water

MDPI

Article

Management Alternatives of Aquifer Storage, Distribution, and Simulation in Conjunctive Use

Andrés Sahuquillo [1,2,3], Eduardo Cassiraga [1,*], J. Jaime Gómez-Hernández [1], Joaquín Andreu [1], Manuel Pulido-Velazquez [1], David Pulido-Velazquez [4], Oscar D. Álvarez-Villa [5] and Teodoro Estrela [6]

[1] Institute of Water Engineering and Environment (IIAMA), Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain; asahuq@hma.upv.es (A.S.); jgomez@upv.es (J.J.G.-H.); ximoand@upv.es (J.A.); mapuve@hma.upv.es (M.P.-V.)
[2] Real Academia de Ciencias Exactas, Físicas y Naturales de España, C. de Valverde, 24, 28004 Madrid, Spain
[3] Real Academia de Cultura Valenciana, C. de las Avellanas, 26, 46003 Valencia, Spain
[4] Instituto Geológico y Minero de España-CSIC, C. Alcázar Genil, 0, 18001 Granada, Spain; d.pulido@igme.es
[5] Department Civil & Environmental Engineering, Vanderbilt University, Nashville, TN 37235, USA; oscar.alvarez.villa@vanderbilt.edu
[6] Secretaría de Estado de Medio Ambiente, Ministerio para la Transición Ecológica y el Reto Demográfico, Plaza de San Juan de la Cruz, 28003 Madrid, Spain; testrela@miteco.es
* Correspondence: efc@dihma.upv.es

Citation: Sahuquillo, A.; Cassiraga, E.; Gómez-Hernández, J.J.; Andreu, J.; Pulido-Velazquez, M.; Pulido-Velazquez, D.; Álvarez-Villa, O.D.; Estrela, T. Management Alternatives of Aquifer Storage, Distribution, and Simulation in Conjunctive Use. *Water* **2022**, *14*, 2332. https://doi.org/10.3390/w14152332

Academic Editors: Frédéric Huneau, Dimitrios E. Alexakis and Pankaj Kumar

Received: 4 July 2022
Accepted: 23 July 2022
Published: 28 July 2022

Abstract: Aquifers are ubiquitous, and their water is easy to obtain with low extraction costs. On many occasions, these characteristics lead to overexploitation due to important water level declines, reduction of river base flows, enhanced seawater intrusion, and wetland affection. The forecasted increase in water demands and global warming will impact the future availability of water resources. Conjunctive use of surface and subsurface waters can help in mitigating these impacts. There are two main conjunctive use strategies: artificial recharge (AR) and alternate conjunctive use (ACU). AR stores waters that are not to be used directly in aquifers. ACU utilizes groundwater in dry periods, while surface waters are preferred in wet ones; this allows the increase of water supply with lower dam storage, economic gains, and environmental advantages. Efficient conjunctive use can prevent soil salinization and waterlogging problems in semiarid countries due to excessive recharge from irrigation return flows or other origins. Groundwater is a neglected and generally misused resource to maintain environmental conditions. When considering the solution to a water resources problem, groundwater should always be part of the design as an alternative or a complementary resource. Aquifers have large inertia, and changes in their volumes are only noticeable after years of observations. Unfortunately, groundwater observation networks are much poorer than surface ones, something that should be changed if groundwater is to come to the rescue in these times of climate change. Human and material resources should be made available to monitor, control, analyze, and forecast groundwater.

Keywords: groundwater; hydrogeology; alternate conjunctive use

1. Introduction

Groundwater use has increased significantly in recent decades because it is cheap and easy to extract and exhibits low variability in quality and flow. However, in some areas, its intense use has produced undesirable depletions, resulting in decreased stored volumes in aquifers and base flow discharging to connected rivers. Groundwater intensive use could also cause seawater intrusion and land subsidence and affect wetlands and ecosystems. Infiltration from excess surface water irrigation and losses in unlined canals has augmented aquifer recharge. It has produced severe problems with drainage and salinization of water and soils in some areas. In general, due to climate change, groundwater intensive use, along with the expected reduction of aquifer recharge and river discharge, can aggravate future hydrological, socioeconomic, environmental, and legal conflicts. In this regard, conjunctive use of surface and subsurface water could increase water availability and be the best economic and environmental solution to solve some of the problems raised by aquifer intensive development [1–3]. Conjunctive use suitability for sustainable water management is not restricted to arid or water-scarce areas. On the contrary, when accounting for the connection between surface and subsurface waters and their mutual interactions, conjunctive use is also advisable in wet and nonstressed areas [4].

The water demands for different uses (urban, irrigation, industrial, and environmental) generally do not coincide in time or location with resource availability from rivers and aquifers. Water must be stored and transported to meet the needs of agriculture, municipal and industrial users, and the environment. Dams are the natural storage for surface water and aquifers for groundwater. Rivers, canals, and aqueducts route surface water from their storage to the point of use, whereas the aquifer is its own distribution system. Both systems are fully connected. Aquifers receive infiltration and return flows from surface water; rivers receive their base flow from the aquifers they are connected to. This interconnection and complementarity will be explored in this paper, emphasizing the critical role that groundwater could play. One should not forget that the total amount of water stored in an aquifer may be tens to thousands of times their average annual recharge and that aquifer response to external stresses is slow—when compared with surface water systems—providing long-term reliability in water supply.

This paper is not intended to be a review paper; rather, it is intended to describe the roles played by the different components of a water resource system and their relationships and discuss alternatives and opportunities to improve water resource management by incorporating aquifers into the solution. It is concluded in this paper that integrated management of large water resource systems requires reliable and abundant data, which can only be obtained from appropriate observation networks and the necessary material and human resources to maintain them. In the final section, there is a call for the ethical responsibility that water resources managers have. Managers must account for the important role aquifers can play in addressing many of the problems that global change will bring and the need to preserve aquifers of good quality for future generations.

2. Surface Waters and Aquifers: Contrasting Behaviors

Under natural conditions, surface and subsurface water hydrological behaviors are different, and so are the information available and the techniques used to analyze them. Flow fluctuations are faster and much more significant in surface water than groundwater. Short- and medium-term streamflow forecasts are generally uncertain, as are the long-term predictions trying to account for climate change. In addition, streamflow is naturally erratic, and its behavior can only be modeled in a probabilistic framework. Conversely, groundwater is more deterministic due to its inherent inertia to change. In aquifers, the volume-to-flow ratio is high, and water residence times can be large, of years or longer. Still, in surface water, this ratio is small, and water residence times are from days to weeks, exceptionally months for large basins [5].

Deferring the decisions and costs of expensive hydraulic constructions by exploiting aquifers more intensively or even above their recharge rate for some years is reasonable. In Israel, the large volumes of groundwater stored in the subsurface coastal and carbonate aquifers were exploited above their recharge to defer the costlier National Water Carrier construction. In other cases, aquifers have allowed, through an unplanned overdraft, the development of primary economic activities, which have been the origin of further economic growth, as was the case in California, southeastern Spain, and other countries. Likewise, groundwater can help mitigate droughts' effects and alleviate drainage problems. Another advantage of incorporating groundwater in global resources management is that it compensates for the uncertainty inherent to surface flow, hydrological parameters, or water demand. In many basins, the influence of global warming on the water stored in snow and glaciers is already producing increasing rates of melting, which will significantly modify the intra-annual distribution of streamflows in the upcoming decades. Climate-change-induced modifications of the hydrological cycle will significantly affect the currently established criteria for water resources management shortly.

In a scenario of greater hydrological variability, conjunctive use becomes more relevant for sustainable management. For instance, the availability of large volumes of water stored in aquifers makes it possible to alternate periods of zero and intense groundwater exploitation, depending on the hydrological conditions. In any case, a long-term groundwater monitoring strategy must be implemented in all aquifers, similarly to the one done with levels, discharges, and quality in rivers and with storage in surface water reservoirs. It is necessary to consider river–aquifer interactions to determine which river sections are (or will be) gaining or losing due to intensive groundwater use. Monitoring variations in recharge due to irrigation return flow is also necessary. The most comprehensive argument for considering aquifers in water management is that, if incorporated into a water resource system, the number of management alternatives is increased. Therefore, the system flexibility increases with a larger number of optimal configurations. It is often possible to achieve alternative optimal operation rules of the system considering the same components and water contributions.

3. Aquifer Storage in Conjunctive Use

Two main possibilities exist for using the storage provided by aquifers: artificial recharge (AR) and alternate conjunctive use (ACU). The most intuitive one is AR, which works by recharging surface water in aquifers during wet seasons, when excess runoff is available, and then using groundwater at an appropriate later time. In contrast, in ACU, there is a plan of when to extract groundwater (mainly during the dry seasons) and when to use surface water (mainly in the wet seasons or when streamflow is above average). The main advantage of ACU is that it allows for balancing water use from the system's different components, water stored in reservoirs and aquifers, accounting for surface flow forecasts and immediate water demands. For this purpose, groundwater storage is computed as the difference between the extreme values of aquifer water volumes, these being high at the end of wet periods and low at the end of dry ones.

A frequent misconception among hydrologists and water planners is to identify conjunctive use mainly with AR practices. In several cases, ACU is much cheaper and easier to implement than AR, particularly in developing countries, because it requires the construction of smaller and simpler infrastructures. Moreover, in addition to being more expensive and complex in operation, AR needs a clear identification of payers and beneficiaries, and system owners need to be reassured that others will not pump the recharged water. Additionally, it needs more complex technical and institutional development, rare conditions in developing countries.

3.1. Artificial Recharge at the End of Large Aqueducts

Some of the older AR cases arose from the need to store the excess water carried to the end of aqueducts. In 1913, the Los Angeles Aqueduct, connecting Owens Valley (at the East of Sierra Nevada) and San Fernando Valley, was built to supply water for direct consumption by the city of Los Angeles, California. The excess water of the aqueduct was recharged in the San Fernando Valley. Groundwater pumping for irrigation in Santa Clara Valley, south of San Francisco Bay, now known as Silicon Valley, caused seawater intrusion and a significant drop in water levels in the aquifer that caused subsidence in the city of San Jose from 0.9 m in 1931 up to 4 m a few years later. The problem was halted during the 1950s by implementing AR of local and imported water through the Hetch Hetchy aqueduct [6]. In 1948, the Orange County Water District (OCWD) imported water from the Colorado River for AR to remediate groundwater level decline and seawater intrusion in Southern California. In 1971, the OCWD implemented two seawater control intrusion barriers using imported potable water and treated reclaimed water [7]. In Israel, the imported water from Kinneret Lake, 220 m below the Mediterranean sea level, is recharged in the coastal carbonate aquifers to be distributed for irrigation and water supply through the National Water Carrier. In the Netherlands, coastal dunes are recharged with water from the Meuse and Rhine; since 1940, around 100 million m^3/year of water have been recharged for urban use for Amsterdam, Leiden, and The Hague.

Large aqueducts, such as those developed in India's ambitious river-linking program, were planned considering only surface water supplies, neglecting the potential of groundwater. However, during the construction of the Krishna-Pennar canal, a reanalysis was made, taking into account past experiences of conjunctive use in the region that resulted in savings of more than 400 million m^3 of surface water that could be used in other areas having supply problems [8].

Europe has a long tradition of performing AR in alluvial aquifers to treat heavily polluted water from rivers. This process's primary function is water treatment, not storage per se. However, the storage function of treated drinking water is used, for instance, in Barcelona (Spain), where up to 20 million cubic meters per year are recharged by wells to be stored in the Llobregat Delta Aquifer when water tanks of the raw water treatment plant are full [9]. Similar AR strategies have been implemented in other places, such as the Thames and Lee rivers valleys in the UK [10].

3.2. Artificial Recharge and Alternate Conjunctive Use in California's Central Valley

The Central Valley Project (CVP) is a federal project built by the United States Bureau of Reclamation (USBR) that manages more than 8 km^3 of water annually, mainly for irrigation. Currently, it includes 20 dams, over 400 miles of conveyance facilities, and 11 km^3 of storage capacity. It was authorized in 1937 and began operating in 1951.

The State Water Project (SWP) is the main component of the 1957 California Water Plan of the State of California [11]. The SWP includes an integrated system of dams and canals parallel to the CVP, designed to efficiently transport large volumes of water from the humid north to the dry, highly populated south. In California, groundwater overdrafts reached five km^3 per year in 1955, causing subsidence in many areas as large as 9 m. Interbasin transfers and AR reduced overdrafts in 1982 to values between 2.5 and 3.1 km^3. The California Water Plan proposed for the Central Valley is the first time in the world that ACU was applied at a large scale. Total storage between existing and new dams amounted to 24 km^3 and the subsurface storage used was 37 km^3. The construction of this project, which includes 33 reservoirs, 29 pumping or generating plants, and approximately 1100 km of canals and aqueducts, started in 1961. In 1966, main civil works were finished, and the Department of Water Resources signed contracts with 30 agencies throughout the state for permanent water services [11,12]. However, the use of ACU to operate the SWP was not implemented as planned. Water agencies have traditionally constructed and run their own projects directly or through arrangements with water rights holders, and most of them used AR instead of relying on ACU [7]. In any case, the large aquifer overdraft continued to be important, and the operation of reservoirs did not consider the application of the ACU to increase the management possibilities. This issue arose, apparently, due to the cumbersome institutional rules on the operation of reservoirs. The USBR federal reservoirs were not considered in the SWP operation.

In the Central Valley, approximately 30 to 40 percent of annual agricultural and urban water demand is met by groundwater on an average year. In contrast, in wet years, groundwater pumping is less, and in dry years, groundwater can provide approximately 50% of the water demand of the state. Between 1962 and 2003, withdrawal from the aquifer provided about 46% of the 22 km^3 of irrigation water required annually. As a result, aquifer system storage was depleted by 70 km^3, and water level heads dropped significantly. The widespread lowering of groundwater levels substantially dewatered many wetlands and streams. Many Sacramento Valley rivers that previously gained considerable summer flows from groundwater in the early 20th century now lose water to the aquifer. Groundwater overdraft in the San Joaquin and Tulare basins continues growing, mainly in the Tulare Basin, the driest and southernmost area in the Central Valley. Increases in groundwater pumping produced more subsidence. When water levels drop below a critical head, the aquifer system compacts inelastically, and the land subsidence becomes permanent. Since the mid-1980s, the valley's average annual overdraft was nearly 2.8 km^3, representing 13 percent of net water use, mainly in the Tulare Lake Basin. Experiments with AR performed in 2017, the wettest year in more than three decades, evidenced the local efforts to recover the aquifer. The implementation of AR strategies recharged approximately 7.8 km^3 of water actively. The methods used for recharging were: applying extra irrigation water to cropland, irrigating or spreading water on fallowed fields, spreading water on open space lands, and directing excess water to unlined canals and riverbeds [12,13].

3.3. ACU Compatibility with AR

Groundwater and surface reservoirs have different storage capabilities. Surface reservoirs routinely provide seasonal storage, whereas groundwater basins provide greater storage capacity and, more importantly, long-term storage. The decrease in river flow due to groundwater pumping takes a long time to be noticed, particularly in large aquifers where users do not perceive this decrease immediately after pumping. In some river sections, after years or decades of intense pumping, important changes can shift a gaining river into a losing one, contributing to aquifer recharge. The interplay between surface and groundwater is evident, and water management should consider them jointly when making analyses and proposing solutions. The final best solution will be one out of many considering several scenarios, including a wide variety of water sources, types and locations of storage, conveyance alternatives, and responding to several kinds of demands [13].

It seems clear that AR and ACU are not mutually exclusive and that AR could be implemented while operating the reservoirs and aquifers with ACU, as commented above for the Central Valley. In the scheme of the seminal paper by Buras [14], in which the author used dynamic programming to optimize conjunctive use for the first time, it is evident that the system analyzed could achieve additional benefits if direct AR from the reservoir were considered as one alternative to augment the storage in the aquifer.

Since decreases in river flow due to groundwater pumping are slow in time and releases of surface reservoirs are fast, changes in aquifers and base flow are perceived immediately, neither by users nor managers. Above all, it is difficult to coordinate the cumbersome state and federal rules to operate large dams with their multiple objectives of water storage, security, flood prevention, and environment preservation. Each county or state's laws in the USA can also decisively influence water resource management. For example, in Arizona, before 1980 when the Groundwater Management Act (GMA) was passed, no mechanisms existed to secure the rights of water users who wanted to recharge water in an aquifer. However, after GMA was approved, AR initiatives increased rapidly, reaching 590 million m^3 in 1997. This statewide management of conjunctive use in Arizona contrasts with the locally based strategies implemented in California, where farmers' organizations make the decisions about conjunctive use. In 1996, the state requested the Arizona Water Banking Authority to store Arizona's unused water diverted from the Colorado River through the Central Arizona Project (CAP). As a result, the water supply for the Phoenix metropolitan area has two sources of surface water, one from the watershed of the Salt-Verde river and the other from the water stored by the CAP in the Salt-Verde River Valley alluvial aquifer [15–17].

On many occasions, the applicability of conjunctive use faces the challenge of overcoming many bureaucratic barriers. In California, the operation of CVP and SWP reservoirs depends on cumbersome institutional regulations. In Texas, conjunctive management of surface and subsurface water has long been recognized as a potential strategy for increasing water availability of limited water resources. It could be said that institutional constraints, including water law considerations, severely limit conjunctive use [15,16], and, as a consequence, it is still possible to find overexploited aquifers and full reservoirs evaporating water [17].

4. Several Cases of Alternate Conjunctive Use

4.1. Plana de Castellón, Spain

In the Mijares basin on the Mediterranean coast of Spain, some 60 km north of Valencia, ACU is being applied. The two existing reservoirs, Maria Cristina and Sichar, with a total storage of 78 Mm^3, experience considerable water losses, on the order of 45 Mm^3/year, which become mostly aquifer recharge. The aquifer seems to have drained to the river on the order of 20 Mm^3/year at the beginning of the 20th century. Now, the river recharges the aquifer on the order of 40 Mm^3/year. About one-third of the area is irrigated alternately with surface water or groundwater, depending on surface water availability in the river and dam storage. In wet years, aquifer recharge increases due to higher rainfall, dam storage, and river losses. A few ephemeral streams are flowing over the aquifer, contributing to recharge. The difference between high and low values for water storage in the aquifer can reach over 700 Mm^3, representing more than four times the existing surface storage.

It is essential to foster ACU not only through adequate institutional and legal mechanisms but also through social conviction of the advantages that implementing ACU could provide. As an example, the farmers were the ones that proposed an agreement, in 1973, to the Spanish Hydrologic Administration that accepted stopping grouting the Sichar and Maria Cristina reservoirs mentioned above, thus allowing aquifer recharge and implementing ACU in the Mijares river basin. Some kilometers to the south, a few decades later, a dam was built in the Palancia river basin over a permeable karstic limestone with the main aim of recharging the aquifer.

4.2. River Augmentation in the UK

Highly efficient aquifer–river management systems have been implemented in the United Kingdom. Groundwater is pumped and piped into some rivers during dry periods to keep the discharges at adequate levels and to meet water supply and environmental demands. Wells are located far apart from the river to minimize impacts on river discharge. These schemes have been called "river augmentation" and have been used systematically in water planning in England and Wales since the Water Resources Act became law in 1963 [18]. Conceptually, river augmentation is similar to ACU.

The Shropshire Groundwater Scheme (SGS) is the largest conjunctive use scheme in the United Kingdom. The SGS operates in drought periods, pumping water from the sandstone aquifer in Shropshire, England, to regulate River Severn flows and dam releases. This regulation protects the environment and ensures a reliable supply for public water abstractions downstream. A computational simulation of the SGS has been used to estimate the compensation flows required to mitigate the recent climatic conditions and optimize water use in the system. The catchmentwide conditions are included in this analysis using the results of a large-scale surface water model of the river [19].

4.3. Regulation of Karstic Springs

Several karstic springs have been regulated in Spain to augment water availability with high-capacity wells for irrigation and urban water supply. In some cases, the best or unique physical possibility has been to locate wells near the spring in the proximity of existing canals or aqueducts, which transport the captured spring flow. In such cases, the influence of pumping from wells is immediate: the spring dries out and changes in flow adjust to the water demand. There are some interesting examples in Spain: the two high-capacity wells near Los Santos River spring near Valencia could pump up to 1.2 m^3/s; 100 m deep wells at the Deifontes spring near Granada could pump 2.25 m^3/s to an irrigation channel; the wells at the Molinar spring provide 0.6 m^3/s for water supply to the city of Alcoy; the wells at El Algar spring near Benidorm provide up to 0.8 m^3/s. The estimated storage capacity associated with these aquifers is also important, and it has been estimated at 40 Mm^3 for the aquifer connected to El Algar spring—almost three times the existing surface storage on the basin—and 40 Mm^3 for the aquifer connected to the Los Santos River spring [2].

Spring discharges in karst aquifers are not easy to model and forecast, which is necessary if they are to be properly included in ACU. Some works addressing hydrograph modeling have been performed by Estrela [20] for the Arteta spring in Navarra, who developed a methodology to identify aquifer recharge and the decaying negative exponential coefficients of the hydrograph components. He found that these decaying coefficients could be interpreted as the main modes of the groundwater flow solution using the eigenvalues method [21,22].

4.4. Other Cases of Alternate Conjunctive Use

The increase in groundwater use in most countries is often caused by the need to supplement scarce surface water supplies during drought periods. In general, incorporating groundwater to supply increasing water demands improves the system's reliability. The increase of groundwater pumping by users during droughts has been a common practice worldwide for decades. To mitigate the effects of the 1991–1995 drought in Spain, the Jucar Basin Water Authority installed 65 high-capacity relief wells in the Valencia Plain aquifer. These wells were not supposed to be used once the drought was over, but they were placed in operation again in later years during subsequent drought periods. The Segura Basin Water Authority adopted the same solution of constructing supplemental relief wells for drought periods. The logical extension of this strategy is that drought mitigation should be an integral part of ACU when groundwater is pumped in dry years and stored in wet ones. From an economic point of view, ACU is advantageous over building new dams. This has been demonstrated in the Madrid Metropolitan Area, where increasing the well capacity to meet the water demand was much cheaper than building a new dam. In general, ACU solutions are more affordable and faster than structural alternatives.

4.5. Stream–Aquifer Systems

In some basins, it is not now possible to store surface water due to a lack of infrastructure, and only aquifer storage is possible. Nevertheless, implementation of conjunctive use is still possible. Some examples can be found in the South Platte and the small Arkansas aquifers with storage capacities of more than 9 km^3 and 2.5 km^3, respectively [15]. In these alluvial aquifers, the delay between increased groundwater pumping and reduction of river flow (controlled by aquifer diffusivity and geometry) can be used to the advantage of conjunctive use. Pumping during the dry season increases water availability equal to the pumped quantities minus the effect of pumping on river flow; this extra pumping is then compensated by recharging the unallocated flows during the wet season. As a result, the net effect is a larger availability of water resources with an acceptable impact on river flow.

Bredehoeft [23] performed an extensive synthetic analysis to demonstrate the benefits of conjunctive use in alluvial aquifers. In his work, he analyzed the impact of pumping in a rectangular aquifer connected to a river on one of its borders and shows the delays between pumping and river flow impacts, how river flow continues to be affected even after pumping has stopped, how the fluctuations in pumping dampen as wells are drilled farther from the river, and how the river–aquifer system reaches a new equilibrium state after 20 years of pumping during which time a large amount of water has been pumped from the aquifer. He also shows that after stopping pumping, the system needs a similar amount of time to return to the initial state. Overall, the main conclusion of this study is that introducing conjunctive use in alluvial aquifers can result in a substantial increase in water resource availability.

Conjunctive use in stream–aquifer systems also benefits the long-term exploitation of aquifers. When exploited independently, aquifers could sustain groundwater pumping over long periods as long as pumping is on the order of the average natural recharge. Unfortunately, such a practice could result in groundwater salinization, rendering it unusable. However, when recharge is increased through the infiltration of excess flows from rivers (through unlined channels, leaking sections, recharge ponds, or dedicated wells), overall water resources increase, and water quality improves. As mentioned in the previous paragraph, an example of these practices can be found on a small scale in the South Platte [24].

In the central USA and worldwide, many alluvial aquifers are conjunctively used; however, there are still many aquifers with similar characteristics on which such strategies have not been implemented. Such is the case in Spain, where in many cases, current practices and legal impediments prevent its implementation, adding to the misconception among many water managers that any aquifer pumping detracts water from the river, forgetting the interplay between surface water and groundwater.

5. Aquifer Recharge and Water Distribution in Large Irrigation Projects

Two cases in southeast Asia are discussed, demonstrating that conjunctive use can be used to solve irrigation problems while preserving water quality.

5.1. Drainage and Salinization Problems

Large irrigation projects in arid and semiarid lands suffer from drainage and salinization problems when recharge increases due to water losses from unlined distribution canals and irrigation returns. Different studies estimate that one-fifth of the irrigated land in the United States and one-third of the irrigated land worldwide suffer from drainage and salinization problems. These problems could be alleviated by lining conveyances, but they can be better solved by efficiently using groundwater in conjunction with surface water without the need for lining.

The management target for heavily irrigated arid areas should be to use existing aquifers, recharged by losses in the conveyance and distribution channels and irrigation returns while maintaining groundwater levels at a certain depth. Additionally, the migration and dispersion of saline groundwater bodies must be controlled. Such management results in augmenting total water availability while maintaining groundwater quality. Any such practice requires extensive hydrogeological analysis and monitoring and long-term simulations of groundwater flow and salinity.

5.1.1. The IBIS Case

The Indus basin irrigation system (IBIS) is the largest contiguous irrigation zone in the world and the food basket of Pakistan's population. It is also a historical site where the drainage and salinization problems described above have occurred, which has served as a testing ground for conjunctive use to alleviate these problems.

The Indus has a total length of 2900 km and a drainage area of 966,000 km^2, with five major tributaries in Punjab. The interfluves are called doabs and are intensively irrigated flat areas. The average annual flow is approximately 170 km^3, of which 84% flows during the Kharif season (June–October) and only 16% during the Rabi season (November–April). Of this flow, 120 km^3 is being diverted for irrigation, and 13 km^3 is required for environmental flow for the coastal areas [25].

Irrigation in the Punjab plain in Pakistan started in the late 19th century under British colonial rule with 14 million ha and had risen to 23 million ha at the end of the last century [25]. The irrigation system consists of 43 canals with a total length of 65,000 km. The canal network contains primary, secondary, and tertiary sections, of which the biggest 15 have a capacity between 280 and 600 m^3/s. They are fed by 19 large dams, such as the gigantic Mangla and Tarbela dams, with 5.5 km^3 and 10.6 km^3 storage, respectively. Most canals are unlined with losses that feed the underlying aquifer.

The problem with drainage and salinization was present during the early years of exploitation. By 1930, groundwater level had risen above the bed of adjacent rivers, reversing hydraulic gradients and the direction of groundwater flow. By 1960, 2 million ha of the initial 14 million had to be abandoned due to groundwater level rises as high as 60 m, occasionally waterlogging the land due to irrigation returns and infiltration through unlined canals.

Initially, the water resources group at Harvard University proposed to drill 32,000 high-capacity wells to pump 70 km^3/year and lower the water levels. The idea was to use fresh groundwater jointly with surface water to increase irrigation and pump salty water to the sea through lined canals. Following these recommendations, the Pakistan government initiated a program called Salinity Control and Reclamation Projects (SCARP) to construct public wells to lower the groundwater table and reduce the risk of soil salinization. Seven SCARP projects were initiated, some of them achieving good results in alleviating or reducing waterlogging and helping to replenish canal water supplies. Others became a failure because they caused unwanted effects on groundwater quality. The demonstration of the SCARP project was followed by an explosion of private wells with undesirable consequences such as the upconing of saline water. The SCARP project was eventually discontinued. Nevertheless, improvements in drainage and a decrease in soil salinity were important achievements [26–30].

More recently, the Rechna Doab, with an area of 35,217 km^2 (close to the size of the Central Valley of California) was selected as a suitable study area to identify combinations of technological and institutional strategies to manage surface and subsurface water conjunctively. The Rechna Doab contains 504 km of branch canals, 240 km of main canals, 373 km of link canals, and about 200,000 wells. At the end of the 20th century, the annual pumping volume was estimated as 12 km^3 from private wells and three km^3 from public ones, providing sustenance to 25 million inhabitants. A surface water–groundwater quantity and quality model [31] was developed to assess future groundwater trends in the area. With dry conditions, the model predicts an overall decline in groundwater levels between 10 and 20 m making groundwater pumping expensive for farmers. In addition, the model also predicts a high risk of water salinization due to vertical up-coning and lateral movement of highly saline groundwater.

5.1.2. Vulnerability DUE to Climate Change

The bulk of the Indus water comes from high mountain headwaters from snow and ice melting. Climate change will increase glacier melting from the 16,300 km^2 of glaciers in the Karakoram, resulting in an increase of the Indus discharge at the head of the basin, which will be subsequently followed by a reduction of natural river flow due to glacier shrinking. Climate change is also expected to affect the South Asian monsoon, which is mainly responsible for discharge during late summer. All these changes will alter the hydrologic cycle and require profound changes in the system's operation. The most important will be to establish alternative storage given that the large dams at the head of IBIS are losing capacity due to the considerable sediment charge that the feeding rivers have. Aquifers are the natural candidates, but their use as alternative storage must be planned and implemented with sufficient anticipation.

It is necessary to simulate the current and future IBIS management alternatives under the pressures of climate change, including using aquifers as potential storage reservoirs to be recharged by infiltration through the distribution network of canals and irrigation ditches.

5.2. Induced Recharge in the Ganges Basin

In their 1975 Science paper, Revelle and Lakshminarayana [32] proposed the creation of what they called the Ganges water machine. With a basin size of almost 800,000 km^2 that accommodates one-tenth of the world population, the Ganges suffers from large seasonal discharge fluctuations due to its topography (a large plain at the foothills of the steep Himalayans) and the monsoon-driven rainfall. Topography prevents the construction of large dams for surface water storage. Monsoon rains, ranging between 1000 mm/year in the west and 2000 mm/year in the east, induce discharges of about 300 km^3 during the monsoon season (July–October) and 70 km^3 during the rest of the year. Consequently, floods occur during the monsoon season, and the discharge during the nonmonsoon months is barely sufficient to meet the demands. Revelle and Lakshminarayana propose to try to capture the monsoon rainfall and store it in the aquifers for its use during the dry season. They propose up to five ways to capture part of the monsoon flows and store them underground: (i) water spreading, (ii) containment of runoff in uncultivated areas by the construction of bunds, (iii) pumping groundwater near the natural drains during the dry season, (iv) pumping groundwater in the dry season along certain tributaries to make space for underground storage, and (v) increasing seepage from irrigation canals during the monsoon season. The estimated water resource availability increase was evaluated at 60 km^3 or more.

Some conjunctive use already occurs in many Uttar Pradesh canal irrigation areas. A 10-year pilot project was carried out by Roorkee University and the state of Uttar Pradesh in collaboration with the International Water Management Institute (IWMI). Monsoon river flows were channeled through earthen canals to irrigate highly water-demanding wet season crops, resulting in seepage water recharge from canals and fields to the underlying aquifers. Groundwater decline stopped, pumping costs diminished, and waterlogging was minimal. Farmers are no longer at the mercy of erratic monsoon rains. Statewide adoption of this practice requires shifting the state's water policy, moving from supplying water only in the dry season to mostly delivering water for recharge during the monsoon rains [31].

6. Water Planning and Numerical Tools

In the coming decades, surface flow will probably decrease in many world basins because of climate change, which will cause more intense floods and droughts. Future shifts in climate dynamics will have two significant consequences for water management. First, it will be necessary to have a greater water storage capacity and perhaps some additional connections for water transfer in some points, for which conjunctive use could help implement mitigation and adaptation strategies. Second, it will be crucial to run many simulations of the water resources system's behavior and plan for alternative scenarios.

A conjunctive use analysis must include all physical components, surface, and subsurface, analyze the influence of climate on surface flows, and include aquifer recharge and the exchanges between the surface and subsurface components of the system, future water demands, and operational and legal constraints. Considering the many uncertainties that some of these components have, the number of alternative scenarios to analyze can be huge.

The California Department of Water Resources (CDWR) developed computational models to support the management of the California Water Plan. Such a set of models are widely known as CALSIM. In the early stages, the lack of a groundwater component was noted as a major deficiency in CALSIM. The peer review of the CALSIM II [33] stated that "without explicit groundwater representation, the model's applicability to planning, policy, and operational problems under future water management and hydrologic conditions could be severely limited". The Sacramento Valley portion of CALSIM II incorporated a groundwater model. Still, in the 2009 upgrading of the CDWP [34], it was considered that such a groundwater model was insufficient to compute the impact of pumping on surface flows. Only in 2013 was the complex surface and subsurface water flow model of the Central Valley of California finished. This model encompasses a surface area of 51,000 km^2, includes 35 stream reaches, and the aquifer is discretized using 35,000 nodes. The model has been successfully used to compute the interaction between rivers and the aquifer from 1972 to 2003 [35] and to improve the estimation of balance components, monthly river contributions, ungauged basin flows, and groundwater pumping. Simulations were made for decreases of 30%, 50%, and 70% of surface water availability for periods of 10, 20, 30, and 60 years. Nevertheless, at the moment of writing this paper, the authors are unaware whether the CALSIM model has been used for the simulation of different strategies of dam operations or other alternatives of conjunctive use.

6.1. Conjunctive Use Simulation

To manage conjunctive use, surface and subsurface water flow components must be simulated together to support decision tools. Currently, there are several techniques to simulate aquifers as a component of water resources systems. Since the beginning of the 1970s, different methods have been developed using finite-difference or finite-element models, discretized in space and time, to represent the aquifer geometry and to solve the groundwater flow partial differential equation. These models consist of a set of linear equations to be solved recursively and sequentially in time, requiring significant data storage and computer time. The most popular code since its publication in 1984 is MODFLOW, developed by the USGS [36]. Its versions include different capabilities to simulate coupled groundwater/surface-water systems. Implementing conjunctive use models requires knowledge about each of the water management alternatives considered, aquifer pumping or recharge, synthetic or historic surface flows, and the operating rules of reservoirs and conduits to simulate piezometric heads and river–aquifer interactions. To alleviate the computational cost, it is possible to create surrogate models to simulate the aquifer dynamics approximately but efficiently. Different methods exist for this purpose, including analytical solutions, influence functions, or the eigenvalue method. In any case, surrogate models should be used alternatively with the full-fledged model to ensure that the approximations introduced by the surrogate models do not impinge on the model prediction capabilities.

6.2. Use of Response Functions

Groundwater was incorporated into the Sacramento Valley portion of CALSIM II (CDWR, 2004) through the use of "response or influence functions", derived from calibrated groundwater models [37–40]. This approach of including groundwater interactions in river basin optimization models, which is well documented and tested, was also proposed in the San Joaquin River model. Still, a calibrated model including all the Central Valley aquifers was not developed until 2013.

The influence functions are a classical technique to develop efficient surrogate groundwater flow models. The influence functions assume the system is linear, reducing the computational time and the storage memory However, the influence functions must include the external actions of all precedent simulation intervals, whose effects could be appreciable at the required time but negligible in upcoming intervals. A solution to consider existing initial conditions is to add fictitious actions that produce initial levels in time zero close to the real ones.

6.3. The Eigenvalue Solution

In classical groundwater models, the linear algebraic system of equations obtained using finite differences or finite elements models are solved iteratively in sequential time steps and provides piezometric heads for all nodes of the aquifer discretization. To subsequently calculate river–aquifer interactions, it is necessary to postprocess the simulated heads at river locations. Likewise, the calculation of aquifer storage requires a similar postprocessing procedure. For large models, performing such postprocessing could be computationally inefficient and time-consuming. Consequently, using finite differences or finite elements models to simulate conjunctive use could be cumbersome if many few decades-long scenarios have to be analyzed.

The eigenvalues method (EVM) is an alternative to finite differences and finite elements. The EVM simulates the aquifer response in an efficient way for its incorporation in conjunctive use models [41] since it provides an explicit expression for heads, flows, or volumes continuously in time. In its original formulation, the EVM requires that the system is linear, that is, that transmissivities be almost constant over time. When dealing with unconfined aquifers, this requirement may be challenging to meet. For this reason, alternative formulations have been proposed to handle nonlinearities such as the one caused by significant drops of the saturated thickness or the disconnection of the aquifer from the river [42]. Another advancement in the application of the EVM is the optimization of the numerical solution by reducing the prediction errors associated with the truncation of the eigenfunction expansions, which makes the EVM even more attractive for its use in conjunctive use simulations.

Compared with finite differences and finite elements models, the advantage of using the EVM is that the solution is continuous in time, there is no need for time discretization, and there is no need for postprocessing to compute river–aquifer interactions or aquifer stored volumes. Spatial discretization is accommodated in the same way as in finite differences and finite elements models using an explicit description of the hydraulic parameters heterogeneity.

The decision support system AQUATOOL [43], developed at the Technical University of Valencia, includes the EVM to simulate the groundwater component of a water resource system. For more than three decades, AQUATOOL has successfully simulated and optimized water resources management models. The explicit incorporation of the groundwater flow dynamics via the EVM is one of the reasons why AQUATOOL is still an extensively used modeling tool in the water resources community.

7. Conclusions

Groundwater is still a neglected and misused resource in many world regions. Conjunctive use of surface water and groundwater could solve many of the water problems associated with the current global climate crisis.

Management of water resource systems requires reliable and abundant data, which are unavailable at the beginning of their exploitation and must be obtained over years of observation and monitoring. Many extensive aquifers have been heavily exploited for many years or decades with pumping exceeding recharge, which has produced significant drops in the levels and volumes of stored water. Excessive pumping has also caused the drainage of river base flows, salinization, and drainage problems. Initially, there is not enough information on the exploitation, hydrodynamic properties, or river–aquifer relationships. Consequently, any conjunctive-use forecast will be subject to great uncertainties, which will be reduced with time as data are collected and assimilated into the model. Data that will be available only with appropriate monitoring and observation networks and the necessary material and human resources to maintain them.

Conjunctive use could be the key to addressing many water resources problems, specifically, the problems that the world will face with increasing demands and climate change projections. These projections imply a reduction in readily available surface water that can be compensated with AR by storing in aquifers excess runoff water from the wet season or fast flood events, or ACU with an adequate operation of dams and aquifers. In general, conjunctive use of surface water and groundwater will increase the reliability and resilience of water resource systems.

There is an ethical obligation to perform a meticulous study, design, development, and implementation of conjunctive use systems to optimize the use of often scarce available water resources. It is fundamental to study the hydrological cycle as a unit, knowing in detail the dynamics of surface and subsurface water components and their mutual relationships and connections and preventing the degradation of groundwater quality.

Simple quantitative analyses of water availability and demands could be enough for small-scale conjunctive use projects. Still, large-scale projects require advanced management models of conjunctive use in which aquifers must be adequately represented. Performing this quantitative analysis is even more relevant when demand exceeds aquifer recharge. In all cases, these quantitative assessments should be accompanied by an uncertainty evaluation.

Sporadic use of groundwater relief wells can help address temporary drought situations without a significant long-term effect on aquifer dynamics. However, when groundwater is to be used as a critical component of the water resource system, it is important and necessary to include it in an integral water resources management system, and it is just as important to have an adequate monitoring network. Such a monitoring network, which must be open to the public and periodically updated and published, should include piezometers to assess the quantitative and qualitative state of the aquifers and gauging stations to determine river–aquifer exchanges, water meters at pumping wells, and records of surface water diversions. To set up and maintain such a network requires an independent, stable, and economically supported structure, which, unfortunately, will not be viable in many countries due to a lack of human and material resources. Unfortunately, in many of those countries that do have the resources, it seems that the institutional concern about the protection of groundwater against pollution is small.

The cases referenced are from the last century because they represent excellent examples of successful and not successful implementations of conjunctive use in its early introduction into groundwater management. They remain good examples. Unfortunately, water managers today still overlook the role that conjunctive use can have in alleviating the pressures that surface water systems may have during drought periods. Those techniques of the past are still as valuable today; although the models and tools for their implementation are certainly more sophisticated, in essence, they are the same.

Author Contributions: Conceptualization, A.S., E.C., J.J.G.-H., J.A., M.P.-V., D.P.-V., O.D.Á.-V. and T.E.; investigation, A.S., E.C., J.J.G.-H., J.A., M.P.-V., D.P.-V., O.D.Á.-V. and T.E.; writing—original draft preparation, A.S., E.C. and J.J.G.-H.; writing—review and editing, A.S., E.C., J.J.G.-H., J.A., M.P.-V., D.P.-V., O.D.Á.-V. and T.E.; supervision, E.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by AGREEMAR Project (PCI2022-133001 funded by Spain's MCIN/AEI/10.13039/501100011033, by European Union's NextGenerationEU/PRTR), the SIGLO-AN project (RTI2018-101397-B-I00) from the Spanish Ministry of Science, Innovation and Universities (Programa Estatal de I + D + i Orientada a los Retos de la Sociedad) and by project eGROUNDWATER funded by the PRIMA programme supported by the European's Union Horizon 2020 research and innovation programme under grant number 1921.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

References

1. Foster, S.; van Steenbergen, F. Conjunctive groundwater use: A 'lost opportunity' for water management in the developing world. *Hydrogeol. J.* **2011**, *19*, 959–962. [CrossRef]
2. Sahuquillo, A. Conjunctive use of surface water and groundwater. In *UNESCO Encyclopaedia of Life-Support Systems*; Silveira, L., Usunof, E., Eds.; Cambridge University Press: Cambridge, UK, 2002; pp. 206–224.
3. Escriva-Bou, A.; Pulido-Velazquez, M.; Pulido-Velazquez, D. Economic value of climate change adaptation strategies for water management in Spain's Jucar basin. *J. Water Resour. Plan. Manag.* **2017**, *143*, 04017005. [CrossRef]
4. Barlow, P.; Ahlfeld, D.; Dickerman, D. Conjunctive-Management Models for Sustained Yield of Stream-Aquifer Systems. *J. Water Resour. Plan. Manag.* **2003**, *129*, 35–48. [CrossRef]
5. Wiener, A. *The Role of Water in Development: An Analysis of Principles of Comprehensive Planning*; McGraw-Hill: New York, NY, USA, 1972.
6. Coe, J. Conjunctive Use-Advantages, Constraints, and Examples. *J. Irrig. Drain. Eng.* **1990**, *116*, 427–443. [CrossRef]
7. Kretsinger, G.; Narasimhan, T. California's evolution toward integrated regional water management: A long-term view. *Hydrogeol. J.* **2006**, *14*, 407–423. [CrossRef]
8. Khare, D.; Jat, M.; Deva Sunder, J. Assessment of water resources allocation options: Conjunctive use planning in a link canal command. *Resour. Conserv. Recycl.* **2007**, *51*, 487–506. [CrossRef]
9. Custodio, E.; Isamat, F.; Miralles, J. Twenty five years of groundwater recharge in Barcelona (Spain). In *International Symposium on Artificial Groundwater Recharge*; Dortmund Deutscher Verband für Wasserwirtschaft und Kulturbau e.V.-UNESCO, DVWK Bull: Hamburg, Germany, 1982; pp. 171–192.
10. Downing, R.C.B. *Groundwater our Hidden Asset*; British Geological Survey: Nottingham, UK, 1998.

11. California Department of Water Resources. The California Water Plan. Report Bulletin No. 3; Department of Water Resources, State of California, Department of Water Resources, Division of Resources Planning. 1957. Available online: https://water.ca.gov/programs/california-water-plan (accessed on 23 July 2022).
12. Hanak, E.; Lund, J.; Dinar, A.; Gray, B.; Howitt, R.; Mount, J.; Moyle, P.; Thompson, B. *Managing California's Water: From Conflict to Reconciliation*; Public Policy Institute of California: San Francisco, CA, USA, 2011.
13. Lund, J.; Munévar, A.; Taghavi, A.; Hall, M.; Saracino, A. *Integrating Storage in California's Changing Water System*; University of California at Davis: Davis, CA, USA, 2014.
14. Buras, N. Conjunctive Operation of Dams and Aquifers. *J. Hydraul. Div.* **1963**, *89*, 111–131. [CrossRef]
15. Blomquist, W.; Heikkila, T.; Schlager, E. Institutions and Conjunctive Water Management among Three Western States. *Nat. Resour. J.* **2001**, *41*, 653–683.
16. Holley, C.; Sinclair, D.; Lopez-Gunn, E.; Schlager, E. Conjunctive management through collective action. In *Integrated Groundwater Management*; Springer: Cham, Switzerland, 2016; pp. 229–252.
17. Wurbs, R. Reservoir Management in Texas. *J. Water Resour. Plan. Manag.* **1987**, *113*, 130–148. [CrossRef]
18. Downing, R.; Oakes, D.; Wilkinson, W.; Wright, C. Regional development of groundwater resources in combination with surface water. *J. Hydrol.* **1974**, *22*, 155–177.
19. Shepley, M.; Streetly, M.; Voyce, K.; Bamford, F. Management of stream compensation for a large conjunctive use scheme, Shropshire, UK. *Water Environ. J.* **2009**, *23*, 263–271. [CrossRef]
20. Estrela, T. Estimación de Parámetros de Recarga y Descarga en un Modelo de Flujo Subterráneo de un Manantial Cárstico. Ph.D. Thesis, Universitat Politècnica de València, Valencia, Spain, 1991.
21. Estrela, T.; Sahuquillo, A. Modeling the Response of a Karstic Spring at Arteta Aquifer in Spain. *Groundwater* **1997**, *35*, 18–24. [CrossRef]
22. Sahuquillo, A.; Gómez-Hernández, J.J. Comment on "Derivation of effective hydraulic parameters of a karst aquifer from discharge hydrograph analysis" by Baedke, S.J. and Krothe, N.C. *Water Resour. Res.* **2003**, *39*, 1152. [CrossRef]
23. Bredehoeft, J. Hydrologic Trade-Offs in Conjunctive Use Management. *Groundwater* **2011**, *49*, 468–475. [CrossRef]
24. Ronayne, M.; Roudebush, J.; Stednick, J. Analysis of managed aquifer recharge for retiming streamflow in an alluvial river. *J. Hydrol.* **2017**, *544*, 373–382. [CrossRef]
25. Basharat, M.; Sultan, S.; Malik, A. *Groundwater Management in Indus Plain and Integrated Water Resources Management Approach*; International Waterlogging and Salinity Research Institute (IWASRI): Lahore, Pakistan, 2015.
26. Fiering, M. Simulation Models for Conjunctive Use of Surface and Ground Water. In *Seminar of Ground Water, Granada, Espagne*; FAO-Spanish Governement: Rome, Italy, 1971; pp. 1–25.
27. van Steenbergen, F.; Oliemans, W. A review of policies in groundwater management in Pakistan 1950–2000. *Water Policy* **2002**, *4*, 323–344. [CrossRef]
28. Jehangir, W.; Qureshi, A.; Ali, N. *Conjunctive Water Management in the Rechna Doab: An Overview of Resources and Issues*; Working Paper 48; International Water Management Institute: Lahore, Pakistan, 2002.
29. Jehangir, W.; Horinkova, V. *Institutional Constraints to Conjunctive Water Management in the Rechna Doab*; Working Paper 50; International Water Management Institute: Lahore, Pakistan, 2002.
30. Qureshi, A.; McCornick, P.; Qadir, M.; Aslam, Z. Managing salinity and waterlogging in the Indus Basin of Pakistan. *Agric. Water Manag.* **2008**, *95*, 1–10. [CrossRef]
31. Khan, M.; Voss, C.; Yu, W.; Michael, H. Water Resources Management in the Ganges Basin: A Comparison of Three Strategies for Conjunctive Use of Groundwater and Surface Water. *Water Resour. Manag.* **2014**, *28*, 1235–1250. [CrossRef]
32. Revelle, R.; Lakshminarayana, V. The Ganges water machine. *Science* **1975**, *188*, 611–616. [CrossRef]
33. Close, A.; Haneman, W.; Labadie, J.; Loucks, D.; Lund, J.; McKinney, D.; Stedinger, J. *A Strategic Review of CALSIM II and Its Use for Water Planning, Management, and Operations in Central California*; California Bay Delta Authority Science Program, Association of Bay Governments: Oakland, CA, USA, 2003.
34. California Department of Water Resources. *California Water Plan Update 2009. Integrated Water Management. Volume 1: The Strategic Plan*; Report Bulletin 160-09; Department of Water Resources, State of California, California Natural Resources Agency, Department of Water Resources: Sacramento, CA, USA, 2009.
35. Brush, C.; Dogrul, E.; Kadir, T. *Development and Calibration the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG*; California Department of Water Resources, Bay-Delta Office, California Department of Water Resources: Sacramento, CA, USA, 2013.
36. Harbaugh, A.W. *MODFLOW-2005, the US Geological Survey Modular Ground-Water Model: The Ground-Water Flow Process*; US Department of the Interior, US Geological Survey: Reston, VA, USA, 2005.
37. Schwarz, H.E. Water resource systems and relations. *Rev. Geophys.* **1975**, *13*, 468–472. [CrossRef]
38. Maddock, T., III. Algebraic technological function from a simulation model. *Water Resour. Res.* **1972**, *8*, 129–134. [CrossRef]
39. Illangasakare, T.; Morel-Seytoux, H. Stream-aquifer influence coefficients as tools for simulation and management. *Water Resour. Res.* **1982**, *18*, 168–176. [CrossRef]
40. Illangasakare, T.; Morel-Seytoux, H. Algorithm for Surface/Ground-Water Allocation under Appropriation Doctrine. *Groundwater* **1986**, *24*, 199–206. [CrossRef]

41. Sahuquillo, A. An eigenvalue numerical technique for solving unsteady linear groundwater models continuously in time. *Water Resour. Res.* **1983**, *19*, 87–93. [CrossRef]
42. Pulido-Velazquez, D.; Sahuquillo, A.; Andreu, J. A two-step explicit solution of the Boussinesq equation for efficient simulation of unconfined aquifers in conjunctive-use models. *Water Resour. Res.* **2006**, *42* , 5. [CrossRef]
43. Andreu, J.; Capilla, J.; Sanchís, E. AQUATOOL, a generalized decision-support system for water-resources planning and operational management. *J. Hydrol.* **1996**, *117*, 269–291. [CrossRef]