CONJUNCTIVE USE OF GROUND AND SURFACE WATERS: CLASSICAL APPROACHES AND CALIFORNIA'S EXAMPLES

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Abstract

Conjunctive use of ground and surface waters is one of several relatively new techniques with ancient roots for improving water system performance. The contemporary application of conjunctive use has become increasingly sophisticated and integrated with other innovative and traditional water management techniques, such as water transfers, water reuse, demand management, and aquifer remediation. Conjunctive use and other innovative operations and management techniques often work best when integrated with traditional options for water system management. Implementation typically requires changes in infrastructure and operations, as well as changes in institutions and institutional arrangements. This paper reviews the benefits, methods, management applications, problems, operations and prospects of conjunctive use of ground and surface waters classically and in California's examples. California's intense water development has motivated the implementation of an elaborate and broad range of conjunctive use strategies focused on flexibility and efficiency in water allocation. These strategies provide new ways of coordinating traditional conjunctive use operations, and are discussed here. .

1 INTRODUCTION

Most regions in the world depend on a mixture of surface and groundwater to supply their water demands. This mix of supplies is especially important in semi-arid and arid regions where seasonal and annual variability in surface water is more pronounced. Humid regions also have seen increased importance of mixed surface and groundwater supplies as populations, environmental concerns, and water demands increase (Skinner 1983, UK Groundwater Forum 1998). Historically, surface and groundwater sources have largely been developed, managed, and used independently. However, as water resources in a region become increasingly exploited, population continues to grow, and imported supplies become more controversial, the potential benefits of coordinated management of surface and groundwater supplies offer significant incentives for change.. In this paper, classical conjunctive use operations and strategies are reviewed and new approaches are analyzed based on California's examples.

California has undergone intensive water resources development to overcome the limitations of its natural hydrology (aridity, seasonal and spatial variability) and attain significant economic and agricultural growth (CDWR, 2003). Groundwater has played an important role in this process with widespread pumping beginning in the early 1900's as major supply for agricultural development. Negative impacts of intense groundwater exploitation later appeared, including aquifer overdraft, land subsidence, higher groundwater pumping costs, wetland or ecological degradation, and saline intrusion in coastal areas.

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Similar problems have occurred in many regions of world. Classical conjunctive use strategies implemented to mitigate these problems take advantage of the usually vast storage capacity and extensive conveyance network of aquifers. Common operations include storage of surplus surface water in aquifers and seasonal alternation on the use of surface and groundwater supply sources.

Classical conjunctive use operations benefit water users through increased water availability and reliability, increased total storage capacity, and reduction in drainage and salinity problems in irrigated and coastal areas. Water quality improvement is possible with more opportunities for blending water of different qualities and use of soil/aquifer media to treat water (SAT- soil aquifer treatment).

However, further opportunities for conjunctive management can be exploited when an elaborate network of water infrastructure, water rights and institutions is present. Examples of these opportunities are found in California, where complex surface and groundwater problems have stimulated development of new approaches for conjunctive use. These approaches are focused mostly on the integration of storage and conveyance infrastructure to allow more efficient and flexible water allocation and conservation, thus broadening the group of beneficiaries and minimizing water conflicts.

Benefits of these approaches include gains in flexibility and cost reduction of system operation, improvement in supply of peak demands without expanding surface infrastructure and more opportunities to phase investments to adapt to progressive increases in water demands. More flexibility on system's operation makes it easier to accommodate environmental demands. The involvement and leadership of users and institutions in the process enhances their ability to better coordinate inter-regional, regional, and local water management, and increases local control and autonomy, compared with large surface projects.

The next section reviews conjunctive use types and operations, and how they have been applied classically and in California considering institutional issues and limitations. The last section concludes with lessons learned in California, and potential applications in other regions of the world.

2 CONJUNCTIVE USE DEFINITIONS AND STRATEGIES

Conjunctive management of surface and groundwater can be defined as the management of water taking advantage of the connection between surface and subsurface hydrology, and their distinct storage capacity, dynamics and other properties. This management should provide greater benefit than if both surface and groundwater systems were operated separately. Implementation of conjunctive use techniques can occur in different temporal patterns, or strategies, according to the region development status and planning objectives (Table 1).

Table 1 – Temporal Strategies for Conjunctive Use

Temporal strategy	Problem	Time Period	Strategy
Drought cycling	Droughts, inter-annual imbalances in water availability and demands	Annual to decadal time-frame	Store and use surface water in wetter years, use more groundwater in drier years
Seasonal cycling	Seasonal imbalances in water availability and demands	Seasonal, within year	Greater wet season use and recharge of surface water, and dry season use of groundwater
Initial intensive exploitation	Initial stage of region development and conjunctive use	Initial development of conjunctive management	Initial intensive groundwater withdrawals support early economic development, deferring or phasing investments in surface infrastructure.
Continuous	Saline intrusion, contaminants dispersion in aquifer	Continuous	Reallocation of pumping and surface water, recharge management, fresh water injection.
Mixed	Combination of above	Mixed	Integrated mixture of above strategies

Temporal patterns are divided into drought, seasonal, initial exploitation, continuous, and mixed strategies. In a drought strategy, demands are supplied with surface water in wet periods and more expensive groundwater pumping is used only to complement the supply in drought years. By using less groundwater and recharging water in wet years aquifer storage is kept higher, being able to provide reliable supply in more extreme drought events without expansion of surface water storage. Given the common multi-year time period of this pattern, more costly groundwater uses and operations often can be reduced and surface supplies used more efficiently (Sahuquillo and Lluria 2003). This strategy relies on an institutional and physical framework capable of delivering surface water effectively so that it can substitute for groundwater use over long periods.

Seasonal conjunctive use strategies operate over shorter periods of time (within a year). Here seasonal, as opposed to inter-annual, imbalances in supply and demand are dampened by using groundwater storage. Surface water use and artificial recharge occur in wet months, with groundwater pumping concentrated in dry months. Water systems also can use groundwater storage for short-term peak demands and emergencies by developing aquifer storage and recovery (ASR) facilities or operations (Pyne 1994, Jones 2003). A seasonal conjunctive use strategy also can be applied through hydraulic connections between streams and aquifers. In the short-term, pumping from wells sited not too closed to the river does not affect the streamflow. Pumped water can be piped to the river to augment streamflow or directly supply water demands during the dry season, affecting the river during the wet season, when river flows are higher and demands are lower.

Initial intensive groundwater exploitation is the desirable pumping of an aquifer at rates that can be higher than the average recharge rate for an initial period of regional development. Historically, this aquifer drawdown often facilitates the economic, infrastructure, and institutional development of a region where financial and institutional resources for large surface systems or conjunctive use are limited. As the region grows economically and its institutions mature, additional surface water infrastructure is built and a sustainable operation can evolve. This development path also allows large-scale infrastructure investments to be deferred or phased. Ultimately, negative consequences of extended initial exploitation (high pumping costs, land subsidence, saline intrusion, soil salinity and drainage problems, and environmental damages) motivate development of larger-scale and more sustainable conjunctive use systems. According to Burt (1967), initial exploitation can be used to overcome the lag between present demand and future alternative resources. For example, early Israeli groundwater development began with a mining stage, characterized by exploitation above safe yields; followed by a recovery stage when alternative supplies become available and finally a steady state stage, when the groundwater averaged its long-term sustainable position (Schwarz 1980). In a reversed scenario, initial, usually unplanned, overexploitation of surface water can lead to recharge rates higher than pumping rates, water table rise and salinity problems. An example is found in Indus Basin, Pakistan, where centuries of intense irrigation and deep percolation losses from unlined canals raised the water table up to 60m (Johnson 1988, Sahuquillo and Lluria 2003;) and severe salinity problems.

Some conjunctive use patterns operate continuously, if the same level of demands is to be maintained or increased. To mitigate saline intrusion, such practices include deep-well infiltration, land reclamation, saline groundwater extraction, artificial recharge, modifying pumping rates and physical barriers (Oude Essink, 2001), but their effective performance is often improved by coordinated use, along with surface water management.

These strategies are not exclusive and the application of more than one defines a mixed pattern. Seasonal strategies can be run with drought strategies complementing its benefits by adding short-term regulation of water availability, especially in years with high volume of surplus floodwater. Drought strategies can be applied with aquifer overexploitation by varying the groundwater pumping according to the amount of surface water available in a given year type and attenuating the impact of the overexploitation process.

3 ELEMENTS OF CONJUNCTIVE USE OPERATIONS AND MANAGEMENT

Operational types of conjunctive use are classified according to their management approach, ranging from limiting decisions to infrastructure design and water use without explicit and variable operational decisions (Passive Management), to flexible condition-varying decisions regarding operation and construction of facilities and water demand for conjunctive use (Active Management). Table 2 summarizes the operations involved in each approach.

Table 2 –Elements of Conjunctive Use Management and Operations

Decision Class	Specific Decisions	Description
Passive Management		
Facilities	Design for incidental recharge	Design or modification of reservoirs, unlined canals, stream channels, etc. to increase groundwater recharge passively operations
	Well capacity expansion	Expand well capacity to allow greater pumping in drier periods
Water users	Relative prices and availability of surface and groundwater	Incentives for farmers to use surface water in wet periods/seasons and groundwater in dry periods/seasons; e.g., setting surface water price below groundwater pumping cost
	Groundwater or surface water substitution	Permanent reallocations of surface water and groundwater to users to improve overall system performance
	Exchange agreements and contracts, water markets	Long-term arrangements to exchange or provide waters from surface or ground waters during wet or dry periods
Active Management		
Facilities	Surface facility operations	Active operation of surface conveyance and surface water storage to increase recharge in wet periods
	Artificial recharge	Construction and active operation of dedicated conjunctive use recharge facilities such as recharge ponds and injection wells
	Treatment of water to improve conjunctive use	Construction and active operation of water quality improvement facilities for groundwater recharge, e.g., desalting facilities, water treatment plants
	Pumping	Active operation of existing and new wells
	Coordinated operation of facilities	Coordinated operation of surface water and groundwater facilities: wells, streams, canals and surface reservoirs
Water users	Exchange agreements & contracts, water markets	Short-term arrangements to take advantage of supply opportunities or respond to short-term scarcity
Coordinated operations	Alternating use and alternating operations	Coordinated operation of many facilities for storage and withdrawal
	Managed stream/aquifer interaction	Coordinated operation to manage stream-aquifer interaction for conjunctive use purposes

3.1 Passive Management

Many conjunctive use systems operate relatively passively, without a formal "management structure" or explicit interventions by governments or regulators. Passive management occurs largely without active operational decisions at the system level (municipality, irrigation district, or regional authority). Passive management may use or permanently modify operations or facilities that already exist, such as incidental recharge, or include the design of fixed facilities, water uses, and policies to support conjunctive use operations, such as providing a constant price structure which encourages users to pump groundwater in dry years and use surface water in wet years.

Passive management might modify the design of canals, reservoirs and streams to increase seepage, providing a significant element of conjunctive use without frequent management decisions. In California's Central Valley, much of the water recharged in conjunctive use schemes is provided by normal operation of unlined channels and off-season irrigation of cultivated lands. The latter is accomplished by irrigating the land prior to planting in years of abundant surface supplies, serving the dual purpose of providing recharge and pre-irrigation.

Natural streams can be modified to include weirs and raise hydraulic heads, expand infiltrating areas, and retain streamflow to increase streambed infiltration and sometimes create wildlife habitat (Oaksford 1985).

On the extraction side of conjunctive use, wells can be added, deepened, or rehabilitated to increase pumping capacity and access to water over a wider range of water table elevations. User's risk aversion coupled with higher variability and uncertainty in surface supplies also motivates increasing pumping capacity to meet demands in extreme dry events (Tsur, 1990). Well rehabilitation programs are a common component of regional conjunctive use schemes.

Non-structural operations include price controls and permanent water reallocations. The availability of surface water at lower prices makes groundwater pumping unattractive in wet years, encouraging appropriately alternating use of resources. Permanent reallocations of water among users can also encourage such alternating use, where less expensive surface supplies are re-allocated to lower valued uses and groundwater is allocated to higher values uses. To lower the water table in regions with salinity problems, demands might be reallocated from surface to groundwater (Johnson 1988; Steenbergen and Oliemans 2002). Reallocating demands from groundwater to surface water might help reduce overdraft, saline intrusion and land subsidence.

3.2 Active Management

Active management for conjunctive use includes building dedicated infrastructure and actively operating existing facilities and uses to take advantage of opportunities from integrated use and operations of surface and ground waters. Active groundwater recharge consists of operating surface reservoirs, canals, and rivers so that seepage is improved in quantity and timing, managing pumping wells close to rivers in stream-aquifer systems to induce groundwater recharge or building dedicated recharge facilities such as infiltration ponds or injection wells. Recharge and pumping operations can be coordinated so that aquifer levels are maintained at intended levels. Pumping capacity can be expanded by well deepening, well rehabilitation, and construction of additional wells.

In some cases, efficient traditional conjunctive use practices have survived. For example, in a mountainous region in Southern Spain, the Alpujarra (Granada province), an ancestral practice of artificial recharge (locally known as *careos*) still continues seasonally, since the time of the Islamic Spain or even before (for over a millennium). It consists on diverting surplus water from the streams during the snow melting season (the Spring) by an extensive network of channels to well-defined, highly permeable areas to replenish groundwater storage, so that the supply of drinking water from the mountain springs during the summer dry months can be guaranteed, while it increasing the moisture of the soil encouraging a dense vegetal cover (Pulido-Bosh and Ben Sbih 1995; Murillo et al. 2002).

For seasonal, short-term imbalances between supply and demand, municipal water systems and other demands can use injection wells for both recharge and pumping of groundwater, a process called *Aquifer Storage and Recovery* (ASR). ASR projects allow the use of aquifer recharge capacity in situations where other recharge methods, like infiltration ponds, are unsuited due to high value of land or unfavorable aquifer conditions, such as presence of confining layers impeding water movement (Pyne, 1994). Aquifer confinement (confined aquifers are preferred to minimize loss and contamination of the injected water), transmissivity (higher transmissivity allows higher injection rates), depth, and quality of native water may limit the feasibility of ASR. (Gale et al. 1997).

Differences in quality among ground and surface waters may require treatment to be used conjunctively. If groundwater has better organic quality while poorer inorganic quality (Helweg 1985), surface treatment facilities may be necessary prior to recharge, and desalting facilities after pumping. Water quality can be managed through blending with other water supplies, or by a process named SAT (Soil Aquifer Treatment). In SAT, water is applied to infiltration basins and treatment occurs in the vadose zone, where removal mechanisms of filtration, biological degradation, physical adsorption, ion exchange and precipitation occur (Kopchynski et al, 1996; Fox et al, 2001). Efficiency in this system depends on soil properties, water quality, and loading rate. Appropriate soil types depend on the constituents to be removed. Kopchynski et al (1996) investigated SAT processes for different soil types and found sandy soils highly efficient in terms of infiltration rates but very poor for nitrogen removal compared to silty and clay soils. Clay soils were more limited by infiltration rates due to algae clogging, which permanently affected the infiltration potential.

Active management strategies can take advantage of existing facilities and groundwater/surface water interaction dynamics to achieve supply objectives and minimize negative effects. Users having access to both surface and groundwater supplies may alternate their use by pumping groundwater in dry periods and surface water in wet periods, while the aquifer recharges after being depleted. Users with groundwater as prime supply may alternate their operations by recharging the aquifer with surface water when it is available and pumping this groundwater storage when needed. The more developed the surface infrastructure (canals, surface reservoirs, inter-ties), the more flexible these operations can be. Alternating use can be implemented as temporary, short-term water exchanges among users. Exchange operations include use of transferred surface supply by a user in lieu of groundwater pumping. The foregone pumping is then accounted as "recharge," credited to the transferor. This operation may be advantageous if the transferor has unfavorable conditions for direct artificial recharge (Brown et al, 2001), or finds it unattractive economically.

Interactions between surface streams and aquifers also can be managed to improve water supply and control externalities like stream depletion and aquifer contamination. Where the aquifer is connected to surface streams, the hydraulic gradient can be controlled with pumping and groundwater recharge. Intensive groundwater pumping lowers piezometric heads below the riverbed to increase stream seepage (Sahuquillo, 1999). In regions with limited control and planning on groundwater use, this situation can be perceived as a negative externality, with stream users being affected by groundwater pumping. Conjunctive use operations of flow augmentation can be used to control such externalities (Morel-Seytoux, 1985). In a flow augmentation scheme, groundwater is pumped into streams in dry periods to maintain minimum streamflow (Downing et al, 1974; UK Groundwater Forum 1999). The lag between groundwater pumping and its effect on the streamflow is an important aspect in finding the ideal location and timing for pumping or recharge. Delay in pumping effects can cause streamflow depletion to occur in wet periods, when streamflow is higher and demands are lower. During low-flow periods, pumped water can be used for river augmentation. These operations are particularly important in basins with intensive groundwater exploitation, where potential conflict among users is present. In coordination with surface reservoir operations, groundwater can be pumped downstream to create space for recharge before reservoir releases.

In California, conjunctive use strategies have been implemented to improve water management providing additional ways to store, transfer, and allocate water. In a system with well-defined surface water property rights, and well-developed surface conveyance infrastructure, users may seek efficient allocations by exchanging water in a market-based system. Active and passive conjunctive use strategies add flexibility to the process by integrating more efficiently the use of surface and groundwater supplies. Examples of common active operations in California includes artificial recharge with the objective of maintaining groundwater basin parameters (e.g. head, hydraulic gradient), storing surplus surface water to maximize groundwater supply in dry years, and Aquifer Storage and Recovery (ASR) projects to cope with short-term, seasonal peak demands. However, recharge water is often supplied by temporary or permanent transfer agreements, or accounted based on surface water use in lieu of groundwater pumping. Users in the water districts of Semitropic and Kern, in California's Central Valley, apply these operations to store surface water through institutional arrangements of *water banks*, for later use in dry years. Other irrigation districts use elaborate of surface water exchanges through surface canals to obtain the water required for artificial recharge, The Calleguas Municipal Water District, in southern California, relies on statewide conveyance infrastructure to import surface water for its ASR project (Jones, 2003).

The institutional complexity of conjunctive use often exceeds the great complexity of its physics, chemistry, and operational logistics. Unlike surface water rights, groundwater is not managed at the state level in California, leaving the coordination of conjunctive use operations to management and cooperation among water storage districts, irrigation districts, and municipal utility districts, with the exception of adjudicated basins under court ruling. While this favors the development of decentralized management and autonomy, it also imposes limitations, given the higher difficulty in sharing control, building trust, resolving differences, and obtaining financing at local level.

The California Department of Water Resources has collected feedback about conjunctive management programs on its Bulletin 118 (CDWR, 2003), and all the main impediments to a cost-effective conjunctive use programs listed were of institutional and legal nature. Impediments found in the study include lack of sufficient federal, state and regional financial incentives; legal constraints regarding water rights; lack of statewide leadership in the planning and development of conjunctive use programs as part of comprehensive water resource plans, recognizing other stakeholders; lack of quality standards for water being recharged or withdrawn; risk that water stored in groundwater may not be recovered; risk of third party impacts; local community participation; and the existence of different agendas among project participants (CDWR, 2003). Not surprisingly, half of the groundwater basins under court ruling are located in areas where large groundwater storage projects operate (Jones, 2003).

Despite the difficulties, efforts to create feasible conjunctive use projects are continuous, specially in integrating them in broader water management plans. The past process of intense surface water infrastructure development is unlikely to be repeated, as environmental concerns and public support in preserving watersheds increase. Groundwater is seen as a key component of the system and its integration with surface water use in conjunctive use programs is being recognized as of critical importance in providing water supply for future economic development.

4 CONCLUSIONS

1) Conjunctive use of surface and ground waters has been applied in most regions of the world where intensive water development has resulted in undesirable depletion of groundwater or other impacts.

2) A broad range of operations can be applied in active or passive management approaches to integrate the use of surface and groundwater supplies and improve supply reliability, quality and costs. These operations can also be engaged in different time frames, based on each region's historical and hydrologic circumstances and objectives.

3) In California, the early intense development of groundwater has brought, along with negative impacts, the users' attention to the necessity of coordination with surface water, while it supported the state economic growth and surface water infrastructure development.

This complex and elaborate water infrastructure system now provides new opportunities for further conjunctive use strategies and operations, in the continuous endeavor to improve performance in water allocation, attend growing demands, reduce operational costs, and minimize conflicts.

4) Benefits in California include classical conjunctive use advantages of supply reliability and increased storage capacity, as well as allowing more flexible and efficient allocation of water, reducing operational costs and contributing to local autonomy. California's recent success in conjunctive use rely intensively on existing infrastructure, especially surface conveyance, require a high level of local coordination and legal flexibility, and well defined property rights. Failure to meet these requirements has led to costly conflicts and adjudication processes. A next important step in future development of conjunctive use strategies is the integration of local initiatives into broader statewide water management, to coordinate local efforts.

5) Despite the requirements presented, many of the operations and strategies can be applied in other regions of the world where further surface development is currently challenged. Environmental concern is global and even regions without intensive past water infrastructure development are finding opposition to new projects such as large surface reservoirs. In these regions, the development of active and passive management strategies, with alternative infrastructure aimed at improving local conjunctive use operations (like artificial recharge, pumping and surface conveyance) may improve water supply flexibility, reliability and quality with less environmental impacts and operational costs.

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