 can be seen as elements of vulnerability for GWEs. However, this list of environmental problems does not consider the economic interests and drivers that guide the GWE on an unsustainable trajectory, which is the reason why, beyond the physical expression of collapse, it is necessary to account for its political, economic and social dimensions. In various cases, GWEs do not face physical scarcity (pumping in aquifers would still be physically possible). Rather, their vulnerability may be due to state intervention, for instance in the absence of strong farmers' lobbies (e.g.

the case of West Bengal; Mukherji 2006), or to protect third parties from the negative externalities of irrigation development. Hence, the vulnerability of GWEs can refer to two distinctive meanings: it can be used, first, to describe a GWE that is subject to a resource conservation policy limiting the capacity of farmers to get access to a lucrative resource (economic vulnerability), but it can also be used to refer to the resource depletion due to overexploitation (resource vulnerability). These two kinds of vulnerability have different implications in the temporal dynamics of GWEs. Economic vulnerability may produce immediate consequences (e.g. for farmers who need to subdivide their land to inheritors and hence intensify,) and yet generate long-term resilience to the few that manage to get access and benefits, while resource vulnerability is a more definitive vulnerability with long-term impacts. The question is a fundamental one: whether to benefit economically quickly from the resource, or whether to withdraw the benefits at a slower rate, over a longer period, at more sustainable rates.

From this analysis of the literature on the collapse of SESs, it appears that a GWE collapse can be characterized either by physical factors or social, economic and political factors. Physical factors include for example a significant drop in the water table, which could prevent a future development of agriculture or other economic activities in the region. Social, political and economic factors include a limited availability of production factors (capital, labor, land, energy and water), the presence of social conflicts on the use of groundwater including environmental lobbies voicing opposition to further physical decline, and the saturation of national and export markets for fruits, vegetables or cereals produced by the agricultural sector.

Looking at agricultural GWEs under threat through the lens of the adaptive cycle

For this study, four GWEs were selected in southern Europe, the area around Almeria town (Spain) and Clain basin (France), and North Africa—the area around Biskra town (Algeria) and the Saiss plain (Morocco; Fig. 2). In the past years, the authors of this paper have been involved in an empirical analysis of these GWEs, which have different characteristics (Table 3), yet are all under threat due to the rapid development of individual groundwater based irrigation.

These GWEs can be situated on the adaptive cycle of the resilience framework:

- Biskra (*far from collapse*) is in the growth phase (r)
- Saiss (*accelerating before collapse*) is approaching the conservation phase (K)
- Clain basin (*preventing the collapse by* “*breaking*” *the speed of development of the GWE*, *but risks of slipping*) is in the conservation phase (K)
- Almeria (*post collapse*) is on the verge of the re-organization phase (α)

At first glance, this framework may appear to be rather deterministic, since the phases identified follow one after the other; however, due to political, social, economic and physical factors, the development of GWEs can follow different paths. This underlines the fact that paths or sequences can be disrupted either through public policies or (often unexpected) external factors and drivers of the system. First, the results for the cases of Biskra and Almeria will be presented, which represent two cases where collapse was either not yet a concern or had been temporarily resolved through increased efficiency and access to additional water resources. Second, the results for Saiss and Clain basin will be presented, two cases where actors are actively preparing for the collapse. This will highlight the way the different GWEs deal with the collapse of SESs.

The “Eldorado” before and after side-stepping collapse: Biskra, Almeria

When considering GWE life cycles, the terms “rapid growth”, “agrarian boom”, “bubble”, “high-value crops”, “social and economic transition” generally characterize the first stages. The exuberance in discourse and practices associated with the advent and coming of age of the GWE shows how attractive it is for farmers to connect to a resource, which is considered, at least in the short term, abundant and able to lift them out of poverty through the creation of wealth. The GWE can thus be seen as an *Eldorado*—a place where wealth can be rapidly acquired—and hence attracts many actors (farmers, service providers, market agents), interested in partaking in the agrarian boom (López-Gunn et al. 2012). This exuberance has been documented in several GWEs across the world: South Asia, southern Europe, North Africa, the USA, Latin America (Llamas 2003; Scott and Shah 2004; Shah 2009; Hoogesteger and Wester 2015; Kuper et al. 2016). There is much less evidence for what happens when the bubble bursts. In this section, the notion of collapse is explored in a GWE which is still thriving (Biskra, Algeria), and a GWE that has partly experienced physical collapse and is partly living on borrowed time due to a particular contextual location (Almeria, Spain).

The groundwater economy of Biskra: no collapse in view

The myth of a possible agricultural Eldorado in the Algerian Sahara was founded on earlier albeit mitigated experiences of large-scale irrigated agriculture in the deserts of Saudi Arabia and Libya, focused on the production of cereals through pivot irrigation systems (Otmane and Kouzmine 2013). It triggered a massive investment by the state from the 1980s to access

Fig. 2 Location of the case studies. The data source was ESRI using 2015 data. The map was created by Eric Masson

groundwater through public and private tube-well schemes, based on the exploitation of very large, but not very actively recharged, sedimentary Saharan aquifers (MacDonald et al. 2012).

Located on the edge of the Sahara Desert, the irrigated area of the district of Biskra increased five-fold from 16,500 ha in 1969 to more than 104,000 ha in 2013, according to data of the ministry of water resources (see Table 4). A total of 94% of irrigation water is currently supplied by groundwater through more than 4,200 wells and 9,000 tube-wells (MRE 2009), a number that has continued to increase according to the river basin agency. There has been a rapid extension of commercial palm groves (about 43,000 ha in 2014 of which about 60% is of the *deglet nour* variety; due to its commercial success, this variety is importantly contributing to driving the GWE), the development of intensive horticulture (17,365 ha in 2014 of which 4,900 ha are under greenhouse for the production of tomatoes, bell peppers, and melons), while maintaining the production of cereals (26,023 ha), according to data of the ministry in charge of agriculture. Traditionally, irrigation was managed collectively by diverting the seasonal floodwater from non-perennial streams to produce cereals and irrigate the palm groves (spate irrigation), or around artesian wells. The access to groundwater was facilitated by the state through public tube-well schemes with deep tube-wells with a high discharge (>100 L/s). Today, collective irrigation schemes serve almost 60% (19,305 farms) of the total number of farm holdings in the district (MRE 2009). However, there has been rapid expansion of private irrigation through individual tube-wells, often reaching 200–400 m depth, which in 2008 served 40% of the farms on 70% of the irrigated area.

The agricultural boom in Biskra was based on a combination of factors. First, it was linked to the availability of land and water resources, combined with a favorable climate for high value crops (early vegetables, dates). Due to the low recharge rates of the very large aquifers, agriculture can be compared to mining, symbolized by the nearby oil fields, leading to a structural decline in water tables (Margat and van der Gun 2013).

Second, the farming systems are mostly based on the pooling of productive resources through sharecropping arrangements, enabling different actors to find solutions for limiting factors such as capital, labor and access to land and water. For instance, the horticultural boom is based on investors bringing in the capital to buy land and access groundwater, lessees bringing in the capital to pay for the inputs (seeds, pesticides, fertilizers, water, land rent) and the sharecroppers supplying their labor and their know-how. A single tube-well, running full time, typically serves 20–40 sharecroppers practicing greenhouse horticulture (Amichi et al. 2015). These

Table 3 Some characteristics of the GWEs studied

Case study	Aquifer system	Climate	Start of groundwater irrigation development	Main farming systems	Situation with respect to the notion of collapse
Biskra (Algeria)	Huge but not very actively recharged sedimentary Saharan aquifers	Arid	In the past, access to groundwater through artesian wells; end of 1970s—start of pumped groundwater use through state implemented collective tube-wells	Date palms, horticulture, greenhouses, cereals	Far from collapse, but mining type of groundwater use
Saiss (Morocco)	Medium-sized aquifer with rapidly declining water tables	Semi-arid	Pumped groundwater use by smallholders through dug-wells and by entrepreneurial farmers by tube-wells from 1990s onwards	Fruit trees, horticulture, cereals. Rapid increase in irrigated area	Approaching the conservation phase. Collapse is anticipated by different actors
Clain basin (France)	Karstic aquifer with rapid recharge but limited buffer capacity	Temperate	End of 1970s—start of pumped groundwater use through private tube-wells	10% of cultivated area irrigated: corn (60%), cereals (20%), pasture (10%), other (15%)	No physical collapse, but strict regulation to prevent the collapse
Almeria (Spain)	Upper aquifer salinized due to intensive pumping and marine intrusion. Current use of a deep aquifer	Semi-arid	First greenhouses were built in the 1960s, through State initiative followed onwards by entrepreneurial small farmers	Intensive greenhouse production (two cycles/year). Access to European markets; 34,000 ha of bell peppers, watermelons, melons, eggplants, tomatoes, green beans, zucchini	On the verge of the re-organization phase. Problems of marine intrusion and increased energy costs due to drop in groundwater levels. Problems of water quality

farming systems stimulated the mobility of many young people who arrived in Biskra to take part in the Saharan “dream”, which provided opportunities for quick monetary gains and upward social mobility (Ouendeno et al. 2015). Farmers were greatly encouraged by the emerging private sector, which handled supplies of agricultural inputs, provided advice and credit facilities.

Third, there is a considerable domestic market for the fruit and vegetables produced in Biskra, which are perfectly integrated into the national market through wholesale markets frequented by merchants from all over the country. Biskra is now the primary supplier area of fruit and vegetables to the national market. In Algeria, food expenditures account for 42% of the household budget with a large part devoted to fruit and vegetables, and this important national market is protected from imports by 30% customs duty on imported fresh produce. Furthermore, the perceived possibility of exporting a small share of the fruit and vegetables produced in case of overproduction is also an encouragement to continue developing the GWE.

Fourth, the “tolerant” state (Brochier-Puig 2004) not only initiated and stimulated access to the confined aquifers through deep tube-wells, but also enabled the expansion of irrigated agricultural land by providing basic infrastructure such as roads, electricity and schools. The agricultural boom matches the state’s objective of transforming the Algerian Sahara into an agricultural Eldorado (Otmane and Kouzmine 2013). Groundwater is officially public property and the 2005 Water Law regulates its access and use. In the field, the practices are different and complex, subject to a dual approach, formal and informal. In the first case, the state is a central actor who provides the authorization to obtain access to and use of groundwater, and often finances the physical infrastructure (tube-well, pump, motor and tubing). In practice, obtaining authorization requires a solid network of contacts including the local authorities and depends on individual or collective bargaining power. It was estimated that by 2014 only about 8,000 out of 17,000 tube-wells were officially authorized by the river basin agency. Moreover, there is no control over the volumes pumped by these tube-wells. The second system is organized around thousands of illegal private tube-wells, which are tolerated by local authorities, who are keen to promote agricultural development, while at the same time ensuring that the owners continue to be aware that their tube-wells are merely tolerated. The official regulation stipulating the need for authorization remains in place, without being completely restrictive, which leads to two access mechanisms to groundwater resources, concomitantly used by the local authorities, depending on the balance of power at the time. These balances are shaped by political actors (expansionist agricultural policies

Table 4 Some key figures on the GWEs of Biskra and Almeria

Parameter	Biskra	Almeria
Rainfall	<100 mm/year	200 mm/year
Total cultivated surface area (ha); part of groundwater	104,000 ha (2013); 94%	170,000 ha (2006) of which 30,000 ha are under plastic
Groundwater decline	Up to 70 m for the Mio-Pliocene aquifer over the past 50 years	Western Lower Aquifer dropped −45 m, while Northeastern Lower Aquifer is now abandoned due to marine intrusion and salinization. Average drop in groundwater level is 20 m
Groundwater use for agriculture (km^3 per year)	1.2 (2009)	Between 0.125 and 0.15 as compared to 0.90 available
Number of farmers	32,175	32,000
Size of farms	Micro plots inside traditional palm groves (<1 ha); 5–30 ha outside these palm groves	Micro plot with an average size of 1.62 ha
Agricultural production	Out of national production: 37% dates; 25% tomatoes	Crops are cucumber, melon, watermelon, eggplant, zucchini, pepper, tomatoes and green beans in relatively similar percentages to generate around 1,000 M euros/year

Sources: Larbes (2005); MRE (2009); Kuper et al. (2016); Corominas (2013); Dumont (2015)

versus conservationist water policies), players in the market sphere (local landowners, agricultural investors and drilling companies) and local government officials, following the logic of any of the preceding categories.

In Biskra, the notion of "collapse" of the GWE, which is still in the *growth phase*, is never referred to and the classical factors that would impede its development (declining water resource, shortage of productive resources, limited markets) do not apply, at least in the short term. There are some rare voices warning about the unsustainability of the GWE, related to the mining of the groundwater resource, the decline in soil fertility or the danger to public health of the unlimited use of pesticides. Farmers regularly complain about labor shortage, the high cost of inputs or fluctuating markets, but the system continues to attract newcomers who bring in new productive resources. Furthermore, the different actors do not appear to have a strong formal view on the need to regulate the direction and the rapid growth of the GWE, so "business as usual" is likely to continue for some time.

The groundwater economy of Almeria: reorganization after the collapse

The story of Almeria, located in Andalusia in southeastern Spain, is that of another Eldorado for agriculture, based on groundwater exploitation and greenhouse crops (Humbert 2000). The Campo de Dalías is a 320 km^2 semi-arid plain located to the west of Almeria (see Table 4). The coastal carbonate aquifer is subject to seawater intrusion and groundwater is mainly used for agriculture (export-oriented vegetable production), urban supply and tourism.

The growth phase in the Almeria region started in the first half of the 20th century. Groundwater based irrigation began in 1916, but the boom of the GWE occurred in the mid-1970s. The increase in groundwater withdrawals was spectacular, rising from 30 Mm^3/year in the mid-1960s to 156 Mm^3/year in 2005 (Cuitó Sabaté et al. 2006). The three main agricultural crops in the area are tomatoes, bell peppers and cucumbers. Groundwater use, coupled with continuing innovations (introduction of greenhouses in the 1960s, hybrid seeds and drip irrigation in the late 1970s, thermal plastic and reinforcement of the structure of the greenhouses in the 1980s, the introduction of pollinators and irrigation automation in the 1990s) doubled agricultural yields between 1975 and 1999. During the same period, the extent of greenhouses in Almeria increased from 3,500 ha in 1976 to almost 25,000 ha in 2000 (Buchs 2016). However, negative externalities appeared, pushing Almeria's GWE progressively into the *conservation phase*, which lasted from the 1980s to the 1990s. A decline in the water table had been observed since the 1970s. The first administrative measures were implemented, although no reduction in water legally available to farmers was introduced, contrary to other cases in Spain where reduced legal quotas for individuals were imposed (López-Gunn et al. 2012). A ban on new tube-wells was declared and increasing the area of irrigated land was forbidden. According to article 38.1 of the 1985 Water Law, the general objectives of hydrological planning were "to reach the optimal satisfaction of water demands, harmonize and equilibrate the sectorial and regional development, by improving [water] quality, economizing and rationalizing its use in harmony with the environment and other natural resources". The aquifers were legally declared overexploited in the late 1980s (Palacios 2000).

The *release phase* started at the end of the 1990s, when the top aquifer was abandoned due to salinization. This area is now subject to local flooding due to high water levels, and drainage schemes are being developed, while groundwater use shifted to the deeper aquifer with major risks of marine intrusion, if the location of tube-wells is not carefully planned (Dumont et al. 2015). Interestingly, at the same time, farmers started to organize themselves, partly because this was required under the Spanish water law for over-exploited aquifers, but increasingly also to defend their collective interests.

The Central Users Board of Poniente Almeriense (or Junta Central de Usuarios del Poniente Almeriense) was created in 1991 as a public corporation spurred by users' initiative incorporating seven municipalities, three industrial users, 38 individual groundwater user groups spanning both public and civil entities and around 118 individual users. In parallel, the users' community of the Sierra de Gádor aquifer (Comunidad de Usuarios del acuífero Sierra de Gádor) also became a public corporation composed of different groundwater users associations (López-Gunn et al. 2012). The main benefit from organizing collectively was their ability to lobby to secure additional resources and also to bargain for cheaper electricity prices, by addressing themselves directly to the electricity companies without intermediaries.

The *reorganization/renewal phase* (α) started at the beginning of the 21st century. A number of solutions were envisioned to address the many externalities due to increased pressure on groundwater resources. These focused on command and control measures. However, due to local lobbying and the key strategic value of groundwater for the local economy, the restrictions were not enforced. The irrigated area more than doubled, from 15,000 to 30,000 ha approximately by 2013, even after the declaration of aquifer over-use. The idea was then to opt for supply-side driven solutions: inter-basin transfers from the Ebro, as envisioned in the 2000 National Hydrological Plan, and the construction of local reservoirs. However, the transfer from the Ebro never happened since the National Hydrological Plan was derailed after a change in government.

There were some tentative steps towards demand-side measures. These measures focused on three aspects: collective action (social base), economic instruments and increased water use efficiency (resource base). Concerning the social base, the 1999 reform of the Water Law and the new orientations of the National Hydrological Plan characterized a clear shift in the Spanish water policy towards economic instruments. The possibility for water markets and water trading were opened. Influenced by experience gained in California, USA (water markets, water banking), new instruments were developed to manage water through economic incentives (demand-side solutions). Officially, there is no water banking in the region, because most of the water rights in the area are private. However, there is a lot of water trading between farmers, which allows greater flexibility in the system since additional water resources can be bought if needed, but it does not necessarily help to recover the groundwater system since it can intensify resource use in specific areas.

Concerning the supply side, political lobbying continued at regional level. Once the option of water transfers vanished, the 2003 *Plan AGUA* envisaged a series of desalination plants, one of which was designed to supply Almeria. Since 2015, part of the supply is now obtained from seawater desalination to reduce groundwater withdrawals to help comply with the EU Water Framework Directive aimed at achieving good ecological status (Dumont 2015). However, the lack of transparency in decision making and an intense debate over who should bear the costs raised questions about the feasibility of desalination as a simple solution to a complex problem (Dumont et al. 2011). The desalination plant has a capacity of almost 100,000 m^3/day, which could be increased to almost 130,000 m^3/day. These additional sources of water are important to keep agriculture going in the Campo de Dalías, although these are not enough to replace groundwater use estimated at 0.15 km^3/year.

In this example of the α phase, the priority was to make the local economy less dependent on groundwater after the collapse of the upper aquifer and the potential risks to the lower aquifer. This was done, first, by diversifying the economy towards tourism; second, by enlarging the resource options through desalination and also increasingly through water reuse. Therefore, one part of the SES, the social base, increased its resilience through the collective action by users to expand and diversify the resource base, but also by becoming increasingly efficient in its overall use of resources (drip irrigation, less use of energy or cheaper energy through collective price bargaining). Their way to solve a situation of groundwater overexploitation was to expand the frontiers of the SES. Intensive agriculture no longer depended exclusively on the quality and quantity of water available in the local aquifer; however, it remained a very resource intensive system both for water and energy use.

Preparing for the collapse: break or accelerate? Saiss, Clain basin

The exuberance connected with GWEs in the Algerian Sahara and coastal Spain, which are referred to as agricultural *Eldorados*, is somewhat tempered in the other cases, probably linked to the shared perception of actors that "collapse" may not be very far away. This hypothesis is illustrated by investigating two contrasted GWEs (see Table 5). In the Clain River basin (France), the state obliged farmers to reduce pressure on groundwater resources to comply with the European Water Framework Directive. In the Saiss (Morocco), the state actively explored ways to increase the supply of surface water to replace diminishing groundwater reserves, while maintaining the agricultural boom. Breaking or accelerating the speed of the development of the GWE before the collapse is the issue in both situations. Most actors, including the state, fear that tough regulations to decrease the groundwater use would entail a collapse of the GWE, or at the least create social and economic problems for certain social categories of farmers.

Table 5 Some key figures on the GWEs of the Saiss and Clain basin

Parameter	Saiss	Clain basin
Rainfall	450 mm/year	700 mm/year
Area under groundwater irrigation / total cultivated surface area (ha)	45,300 ha/220,000 ha	28,000 ha/267,000 ha
Groundwater decline	Annual deficit of 0.1 km^3. Over the past 30 years, decline of 10 m for the phreatic aquifer; 25–65 m for the confined aquifer	Annual deficit of 0.015 km^3
Groundwater use for agriculture (km^3/year)	0.27 (2010)	0.033 (2012)
Number of farmers	42,700 farms (1996), of which probably less than 50% irrigate	656 (only irrigated farms)
Size of farms	75% of farms own 5–15 ha	25–85 ha (irrigated area)

Sources: General Agricultural Census of 1996 (Morocco); ABH (2011); Figureau et al. (2015); Moreau et al. (2015)

The groundwater economy in the Saiss: instead of changing the pace, looking for alternative water resources

The Saiss is a rich agricultural plain in Morocco, close to the cities of Fes and Meknes. Covering 220,000 ha, in the past, the Saiss was mainly known for rainfed crops (cereals, vineyards, olive trees). Due to droughts in the early 1980s, together with liberalization of the agricultural sector, there was a tremendous increase in the extent of land irrigated with pumps. During this "growth" phase, farmers had massive access first to the phreatic aquifer through wells (15–50 m in depth) and, from 2000 onwards, to the Lias confined aquifer through tube-wells from 120 to 200 m in depth. A survey by the Ministry of Agriculture in 2012 showed a total irrigated area of about 49,600 ha (20% of the total area), of which 45,300 ha depended on pump irrigation (see Table 5). Today, irrigation caters principally for orchards (olives, plums, peaches, apples), vineyards, horticulture (onions, potatoes), and fodder crops.

In the Saiss, there are visible signs of a possible collapse of the GWE. According to the river basin agency, water tables in the phreatic aquifer decreased by about 10 m between the early 1980s and 2005, with a sharper decline after 2000, when water tables decreased by about 1 m/year (ABH 2011). The drop in groundwater level was even more marked in the confined aquifer. In the west (Meknes area), the decline was 65 m between 1979 and 2004, i.e. 2.6 m/year. In the east, the drop was 20–25 m over the same period. Many small-scale farmers lost their (limited) access to groundwater when their wells ran dry. Referring to a specific area within the Saiss, Kuper et al. (2016) mentioned that 97 wells out of 170 (most of which had been installed over the past 25 years) were no longer functioning in 2014. These farmers, who had used groundwater for horticulture, withdrew from the GWE and reverted to rainfed crops (cereals, forage) and livestock. Larger-scale farmers with access to tube-wells were less affected, since tube-wells are generally 120–200 m deep, and water came up to within 30–40 m from the surface due to the pressure of the confined aquifer. Lowering the pump in the tube-well can therefore compensate for declining water tables, although in some cases the pump and motor needed to be replaced, since more power is required to pump up water. This additional investment was often out of reach of smaller farmers.

The sharp increase in the production of fruit (apples, grapes, plums for prunes) and vegetables (onions, potatoes), was stimulated by Morocco's agricultural intensification policy. The 2008 "Green Morocco Plan" even led to problems of congestion in domestic markets (Sellika and Faysse 2015). This in turn resulted in market prices that were much lower than envisaged at the time of investing in intensive agriculture. Falling prices linked to increased production costs (fuel and labor) were perceived as a threat by local actors, much more than the decline in groundwater resources. Some small-scale farmers thus reverted to less risky crops such as tobacco (under contract) or rainfed cereals.

The GWE thus already lost some of its protagonists without going through a *conservation* phase and most actors are aware of the possibility of a physical or economic collapse. Their strategy to deal with this varies. The river basin agency, along with the Ministry of Agriculture, under pressure from a powerful agricultural lobby made up of large-scale farmers, succeeded in attracting the attention of the state to obtain freshwater resources for the Saiss, by planning the diversion of surface irrigation water to a 30,000 ha irrigation scheme from the planned M'dez dam for which feasibility studies are underway. These farmers envisage continuing with current farming systems (e.g. fruit trees), by obtaining access to a new water resource provided by the state against the diminishing availability of groundwater. Since they have invested in fruit trees, often subsidized in part by the state, it is more difficult for them to change cropping systems than the small-scale farmers practicing mostly annual crops. Although in principle the M'dez water should benefit all farmer categories, while ensuring the preservation of the aquifer system, the large-scale farmer lobby may be sufficiently strong to obtain the lion's share of surface water. In addition, the drinking water authorities in the cities of Fes and Meknes are in the process of replacing their current use of groundwater with surface-water supplies from existing dams, which will free up additional groundwater supplies to farmers without them having to pay for the substitution process. According to the river basin agency, the projected allocation from the dam, 100 Mm^3, corresponds to the annual groundwater deficit in the Saiss.

The limits of the agricultural boom and the associated risk of collapse are not only perceived by the river basin agency and farmers, but also by the service providers in the GWE that were interviewed for this study. The craftsmen in charge of providing the hydraulic infrastructure (tube-well, pump, engine, pipes, drip irrigation), who have accumulated a lot of experience in dealing with the daily problems of the GWE, are now turning to new markets and opportunities. Travelling to new agricultural zones up to 250 km away, these providers sell their expertise to farmers in more profitable emerging or booming GWEs.

The groundwater economy of the Clain River basin: preventing collapse?

The development of the GWE in the Clain basin followed a very similar pathway to that of many groundwater basins in southwestern France (Figureau et al. 2015). Benefiting from a temperate climate, agriculture was traditionally rainfed. Farmers only invested in the construction of wells after the 1976 drought. The main resource exploited is a karst limestone aquifer (Dogger), which is well connected to rivers. Access to groundwater, which was first considered by farmers as an insurance policy, progressively supported the development of more intensive and diversified agriculture, with the development of high added-value crops such as certified seeds, tobacco, fruit (melons) and vegetables. Farmers faced no administrative constraints on expanding groundwater use until the beginning of the 1990s, which marked the end of the *exploitation* phase (r).

The transition towards the *conservation phase* (K) was triggered by the environmental externalities associated with increased groundwater abstraction: the discharge of groundwater dependent rivers decreased sharply, some stretches even ran dry, leading to conflicts with recreational users and environmental NGOs. The state responded by declaring the basin a restriction zone in 1994, which made it possible to restrict the drilling of new wells, as well as regulating abstraction during the irrigation season. Next, the state installed a network of 26 piezometers to monitor groundwater levels. When the water table dropped below an emergency level, farmers were subject to progressive irrigation restrictions. The third step (implemented in 1999) consisted in allocating a specific annual water volume to each farmer. Individual allocations were calculated based on the analysis of past water use. The allocation rates of farmers who could demonstrate that they actually used the water were renewed every year for, but were lost (without compensation) by farmers who reducing irrigated area or water use. At the end of this K phase, approximately 10% of the total cultivated area in the Clain basin is irrigated (mainly with groundwater), and about 15% of the farms have access to groundwater (Figureau et al. 2015; see Table 5).

As part of the implementation of the 2000 EU Water Framework Directive and of the 2006 French Water Law, new hydrogeological studies were conducted to refine the calculation of the *safe yield*. The result was that abstraction would need to be reduced from 33 Mm^3 from the 2012 situation to the 17 Mm^3 by 2017 (Figureau et al. 2015). The GWE is on the verge of collapse, not because of resource depletion, but because of the regulatory constraints.

Since 2010, stakeholders are actively involved in a negotiation, which will shape the *re-organization phase* (α). Reorganization relies on three main pillars. The first pillar consists in developing medium-size reservoirs (250,000–500,000 m^3) that can be filled by pumping groundwater in winter, when the groundwater level is high. The underlying concept is capturing part of the recharge that occurs in winter, but which cannot be stored in the groundwater reservoir due to high hydraulic connectivity with rivers. These reservoirs are financed and owned by newly established "water cooperatives", with financial support from the Basin Agency. The second pillar consists in establishing an agricultural groundwater users' association, which is officially attributed a global water allocation and made responsible for apportioning water among farmers (Moreau et al. 2015) and enforcing these entitlements (Figureau et al. 2015). These associations will also coordinate groundwater allocation including the allocation of water stored in the newly developed reservoirs. The third pillar involves the development of a territorial project proposing a long-term agricultural development strategy, which must be developed by involving all stakeholders in the basin through a formal contract. It must comprise four steps aiming at: (1) reducing (ground)water abstraction; (2) the construction of substitution reservoirs; (3) the development of water conservation practices; and (4) the reorientation of agriculture towards less water-intensive crops.

At the time of writing (2016), this GWE is a counterexample of the general trend towards physical collapse, as its management reflects concern for long-term impacts and it results from an active political economy. However, the French legislator is taking a risk by putting so much stress on this GWE that there is a risk of losing competitiveness and thus provoking its collapse due to economic factors. Also, the reaction of farmers' lobbies and hence the outcomes of this strategy cannot be completely predicted.

Discussion

Early signs of collapse

What were the early signs of collapse of the different GWEs? The analysis of the case studies showed that collapse is not only linked to physical factors, but is rather embedded in social, economic and political conditions, which means that different indicators can be identified to announce the collapse of a GWE. While in the Saiss and the Clain basin, local actors openly discussed the possible collapse based on a variety of indicators, this was not the case in Biskra and is no longer the case in Almeria; however, the analytical distinction of these two pairs of case studies does not apply for all indicators.

First, declining water tables can be observed in all the case studies; however, this decline was not always interpreted in the same way. For instance, in Biskra, the aquifers are very large and local actors merely reacted to the drop in the water table by deepening their tube-wells. Energy cost is rather low in this oil-producing country and many tube-wells are operated collectively, which means that the investment costs are shared. In the case of Almeria, the cost of irrigation is low, as compared to the gains obtained by farmers estimated at 60,000 euros/ha (López-Gunn et al. 2012). In contrast, in the Saiss, the rapid decline of the groundwater level in the phreatic aquifer required farmers to explore the confined aquifer, which meant switching from shallow wells to deep tube-wells. This meant that quite a large proportion of small-scale farmers were no longer able to adapt to the drop in the water table and were excluded from the GWE. Even large-scale farmers had to adapt their pumping equipment, switching to submersible pumps and connecting to the electrical grid, which explains that farmers are increasingly conscious of declining water tables. In the Clain basin, declining water tables became an issue especially when surface-water streams were affected.

A second indicator that is increasingly cited in the literature is the deterioration of groundwater quality (Llamas and Martínez-Santos 2005b). In Almeria, the groundwater decline in the phreatic aquifer led to seawater intrusion and salinization, prompting farmers to aim for a deeper aquifer, which has natural geological protection against seawater intrusion; however, this aquifer is also considered to have poor quality under the EU Water Framework Directive (Corominas 2013). In the case of the Saiss, some wells were also abandoned due to increased salinity, but in the majority of cases, farmers have not experienced such problems. The same is the case in the Clain basin and in Biskra. In all cases, irrigation was coupled with intensive use of chemical products, which can lead to groundwater pollution and public health risks. The paradox is that most of the farmers do not protect themselves well against these health risks, even when using pesticides and fertilizers in greenhouses (Biskra), even though they were very conscious of these risks.

Third, GWEs often represent an intensive mode of agricultural production, highly dependent on the availability of production factors, including capital, labor, land, water and energy. In all the case studies, the farmers complained about bottlenecks in at least one of these resources. However, local actors interpret these constraints as issues that need to be solved in order to be able to continue intensive groundwater-based agriculture. In Biskra, local actors designed farming systems to pool these different resources (Amichi et al. 2015). In Almeria, farmers have probably been far more successful in collective action to reduce energy use and energy costs than to reduce groundwater use. Even in the two other case studies, farmers generally managed to deal with problems related to the availability of production factors. In the Saiss, farmers envisage shifting to solar energy to further reduce the energy bill.

Fourth, GWEs are very much integrated in national and export markets. Some of these markets showed signs of saturation, for example, for onions or apples in the Saiss in 2013 and 2014 and tomatoes in Biskra in 2015. Farmers are thus becoming increasingly aware of the economic vulnerability of partaking in a GWE.

Fifth, the environmental impacts of intensive groundwater use were made visible early on in the Clain basin, due to the many connections between surface streams and groundwater in karstic conditions. This provided sufficient (early) evidence to prompt the environmental lobby to further its case. These environmental impacts could also be observed in the other case studies, for example, in the Saiss many natural sources have dried up over the past 30 years. However, this was generally attributed to the "droughts", thus delinking this issue from the intensive use of groundwater. The absence of an environmental lobby taking up this issue is probably at the origin of the absence of reaction of local actors.

Sixth, according to life cycle analyses of GWEs, collapse is associated with social conflicts and strife. In the case studies, however, latent conflicts were often identified, but were only publicized when collective action became possible through farmers' or conservation lobbies, for example in the case of Almeria or the Clain basin. In contrast, in the absence of lobbies, a process of silent exclusion and marginalization occurred and social conflicts remained invisible, as shown by Ameur et al. (2017) for the case of the Saiss.

The strategies actors use to deal with early signs of collapse

How do the different actors (the state, farmers' and conservation lobbies, intermediaries, and farmers) deal with early signs of collapse? The trajectory of GWEs in the different case studies were based on a kind of institutionalized compromise reached between the different protagonists, including at the state level and depend, as elsewhere, on the particular governance system in place (Theesfeld 2010). These actors have different roles and responsibilities in these GWE, but most are focused on removing obstacles in order to be able to continue using groundwater for intensive agriculture.

In the academic literature, studies dealing with the management of common pool resources and SESs often disregard or underplay the role of the state, since its role is limited to guaranteeing the rules of the game (Fofack et al. 2015). In the case studies, the state appeared not so much as a regulator, but more a facilitator and accelerator in the development of GWEs. The state operated through subsidies for agriculture and irrigation equipment and by searching for alternative water resources (dams, desalination, deep tube-wells or water transfers), for example in the case of Almeria under the influence of a strong farmers' lobby (López-Gunn et al. 2012) or in the case of the Saiss through more informal lobbies (Kuper et al. 2016). It encouraged and often financed the technologies used in GWEs, based on a view of progress embedded in public policies dealing with agriculture, energy and food production, in particular in the Saiss and Biskra. Access to land and water was facilitated by a set of laws enabling existing farmers without formal property rights over land or water to obtain them—legalizing existing boreholes for instance—and to new farmers arriving from elsewhere and using capital-intensive modes of production, to establish themselves in the local areas of production. One could talk of a "tolerant state" (Brochier-Puig 2004) that encouraged the development of GWEs for economic reasons, but without always taking the social and ecological consequences of these agricultural transformations into account. The various services of the state in charge of agriculture, economic development, and protection of water resources had different and sometimes divergent interests, but generally let the GWEs develop and head towards collapse to maintain social peace, especially in cases where farmers' lobbies were powerful political forces, for example in Almeria. In the Clain basin, the development of the agricultural GWE was slowed down by strong political pressure from civil society, which refused to accept an environmental collapse of the system, in particular the drying up of rivers. However, it can be argued that in that case, public authorities were also aiming for social peace, but in a different way due to the socio-political context with the presence of conservation lobbies.

Many intermediaries—in many ways an important secondary associated linked economy—are the providers of agricultural inputs such as crop seeds, fertilizers, pesticides; providers of pumps, drip irrigation, engines; drillers and other intermediaries providing a wide range of services; those handling the marketing of agricultural products—which also ensure and benefit from the engine room of the GWE that continues to run. These intermediaries developed, in what sometimes was a sophisticated process of "bricolage", a suite of engineering solutions suited to a wide range of problems, including the drop in water tables. Tube-wells, pumps, engines, drip irrigation equipment were continuously adapted to perform more efficiently, supporting a more intensive exploitation of resources thanks to technology. These actors keenly observed the development pathways of GWEs and their skills were actively sought by farmers for the specific task of dealing with some of the early signs of collapse, e.g. declining water tables or bottlenecks in the availability of production factors—for example, Lejars et al. (2017) showed the important role input providers played in the Saiss and in Biskra in providing credit to farmers. However, intermediaries also have a great sense of business, reacting rapidly to the trajectory of GWEs. In the Saiss, for example, tube-well drillers understood by 2012 that the demand for drilling new tube-wells was going down, due to saturation on some of the agricultural markets. Their strategy was then to develop new markets elsewhere. The intermediaries are, therefore, probably the actors that react the quickest of all to the early signs of collapse, either by finding solutions to emerging problems or by quitting.

Further, a wide range of farmers became involved in the GWE, from family farmers to new agricultural entrepreneurs. In the Saiss, some family farmers were attracted by the potential high economic returns of the GWE and shifted from a traditional mode of farming to intensive (but riskier) forms of agriculture. These transformations sometimes act as the "siren songs" of the GWE for family farmers, who may not be able to meet the challenge of this new world. Attracted by the (apparently) easy profits, family farmers sometimes sold their livestock to increase their capital to try their luck with high-risk investments, which in some cases, can be really profitable, but in most cases can end in bankruptcy. These farmers interpreted the early signs of collapse as a reason to quit the GWE. For other farmers, the way to adapt to this rapidly changing context was to stay informed and remain connected with strong knowledge networks (public authorities, universities, private firms, etc.). Collective action through farmers' lobbies thus appears to be one way to deal with the rigidities created by the development of GWEs and (sometimes) by the solutions proposed by public policies to overcome resource depletion. However, it is interesting to note that in the majority of cases studied here, there is no real voice (or only hushed tones) expressing social or ecological viewpoints, no conservation lobbies, at least in Biskra and the Saiss, and difficulties for water agencies and conservation lobbies to develop audible arguments in favor of the environment, in a context of strong agricultural lobbies.

Implications of the collapse: release and re-organization for a new SES?

Local actors generally consider GWEs as Eldorados, particularly in the early stages of their life cycle (Shah et al. 2003). The case studies reported here show that in the long run, and particularly around the moment of collapse, winners and losers can be distinguished. The winners are those who succeeded in appropriating the GWEs and can reconvert to other activities before collapse occurs. This will result in the re-organization of society if groundwater acts as an "enabler of important rural socio-economic transition" (Allan 2007).

The losers are those who obtained no access or, worse, who were attracted but subsequently excluded from the GWE, and may have lost part of their capital and work force (Mukherji and Shah 2005; Ameur et al. 2017). The impacts on the water resources are obvious: decline of water table, pollution, salinization, etc. All these impacts question the future use of these resources.

Along with the adaptive cycle, the (fear of) collapse of a GWE can lead to a search for alternative water resources (Almeria, Saiss, Clain basin) and possibly to release (Ω) and re-organization (α) phases. However, all the actors of the GWEs are not able to connect to these phases and new frontiers (in time and space) appear, defining new SESs-based artificial boundaries (in the case of a desalination plant, artificial recharge of aquifers or water basin transfers). Thus, in contrast to the dominant discourse on water demand management, management of collapse situations suggests a "supply" logic of mobilizing new water for the Ω phase, but the question is, who will be able to take part in the new SES? The case of the Clain basin, where demand management is attempted, shows that even in this case, additional water resources were mobilized by the state (small surface-water basins) in order to encourage farmers to decrease pressure on water resources.

Conclusions: preparing for collapse?

This paper shows how the social, economic and political organization of GWEs can lead to their demise. Beyond the four case studies examined in this paper, the large number of GWEs under threat in (semi-)arid areas should present a warning regarding their possible collapse.

The comparative analysis of the four case studies demonstrates the usefulness of the adaptive cycle as a metaphor enabling to question and discuss the dynamics of agricultural GWEs. The case studies show that the collapse of GWEs does not necessarily mean the end of the story. Collapse can happen and this situation is not always synonymous with a total disaster for the stakeholders and for the groundwater resources. This is the reason why it is important to prepare for collapse because it can have severe and irreversible consequences in some cases, but it can also mean new opportunities and changes.

From the analysis developed in this paper, two kinds of recommendations can be identified. First, from a theoretical and analytical point of view, the analysis of the trajectories of the different GWEs studied here suggests that it is necessary to go beyond the phases identified in the literature on the dynamics of GWEs to better understand the factors explaining the possible collapse of these SESs. It is also important to deepen the analysis of the possible outcomes of such situations of collapse, so as to identify the various strategies developed to overcome these situations. In this respect, this paper has mainly explored empirically the first two phases of the adaptive cycle, but more work is needed to better understand the variety of possible trajectories.

Second, from a political point of view and given the possibility of collapse of these GWEs for physical, economic or political reasons, various options and strategies can be considered by the actors. This paper illustrates these options using the metaphor of a spaceship, following the method mobilized in the adaptive cycle, often presented as a metaphor itself (Walker et al. 2004). The first option is to prepare for a soft landing, by activating the brakes before the collapse. Another option is a "touch and go" strategy. However, this strategy necessitates moving from the idea of a groundwater economy to one of a groundwater socio-ecology, taking into account the social and environmental impacts of the exploitation of groundwater resources. Resilience thinking may be a little optimistic about the possibility for "release" when it concerns groundwater. On the one hand, release may lead to changing the resource base as well as the actors involved. On the other hand, there is no single "pilot" in the spaceship and all the actors are busy dealing with different parts of a larger interconnected system. The resilience of SESs to collapse might be higher if the different actors understood the systemic nature of groundwater-dependent agricultural economies and acted accordingly, without generating irreversible effects. However, awareness of the resource and economic vulnerability of GWEs remains low in the political sphere, as it is among most GWE stakeholders, which rather suggests a continued pattern of "supply" logic, i.e. mobilizing new water resources. In many cases, farmers are fully aware of what is going on. They are just trapped in a situation and consider that only the political sphere has the capacity to release them from this trap. This indicates limited success in fine-tuning the groundwater socio-ecology to account for the social and environmental impacts of the exploitation of groundwater resources but nevertheless success in achieving an efficient groundwater use.

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