CHAPTER 7

Conjunctive use as potential solution for stressed aquifers: social constraints

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ABSTRACT: Aquifers can provide water resources storage, distribution and treatment that can be combined with surface water resources and hydraulic structures to augment water availability more economically and in a more functional manner. The paper describes the two major types of conjunctive use in existence. These are alternative conjunctive use systems and comprehensive systems. They differ in the use of subsurface storage. The simplest system is alternative conjunctive use in which 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. This strategy allows water supply to be increased without the need to augment surface storage. The other system is termed comprehensive conjunctive use. In this system surface water is closely related to artificial groundwater recharge and a more complex infrastructure is required for its successful operation. The economic implications of conjunctive use advantages and the need for integrating groundwater into water resources planning and management are discussed. The chapter also discusses the existing laws defining water rights, in addition to rules and institutions, which are critical to permitting or hampering the application of conjunctive use. Conjunctive use potential in the developing world is analyzed. Lately the need for integrating groundwater resources in water resources planning is advocated plus the need for more advanced methods of analysis of the most complex water systems involved.

1 INTRODUCTION

Certain characteristics and behaviour of surface water and groundwater systems are complementary and can be used to solve water quantity and quality problems more adequately and economically if both sources are used concurrently. Aquifers can provide storage, transmission and treatment facilities that parallel those of surface reservoirs, canals and pipelines and water treatment plant.

Groundwater is a significant component of many watersheds and basins that is essential for sustaining stream flow during dry periods, the so-called base flow. Aquifer storage, provided by a relatively small fluctuation of groundwater head in unconfined aquifers, allows the use of subsurface space to supply water for human and environmental needs, or for storing surface or subsurface water in wet periods in the same way artificial surface storage operates. Very often the storage provided by unconfined aquifers substantially exceeds available or economically viable surface storage. The fact that aquifers extend over ample areas of a basin means that the benefits of water storage are added to those of distribution and conveyance. Aquifers also perform a conveyance function although it must be said that this cannot compete with the higher flows conveyed by rivers or large canals. Long-term storage in and passage through a groundwater aquifer and non-saturated zone generally improves water quality by filtering out pathogenic microbes and many, although by no means all, other contaminants.

One important aspect to consider in groundwater management is its easy exploitation plus the generally lower cost of groundwater development in relation to dam and canal construction. Adequate planning and management of the different and complementary characteristics of surface and subsurface components through conjunctive use of surface and groundwater can achieve greater yields and economic and/or functional advantages than separate use of both components.

Groundwater has traditionally been used all over the world to back up supply for times of shortage and this practice constitutes a type of conjunctive use. The use of groundwater can also serve to defer the construction of costly surface water supply projects even at the expense of temporary overdrafting of the aquifer.

Another unquestionable argument in favor of the joint consideration of ground and surface water is the fact that they are hydraulically connected to a greater or lesser extent. Hydraulic works and the use of surface water and groundwater affect each other and other components of the hydrologic cycle. Groundwater recharge can be augmented by replenishing surface reservoirs or by return flow irrigation. Excessive return flow irrigation and canal losses in arid areas can produce drainage problems and an increase in salinity. Recharge to underlying aquifers from losing streams can decrease as a result of water being diverted upstream. Owing to 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 that must be addressed. In most of these scenarios conjunctive use is suitable for bringing out the positive effects and playing down the negative ones (NRC 1997).

The strongest argument in favor of conjunctive use is given by 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 (Sahuquillo 1985, 2000). Likewise, conjunctive use can be applied to obtain a better or cheaper solution to existing problems. Its aptness is not restricted to applications in arid or water scarce areas. On the contrary, if surface water and groundwater relationship and mutual influence are considered, conjunctive use is advisable in most areas including cases where scarcity or pollution problems exist. In most developed countries structural solutions are being questioned and a trend is gaining ground in favor of a better management of the existing elements rather than heavy investment in new construction. The most favorable and less controversial sites have already been built, keeping pace with a greater environmental conscience. In addition to environmental problems, large-scale hydraulic constructions imply legal, economic and social problems both in the developing and developed world. From now on, conjunctive use alternatives should be considered right from the start as a means of extending existing water resources.

Aquifers can constitute a source of water, and perform complementary functions of water storage, distribution and treatment that comprise classic components of a surface system. 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 hydrologic variability can provide economic, functional and environmental advantages. In order to quantify the potential benefits, more complex models are needed and much more alternatives have to be analyzed. Hitherto, water quality and contamination have only been indirectly or qualitatively considered in conjunctive use analysis. Only in some cases have total dissolved solids or gradient restriction used as surrogate parameters been explicitly modeled.

As with most human activities, the practice of conjunctive use is subject to and governed by many political, social and economic factors. The advantages to be obtained by putting conjunctive use into practice depend on physical factors, but rules and institutions permit or hamper its use. Rules governing water use, such as laws defining water rights, are critical. Water rights affect incentives for involvement in conjunctive management. Other aspects affecting conjunctive use are organizational. Conjunctive use can involve acquiring, transporting and storing water across different facilities so they can be organizationally complex. The more organizations are involved, the higher the transaction costs involved and the more they inhibit successful development and implementation of conjunctive use projects (Heikkila *et al.* 2001).

2 WHAT IS THE CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER?

The conjunctive use of surface water and groundwater, simply known in its abbreviated and extensively accepted form of conjunctive use, is a procedure for optimizing water resources for quantity and cost. It is also termed conjunctive water management and can be defined as the management of surface and groundwater resources in a coordinated operation for the purpose of ensuring that the total benefits of such a system exceed the sum of the benefits that would result from uncoordinated management of the separate components. In order to quantify the potential benefits, more complex models are needed and much more alternatives have to be analyzed.

3 METHODS OF CONJUNCTIVE USE

Two major types of conjunctive use systems are being employed, namely alternative conjunctive use systems and comprehensive conjunctive use systems. They differ in the use of subsurface storage. The simplest type is alternative conjunctive use referred to as passive conjunctive use by Todd & Priestadt (1997). In alternative use, the 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. Operating in this way, storage is provided through differences between extremes in the aquifer water levels, which are high at the end of wet periods and low at the end of dry ones. The other type is termed comprehensive by Todd (1980). In this system surface water is closely related to artificial groundwater recharge and a more complex infrastructure is required for its successful operation. Each type has its best application under different conditions of climate, geology, water supply availability, legal and regulatory environment and economic development.

The integration of conjunctive use into water resources planning and management offers great potential for enhancing the efficiency and cost effectiveness of regional water projects. This has been demonstrated by its advanced development and extensive use in developed countries like the USA, Israel and others. Its application to projects in developing countries will contribute towards solving many of their water supply problems and crises.

One new application for conjunctive use is to control the quality of a water supply. This use is currently limited to potable water for townships in developed countries. However this practice will become more extensive as world population increases and the contamination of both surface water and groundwater reduces the availability of potable water. This new branch of conjunctive use will include the treatment of effluent for reuse by applying the soil aquifer treatment (SAT) technique. The importance of reclaimed waste water is increasing owing to the forecast rise in urban population and in the future will comprise an important source of water that has to be duly integrated with other existing water resources.

In some cases planned overdraft can be carried out. This has been called *one-time reserve* and consists of pumping large quantities of groundwater for a long period of time, even as long as decades, before commencing the systematic use of surface water (Mandel 1967). This practice has been carried out in Israel to defer the construction of costly surface water projects. Temporary overexploitation of the aquifer system can precede the development of the more expensive surface water component of the alternative conjunctive use system. This is termed *deferred perennial yield* and in the USA has been employed in certain groundwater basins to eliminate wasteful subsurface outflow and losses by evapotranspiration from areas with shallow water tables (Todd 1980). Another strategy applied is to undertake several successive overexploitation stages (Schwarz 1980). A similar strategy has been proposed by Foster (2000), which could be successful if the necessary safeguards are adopted to avoid technical, legal and economic flaws.

Aquifer-river systems can be grouped with alternative conjunctive use operations if both of the two components are used in a coordinated management mode for water supply.

3.1 *Alternative use of surface water and groundwater*

In alternative conjunctive use, groundwater is generally used by preference over surface water during dry periods. Conversely, its use decreases and that of surface water increases during wet climatic cycles when more water is flowing in rivers and stored in reservoirs. In this type of conjunctive use a percentage of the water demand can be supplied by more than one source. As a portion of the water demand is allowed to be supplied alternatively from different sources depending on the situation of each component, whether surface or subsurface, the system can provide a higher water demand. In the case of surface water, its cost may not be totally related to the actual climatic conditions. If the surface water supply comes from several watersheds, dry conditions may prevail in some but not in others. Meeting demand by surface water from the watersheds that have wet climatic conditions may still be less expensive than pumping groundwater. The water supply for the Phoenix metropolitan area is an example of this type of scenario. This city, with its current population exceeding 3.5 million and located in the semiarid region of the Southwestern USA, has three principal potable water sources for supplying its demand. Two are surface water –one from the Salt-Verde rivers watershed and the other from the Colorado river watershed. The third source is groundwater from the extensive alluvial Salt River Valley aquifer system. When drought conditions prevail in the Salt-Verde rivers watershed they may not affect the Colorado river watershed. The water from the Colorado river, even though it is conveyed via the Central Arizona Project (CAP) Aqueduct over a distance of more than 200 km, proves to be less expensive than pumping groundwater from the deep wells of the local aquifer system.

Groundwater has been used extensively to supplement the limited surface water during dry climatic conditions, since improving the reliability of the system achieved with the use of groundwater at the right moments proves of even greater value than increasing supply. Without increasing surface storage, alternative conjunctive use schemes made use of this possibility to increase the firm yield. Water availability as well as groundwater in storage can be increased using more surface water during wet years, while lowering groundwater pumping as much as possible during the process, in areas where aquifers are used in dry or not so wet years. In many cases some new connecting elements have to be built or enlarged. One important aspect we need to stress is that this type of operation achieves a greater use of surface water without having to resort to artificial recharge. Similarly, for a fixed water demand, reliability can be increased by additional pumping. This works very well in regions where a certain amount of surface storage exists and there is no need to store in aquifers relatively intensive quantities of local or imported water during short periods of time. Losing rivers and leaking surface storage sites can be helpful for this type of conjunctive use.

Surprisingly enough, this obvious possibility of regularly using more surface water in wetter periods has not been applied very often. In many Mediterranean basins in Spain, besides the fields traditionally irrigated with prior rights, additional areas were irrigated with surface water in humid years. After the rapid increase of aquifer exploitation in the 1960s, they were integrated smoothly into the existing systems. So more surface water was used during wet periods and more groundwater was pumped during drought periods. In all such cases the schemes were proposed and handled by the users. In other cases, canals have been built by the relevant water authority to substitute groundwater by surface water in areas partly irrigated by groundwater. In further cases diverted surface water is insufficient to irrigate the entire area concerned and varies from dry to wet years, so alternative conjunctive use is instigated. More recently some of these existing practices in the Valencia region have been legally approved and additional alternative use schemes proposed.

The California Water Plan proposed a large-scale alternative conjunctive use for the Central Valley that is the first and largest planned scheme of this type. The total proposed storage between existing and proposed dams amounted to 24,000 Mm^3, and the subsurface storage used, bearing in mind the difference between forecast highest and lowest groundwater levels, was 37,000 Mm^3 (Fig. 1). By using this subsurface storage more surface water would be supplied without having to use artificial recharge (CDWR 1957). Notwithstanding, supplementary use of artificial recharge was envisaged in the plan. The proposal was not implemented as planned. Most likely owing to the extremely dif-

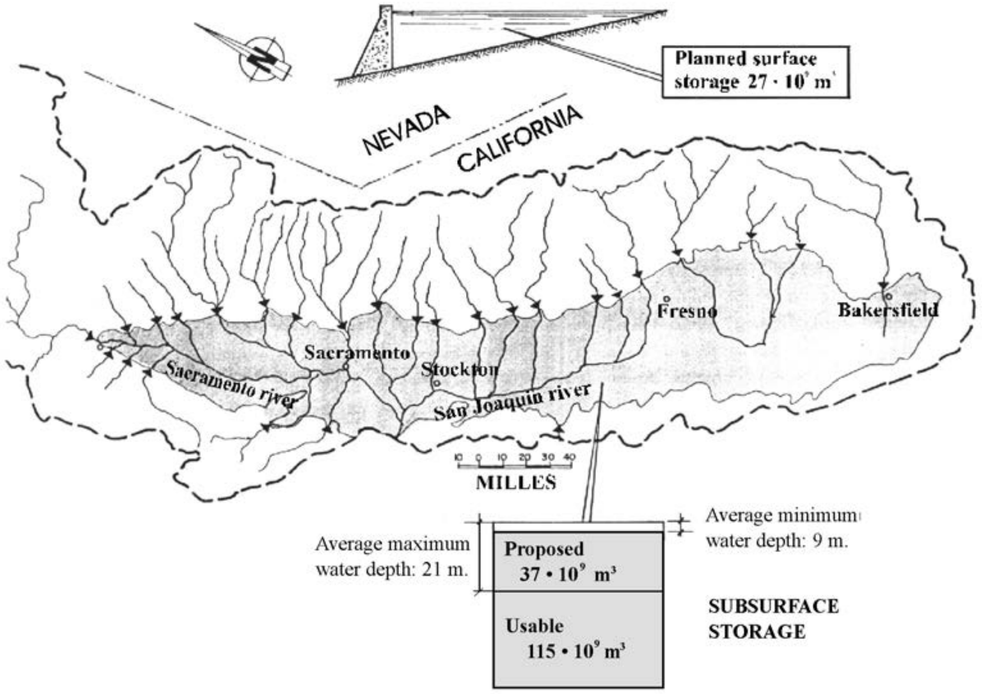

Figure 1. Conjunctive use in the Central Valley. California, USA. Modified from CDWR 1957.

ficult task of overcoming the legal, social, institutional and social problems in a large and complex area with a long history of federal, state and local water developments. Instead, many individual projects were built, including dams, canals and artificial recharge schemes. Later on in many areas *in-lieu recharge* was applied to satisfy a demand of water when there exists the possibility of using surface water that cannot be stored.

In the Mijares basin on the Mediterranean coast of Spain, 60 km north of Valencia, alternative conjunctive use is being carried out. There are three storage reservoirs, one upstream in the Mijares river with 100 Mm^3 of capacity, the second, downstream in the main river and the third in a non permanent tributary with 50 Mm^3 and 28 Mm^3 of storage respectively. Those last two reservoirs built in karstified limestone undergo substantial water losses, in the order of 45 Mm^3/yr, that recharge the old quaternary aquifer of La Plana de Castellón. The Mijares river also loses around 45 Mm^3/yr that recharge the aquifer with a water table that is 20 to 40 m below. About one third of the irrigated surface is supplied alternatively with surface water or groundwater, depending on how much surface water is available in the river and stored in reservoirs. Traditional irrigated fields cover one third of the total irrigated area using surface water while the other two thirds together with urban and industrial needs are covered exclusively by groundwater (Fig. 2). When more surface water is available, aquifer recharge increases, not only due to higher rainfall, but also to higher storage and river losses, in addition to recharge from some ephemeral streams flowing over the aquifer. The difference between high and lower volumes of water in storage in the aquifer can be as much as over 700 Mm^3, around four times the existing surface storage (Fig. 3). This means a very large percentage of the average surface water in the basin can be used. Simulation showed that alternatives involving larger areas irrigated alternatively using both surface water and groundwater could increase water availability slightly. Alternatives using artificial recharge scarcely augment water availability since a large portion of the total water resources are already captured.

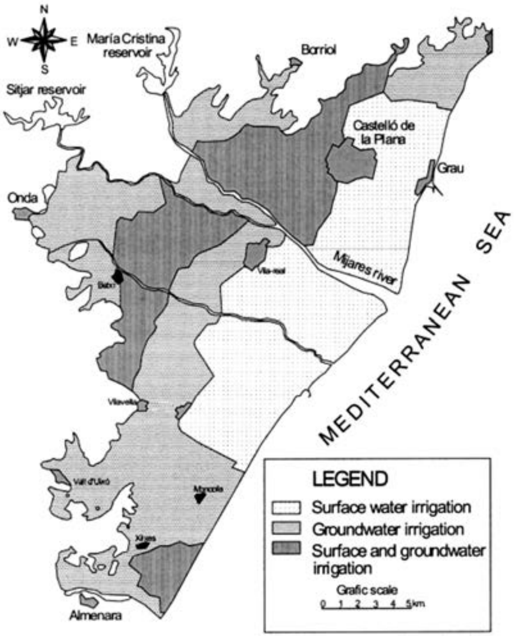

Figure 2. Conjunctive use in La Plana de Castellón, Spain.

A project to improve irrigation efficiency is currently being implemented in La Plana de Valencia area. This improvement will largely reduce aquifer recharge from surplus irrigation return flow and consequently its discharge to the Júcar river and the Albufera lake, south of the city of Valencia. This can produce negative repercussions on downstream surface water users and on the lake ecology. Additionally, La Plana de Valencia aquifer, although largely misused owing to the existence of extensive surface water resources, became an important component in the regional water resources system. Being a component of an alternative conjunctive use scheme it is easily capable of supplying enough water in drought periods and of implementing other uses, including a local water transfer to Alicante province in the south. In the same system the Júcar-Turia canal has been built to provide water to groundwater irrigators. In fact, the higher altitude areas to the west of the scheme continue to be irrigated with groundwater. The eastern areas, on the right bank of the canal, use more surface water in wet years while pumping more groundwater during dry ones. At the end of the 1991–95 drought period the Júcar Basin Water Agency, in conjunction with the Regional Ministry of Agriculture, drilled and installed 65 large capacity wells near the main canals in La Plana de Valencia area. They scarcely began to operate as the drought ended soon after the wells were installed, but a solution has been initiated to solve future drought problems. The concept of alternative conjunctive use is used all around the region as can be seen in Figure 4, where the areas irrigated by surface water alone, groundwater alone and jointly by both sources are indicated.

Instead of building new dams, alternative conjunctive use has been used to increase the capacity of the water supply system in the

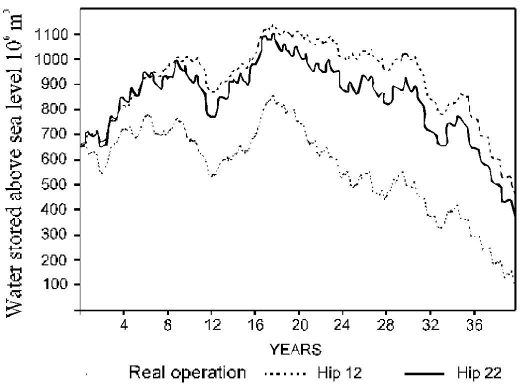

Figure 3. La Plana de Castellón aquifer. Change in storage for different conjunctive use alternatives.

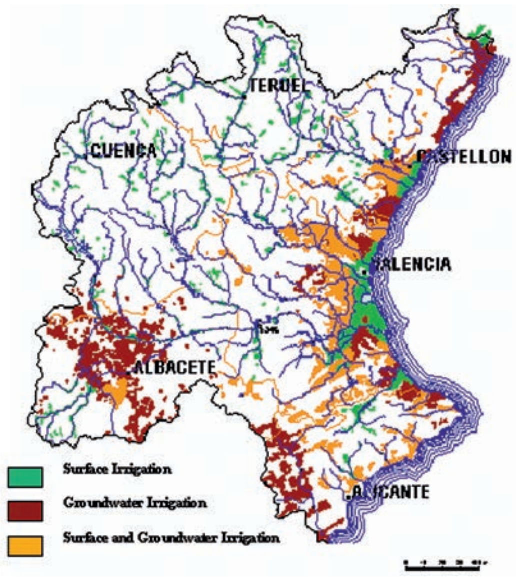

Figure 4. Conjunctive use in the Júcar basin, Spain.

Madrid metropolitan area. The existing capacity of wells has been increased up to 4 m^3/s, and additional increments have been envisaged. Thus an insurance against drought is provided increasing the guarantee of water supplies. Simulations of the conjunctive use show that a global increase in the annual firm yield is between two and tree times each m^3 of groundwater pumped (Sánchez 1986). The increase in yield mainly stems from a higher use of surface water in wet years.

Overexploited aquifers can be alleviated through conjunctive use with existing or projected surface water elements, although in some cases pumping patterns or their capacity have to be changed in some locations. This is the case in the Campo de Dalias aquifer being operated jointly with the new Beninar dam in the Adra river in Almeria, in the arid Southwestern Spain. Similar possibilities exist in many other schemes, as for instance in Los Arenales aquifer, where water levels have been decreasing steeply, operated jointly with the new Mingorria dam in the Adaja river in central Spain.

3.2 *Use of karstic springs*

Karstic aquifers in Spain are usually exploited with wells distributed all over the aquifer. In many cases it is difficult to site the wells owing to the often complicated topography of karstic terrain. In some cases the only, or most convenient, possibility available has been to locate wells near the spring, in the vicinity of existing canals or aqueducts used to transport the spring flow. In such cases pumping has a rapid effect on the spring flow. As pumping is carried out to augment the spring flow when natural flow is below existing water demand, the spring dries out and all the water required must be pumped once pumping starts. Operating in this way means that supply can be increased well over the natural flow of the spring during the irrigating season for urban or industrial purposes. Consequently, the usually large variations of flow in many of these karstic springs has been accommodated to water demand. The use of an aquifer as a subsurface reservoir is very intuitive when the spring dries out. In many cases very high flows have been obtained in wells –up to 1,200 L/s in two wells in Los Santos river spring in Valencia, Spain. In the Deifontes spring near Granada in Southern Spain, more than 2 m^3/s was provided for five 100-m deep wells. In other cases, the spring constitutes a component of more complex schemes. An example of this is the most interesting Marina Baja water supply scheme in Alicante province, some 100 km south of Valencia. The components involved are two dams and two aquifers one of which feeds El Algar spring, and reclaimed treated waste water used for irrigation purposes that is exchanged for fresh water for urban use. Alternative use of groundwater and surface water and the regulation of El Algar spring by wells solved the acute supply problem suffered by a very important tourist area near Alicante on the Mediterranean coast of Spain. The two wells near the spring can pump up to 400 L/s each and are used exclusively during dry periods. The underground storage provided by the aquifer during the extended drought of 1980–86 was estimated to be in the order of 40 Mm^3, three times the existing surface storage. There are interesting additional possibilities in karstic areas in Spain for regulating springs that could be included in more complex conjunctive use schemes.

3.3 *Aquifer-river systems*

Aquifer-river systems can be considered as a subgroup of alternative use. Here groundwater is used for complementing surface water in drier years or seasonally in the driest periods of the year and artificial recharge is less important. The alternative use concept can be applied to alluvial and other small aquifers in conjunction with the rivers connected to them. The particular feature involved here is that the mutual influences between river and aquifers are relatively more rapid that in other aquifers. Aquifer storage causes a delay between well pumping and a decrease in river flow, because this river-aquifer interaction is of foremost importance. The specific delay depends on the distance from the pumped well to the river, the aquifer-river connection and the aquifer geometry and diffusivity (ratio of transmissivity to aquifer storativity). Pumping during dry periods increases water availability in the same amount as the pumped quantities minus the effect of pumping on river flow. A part of the effect of pumping over river flows subsequently carries on over wet periods, when river flows are higher and demands lower (Fig. 5). Subsurface storage is created by groundwater level descent as a result of aquifer pumping. After pumping ceases, the depression on groundwater levels drops. An example of aquifer-river conjunctive use system can be seen in the irrigation of the valleys of the Arkansas and South Platte rivers in the state of Colorado in the USA. The extensive agriculture in this area relies on the coordinated use of surface water from these two major rivers and groundwater from the two large alluvial regional aquifers (Heikkila *et al*. 2001). The South Platte is connected to an aquifer estimated to contain more than 9,000 Mm^3 and the aquifer connected to the Arkansas river contains around 2,500 Mm^3. Possibilities of conjunctive use of aquifer-river systems were soon established and a great many techniques and methodologies were developed to analyze them (Moulder & Jenkins 1963, 1969, Morel-Seytoux *et al.* 1973).

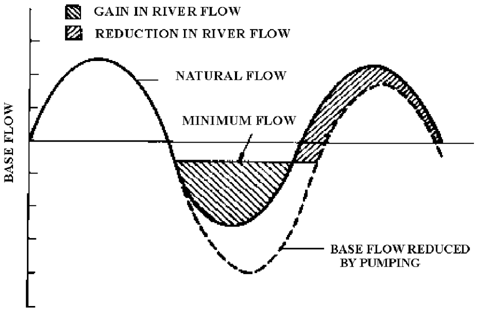

Figure 5. River augmentation with groundwater (after Downing *et al*. 1974).

In Colorado, a conflict emerged in the 1960s between surface water users and groundwater users when intensive pumping in the aquifer affected river flow. Conjunctive management of both resources solved the conflict. Colorado's prior appropriation doctrine allocates water rights on the basis of time priority for both surface and groundwater. Since surface water was developed earlier than groundwater, most surface rights have priority to most groundwater rights that are considered tributaries. Pumping tributary groundwater lowers surface water flows; this prevents the use of groundwater. To solve this conflict, Colorado introduced tributary groundwater use in the prior appropriation, taking into account the effect of groundwater pumping over river flow and forcing groundwater users to release the relevant compensation to the river flow. This practice was known as *river augmentation*. Temporary augmentation plans exist in both rivers. Any irrigators wishing to continue or increase their pumping must be granted permission by the State Engineer with estimates of the water they will pump and in addition the amount of water that they will put into the river to satisfy prior rights. Organizations in both basins have been merged to help small irrigators solve administrative problems. Without them each well owner would have to search for and negotiate agreements for surplus water, and make it available to the State Engineer, who in turn would have thousands more plans to keep track of and well owners to monitor (Heikkila *et al.* 2001). In the South Platte some artificial recharge is undertaken to supplement stream flow, the fact that it exists here and not in the Arkansas probably being due to the smaller width of the aquifer that will produce a faster return of recharged water to the river.

In the UK a very efficient use is being made of aquifer-river systems. Aquifers are mainly in consolidated rocks, limestone, sandstone and chalk. They are generally small in size and their storativity is less than in alluvial deposits, which means that pumping has a relatively fast effect on river flow. Groundwater is pumped and piped into certain rivers during dry periods to maintain adequate flows in them to meet requirements, including water supply and environmental demands. These schemes have also been termed *river augmentation* and are used systematically in water planning in England and Wales (Downing *et al.* 1974, Skinner 1984). Of course, some of the additional pumping in dry periods is carried out to provide direct water supply to other demands. Some of the advantages of river augmentation over other alternatives for increasing water availability are their lower cost and their flexibility of development. Forecasts for future water demands have been very volatile and very frequently the actual demand for water has been much lower than envisaged. Other advantages are the possibility of exploiting resources that would not otherwise be used, because they are far away from demand centres or have local pockets of poorer quality groundwater or high nitrate concentration. In most cases the implementation of river augmentation schemes developed in the UK have been preceded by a substantial program of groundwater investigation to establish the fact that the aquifer's yield and storage characteristics are adequate, to establish the net gain and to establish water quality constraints. These may be important both in scheme design, if blending of poorer quality water is to take place, and also be relevant to ecological interests. Finally, investigation is called for to establish and investigate any potential public or environmental concern (Skinner 1983). Net gain is a measure of a combined groundwater and river water resource scheme, which takes into account the fact that exploitation of the aquifer will deplete the natural flow in the river and thus reduce the natural catchment's yield. For augmentation schemes the net gain is the proportion of the water discharged to the water course which contributes to increased river flow. It can be determined by flow measurements and correlation with unaffected catchments or by modelling.

3.4 *Transformation of the aquifer-river relationship owing to groundwater extraction and irrigation*

Heavily exploited aquifers can change their relation with a previously gaining river that is converted to loser thereby increasing the possibilities of storing water in the aquifer. A well-known case is the Lower Llobregat river that became a loser after the aquifers where heavily pumped. La Plana de Castellón aquifer, previously mentioned, appeared to have been draining in the region about 20 Mm^3/yr into the Mijares river at the beginning of the 20th century but now the river recharges in the region of 40 to 50 Mm^3/yr to the aquifer. This situation is very common in many permanent rivers on the Mediterranean coast of Spain, where most rivers lose water recharging the aquifers at the entrance to the coastal plain, in many cases this reversal being produced by aquifer exploitation. This situation can be utilized to augment aquifer recharge, in some cases through adequate water releases from dam storage and well-planned operation of surface storage.

Water loss by flows in unlined canals and by crop irrigation infiltrates and eventually reaches the aquifer. It is frequently referred to as incidental recharge. Storm water releases from dams that infiltrate from river channels are also included in this type as are losses from surface water impoundments. Incidental recharge is frequently used as part of conjunctive use schemes to mitigate the effects of groundwater pumping. When incidental recharge is extensively applied the systems have been frequently referred to as limited conjunctive use systems (Todd & Priestadt 1997). Surface water losses by infiltration from unlined delivery canals, ditches and from overirrigation of crops has been used to control groundwater decline in large conjunctive use projects. This methodology is employed in Imperial County, California, one of the largest agricultural regions in the USA.

3.5 *Alleviation of land drainage and salinization in irrigated areas and conjunctive use*

In many irrigation projects aquifer recharge has increased owing to water losses from conveyance and distribution systems in addition to the infiltration surplus of applied water. Such increments in aquifer recharge can increase the potential for groundwater development, and in arid zones have also produced drainage and salinity problems owing to rising groundwater levels. This is a habitual problem of large surface irrigation projects in arid countries. The Planning Commission of the Government of India has recognized problems of water logging as a result of water table rising which is about 1 m/yr on average in several schemes (Sondi *et al*. 1989). Consequently they suggested, in addition to enhanced water use efficiency, increasing groundwater use jointly with canal water to augment supplies and prevent land deterioration. The total area affected by waterlogging due to both groundwater rising and poorly controlled and inefficient irrigation was estimated in 1990 at 8.5 million ha, while other estimates pointed to 1.6 million ha (Burke & Moench 2000).

The drainage and salinity problems created in the Punjab Plain in Pakistan has the same origin of surface water infiltration along the irrigation system of the Indus river and its tributaries. Irrigation started to be intensively developed in the late 19th century under British colonial rule. During each year of the mid-20th century 25,000 ha had to be abandoned, and 2 million ha out of a total of the 14 million ha irrigated were abandoned in 1960. The irrigated area is dominated by 43 large-scale canals involving a total length of 65,000 km, in addition to secondary and tertiary canals. The 15 largest have capacities of between 280 m^3/s and 600 m^3/s. They are fed by several large dams including the Mangla dam and the Tarbela dam with 5,500 Mm^3 and 10,600 Mm^3 of storage respectively. Most canals are unlined and undergo heavy losses that feed the huge aquifer below. Water levels rose 20 to 30 m, and up to 60 m in some places, over the course of 80 to 100 years. The problem has been the subject of intensive studies as from the 1960s. The water resources group of Harvard University proposed drilling 32,000 high capacity wells to pump 70,000 Mm^3/yr to lower the water table, taking out the pumped salty water to the sea through lined canals and using the fresh groundwater jointly with surface water to increase irrigation (Fiering 1971). A public tubewell development denominated Salinity Control and Reclamation Projects (SCARP) started. Since drainage projects do not provide an immediate economic profit most groundwater pumped from wells was freshwater that was used to increase irrigation. In the same way the policy of pumping saline water and lining canals to prevent the infiltration of salt water was not addressed. On the contrary, when brackish water was pumped into a well it was blended with surface water for irrigation purposes. As a result, the salt balance of the aquifer rose instead of falling. In some areas pumping and mixing of water of diverse salinities has increased salinity erratically. Nevertheless, fairly substantial improvements in drainage and a drop in soil salinity were achieved. Another important aspect not considered in early plans was the private sector's capacity to obtain funding to develop groundwater and drill deep high capacity wells, a capacity that was triggered by SCARP work, (Burke & Moench 2000, van Steenbergen & Oliemans, in press). Some analysts argue that groundwater overexploitation exists in the Punjab but the information on the subject is not clear. In any case the target in heavily irrigated arid areas in the Third World is to use existing aquifers, additionally recharged by return flow irrigation and by surface water infiltrated in the conveyance and distribution canals, jointly with surface water, while maintaining groundwater levels below prescribed heads to contain salinity and drainage problems. It is equally important to control migration and disturbance of the more saline groundwater bodies so that groundwater quality can be maintained in addition to augmenting total water availability. A great deal of hydrogeological analysis and monitoring is needed in addition to the long term simulation of groundwater flow and salinity.

The same drainage and salinity problem exists in Egypt, Northern China and the Asiatic countries of the former USSR where Kats (1975) suggested the joint use with surface water of the estimated 25,000 Mm^3 drained annually from irrigated lands. Losses in canals and distribution systems can be lowered by lining conduits, but if losses feed usable aquifers and conjunctive use is carried out, it can be more advisable to leave canals unlined, unless drainage problems exist and water losses contribute to maintaining too high a groundwater level (Task Committee on Water Conservation 1981).

3.5.1 *Comprehensive conjunctive use of surface water and groundwater*

In comprehensive conjunctive use systems surface water is actively developed for deliberate aquifer storage and groundwater pumping is controlled. These systems have many interrelated components and are composed of storage, diversion, treatment, recharge, extraction and delivery facilities. These systems are usually planned, designed and constructed by engineers, water planners and water utility operators. In some cases not all the components previously described are included. Other facilities are added as the need arises by water demand increase over time. Some of these systems, particularly those for agricultural irrigation, may have started as surface water facilities consisting only of dams, surface reservoirs and water conveyance units. Wells were then added and even alternative conjunctive use was employed for some time. With the advent of new surface water sources, like that from imported water, there was a need to store the unused supplies. Artificial groundwater recharge facilities were then constructed and added to the system. At this time or shortly after, the use of reclaimed water was introduced and this component was added to the system. Typical examples of these systems are those operated by the Metropolitan Water District of Southern California (MWD) and the combined Salt River Project (SRP) –Central Arizona Project (CAP) system. The former is the principal water purveyor for the large Los Angeles, California metropolitan area with a population in excess of 17 million. The latter provides water for municipal, industrial and agricultural uses to the Phoenix, Arizona metropolitan area with a population of over 3.5 million and the highest growth rate in the USA. Conjunctive use practices employing these systems are not only comprehensive, combining the use of groundwater with local, imported and reclaimed surface water, but are also integrated. An integrated water management system takes into account not only water supply objectives, but also related goals such as water quality management and environmental factors like the maintenance of streamflow and riparian habitats (Todd & Priestadt 1997).

The success of comprehensive conjunctive use depends on the availability of large storage capacity in the aquifers capable of retaining sufficient volume of surface water to meet future supply demands. Artificial groundwater recharge is an indispensable component of this type of conjunctive use system. The surface water to be stored can come from any available source. It could be from local rivers and their tributaries, from municipal, industrial and agricultural recycled water, from desalted water or from an imported water source. Aquifers offer very positive advantages as storage reservoirs. The main ones are no water loss by evaporation, the need for only small land parcels to site the recharge facilities, the potential for water treatment by natural, biological, physical and chemical processes, stable water temperature and natural water conveyance to wells. Perhaps the most important attribute of artificial recharge is its very low cost compared to that of storing the water in surface impoundments (Lluria 1987).

There are several concepts and terms that are commonly used along with comprehensive conjunctive use systems. These appear in the literature of this water management technique. One is water banking. It is defined as a conjunctive use operation that stores surface water in aquifers by artificial recharge techniques during wet years or when surface water from importation or recycling is available in surplus quantities and extracts it for use during dry periods or when water demand has increased beyond the forecast annual level. The other important concept is that of indirect or *in-lieu* recharge. It describes a conjunctive use operation consisting of delivering a volume of surface water to a predominantly groundwater user who then refrains from pumping that same volume of water during an established time period. By following this procedure the local aquifer has an opportunity to recover by natural recharge. However, this recovery is limited and controlled by local and regional climatological and geological factors. Recovery will be slow in arid and semi-arid regions and in confined and fractured bedrock aquifers, while in humid temperature and subtropical regions and in alluvial and glacial aquifers the recovery could take place in a relatively short period of time. In the state of California, *in-lieu* recharge is sometimes considered an integral conjunctive use method and not just part of one (Jaquette 1981, AGWA-WEF-MW 2000). In the state of Arizona, *in-lieu* water is legally defined as "water that is delivered by a storer to a groundwater savings facility pursuant to permits issued under the Underground Storage, Savings and Replenishment Act (a law passed by the state's legislature) and that is used in an active management area (an area with groundwater overdraft) by the recipient on a *gallon-for-gallon basis* for groundwater that otherwise would have been pumped from within the active management area".

Comprehensive conjunctive use systems originated in the state of California, in the USA. They are now operating or are being implemented in the other states of the semiarid southwestern region of North America including Mexico. During the decade of the 1980s, these systems were adopted with certain modifications in the eastern and northwestern humid regions of the USA and in Canada. In the systems of the southwestern regions of North America the predominant artificial groundwater recharge method is direct surface recharge, frequently referred to as water-spreading. This consists of direct percolation of the surface water from recharge basins constructed on highly permeable soils to the aquifer. The aquifer has to be unconfined to receive the surface water. The recharge basins are located predominantly in or near the channel of a river and the aquifers are in most cases alluvial. Water-spreading facilities are more cost-effective when they store large volumes of water and when the required infrastructure is already built and in close proximity to the recharge site (Lluria & Fisk 1995). The comprehensive conjunctive use method that originated in the Eastern USA uses direct subsurface methods. It was first employed in the state of Florida, and its use was originally and still remains predominantly for drinking water supply. It is known as aquifer storage recovery (ASR) and consists of the underground storage of treated water during periods of low demand and its recovery for potable water uses during periods of high demand. The recharge operation is carried out with dual-purpose wells that both inject the water into the aquifer and recover it by pumping. This method is well suited for use in areas where direct surface recharge is not applicable. Areas where the usable aquifers for storage purposes are confined or where upper unconfined aquifers are contaminated can benefit from this technique. Storage of potable water is carried out by several municipal water utilities in the deep confined Floridian aquifer in the state of Florida where the practice of ASR has been very successful (Pyne 1989). ASR is also used in arid and semiarid regions like Kuwait and in Las Vegas in the state of Nevada in the USA. It is becoming an important water resources management tool in the UK and in several other northern European countries. The groundwater reservoir in the Palaeogene sands and chalk aquifers existing beneath the London clay in the Thames river was first exploited in the 18th century. Over the next 200 years the aquifers were heavily pumped. The water level gradually fell and saline water from the tidal Thames river intruded into the aquifers. For this reason and owing to a 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 19th and early 20th centuries. Between 1800 and 1965 the aquifers in the central part of the London basin provided some 5,700 Mm^3. But the chalk aquifer is still used in the Lee Valley, and is recharged through wells during the winter with treated water from the Thames and Lee rivers. In Spain artificial recharge is scantily used. Up to 20 Mm^3/yr of treated potable water from the Barcelona supply is recharged by dual purpose wells, to be stored in the Delta of Llobregat 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 Llobregat river (Custodio *et al.* 1969, UK Groundwater Forum 1998).

The unit cost of recharge using ASR is considerably higher than using water spreading. The volume of water that a well or a group of wells can recharge is considerably less than that which a basin or group of basins, sited on permeable soil, can percolate. In most cases the cost of construction, operation and maintenance of a well is considerably higher than that of a recharge basin. Thus, given that favorable hydraulic conditions prevail in surface and near surface soils and in the unsaturated zone, that the receiving aquifer is unconfined and that there are no sources of contamination from the surface to the aquifer and within this, water-spreading is the favorable recharge alternative. If however all the infrastructure wells and conveyance system already exist, the ASR system can be a cost-effective supplementary system to water-spreading systems (Lluria & Macia 1997).

The objective of artificial recharge of alluvial aquifers in many industrialised countries in Central Europe is not to store water or alleviate overexploited aquifers but rather to use the purifying capacity of the non-saturated zone the water has to cross before arriving at the aquifer. Artificial recharge in the Rhine alluvial aquifers began in the late 19th century. The Rhine water is highly polluted owing to the intensively industrialised and populated basin that drains parts of six nations –Switzerland, France, Austria, Luxembourg, Germany and the Netherlands– with more than 32 million habitants that contribute to its pollution and depend on the river for water supply. For decades the quality of the recharged water was excellent, but the increase in industrialisation caused an important increase in river pollution. As a result, the quality of the recharged water decreased and forced the waterworks to use sophisticated water treatments (Wilderer *et al.* 1985). Since the mid-19th century dune water along the Dutch coast was used for the drinking water supply of Amsterdam in 1853 and The Hague in 1874. The augment of needs made insufficient the aquifer resources. In 1955, the dunes in The Hague begun to be recharged with surface water of the Rhine and in 1957 the Rhine water transported 80 km from the Lek river started to recharge the dunes near Amsterdam and in the northern part of the Netherlands. The polluted surface water is pre-treated before the transportation to the dunes with flocculation, sedimentation, coagulation, rapid sand filtration and chlorination. Organic substances are partly removed during the infiltration process. The primary aim of artificial recharge in the Dutch dunes was neither storage in the aquifers nor improving water quality, although both functions are performed, but restoration of the equilibrium between fresh and saltwater in the dunes (Piet & Zoeteman 1985).

3.6 *Comparison of conjunctive use methods*

In arid areas surface water is usually less important and its variability is extremely high. Alternative conjunctive use loses some of its advantages, and has no point when water is imported through large canals or aqueducts. In schemes such as these, artificial recharge is the appropriate option. Southern California, Israel and the Central Arizona Project are perfect examples of it. Surface water, in areas where alternative conjunctive use is employed, usually has a wide temporal variability, but flow is not as sporadic as it is in classic ephemeral rivers in arid environments, even though permanent rivers frequently exist in the wetter upper part of a basin that can be used jointly with aquifers in dryer downstream reaches. In most cases this topology is suitable for the alternative use concept.

Very often artificial recharge has been identified with conjunctive use thanks to the prestige of the water schemes applied in Israel and Southern California, thereby relegating other options or excluding them altogether, and these may perhaps be more fitting in different situations. This can be true in less economically and technically developed countries, where the influence of artificial recharge operation and maintenance cost in final water could be high for irrigation needs. Artificial recharge requires adequate technical operation and monitoring and permanent supervision. Furthermore it cannot be implemented without well-identified users, disposed to pay the operation and maintenance cost of recharge, users who would additionally need to be reassured that the recharged water will not be pumped by others. This involves a high degree of institutional development that is far from being achieved in most countries. These difficulties hamper the development of large-scale artificial recharge projects in extensive irrigation districts unless they are operated and supported by governments. In any case, it appears advisable to benefit whenever the possibility exists of enhancing aquifer recharge through the losing reaches of certain rivers or leaking reservoirs though appropriate utilization of dams. Besides the development of methods for enhancing natural aquifer recharge or lowering the cost of artificial recharge should be promoted.

One important initiative to address overdraft in the state of Gujarat in India has emerged through a spontaneous and popular movement for groundwater recharge that began around 1990 (Burke & Moench 2000, van Steenbergen, this volume). Hindu religious organizations and civil institutions have supported this movement that is interesting in many aspects. Although there is no data available on the amounts of water recharged at Gujarat, the main difficulty seems to be the scarcity of water available for recharge in very arid areas, even though this can vary in different hydrologic conditions.

Alternative use apparently affords possibilities and opportunities particularly in all social and economic situations. In most Spanish basins it is possible to implement alternative use schemes. In any case, the possibilities depend on the variability of surface flows, aquifer storage, location and water volumes required by the different demands, aquifer situation and properties and their relation with rivers. But as a general rule, advantages can be obtained whenever there exists an aquifer, a river with or without a dam, or the possibility of building it, and unsatisfied demands for water. Users have promoted most of the alternative use schemes in the Mediterranean coast of Spain. They appear to work easily and without any major problems and they are accepted by the river basin agencies where they are located and by the water authorities of Spanish central government. Most existing alternative use schemes started before 1985, when the existing water legislation was changed. Prior to 1985, groundwater was private property appropriated by its use. After the new 1985 Water Act came into force, non-appropriated groundwater has the same public consideration as surface water and both surface water and groundwater are appropriated through a permit process. It is clear that La Plana de Castellón-Mijares river, the Júcar-Turia canal cases, and most alternative use schemes in the Júcar basin would not have encountered any problems with the current Act as they did not exist under the previous 1857 Act. The schemes of La Plana de Valencia and the inclusion of wells in the Madrid water supply system began after the law was changed in 1985 and for the moment no particular problems are envisaged. The only case where some problems have arisen is in the Marina Baja scheme as a result of the susceptibility of El Algar spring irrigators who were afraid of the heavy influence of urban and tourist industry users and therefore raised some objections. In general, institutional or legal problems are not expected to be encountered over adding a new dam, canal or aqueduct to an existing system in order to complement groundwater deficits with variable water flow, or to enlarge groundwater through alternative conjunctive use. Probably the same would appear true for introducing additional pumping in an aquifer in dry years in order to augment water availability, as is the case with the Madrid aquifer. Problems can arise in cases of a high competition for water, if aquifers are heavily pumped or in the case where an aquifer is overexploited. Nevertheless, there will always be groundwater users involved in different hydrologic, economic or social situations who are less inclined towards conjunctive use or object to certain alternatives. Negotiations are always necessary plus the creation of a groundwater users association, as required by Spanish law but actually applied in very few cases, which would seem advisable in the most important aquifers. At all events some kind of negotiation may prove necessary or advisable.

4 CONJUNCTIVE USE POTENTIAL IN THE DEVELOPING WORLD

Over the past 20 years many nations have increased groundwater exploitation for agricultural irrigation purposes. Groundwater resources have been underpinning the *green revolution* in many Asian nations. Access to groundwater for irrigation purposes is making a very positive impact on subsistence and income for poor farmers, and in many cases also reduces the need for the rural poor to migrate during droughts. Groundwater use reduces agricultural risk and enables farmers to invest and to increase production. Some governments in developing countries have encouraged groundwater development to meet the needs of rural populations as a mechanism for increasing their political popularity, regardless of considering the condition of aquifers. Virtually all Indian government organizations concerned with groundwater development promote resource exploitation rather than resource management; and well drilling and pumping energy remain highly subsidized despite widespread evidence of aquifer overdraft (Burke & Moench 2000, Foster 2000, Burke, this volume, Deb Roy & Shah, this volume, Moench, this volume).

In some countries, electricity tariffs for agricultural use are very low, and in some instances an annual flat rate is applied independent of consumption, and well construction is also subsidized. Groundwater undervaluation leads to inefficient allocation and overdraft. National water laws generally exist in developing countries, even though water institutions used to be understaffed and weakly funded, but increasing their financial budget and improving the legislations and regulations is not sufficient to improve matters. There most probably remains an enormous task of evaluating the hydrologic and hydrogeological resources, including their uncertainties and relevant aspects concerning their interaction, water quality and vulnerability to pollution, in addition to other technical and economic aspects (Foster 2000). Conjunctive use can undoubtedly improve some of the existing problems, such as the previously mentioned proposal by the Planning Commission of the Government of India.

Conjunctive use can undoubtedly increase water availability in many existing or planned schemes where both surface water and groundwater resources exist. In some cases conjunctive use is claimed to be applied but only when advantage is taken of the conveyance, distribution or storage capacity of its components and the system is properly operated can it be properly considered as conjunctive use. Both major types of conjunctive use, alternative and comprehensive have the same water management goals of increasing total water supplies and their reliability. They accomplish these goals in very similar ways. In both systems aquifer storage plays a key role. Basins with drainage problems pointed out by the Planning Commission of the Government of India and areas with overexploited aquifers where surface resources are also important are clear options for analyzing alternative use possibilities. Integration of groundwater is also a clear option for the enlargement of surface water systems via conjunctive use, whether by alternative conjunctive use, artificial recharge or both, although for irrigation demands in less developed countries alternative conjunctive use appears to have more possibilities. In any case, each project should be addressed knowing the physical, political, legal and institutional aspects involved, including the idiosyncrasy and cultural aspects of the population.

One of the most interesting aquifers in India is the Ganges basin filled with unconsolidated alluvial deposits to a depth of 6,000 m and receiving an annual average rainfall of 1,500 mm, with a tremendous amount of water in storage and connected to the fifth largest river in terms of annual flow in the world. Results of models appear to indicate that low flows in the dry season at the Farakha dam, near the Bangladesh border, will suffer intense decline if groundwater extraction in the aquifer continues to grow (Burke & Moench 2000). Nevertheless river flow augmentation by high capacity wells to offset possible flow declines appears to be a promising possibility and would extend the possibilities of increasing water availability. In addition, the possibilities of artificial aquifer recharge from the Ganges water diverted through recharge wells and/or unlined canals as suggested by Chaturvedi & Shirastava (1979) are worth studying in depth.

Both major types of conjunctive use, alternative and comprehensive, have the same water management goals of increasing total water supplies and their reliability. They accomplish these goals in very similar ways. In both, aquifer storage plays a key role.

5 INTEGRATION OF GROUNDWATER IN HYDROLOGIC PLANNING

In drought periods groundwater can help to lower water deficits if it is pumped above normal. There are aquifers that can be incorporated very easily into many hydraulic systems based mainly, or exclusively, on surface water. Pumped water can be incorporated into a canal, river or storage element, or indeed be used directly. In many cases this can be done without having to build any major conduit or component. In others, some additional component does have to be added, but generally involves minor costs and construction delays. Consequently, after the 1960s increase in groundwater pumping has been used to alleviate drought in many countries. In Europe, groundwater exploitation was increased during the 1975–76 drought. In the UK such a policy was carried out in England and Wales in aquifer-river systems where some of the pilot studies for *water augmentation schemes* had been carried out in previous years. The augmentation concept in river-aquifer systems is used in the South Platte and Arkansas rivers in the state of Colorado. In the western states of the USA an increase in groundwater pumping is advocated during drought periods and so is conjunctive use in general. In most cases including California and Arizona, artificial recharge is used to store unused surface water and to store imported water. In California, increased groundwater use has contributed towards lowering the effects of periodic droughts, and recently different criteria exist for water supply during wet and dry years, with groundwater use during such periods being significantly increased.

In Spain, in addition to significant cases of alternative conjunctive use mainly in the Júcar basin, users increase groundwater pumping in dry years although it must be said that reliable statistics do not exist. A precise knowledge of existing water use, surface water intakes, pumping from aquifers and irrigation for industrial and urban purposes plus return flow to rivers and aquifers appears to be called for if water resources are to be managed appropriately. In general terms, these data are imprecise and of scant reliability in many countries. In emergency situations all these resources could be required, and the influence of changes in water use during such periods on water quantity and quality is also of prime importance. This leads on to the need for fully integrating groundwater with other water resources in all planning and management stages –a much more complicated issue. The application of conjunctive use adds the complexity of how to operate each storage element of the system, dam or aquifer, as a function of the state of each component, to the problem of predicting surface flow. In addition, mutual influences between surface water and groundwater impose the need for much more complex models extended to much lengthier periods of time if stochastic simulation of hydrologic time series are required. An integrated conjunctive system dynamically conceived and enlarged, and operated in line with the particular features existing in water demands, including water quality problems and hydrologic variability and uncertainties, can provide important economic and functional advantages. The price to be paid for this is the need to analyze many more alternatives with more complex tools.

Conjunctive use should not be limited to arid zones; nor should it be utilized solely in areas with problems of water scarcity or quality. Relevant cases of conjunctive use in humid zones are the *river augmentation schemes* in the UK mentioned above. If groundwater is fully integrated into water planning and management, more efficient schemes can be achieved obtaining technical, economic and environmental gains. One important aspect is the improved guarantee of water yields as a result of aquifer integration. But no less important in some cases is the buffer role provided by the large quantities of water stored in many aquifers. This allows a tempering of the uncertainties encountered in the water demand or hydrologic parameters related to river discharge, aquifer recharge, hydrodynamic aquifer parameters or river-aquifer interactions. An appropriate monitoring and data acquisition program of both surface and subsurface components can improve hydrologic knowledge. Consequently, system operation should be adapted to the improved parameters and data, but if uncertainties are duly taken into account, the resulting changes should only involve small investments and supplementary costs in many cases.

Failing to take these possibilities for meeting water demands into account entails high investments that can be avoided, and forgoing the guarantees and increases in water availability provided by the integration of aquifers into water resources systems. Improvement in its guaranteeing role is surely the main reason why conjunctive use appears to be gaining acceptance in many areas, even though more comprehensive methods of analysis are not always employed.

The planning of surface and subsurface components in alternative use schemes is far more complex than in schemes including artificial recharge. In the latter the distribution of pumping operations and artificial recharge in the aquifer is crucial, as they constitute the local transport and distribution for water. For moderately complex alternative use schemes involving several aquifers, dams, aqueducts and water demands units, planning and operation of the whole system can be exceedingly complex. In such systems operation is even more complex if uncertainties in future surface water availability are taken into consideration. This issue depends on the state of the system including the surface and subsurface components, river flow and water quality.

Simulation models of conjunctive use of groundwater and surface water must be capable of reproducing, or of generating in the most general cases, flows in rivers, canals and aqueducts, water-levels in aquifers and water transfers between rivers and aquifers including return flow of applied water. The behaviour of different water requirements and physical and environmental restrictions should also be included. One issue in the hydrologic modelling of complex systems is the level of complexity in aquifer models necessary for a specific application. Simulating a large number of alternatives for aquifer operation with finite differences or finite elements *distributed models* to achieve the required accuracy calls for lengthy computer times. The Department of Hydraulic and Environmental Engineering of the Politechnical University of Valencia has developed an SDS named AQUATOOL with a very efficient and user-friendly interface for designing the system, access to data bases and model parameters, alternative formulations, data input and output. Result presentation and report editing has been developed to optimise and simulate complex systems including conjunctive use. This method can handle several tens of dams, aquifers and demand areas including rivers, canals and aqueducts, includes return flow to surface water or aquifers and aquifer-river interaction and can also handle most non-linearity scenarios. It has been applied in many Spanish basins; the model for the Segura basin for instance has 15 reservoirs, 93 canals, 19 aquifers and 50 demand areas. Aquifer simulation is explicitly carried out using the eigenvalue method that simulates distributed aquifers with the same precision as that obtained with finite differences or finite element methods, without any loss of precision (Sahuquillo 1983, Andreu & Sahuquillo 1987, Andreu *et al.*1996). The program allows monthly simulations to be made of complex conjunctive use systems over the course of 50 or more years in just a few minutes on a PC. Analysing many alternatives including uncertainties in hydrologic, hydrogeological or economic parameters is quite easy. One of the advantages of analysing alternative conjunctive use in this manner is the possibility of performing simulation with large hydrologic series in key points of the system to check the behaviour of the system during different uncertain hydrologic conditions.

6 CONCLUSIONS

Groundwater use for water supply and irrigation is constantly on the rise all over the world. This rise has been particularly important in developing countries where it has constituted one of the main supports backing the *green revolution*. In many cases the increase in groundwater extraction has created, or is in the process of creating, serious water level declines that increase pumping cost, decline in river base-flow, land subsidence problems and environmental problems. For this reason there is a growing interest both in groundwater resources and in the advantages that can be provided by conjunctive use of groundwater and surface water.

Conjunctive use through the different and complementary characteristics and behaviour of surface water and groundwater make it possible to solve the specific needs of water quantity and quality more adequately and economically than if both resources are used separately. Groundwater can provide additional resources in addition to the means for water storage, distribution and treatment, which can be combined advantageously with surface water resources.

Artificial recharge is used to store local or imported surface water in the arid zones of developed countries such as the cases of California, Arizona and Israel –the best known and emblematic. The generally elevated cost of transporting, treating and recharging water prevents its generalized use for irrigation purposes in developing countries where the so-called alternative conjunctive use can be adequate for increasing water availability in several cases. One such case is where irrigation with surface water has created salinity and drainage problems. The yield of surface water projects can be augmented if groundwater is included in the system or operated jointly with surface components without needing augment the surface storage capacity. Lately the capture of river flow can be increased through *water augmentation* schemes or aquifer-river systems. Increase of availability is achieved due to passing the effect of the groundwater pumping to subsequent periods of river flow. This concept could be analyzed for use with large capacity wells in high transmissive aquifers like the alluvial aquifer of the Ganges river, perhaps combined with the possibility of using artificial recharge.

Above mentioned possibilities lead on to the need for fully integrating groundwater into other water resources in all planning and management stages. This in turn implies the need for more complicated models in view of the need to represent surface water, groundwater and river-aquifer flow interchange during much larger modelling periods. The need for modelling over lengthy time periods stems from the fact that groundwater evolution in large aquifers is quite slow as a result of the large amounts of groundwater in storage in large-scale aquifers and of surface flow variability. Different time scales in the behaviour of groundwater and surface water components impose restrictions that should be addressed with adequate models.

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