CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER

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Summary

The different and complementary characteristics and behavior of surface water and groundwater make it possible to solve specific needs of water quantity and quality more adequately and economically than if both resources were used separately Groundwater can provide additional resources as well as a means of water storage, distribution, and treatment, and groundwater can advantageously be combined with surface water resources. Likewise, groundwater possesses other advantages such as its adaptability to a progressive increase in water demand, the possibility of temporary over-exploitation as a means of deferring costly construction projects for mitigating the effects of droughts, and alleviating drainage problems. Another virtue of groundwater in conjunctive use schemes is the insurance role it plays in offsetting the uncertainty surrounding surface flow, hydrological parameters, or water demand.

This chapter describes current types of conjunctive use. Aquifer storage can be used through artificial recharge, in alternate conjunctive use, and in aquifer–river systems. In

alternate conjunctive use, groundwater is used more in dry periods; its use decreases and, conversely, surface water use increases at times when there is more surface water available in rivers or stored in surface reservoirs. This strategy enables water supply to be increased without needing to either augment surface storage or resort to artificial recharge, thanks to the use of natural aquifer storage. This article discusses information needs, uncertainty aspects, and the economic implications of conjunctive use, in addition to the advantages of, and need for, integrating groundwater into water resources planning and management. Finally, the methods existing for analysis of complex conjunctive use schemes are briefly described.

1. Introduction

Groundwater is usually a significant hydrological component of watersheds and basins. Average drainage from aquifers in continental areas is in the order of 30% of stream flow, and this is essential for sustaining stream flow during dry periods—the so-called "base flow." The magnitude of aquifer recharge, the large volumes of water usually stored in them, the ease with which they are utilized, and the generally lower cost of groundwater development all make their use very attractive.

Wise utilization of the different and complementary characteristics of surface and subsurface components through conjunctive use of groundwater and surface water can achieve greater yields and economic and/or functional advantages than separate management of both components. One of these characteristics is the existence of large volumes of water stored in aquifers, from tens to hundreds of times their annual recharge. In the same way, the volume of aquifer storage provided by a relatively small fluctuation in the piezometric head in unconfined aquifers considerably exceeds available or economically feasible surface storage. This allows both the use of water in storage during dry seasons or periods, and the use of the subsurface space for storing surface or subsurface water. The existence of aquifers over a large proportion of the area of a basin adds distribution and conveyance to the benefits of water storage. Moreover, long-term storage in and passage through a groundwater aquifer generally improves water quality by filtering out pathogenic microbes and many, although by no means all, other contaminants.

Naturally, surface water provides some unique services such as navigation, power, and flood control, but many uses are common to both surface and groundwater (irrigation, municipal and industrial uses, and joint environmental benefits such as wetland maintenance). In fact, groundwater has traditionally been used worldwide to back up supply for times of shortage, and this represents a certain type of conjunctive use. Groundwater can produce other unique environmental benefits related to base flow and riparian habitat preservation. In addition, groundwater and surface water are hydraulically connected, so any contamination in one can migrate to the other.

Hydraulic works and the use of surface water and groundwater have a mutual effect on each other and other components of the hydrological cycle. Groundwater recharge can be increased by filling surface reservoirs or by return flow irrigation. Excessive return flow irrigation and canal losses in arid areas can produce drainage problems and increase of salinity. Infiltration to underlying aquifers from losing streams can decrease as a result of upstream water diversion. Because of the changes produced in the sequences of river flow, surface storage can increase or decrease recharge in downstream aquifers located below losing reaches of the river channel. Groundwater pumping can cause depletion of surface or spring flow and can produce other externalities such as land subsidence or destruction of riparian habitats. These effects can produce legal and economic problems which must be addressed. In most of these scenarios conjunctive use is suitable for bringing out the positive effects and playing down the negative ones.

The strongest argument in favor of conjunctive use is the fact that aquifers provide alternatives not only for augmenting the number of components but, above all, for increasing their functionality and therefore the likelihood of their being more effective. Although in most areas groundwater is scarcely considered by managers, it can provide useful solutions to many problems. Likewise, conjunctive use can be applied to obtain a better or cheaper solution to existing problems. Its suitability for such applications is not restricted to arid or water-scarce areas. On the contrary, if surface and groundwater relationship and mutual influence are considered, conjunctive use is advisable in most areas, including cases where scarcity or pollution problems exist.

Aquifers can constitute a source of water and perform complementary functions of storage, water distribution, and treatment that comprise classic components of a surface system. The water distribution role in aquifers is directly related to the storage function. A conjunctive use system of both surface and subsurface components, dynamically conceived and expanded and operated in a manner that keeps abreast of water demand and hydrological variability, can provide economic, functional, and environmental benefits. In order to quantify the potential benefits, more complex models are needed and more alternatives have to be analyzed. Hitherto, water quality and pollution have only been indirectly or qualitatively considered in conjunctive use analysis. Only in some cases have total water salinity or gradient restriction, used as surrogate parameters, been modeled explicitly.

In recent years structural solutions have been under question and a trend is gaining ground in favor of better management of the existing elements rather than heavy investment in new construction. In many countries the time for building new dams is probably over. The most favorable and less controversial sites have already been built, keeping pace with a greater environmental conscience. From now on, conjunctive use options should be considered right from the start as a means of extending existing water resources (see *Groundwater Recharge*).

2. Types of Conjunctive Use

2.1. Planned Overdraft

In spite of the grave problems caused by aquifer overdraft, in some cases, huge volumes of water stored in some aquifers—the so-called "one-time reserves"—can be used as a source of water for decades. This has been carried out in Israel to defer costly projects and has been postulated elsewhere. Over-exploitation can precede the development of surface resources. In a subsequent stage, surface water can be used jointly with groundwater, taking into consideration the perennial yield. The delay time for building expensive components must be used to collect more hydrological data and carry out the required studies for cutting down the hydrological and technological uncertainties. This has been termed “buying time” (see *Sustainable Groundwater Use and Over-exploitation*).

2.2. Use of Subsurface Storage

There are two possibilities for utilizing the storage provided by aquifers. The first and most intuitive is through artificial recharge. The second is through alternate use of groundwater and surface water. In alternate use, target yield is obtained in dry years through increased pumping. When more than average water is available in streams or surface storage, more surface water is used, allowing more groundwater to remain in storage. While maintaining average groundwater pumping, water resources availability increases without augmenting surface storage. Improvement comes from the augment of subsurface storage by increasing pumping during dry years and by leaving more groundwater in storage in wet ones. Both possibilities of artificial recharge and alternate use are not mutually exclusive. In fact there are many sites where both are applied even though one of them predominates.

2.2.1 Artificial Recharge

Artificial recharge has been used in the past to store surface flows or non-utilized surplus water that would otherwise be lost. More recently it has been used to improve aquifer management, including reduction of water level drop, and seawater intrusion recovery. In many countries in northern and central Europe aquifers are widely used to take advantage of soil and vadose zone faculties for filtrating and treating polluted recharged surface water. This article does not regard this practice as conjunctive use. In certain cases artificial recharge is used to prevent land subsidence caused by groundwater head depletion and for other purposes related to sewage water treatment and reclamation or to environmental and pollution problems. This too will not be considered here as a particular type of conjunctive use. On the other hand, the practice of mixing aquifer waters with different chemical compositions to dilute chloride, nitrate, and other contaminants is an interesting, albeit not very widespread, objective in conjunctive use schemes. It is used in Israel where the water imported from Kinneret Lake is saltier than the water in the coastal and calcareous aquifers where water is recharged for storage. Artificial recharge of surface water with low nitrate content has been proposed in the Castellon de la Plana Aquifer in Spain in order to lower its high nitrate levels.

In Israel in a planned way, and spontaneously in southern California, aquifers were over-exploited from early stages of hydraulic development. Soon scarce local surface water and subsequently imported waters were recharged into aquifers. Artificial recharge has been employed in many arid areas in the world, but it is in the areas mentioned above that artificial recharge has been extensively used. In further stages there, sewage effluent has been recharged in some aquifers after having been subjected to advanced treatment processes. Sewage reclaimed water from an advanced treatment facility is recharged in the wells of the hydraulic barrier constructed to protect the Los

Angeles coastal aquifer from seawater intrusion in southern California. Equally, in the Dan region in Israel treated sewage effluent from the metropolitan area of Tel Aviv is recharged in sand dunes to be subsequently pumped for accepted uses.

The groundwater reservoir in the Palaeogene sands and chalk aquifers beneath the London clay in the River Thames basin was initially exploited in the eighteenth century. Over the following 200 years the aquifers were heavily pumped. The water level gradually fell and saline water from the tidal Thames intruded into the aquifers. As a result of this and of the change in the pattern of water use, aquifer pumping decreased, but the availability of water below London made a significant contribution to the economic development of the city in the nineteenth and early twentieth centuries. Between 1800 and 1965 the aquifers in the central part of the London Basin provided some 5700 million cubic meters of water. The chalk aquifer is still being used today in the Lee Valley, and is recharged during the winter through wells using treated water from both the Thames and the River Lee.

In Spain, artificial recharge is relatively uncommon. Up to 20 million cubic meters per year of treated potable water from the Barcelona supply is recharged, to be stored in the Llobregat Delta Aquifer when water tanks of the raw water treatment plant are full. Upstream of the delta apex, the alluvial aquifer is recharged with surface water in losing reaches of the River Llobregat.

Artificial recharge is usually expensive, whether it is carried out with wells or through infiltration ponds. The water to be recharged generally needs to be desilted and treated to prevent clogging, and ponds and wells have to be cleaned and unclogged. The recharge capacity of wells cannot be regenerated to operative flow levels after a certain period of time has elapsed, and the wells have to be replaced. Infiltration in losing rivers, ephemeral streams and alluvial fans can be significant in many cases, and technical possibilities exist for economically enhancing this. The origin of recharged water can be settled or unsettled, and it can stem from surface runoff or water stored in reservoirs and discharged at appropriate times to losing river channels. Unintentional aquifer recharges from pervious reservoirs in some Mediterranean karstic areas in Spain presents many practical advantages, and the possibility of deliberately building pervious reservoirs has been suggested at several sites. It is in California that by far the most water is recharged, around 3000 million cubic meters per year. In Spain, artificial recharge will undoubtedly be used in the near future at more sites to solve localized problems, but it is not expected to solve any major difficulties. Alternate use schemes, as in many other countries, appear to be a more attractive proposition and are discussed below.

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Biographical Sketch

Andrés Sahuquillo holds both a Civil Engineering degree and a Ph.D. from the Technical University of Madrid. He has a chair in Environmental and Hydraulic Engineering at the Technical University of Valencia. His research interest covers the field of water planning and management with emphasis in groundwater, conjunctive use of groundwater and surface water, and groundwater modeling. He has authored about 200 papers in national and international meetings, symposia and journals, some in peer reviewed journals. He has been reviewer of the journals *Advances in Water Resources*, *Hydrological Sciences Journal*, *Transport in Porous Media and Water Resources Research* and associate editor of *Hydrological Sciences Journal*, *Water International*, and several national journals. He is a habitual reviewer of CICYT, the Spanish agency for research funding, and has been a consultant to UNESCO and IAAE. He has been a member of the Spanish Environment National Council, and currently is a member of the Spanish National Water Council and a correspondent member of the National Academy of Sciences. Also, he is a member of the International Association of Hydrogeologists, International Association of Hydrological Sciences, International Water Resources Association, American Geophysical Union, American Society of Civil Engineers, and European Geophysical Society.