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Groundwater is not a Common-Pool resource: Ordering sustainability issues of groundwater use

Aurélien DUMONT*

*Universidad Complutense / Water observatory of the Botín Foundation, J.A. Novais
12, 28040 MADRID, Spain *adumontv@gmail.com*.

Abstract: This paper primarily deals with sustainability issues linked to groundwater use. First, it shows that the debate on the traditional indicator to assess overdraft situations – average abstractions higher than average recharge – fails to introduce many dimensions of sustainability. A dynamic description of the effects of pumping and the introduction of the concept of capture, defined as the sum of the reduction of aquifer discharge and increase of recharge, allow identifying and classifying the impacts of pumping by order of appearance: downstream and ecological impacts happen before stock impacts that reduce availability of groundwater for current and future users through higher pumping costs. As the definition of groundwater as a Common-pool resource (CPR) is based on the occurrence of stock impacts, it transcribes a particular characteristic of the resource that ignores its ecological and basin-wide functions. Thus, the validity and reproducibility of any recommendation from economic modeling or governance proposition (e.g. collective action) based only on stock impacts or groundwater as a CPR should be questioned.

Key words: capture; collective action; CPR; hydro-economic modeling

Introduction

Groundwater interaction with surface water bodies and dependent ecosystems are increasingly an issue of interest and it is now fully recognized as essential in the maintenance of ecological flows and aquatic ecosystems conservation (Sophocleous, 2007). However, these advances have still not been fully integrated in the debate on groundwater use sustainability or in the definition of groundwater over-exploitation

indicators. The view that available groundwater resources amounts to the mean recharge of an aquifer is still present not only among non-specialists but also within the sphere of hydro(geo)logy or social and economic studies of water. Adding to the technical uncertainties linked to the determination of this value, the operability of this criterion has been yet challenged by the consideration of the multiple issues linked to the application of the concept of sustainability to groundwater use (Alley and Leake, 2004; Devlin and Sophocleous, 2004). The multiple values and costs for society generated by groundwater abstraction means that assessing its sustainability is no longer only a technical issue, but should involve necessarily a complex socio-economic valuation (Custodio, 2002).

A first objective of this paper is to challenge the traditional definition of the availability of groundwater resources, through a detailed consideration of the successive impacts linked to groundwater pumping and reconsidering the role of groundwater within basin management and in relation to dependent surface water bodies and ecosystems. This will allow introducing the sometimes overlooked role of technical expertise within a decision-making process that imply a wide range of socio-economic issues. A second objective is to review some possible implications for the validity of conclusions and recommendations of some economic models or social sciences approaches regarding groundwater governance, particularly the definition of groundwater as a Common-pool resource (CPR).

THE TRADITIONAL INDICATOR: AVERAGE RECHARGE

The traditional approach to define aquifer overdraft is to consider the average aquifer recharge as the threshold for safe pumping (“safe yield”), as it would not jeopardize the aquifer stock in the long run. A first debate on the operability of such a criterion deals with the methods of calculation of the recharge, as the margin of error is usually quite high and the value varies under natural and exploited conditions, which can be the source of many mistaken views (Custodio, 2002). The period on which average abstractions should be balanced with average recharge is also an issue. Under arid or semi-arid climate, precipitations and recharge are subject to high inter-annual variability and period of returns of climatic episodes able to replenish groundwater stock can be large.

Moreover, introducing the mean recharge as the main indicator for a sustainable use of groundwater is commonly understood as a way to maintain the aquifer reserve for a continuous use in the future. Nevertheless, this objective can be considered as the result of a particular interpretation of sustainability (Custodio, 2002; Alley and Leake, 2004;) as a general framework would imply to compare the costs linked to the adverse impacts of groundwater abstraction to the value obtained by society from the use of this resource, e.g. in terms of public health or economic development, in an intertemporal valuation. However, basing the assessment on a balance operated by society to discard the use of mean recharge as an indicator of sustainability, while having the merit to reintroduce the debate on a more general framework, should not

ignore a series of issues that can be technically assessed to question the validity of the indicator based on mean recharge, as illustrated in the following section.

ORDERING THE IMPACTS OF GROUNDWATER PUMPING

Dynamic of groundwater associated to pumping

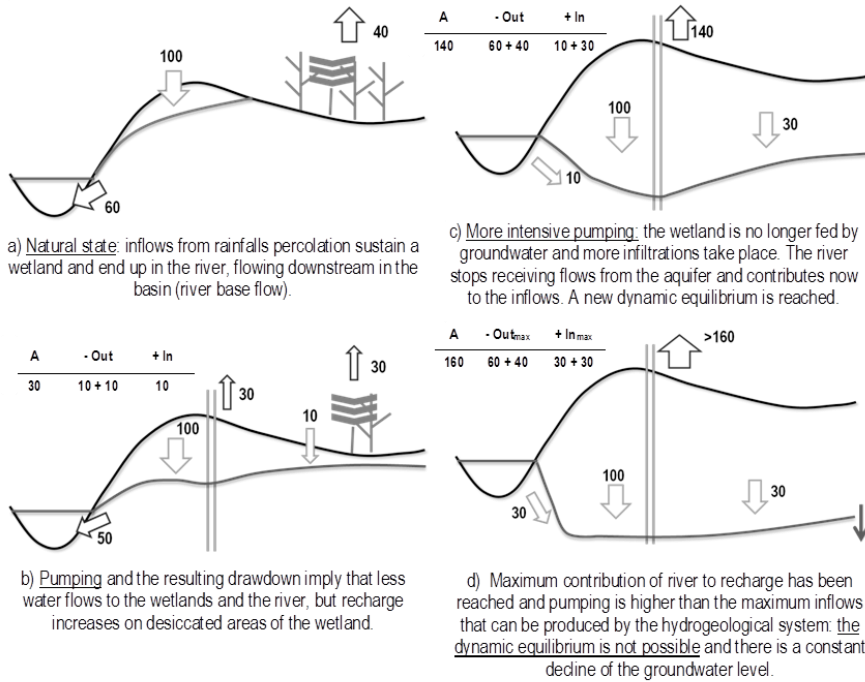
In order to assess the real ecological and downstream consequences of groundwater pumping, it appears necessary to have a dynamic approach of the implications of pumping. Figure 1 presents schematically a typical aquifer connected to a wetland and a river stream. In the natural state, water flows into the aquifer and finally discharges to the river and the wetland or feeds phreatophyte plants. Thus, the whole amount of the natural recharge constitutes a resource for downstream users and ecosystems.

The decline of the level associated to pumping reconfigures the conditions of the interaction between surface and groundwater flows. When pumping starts (the transient state in Figure 1) a fall of groundwater level takes place in the vicinity of the well. This perturbation will spread within the aquifer at a velocity depending on the aquifer's physical characteristics until reaching an area of natural discharge (e.g. spring, river, phreatophytes) where the outflow will decline. An increase of inflows towards the aquifer can also take place as a consequence of the drawdown where infiltration was previously prevented by a groundwater table reaching the land surface (rejected recharge) or when a gaining stream is converted to a losing stream. The sum of the decrease in outflows and increase in inflows is defined as the *capture* resulting from pumping (Theis, 1940; Bredehoeft *et al.*, 1982). Once a dynamic equilibrium, characterized by a stable groundwater level, is attained, groundwater abstractions equal capture (Figure 1). Depending of the situation, the new dynamic equilibrium can take many years or decades before being attained, resulting in a groundwater level decrease on a potentially large area. This is also the case when pumping exceeds the maximum capture that can be produced by the system.

Another point that is illustrated by this example is the actual consequence of the consumption of the water initially contained in the aquifer. This consumption is commonly presented as problematic since it implies that water that accumulated in the aquifer sometimes during many centuries is consumed and not conserved for future generations. However, the depletion of the stock will be compensated by future capture, as the aquifer replenishes when pumping stops, affecting surface water and ecosystems during many years. These impacts may be the main issue in a more or less near future and the time frame of this affection should be considered. In fact, these delayed effects, which are associated to the drop of the water table, take place for every groundwater pumping and are the symmetric effects of the delayed impacts in the transient state (Figure 1).

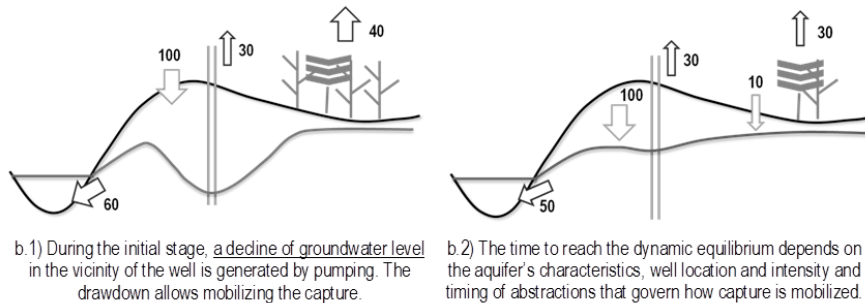
Thus, the characterization of capture – where, when, how long and how much outflows decrease and inflows increase – appears as the essential information in a sustainability assessment of the use of groundwater. The knowledge of natural initial

Dynamic equilibrium: abstractions (A) equal captures (diminution of outflows -Out + increase of inflows +In)

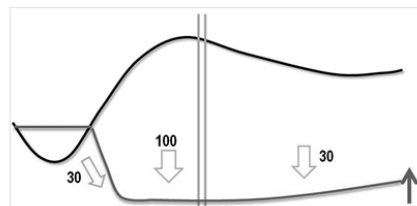


In every configuration (apart from case d), level stabilizes: level stability is not an indicator of the absence of detrimental impacts. It is also problematic to speak about recharge as a fixed constant: total inflows in the presence of pumping are higher than in the natural state in many situations.

Transient state: ecological and base flow impacts may be temporally not detected



Pumping stops: the replenishment of the aquifer implies a continuous impact on surface water



Once pumping stops, starting from every situation described above, the groundwater level rises to recover the initial state through capture of surface water. From a transient situation, this effect implies that stronger impacts on surface water can be noticed a long time after pumping stops.

Figure 1 Dynamic of groundwater pumping: capture and temporal effects.

recharge or dynamic recharge may help in this process in certain contexts but cannot be considered as a necessary step and can be misleading as a general approach.

A hierarchical ordering of sustainability issues

The adverse consequences of the intensive use of groundwater (e.g. higher pumping costs, ecological impacts, land subsidence) are presented many times indistinctively; however, the different impacts take place successively depending on the intensity of pumping (Figure 1). First, the mobilization of capture implies both the reduction of the flows to the river that will affect resource availability for users and the environment at the scale of the whole river basin (*downstream impact*) and ecosystems directly depending from groundwater discharge (*ecological impact*). Both impacts are likely to take place simultaneously. However, depending on the local setting, a preeminence of the downstream or ecological impact can be identified, as the following examples in Spain will illustrate.

The conservation of a certain amount of flows towards rivers and ecosystems implies a limited magnitude of water table drawdown. It is only when more intensive pumping is reached, with a higher capture of surface water flows, that a continuous drop of the groundwater level occurs and that other impacts commonly associated to overdraft and sustainability, such as higher pumping costs, start occurring. We will refer to these impacts as *stock impacts*. Downstream, ecological and stock impacts are successive and cumulative (Table 1).

Table 1 Successive and cumulative impacts associated to groundwater use.

Order	Impact	Scale / Who is concerned?	Technical information
1	Downstream impacts	All water users and stakeholders in the river basin	Availability of water resources at basin scale
1'	Ecological impacts	Aquifer and associated ecosystems users	Resilience of ecosystems to a drop in groundwater inflows
3	On connected aquifers	System of connected aquifers	<i>Particular case of "basin impacts".</i>
4	Marine intrusion	Aquifer users	Maximum pumping to prevent marine intrusion
5	Stock impacts	Aquifer users	Maximum inflows
All	Stock depletion / Future capture	"Society in general"	Time to recover the stock = Time with operant capture

All these impacts take place until the aquifer is replenished to its natural initial state.

A limitation to this classification would be the situation where a transient state lasts and a dynamic equilibrium is not reached: stock impacts would be important before capture is fully mobilized (downstream and ecological impacts). However, this consumption of the stock would be compensated by future capture of surface water flows (Figure 1) and this should be taken into account. Other types of impacts could

be identified, even if they correspond to more particular cases. For instance, underground flows are transmitted between aquifers and usually pumping this underground flow is likely to take place after downstream and ecological impacts. In the case of coastal aquifers, the continuous fall of groundwater level will lead to marine intrusion once the maximum capture of fresh water has been mobilized.

Technical data and scale of integration of the successive impacts

As described previously, the focus of hydrogeologists and society in general has been on stock impacts. They would be prevented by limiting abstractions to the mean recharge. Nevertheless, both downstream and ecological impacts need integration in a sustainability framework of the use of groundwater to assess their acceptability as compared to the value generated by groundwater use (see Pierce *et al.* (2013) for similar considerations). Specific data and indicators are needed (Table 1) and hence the implication of technical scientists. For instance, damages on dependent ecosystems or affection to river base flows according to different intensity of pumping is an essential information (Sophocleous, 2007). The impacts are not linear, and scientists will potentially determine a threshold (tipping point) from which ecosystems could be particularly affected. It is around these thresholds that sustainability issues are particularly relevant (Pierce *et al.*, 2013). The role of experts is to introduce this knowledge in the debate on sustainability.

Depending on the local setting, the upper order impacts may be considered non-relevant or some impacts do not take place. For instance, for a coastal aquifer that discharges entirely into the sea, there is no necessity to transmit flows to downstream users. In addition to representing various issues regarding sustainability, the successive and additive categories of impact imply different scales of management and stakeholders who should be involved in the sustainability assessment (Table 1). In a river basin where water resources are fully allocated, downstream impacts generated would not be accepted unless a reallocation of water from other users is concerted. When ecological issues are at stake, like for a groundwater-dependent wetland, the conservation of the wetland should be integrated into the aquifer planning objectives. On the contrary, when concerns are mainly relevant for aquifer users, the role of public authorities and other stakeholders could be reconsidered.

Three examples in Spain

La Loma Aquifer is located within the Guadalquivir river basin headwaters. This carbonate aquifer, mostly confined, presents an unconfined section connected with the Guadalimar river, a tributary of Guadalquivir river. Intensive groundwater pumping is a relatively new phenomenon in the area, as it is associated to the boom of olive groves irrigation from the middle 1990s, linked to favorable economic conditions for this crop. Groundwater is obtained through wells attaining a depth up to 700 m in the confined part of the aquifer. This groundwater has infiltrated into the aquifer up to 25,000 years ago and many users have the perception that they are “mining”

groundwater. However, intensive pumping fully remobilizes underground flows. In the case of a confined aquifer, a new equilibrium is attained rapidly and a decline of the groundwater level is observed on a large area. Thus, the Guadalimar river is now likely a losing stream or, at least, receives less outflows from the aquifer. The consequence of pumping is a depletion of surface resources for downstream users, which is problematic since the Guadalquivir basin is a closed basin, with no further available resources. The Guadalquivir basin Authority has recognized this situation and abstractions in this area are not formally registered. The new uses for olive irrigation should have been obtained from a reallocation of resources at basin scale.

Western Mancha Aquifer is located in central Spain, within the Upper Guadiana Basin (UGB), and covers an area of around 5,000 km². The semi-arid climate of the UGB presents a high seasonal and annual variability of precipitations that reach 415 mm/year on average. The entire Guadiana river basin presents two clearly contrasted domains. While the middle and lower stretches of the basin are characterized by the predominance of surface water use, regulated through big dams, the UGB is a plain marked by the constant interaction between a complex system of interconnected aquifers and the surface water bodies and wetlands. Natural outflows of this aquifer are principally sustaining the Tablas de Daimiel wetland, a National Park recognized by the UNESCO and Ramsar Convention, and the resurgence of the Guadiana river. However, this outflow has been affected by intensive groundwater pumping in the last forty years, leading to deep ecological impacts on the wetlands and drying out the resurgence of the river. Thus, the two first categories of impacts (downstream and ecological) are an issue for groundwater use within this aquifer. Nevertheless, as the river flows that are naturally transmitted from the Upper Guadiana to the middle and lower stretches of the basin represents a limited fraction of total basin resources, downstream impacts are of limited concern. The main issue appears to be the maintenance of groundwater flows towards the wetlands.

Thanks to the intense precipitations since the year 2010, the level of the aquifer has risen to the point that some resurgences of groundwater have been described. If sustainability issues were only tied to the maintenance of aquifer stocks, the excessive pumping of the last forty years could be considered as sustainable as this kind of climatic events could reconstitute the stock. However, the return periods of such events is overly high relatively to the conservation of the outflows to the wetlands and a detailed assessment of acceptable reductions in groundwater outflows is necessary.

Campo de Dalías Aquifer is a coastal aquifer located in the south-east of Spain (Andalusia region). It is famous for being the location of the highest concentration of greenhouses in the world (20,000 ha), dedicated to the production of fruits and vegetables during the winter season. The main aquifer is a carbonate aquifer, that is recharged from nearby mountains, the Sierra de Gádor, and the natural outflows of this aquifer are submarine springs and springs located at the foot of the mountain. Due to its location on the coast, downstream impacts are not occurring. Drawdown resulting from intensive pumping made an end to the spring at the mountain basis, and the majority of submarine springs. Even if these areas of discharge may have been

valuable from an ecological perspective or as local source of fresh water, this value has not been recognized by society and ecological impacts derived from groundwater pumping are not a current concern. The main issue is associated with marine intrusion and rising pumping costs.

Table 2 presents the relevant impacts for the management of these three cases.

Table 2 Impacts associated to groundwater use for the three cases in Spain.

Order	Impact	La Loma	Western Mancha	Campo de Dalías
1	Downstream impacts	✓		
1'	Ecological impacts	✓	✓	
3	On connected aquifers	?	✓	
4	Marine intrusion	Inland	Inland	✓
5	Stock impacts	✓	✓	✓
All	Stock depletion / Future capture	A few years once pumping stops (fractured carbonate aquifers well connected to areas of capture)		

IMPLICATIONS FOR MODELING AND GOVERNANCE

The vision of aquifers as stocks of groundwater, and the associated water budget myth (Bredehoeft *et al.*, 1982), and criterion to assess sustainability based on recharge is certainly the most usual approach because it appeals to our common sense. Hence, it is not surprising that this view is also majoritarially reproduced within the economic, social and policy approaches of groundwater management.

For instance, economic modeling of groundwater has essentially dealt with stock impacts (e.g. rising pumping costs, reduced availability, intertemporal allocation), with the objective to model the interactions of a same aquifer users to assess the conditions of optimal use of the resource or to consider other policy issues, such as the introduction of property rights or the role of public regulation, according to current and future objectives (Provencher and Burt, 1993). In this approach, the intrinsic nature of groundwater is linked to stock externalities. However, by disregarding downstream and ecological impacts, these models cannot pretend to represent the totality, or a general approach, of the range of issues associated to groundwater sustainable use. Introducing these impacts would change substantially the optimal conditions of groundwater use or the conclusions and recommendations of these models. A typical example is the so-called “Gisser-Sánchez effect” (Gisser and Sánchez, 1980), stating that there would be no benefit for public regulation as compared to free market conditions. Among the discussions around the numerous assumptions of the model, Esteban and Albiac (2011) showed that the conclusions are very different when introducing ecological impacts. Furthermore, a particular attention should be dedicated in the design of models of conjunctive use of surface and ground water. Many times, the latter is only considered as an additional more expensive source, that compensate surface water shortage and the impact of pumping

on river flows is poorly introduced.

Additionally, this is based on stock impacts, that groundwater is defined as a CPR. More precisely, a CPR is characterized by rivalry (in addition to non-excludability) and only direct aquifer users are traditionally identified as affected by this rivalrous character of groundwater use. Thus, in the same way that stock impacts do not characterize groundwater in general, this resource should not be qualified as a CPR *a priori* as it takes us to ignore downstream and ecological impacts. Even if the full implications of this remark cannot be analyzed in depth in this communication, it can be noticed that the CPR nature of groundwater constitutes the entry point for the proposition of collective action by the users of an aquifer, as a mode of governance (Ostrom, 1990). Yet aquifer users are not the only stakeholders concerned with of the upper order impacts (Table 1). In addition, “CPR problems” would be theoretically resolved if direct groundwater users integrate in their decision the impacts they are confronted to: stock impacts. However, the stabilization of groundwater table is not an objective *per se* (Figure 1). Furthermore, the successful experiences of collective action – another (more pragmatic) basis for its promotion – can also be questioned. The indicators of success should reflect all the impacts associated to groundwater pumping or it must be justified that upper order impacts are not relevant or not taking place. Thus, the reproduction of successful modes of governance should be promoted in similar contexts and success attested in specific situations should not serve as the basis to support collective action in relation to groundwater governance in general. Various examples from California presented by Ostrom (1990) as successful concern coastal aquifers or aquifers sustaining intermittent river streams, whose conservation may not have been recognized as an issue. On the other hand, the stabilization of level is the first condition to recover groundwater functions for river base flows and ecosystems (Table 1), and the aquifer users participation seems necessary. Anyway, institutions for the governance of groundwater should consider its integration within river basin as the rule, as proposed by Foster and Ait-Kadi (2012) and Ross and Martinez-Santos (2009), who reviewed also the real potentiality of the CPR approach.

Conclusions

In the same way that the topography of the land surface controls surface flows, the destiny of water that infiltrates into the ground is governed by the “topography” of the piezometric surface. Groundwater pumping affects this topography and reorganizes the flows in and out the subsoil. The introduction of the concept of capture, which focuses on identifying where, when, how long and how much these exchange flows are reorganized (even once pumping stops) is fully coherent with this view. Moreover, it allows ordering the successive impacts associated to groundwater pumping. Adding the dimension of sustainability implies considering additionally the acceptability of this mobilization of the capture (downstream and ecological impacts) and subsequent impacts (stock impacts, including future capture).

Thus, even if there is no consensus among hydrogeologists on whether an aquifer

could be managed on sustainability principles without introducing the value of recharge (Bredehoeft *et al.*, 1982; Devlin and Sophocleous, 2004), the approach based on capture has the virtue of making explicit the possible impacts of groundwater pumping in a dynamic and detailed view. Additionally, this approach would certainly benefit from the full integration of the knowledge on surface-groundwater interactions and groundwater-dependent ecosystems, that has largely improved in the last years.

Not considering any longer groundwater as a stock fed by recharge is not only a technical issue. The definition of groundwater as a CPR per nature characterizes the resource relatively to the presence of a stock and the consequence of its consumption on the aquifer users as an intrinsic attribute. Essential issues, namely downstream and ecological impacts, are overlooked then. Thus, policy and governance recommendations or conclusions from economic modeling, that consider only CPR problems or the reproduction of successful experiences in contexts that are fundamentally different should be questioned. Groundwater should be primarily apprehended through its integration within the river basin and as a fundamental source to sustain dependent ecosystems and ecological flows.

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