Groundwater Conjunctive Use

Andrés Sahuquillo

Abstract

The volume of water stored in aquifers varies from tens of times the annual recharge in small aquifers, to thousands of times in big ones, and additionally, the volume of aquifer storage provided by a relatively small fluctuation in the piezometric head in most unconfined aquifers exceeds considerably the available or economically feasible storage in dams. In many cases, aquifers used in conjunction with surficial components meet water needs, avoiding more expensive structures, less appropriate for the environment. Two conjunctive use methods exist: artificial recharge and alternate conjunctive use (ACU). Artificial recharge stores volumes of water that cannot be used directly. With ACU, more surface water is used during wet periods and more groundwater in dry ones. This allows the increase of water supply with lower dam storage and important socioeconomic and environmental advantages. Modelling of groundwater and surface water components jointly is needed in the most contentious or complex cases, particularly in systems of various dams, aquifers and conduits, with multiple alternatives for periods of several tens of years. Variability of the surface contributions aggravated by the uncertainties of climate change requires simulating more alternatives. The eigenvalue method simplifies modelling greatly. Aquifer heads can be explicitly calculated only at given points, the aquifer–river flow interaction in various river stretches, volumes stored in the aquifer or different areas of the aquifer and flow exchanges between several couples of two contiguous areas. But even in many developed countries, groundwater is not duly considered by decision makers and government officials, so the problems caused by intensive exploitation (overexploitation) or misuse of aquifers are exaggerated, thus down placing the important role of aquifers in favour of water works that are more expensive and less environmentally friendly. Consequently, this involves ethical considerations.

Keywords

Conjunctive use • Modelling • Eigenvalues • Ethical use

1 Introduction

Groundwater use has increased dramatically worldwide in recent decades, especially for irrigation and urban uses in arid and semiarid regions. A decisive reason for the increased exploitation of groundwater, in addition to its ubiquity, is that it is cheap, easy to exploit and with low variability in quality. Intensive pumping has produced in some areas significant decrease in aquifer levels, in the water volume stored in them, and in the base flow of the rivers, seawater intrusion, land subsidence and has affected wetlands intensely. The increase in water demand for urban, industrial and agricultural uses and the possible influence of climate change on the decrease in recharge of aquifers and river flows in some regions can aggravate socioeconomic, environmental and legal problems (Llamas and Custodio 2003; Sahuquillo et al. 2005). This is a concern that extends to the future availability of water resources. The main ethical and moral aspects of intensive use of groundwater, coastal aquifers use and reserve depletion refer to damage to current and future third persons, as well as the environment and the services it provides to humans. Aquifer overexploitation, which often is perceived as something ethically bad, is not necessarily detrimental if it is not permanent. Custodio (2002) provides a more adequate view of the problem and proposes replacing the denomination of overexploitation by that of intensive use. In this work, it is considered the integrated management of surface and underground water

A. Sahuquillo (✉)
Royal Academy of Sciences of Spain and Technical, University of Valencia, Valencia, Spain
e-mail: asahq@hma.upv.es

M. Abrunhosa et al. (eds.), *Advances in Geoethics and Groundwater Management: Theory and Practice for a Sustainable Development*, Advances in Science, Technology & Innovation,
https://doi.org/10.1007/978-3-030-59320-9_19

resources that affects the well-being of people and the environment in a decisive way.

In addition to their annual recharge, small aquifers store, a volume of water tens of times greater than their annual mean recharge above the level of the rivers, being thousands of times their recharge in large ones, increasing in little penetrating rivers and poorly connected with the aquifers. It is the so-called one-time reserve, in which volume stored below channels are not counted. Additionally, storage provided by relatively small fluctuations in piezometric heads in unconfined aquifers exceeds considerably the available or economically feasible storage in dams. Key aspects in conjunctive use systems are (a) the flow variability of river flows aggravated by climate change uncertainties and (b) the slowness of changes in the aquifer due to the big water volumes of water involved, which can only be known after years of observations and careful analysis of their behaviour provided by a well-planned monitoring network and detailed knowledge of the aquifer's exploitation. Monitoring that must be permanently maintained at an adequate level similar with that happens with the flows and quality of rivers and volumes in reservoirs.

It is necessary to keep in mind the relationship of aquifers with rivers, in which sections the rivers are winners, in which they are losers or the sections that being winners become losers due to the exploitation of the aquifers.

2 Conjunctive Use of Groundwater and Surface Water

2.1 Alternate Conjunctive Use and Artificial Recharge

The more direct solution to solve some of the problems raised by aquifer intensive development and to increase the availability of water is in many cases the conjunctive use of surface and groundwater (Foster and Steenbergen 2011; Sahuquillo 2002, 2010). The more intuitive action is through artificial recharge of the aquifer. It has been used in many parts of the world to store local or imported water in aquifers. The second is alternate conjunctive use (ACU). With ACU, groundwater pumping is reduced in wet periods and the surface water use increases. On the contrary, during periods of reduced surface water availability, groundwater pumping increases. Groundwater storage increases in wet periods, decreasing in dry ones. In many cases, aquifers have being pumped well above their recharge in Israel in a planned way, to defer building of the National Water Carrier. In California, south-eastern Spain and in many other places, the large water volume in aquifers has allowed, through unplanned overexploitation, the development of primary economic activities, which have been the origin of a further economic growth (Sahuquillo 1985, 2002, 2010; Custodio et al. 2017). Aquifer water content and storage allows both the use of water during dry seasons or droughts and the use of the subsurface space (van der Gun and Custodio 2018) for storing imported water. In fact, groundwater use has traditionally been augmented worldwide to back up supply in times of shortage or drought. In most of the Mediterranean river basins in Spain, vulnerability to droughts is reduced by the increased exploitation of aquifers, as it is also done in many other countries. This involves a certain type of conjunctive use. To meet the water demands in droughts, the water agencies of the Júcar and Segura basins, in Spain, built batteries of large capacity wells. A relatively small sporadic pumping of groundwater from aquifers, instead of the construction of a new reservoir, can be used to increase the resources of many low guarantee irrigation systems. The same can be done, with obvious economic and environmental advantages, to alleviate possible declines in river flows due to climate change in areas prone to become dry. In California, ACU was suggested in the San Joaquin River Basin as early as in the 1930s. Later, in the California Water Plan in the late 1950s, it was projected to apply ACU massively by storing local and imported surface water, adding new reservoirs to the existing ones with a total storage to 24 km^3, and a foreseen subsurface storage of 37 km^3. The idea was later replaced by artificial recharge and was forgotten, but somehow re-emerged later in what has been called "in lieu recharge", using sporadic surface water runoff instead of pumping from aquifers. Artificial recharge and ACU use are fully compatible (Jaquette 1981). A local example of ACU is the Mijares River Basin, in eastern Spain. Two of the three existing dams were built in karstified limestone and have important leaks that recharge the Plana de Castellon aquifer. The river also recharges the aquifer. About one-third of the local irrigated surface area is supplied from surface water, another third and the urban water with the aquifer, and the other third alternately depending on the river flow and the water stored in the reservoirs. Storage achieved by applying the ACU concept would be the groundwater volume stored at the end of a wet cycle less the volume at the end of a dry one, over 700 hm^3 of the Plana de Castellón aquifer. This is more than four times the existing surface storage. This makes it possible to use a very high percentage of the annual average river flow. It is important to note that the operating rules of the system were proposed by the farmers' association and legally approved in 1973. Throughout other Spanish Mediterranean basins, it is usual to increase groundwater pumping in dry years (Sahuquillo 2002, 2003, 2017). Adequate operation rules of an ACU scheme with storage in dams and aquifers is important to improve results but is much more complex than in the case of systems with only surface reservoirs. The decrease in the river flow due to groundwater pumping is slow, especially in large aquifers, and is not perceived immediately by users. In some sections of the river, years or decades after intense pumping, there are changes from a gaining river to become a losing one and can even contribute to recharge the aquifers. The use of the UCA has the potential to solve current or future scarcity problems and those that may pose climate change, in many cases without the need to build new reservoirs. But those are solutions that need an important knowledge of groundwater. Something that is not usual on the agenda of decision makers because aquifers cannot be opened, at less at the usual time frame politicians usually remain in the government.

2.2 Relief of Drainage and Salinization Problems in Irrigation Areas in Arid and Semiarid Zones

Aquifer recharge has increased because of water losses from unlined distribution canals, in addition to the infiltration of return irrigation water. Increments in aquifer recharge augment the potential for groundwater development, and in some zones, they also create drainage and salinity problems by rising groundwater levels. This is a customary problem of large irrigation projects in arid and semiarid lands. Increased and more efficient use of groundwater can help to prevent these problems.

A classic example is the irrigation in the Indus River Basin (Sahuquillo 1985, 2002, Custodio 2010), which started to be intensively implemented in the late nineteenth century under British colonial rule. The irrigation canals are fed by several big dams. The largest ones are the Mangla Dam and Tarbela Dam, with 5.5 and 10.6 km^3 of storage, respectively. Most canals are unlined, having significant losses that feed the huge aquifer below. During the last 80–100 years, water levels in this aquifer rose between 20 and 30 m, and up to 60 m in some places. In the middle of the last century, 25,000 ha were abandoned every year. In 1960, 2 million hectares of a total 14 were abandoned. A Salinity Control and Reclamation Project was initiated by the Pakistani government to drill high capacity wells to lower the water levels and pump the saline groundwater water out of the aquifer, to be disposed downstream. Irrigators began a very intense exploitation of the aquifer, producing an important water table drawdown, which prompted the government to paralyse the project. The problems of drainage decreased in upstream areas, but drainage and salinization problems persisted in the area and downstream.

Similar drainage and salinity problems exist in most arid countries, jointly with subsidence problems. Losses in canals and distribution systems can be alleviated by lining the conductions. However, if infiltrated water feeds usable aquifers and conjunctive use is practiced, it could be more convenient to leave canals unlined, unless drainage problems persist, and water losses produce excessively high aquifer levels. Conjunctive use can contribute to improve water use efficiency and regional environment of irrigated areas.

Foster et al. (2010) comment some impediments to promote a more rational conjunctive use in areas commanded by irrigation canals. These impediments are the socio-political dominance of farmers in areas excessively endowed with surface water. They refuse to reduce canal intakes. Water resource and irrigation engineers have an inadequate understanding of conjunctive use and the potential role of groundwater. The responsibility for surface water and groundwater development and/or management is split, with organizations and agencies that tend to 'mirror' historical irrigation water supply realities and perpetuate the status quo.

3 Analysis of Conjunctive Use Systems

3.1 General Issues

Water storage provided by conjunctive use allows: increasing water availability without augmenting surface reservoirs, inclusion of aquifer as an additional water source, advantages in aquifer storage and distribution, increasing water supply guarantee, drought mitigation, decrease of aquifer exploitation and in some arid areas the reduction of drainage problems caused by irrigation return flows. Alternatives of conjunctive use for the development of water resources or the expansion of existing ones should be considered instead, or in addition, to the construction of new dams.

The possibility of storage in aquifers is significantly higher than that in existing or possible dams. Lund et al. (2014) give an economically viable capacity in California of about 180 km^3 for storage in aquifers, compared to about 50 km^3 in surface reservoirs. The ground and surface storage used in the relatively small Mijares Basin amounts respectively to 0.7 and 0.15 km^3. The ability to utilize additional water storage in California varies greatly with its location, the availability of water conveyance capacity and the operation of the system to integrate groundwater, surface water and conveyance facilities,= and brings out ACU, emphasising that many conjunctive use efforts rely on in lieu recharge. The lack of conveyance capacity to bring stored water to or from reservoirs or aquifers, water rights, contract constraints and regulatory limitations limits the effective use of available storage space.

3.2 Models as Water Planning and Decision-Making Tools

Models have become essential tools for analysing complex systems to adequately evaluate their performance. The analysis of conjunctive use must include the physical components, the flow interchanges between groundwater and surface water, the supply facilities for different in-stream and off-stream uses and the operating rules that are crucial for the different alternatives. The same set of structural facilities can produce very different yields, depending on the operation of the system. In the case that the variability of river flows increase in the coming decades, in addition to flow decrease in some basins, could cause more intense floods and droughts. The latter has two important consequences: (1) it will be necessary to have a greater water storage capacity, where conjunctive use would be useful, and (2) it will be crucial to perform much more simulations of the behaviour of each system, with different operating rules, for dry and wet time series and large periods, as well as for more intense droughts.

The California Department of Water Resources (CDWR) has been developing models for the management of the California Water Plan. The lack of a groundwater component was noted as a major deficiency in the first CALSIM (California simulation model) Peer Review, and in the 2009 upgrading of the California Water Plan (CWP), it was considered that models were not sufficient to model the impact of pumping on surface flows. Only in 2013 was finished the complex surface and groundwater flow model of the Central Valley of California, with a surface area of 51,000 km^2, 35,000 nodes and 35 stream reach where exchange of aquifer–river flow were determined.

3.3 The Eigenvalue Solution

In classical groundwater models, the algebraic linear system of equations obtained using finite differences (FD) or finite elements (FE) are solved in sequential time steps, providing water heads in all cells of the aquifer. The simultaneous simulation of the surface and underground systems is cumbersome if many alternatives of a few decades have to be analysed, considering adequately the aquifer–river relationships. To calculate the flow exchanges between the river and the aquifer in a period of time, it is necessary to calculate them from the aquifer heads in the period that are being calculated. The eigenvalue method solves explicitly the linear partial difference (PD) flow equation, considers constant in time transmissivity, storativity and boundary conditions and computes directly and very easily the heads, flows and volumes required. It uses the same parameters of a calibrated model in FD or FE. The eigenvalues method discretizes the space in N nodes or cells, like in usual FD or FE models, but not discretizes time. It solves the flow equation explicitly and continuously in time, obtaining N ***modal orthogonal components***. Each ***mode*** has an eigenvalue α_i, always positive, and their corresponding eigenvector $a_{i,1}$, $a_{i,2}$, $a_{i,3}$, … $a_{i,N-2}$, $a_{i,N-1}$, $\alpha_{i,N}$. The eigenvalue computation has to be performed only once, and for any recharge or pumping, the solution is explicitly given by a vector $\bar{\mathrm{L}}_{(t)}$ of the intensity of the ***modes***, crucial in case of many alternatives and long simulation periods. It is an exact solution of the problem but given on a different orthogonal basis than that of the heads in the aquifer cells. If the storage vector of the aquifer model is SF_1, SF_2, SF_3, … SF_N) orthogonality is expressed by

$$\sum_{k=1}^{k=N} a_{i,k} a_{j,k} \mathrm{SF}_k = \delta_{i,j};\, 1 \text{ if } j = k, \quad \text{and } 0 \text{ if } i \neq j \qquad (1)$$

The orthogonal base in the classic solutions of FD or FE is (1,0,0 …0.0,0,0), (0,1,0,0, …0,0),…. (0,0,0, … 0,0,1). As in other physic problems, the solution could be given with enough accuracy considering a limited number of eigenvectors. What is an additional important help to simplify the solution. The calculations to determine in each time interval, the J levels, flows and volumes, would be those of the product of a $J \times E$ matrix, E being the number of modes considered. that in most cases is an important improvement.

There are a small number of dominant modes, and the others are much less important. With a much-reduced number of components, the results are almost identical to the FD or FE solution, especially when calculating the aquifer–river flow. From the previous situation $\bar{\mathrm{L}}_{(t)}$ and pumping or recharge in the period, a new $\bar{\mathrm{L}}_{(t+\Delta t)}$ vector is obtained explicitly by a very simple state equation. Moreover, not all N heads values at each time period are needed. What is needed are the heads in a few points, the flow between aquifer and river at given stretches, the ground water volume stored in the aquifer or in different areas of it and the flows between some adjacent zones. For each mode, the components of those heads, flows and volumes are linear combinations of the piezometric heads and can be calculated directly (Sahuquillo 1983, 2013; Andreu and Sahuquillo 1987; Sahuquillo et al. 2010; Alvarez-Villa 2014).

In the management problems, it is convenient to define the external actions on the aquifer with a limited number of elementary unit actions J, (top left of Fig. 1). The component li of the vector $\overline{L}$ of each elementary action of intensity P_j is distributed among all modes by the pre-calculated coefficients $b_{i,j}$, whose sum is unity (bottom left of the Fig. 1). The component of the recharges of each node would be:

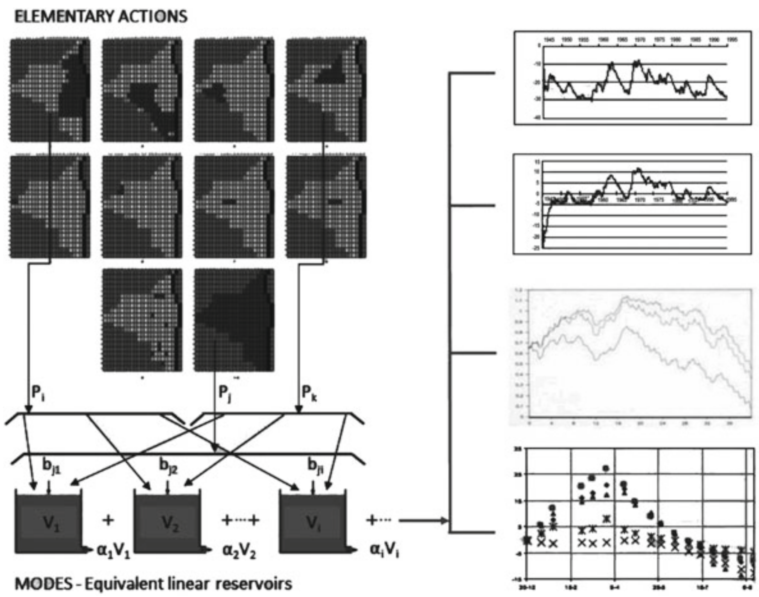

Fig. 1 Simulation of elementary actions, modes, heads, flows and volumes

$$R_i(t) = \sum_j b_{i,j} P_j \quad (2)$$

It would behave as a single-cell deposit with a volume $V_i(t)$ at time $t + 1$ would become

$$V_i(t+1) = V_i(t)\mathrm{e}^{-\alpha_i \Delta t} + R_i(t)\Delta t \quad (3)$$

Vector $\overline{V(t)}$ or their corresponding $\overline{L(t)}$ easily provides the heads, flows and volumes for each mode, as commented above and shows the right column of the Fig. 1. In each time interval, the calculations to determine, the J levels, flows and volumes of the aquifer would be those of the product of a $J \times E$ matrix, E being the number of modes considered. This is an important improvement in most cases.

For simple geometries, there are analytical solutions, which can be used when the knowledge of the aquifer is limited (Sahuquillo and Andreu 1986; Sahuquillo et al. 2010). Until now, the eigenvalues method has been applied only in some aquifers, due to the limited knowledge of the relationship of many aquifers with surface water in most of our aquifers. It seems obvious that its greatest advantage is in applying it to complex systems of conjunctive use with multiple components.

4 Related Ethical Issues and Final Remarks

The conjunctive use of surface and groundwater is mostly an improved aquifer management engineering method which is preferably oriented towards water quantity, although groundwater salinity and contamination problems can and should be addressed as well. This implies the technical, legal and administrative capacity to implement actions that do not disturb other rights and preserves the environmental values and services that are socially advisable under the point of view dominating at a given moment.

Groundwater is a neglected and generally misused resource. It can solve and is solving innumerable water demands for irrigation and industrial problems, an essential component in the environment, an integral part of the hydrological cycle and a component of water resource systems. Groundwater pumping produces a reduction in the flow of rivers or springs and other negative externalities, such as subsidence of the land or deterioration of wetlands and aquatic habitats. In addition to renewable water resources on an annual scale, it has reserves of tens or thousands of times its annual resources in large aquifers. To the resources and reserves available in the aquifers, it has to be added their capacity to store local or imported water through artificial recharge or ACU. It is a moral and ethical obligation to know, use and protect them, estimating in each case the results of their use and limiting the degradation of groundwater quality as much as possible by avoiding contamination. When using aquifers, the relationship between surface and groundwater should be considered. A quantitative analysis must be carried out, which can be done using simple tools when the recharge of the aquifer used exceeds demand widely. But in cases where the use of aquifers is important, advanced management models must be used. In any case, quantitative assessments should be accompanied by estimating the possible uncertainty. The possibility of increasing available resources or increasing the guarantee of supply with small sporadic pumping was discussed above. In cases of important use, temporary information on aquifer pumping and water quality is required and an adequate piezometric network should be established, as well gauging stations to determine river–aquifer flow exchanges. It is advisable to have annual records of surface water diversions and aquifer pumping. Data must be of permanent open access, and periodically published and updated. An independent, stable and economically supported structure is required, which allows maintenance, data collection, process and regular publication.

Unfortunately, in most countries, conjunctive use schemes that could provide obvious economic and social advantages have not been planned and water agencies lack the human and material resources to management and knowledge of the systems. In addition, the lack of employees with hydrogeological training in water agencies is notoriously insufficient and the institutional concern about the protection of groundwater against pollution is small.

Acknowledgements The author acknowledges the comments, revisions and important contributions to the manuscript of Professor E. Custodio.

References

Alvarez-Villa OD (2014) Efficient simulation of the river-aquifer relations in conjunctive use systems applying reduction techniques on linear time invariant models. Technical University of Valencia, Spain, PhD Thesis (in Spanish)

Andreu J, Sahuquillo A (1987) Efficient aquifer simulation in complex systems. J Water Resourc Plann Manag Div 113(1):110–129

California Water Plan Update (2009) Department of Water resources. State of California

Custodio E (2010) Intensive groundwater development: a water cycle transformation, a social revolution, a management challenge. In: Martínez–Cortina L, Garrido A, López–Gunn E (eds) Rethinking water and food security. Fundación Botín and CRC Press, pp 259–298

Custodio E, Albiac J, Cermerón M, Hernández M, Llamas MR, Sahuquillo A (2017) Groundwater mining: benefits, problems and consequences in Spain. Sustain Water Resour Manag 3:213–226

Foster S, van Steenbergen F, Zuleta J, Garduño H (2010) Conjunctive use of groundwater and surface water from spontaneous coping strategy to adaptive resource management. World Bank, Washington

Foster S, van Steenbergen F (2011) Conjunctive groundwater use: a 'lost opportunity' for water management in the developing world? Hydrogeol J 19:959–962

Jaquette DJ (1981) Efficient water use in California: conjunctive management of ground and surface reservoirs. In: Beard LR (ed) Water for survival. J Hydrol 51:187–204

Lund J, Munévar A, Taghavi A, Hall M, Saracino A (2014) Integrating storage in California's changing water system. U.C. Davis California. S.D. Bechtel, Jr. Foundation https://watershed.ucdavis.edu/library

Llamas MR, Custodio E (2003) Intensive use of groundwater. Challenges and opportunities. Balkema

Sahuquillo A (1983) An eigenvalue numerical technique for solving unsteady groundwater models continuously in time. Water Resour Res 12:87–93

Sahuquillo A (1985) Groundwater in water resources planning: conjunctive use. Water Int 10(2):57–64

Sahuquillo A, Andreu J (1986) Quantitative analysis of the interaction between ground and surface water by the eigenvalues method. In: Water C (ed) Gorelick SM. IAHS Press, Use, pp 51–60

Sahuquillo A (2002) Conjunctive use of surface water and groundwater. In: Silveira L (eds) UNESCO Encyclopaedia of Life-Support Systems. EOLSS, Cambridge

Sahuquillo A, Capilla J, Martinez Cortina L, Sanchez-Vila X (eds) (2005) Groundwater intensive use. International Association of Hydrogeologist Selected Papers, Balkema

Sahuquillo A, Cassiraga E, Solera A, Murillo JM (2010) Modelos de uso conjunto de aguas superficiales y subterráneas. Instituto Geológico y Minero de España y Universidad Politécnica de Valencia, pp 1–328

Sahuquillo A (2013) Potential and merits of the eigenvalue method to simulate the conjunctive use of groundwater and surface water. Br J Environ Clim Change 3(3):480–498

Sahuquillo A (2017) Water storage and conjunctive water use. In: Ziolkowska JR, Peterson JM (eds) Experiences and management approaches in the USA and Europe Elsevier, pp 382–402

van der Gun J, Custodio E (2018) Governing extractable subsurface resources and subsurface space. In: Villholth K-G, López-Gunn E, Conti K, Garrido A, van der Gunn J (eds) Advances in groundwater governance. CRC Press, pp 389–409