
Ending groundwater overdraft in hydrologic-economic systems

Julien J. Harou · Jay R. Lund

Abstract Groundwater overdraft occurs when extraction exceeds both natural and induced aquifer recharge over long periods. While ultimately unsustainable and invariably having detrimental effects, overdrafting aquifers is common and may be temporarily beneficial within a long-term water management strategy. Once a region chooses to end overdrafting, water management must change if increased water scarcity is to be avoided. Integrated water-management models allow aquifers and overdraft to be analyzed as part of a regional water-supply system. Incorporating economics into the model establishes a framework for evaluating the costs and effects of groundwater management actions on the entire system. This economic-engineering approach is applied in a case study of the Tulare Basin in California, USA, where previous economic studies showed optimal pumping depths have been reached. A hydro-economic optimization model is used to study the economic effects and water management actions that accompany ending overdraft. Results show that when overdraft is prohibited, groundwater banking using conjunctive-use infrastructure built between 1990 and 2005 largely annuls the cost of not overdrafting. The integrated economic-engineering approach quantifies effects of groundwater policies on complex regional water-resource systems and suggests promising strategies for reducing the economic costs of ending aquifer overexploitation.

Received: 7 February 2007 / Accepted: 11 March 2008
Published online: 29 May 2008

© Springer-Verlag 2008

Electronic supplementary material The online version of this article (doi:10.1007/s10040-008-0300-7) contains supplementary material, which is available to authorized users.

J. J. Harou (✉)
University College London Environment Institute
and Department of Civil, Environmental and Geomatic Engineering,
University College London,
Gower Str., London, WC1E 6BT, UK
e-mail: j.harou@ucl.ac.uk

J. R. Lund
Department of Civil and Environmental Engineering,
University of California - Davis,
Davis, CA 95616, USA
e-mail: jrlund@ucdavis.edu

Résumé La surexploitation de l'eau souterraine intervient lorsque le prélèvement dépasse la recharge à la fois naturelle et induite de l'aquifère sur de longues périodes. Quoique non durable en fin de compte et ayant invariablement des conséquences préjudiciables, surexploiter les aquifères est courant et peut être avantageux temporairement dans une stratégie de gestion de l'eau à long terme. Une fois qu'une région choisit de mettre fin à la surexploitation, la gestion de l'eau doit changer si une rareté accrue de l'eau doit être évitée. Les modèles de gestion intégrés de l'eau permettent aux aquifères et à la surexploitation d'être analysés en tant qu'éléments d'un système régional d'alimentation en eau. L'incorporation de l'économie dans le modèle établit un cadre pour évaluer les coûts et les conséquences des actions de gestion de l'eau souterraine sur le système dans son entier. Cette approche d'ingénierie économique est appliquée à une étude de cas du Bassin de Tulare en Californie, U.S.A., où des études économiques antérieures ont montré que des profondeurs optimales de pompage ont été atteintes. Un modèle d'optimisation hydro-économique est utilisé pour étudier les conséquences économiques et les actions de gestion de l'eau qui accompagnent l'arrêt de la surexploitation. Les résultats montrent que lorsque la surexploitation est interdite, le prélèvement d'eau souterraine mettant en œuvre l'infrastructure pour l'emploi conjoint des eaux superficielles et souterraines construites entre 1990 et 2005, annule dans une large mesure le coût de l'arrêt de la surexploitation. L'approche intégrée d'ingénierie économique quantifie les conséquences des politiques de l'eau souterraine sur des systèmes régionaux complexes de ressources en eau et suggère des stratégies prometteuses pour la réduction des coûts économiques résultant de l'arrêt de la surexploitation de l'aquifère.

Resumen La sobre-explotación de aguas subterráneas ocurre cuando la extracción excede tanto la recarga natural como inducida del acuífero en períodos prolongados. Aunque en última instancia es una práctica no sustentable y que invariablemente tiene efectos perjudiciales, la sobre-explotación de acuíferos es frecuente y puede ser temporalmente beneficiosa dentro de una estrategia de corto plazo de gestión del agua. Cuando en una región se decide finalizar con la sobre-explotación, la gestión del recurso debe cambiar a fin de evitar la escasez de agua. Los modelos de gestión integrada de los recursos hídricos

permiten analizar los acuíferos y la sobre-explotación como partes de un sistema regional de abastecimiento de agua. La incorporación en el modelo de aspectos económicos establece el marco para evaluar los costos y efectos sobre el sistema completo de acciones relacionadas con la gestión del agua subterránea. Esta aproximación económica-ingenieril se aplica a un caso de estudio en la Cuenca Tulare (California, USA), donde los estudios económicos previos demuestran que se han alcanzado profundidades óptimas de bombeo. Se usa un modelo de optimización hidro-económico para estudiar los efectos económicos y las medidas de gestión que se relacionan con la finalización de la sobre-explotación. Los resultados muestran que cuando se prohíbe la sobre-explotación, el almacenamiento de agua subterránea usando infraestructura de uso conjunto construida entre 1990 y 2005, anula en gran parte el costo de no sobre-explotar. La aproximación integrada económica-ingenieril cuantifica el efecto de políticas hídricas en sistemas regionales de recursos hídricos y sugiere estrategias promisorias para reducir los costos económicos de la finalización de la sobre-explotación de acuíferos.

Keywords Over-abstraction · Integrated groundwater management · Hydro-economic modeling · Tulare Basin · USA

Introduction

Overdraft is long-term groundwater extraction at unsustainable rates manifested by steadily decreasing regional groundwater levels over a period long enough to overlook seasonal and drought effects. This paper concerns groundwater overdraft and its cessation. The first three sections provide a general discussion of groundwater overdraft including negative and beneficial consequences, managed and unmanaged ways to end overdraft, and economic considerations. The objective of this first part of the paper is to describe overdraft and the drivers behind it within the wider context of engineered, economic, and environmental water resource systems.

By choice or necessity, governments or communities may choose to cease overdrafting groundwater (Custodio 2002; Blomquist et al. 2004; Kretsinger and Narasimhan 2006). Societies respond to groundwater depletion by augmenting, conserving, and reallocating existing supplies (Molle 2003; Konikow and Kendy 2005). However, transitioning to sustainable groundwater management with the least negative impacts and cost remains a challenge. Solutions to overdraft often involve the entire water-resource system since they must make up for lost water supply. Integrated management models are indicated since they strive to represent all relevant parts of the system. The second part of this paper is a modeling case study of water management and economic adaptation for California's Tulare Basin with a hypothetical "no overdraft" policy. The integrated management model used in the study is a hydro-economic optimization model (Draper et al. 2003). Conjunctive use of surface and groundwater

appears as the best way for this region to stop overdraft with the least increase in water-scarcity cost. The model shows that conjunctive use infrastructure built between 1990 and 2005 would reduce water-scarcity costs to levels that existed with overdraft but without the new infrastructure. The objective of this second part of the paper is to demonstrate that groundwater management policies and solutions to groundwater problems can be beneficially analyzed with integrated hydro-economic models.

Overdraft and its consequences

Overdraft exists in many regions and has recently been described and labeled differently by several authors. Konikow and Kendy (2005) use the term groundwater depletion to describe extraction that causes persistent head declines in renewable aquifers or the mining of fossil aquifers. They add that groundwater depletion consists of a reduction of aquifer volume or a reduction in the usable volume of fresh groundwater within an aquifer. Overdraft is a form of "overexploitation"—a general expression referring to any groundwater development that engenders consequences that are negative or perceived as such, and is sometimes called "intensive groundwater development" to refer to the often beneficial economics of the early years of overdraft (Custodio 2002; Custodio and Llamas 2003). Correctly diagnosing an overdraft condition may not be straightforward since transient pumping effects may cause recharge and discharge of the aquifer to adjust over long periods (Theis 1940; Bredehoeft et al. 1982; Custodio 2002).

Adverse effects of overdraft can include: uneconomic pumping conditions, water quality degradation through induced intrusion of saline or poor quality groundwater, flow reduction in streams, wetlands and springs, land subsidence, interference with pre-existing water uses and water rights and a gradual depletion of groundwater storage (Sophocleous 2003; Zekster et al. 2005). These problems in turn threaten the long-term sustainability of overlying economic activities and society. Land subsidence can increase flooding and drainage problems and disrupt infrastructure such as sewers and aqueducts. By lowering the potentiometric surface, overdraft may induce intrusion of lower quality waters (seawater, saline groundwater, contaminant plumes, or contaminants in the sediment or rock matrix) into aquifers, although these conditions also can occur in non-overdrafted aquifers. Consistent lowering of the water table can dry up wells, drain springs and wetlands and turn perennial streams into desert washes. In karstic aquifers, where flow occurs through fracture systems or in other aquifers with complex geology, lower groundwater levels may abruptly close hydrogeologic connections and cause drops in flows from springs or capacities of well systems. Any reduction of groundwater storage is detrimental if it threatens future water supplies, especially during drought. Pumping that permanently lowers water levels increases pumping costs for all pumpers for all future time. If these extra costs over time decrease economic productivity of a region, overdraft

has a negative economic effect, discussed later. The possible negative effects of aquifer overdevelopment on third parties are referred to as externalities, in economic parlance, and are also discussed later.

Groundwater overdraft is generally considered as a problem due to harmful environmental, ecological, economic and social effects. Whether a case of overdraft is “bad” depends on hydrogeologic considerations as well as regional economic and environmental conditions and the availability of other water sources. Recently, a more balanced view of intensive groundwater development has been proposed (Custodio 2002; Llamas and Custodio 2003; Llamas and Martínez-Santos 2005). Periods of overdraft sometimes have benefits for regional water supply and local socio-economic development. Temporarily intensive use may be acceptable or even desirable for a time under some conditions. A lower water table may enhance water supply and water quality and produce other benefits. Lowering a water table may reduce evapotranspiration losses, soil salinization and create storage capacity for artificial recharge water banking schemes. Groundwater banking, as practiced in Kern County (California) to great benefit, depends on storage capacity created by historic overexploitation (Andrews et al. 1992; Vaux 1986; Meillier et al. 2001). A thicker unsaturated zone also may increase protection from pollutants in the soil or vadose zone. When artificial recharge was implemented to counter long-term overdraft in the town of Yucca Valley (California), the rising water table reached nitrate-contaminated waters from local septic systems. Local groundwater nitrate concentrations rose from a background concentration of 10 mg/L to more than 90 mg/L (Nishikawa et al. 2003). Low water tables provide a buffer against surface-borne contaminants and may delay or reduce aquifer contamination. Additionally, intensive groundwater development may induce additional aquifer recharge (Johnston 1997; Llamas and Custodio 2003). Finally, intensive use of groundwater may spearhead economic development of a capital-poor region.

Ending overdraft

Table 1 summarizes different ways overdraft can end. The various water augmentation, conservation and reallocation

strategies are roughly arranged in order of their proactive nature, from unmanaged depletion to seasonally managed conjunctive use schemes. Options for ending overdraft also are described by Harou and Lund (2007).

Increased capture

When an aquifer is developed, it may respond over the long-term by inducing recharge from surface water sources and (or) by decreasing discharge to streams and springs (Theis 1940). The sum of these two flow components, termed “capture” (Bredehoeft et al. 1982; Bredehoeft 1997, 2002), is dynamic and depends on aquifer properties and geometry. The increase in aquifer inflow may originate from three main sources: (1) increased percolation due to irrigation surplus, changed soil characteristics and decreased evapotranspiration, (2) induced recharge from surface water bodies and (3) induced recharge from neighboring aquifers or groundwater basins. The initial lowering of the water table sparked by pumping will stop if capture and pumping stress reach a new equilibrium. An extraction rate that may have initially appeared as overdraft may later reveal itself to be sustainable, albeit at some loss of local surface water or aquifer discharge. If groundwater pumping exceeds available capture and the two do not equilibrate, their difference will be drawn from storage and groundwater levels will continue to decrease.

Economic or physical depletion

Groundwater is an exhaustible resource in aquifers that have limited natural recharge, cannot induce additional recharge and cannot be physically or economically recharged by artificial means. This is the case, for example, of isolated, confined aquifers containing ancient groundwater or of aquifers in arid areas remote from surface waters. The analysis tools of nonrenewable resource economics address efficient intertemporal allocation of water in this case (Hotelling 1931). If the incentives caused by the common-property context are not addressed, unmanaged exhaustion is likely to occur. Groundwater levels will decline until physical or economic depletion. In the case of deep aquifers, groundwater elevations will decline until marginal-pumping costs

Table 1 Options for ending overdraft

Degree of management	Groundwater management strategy	Variations and methods
No management	Increased capture Depletion (unmanaged)	Groundwater development increases capture and stabilizes water levels Groundwater extracted until pumping cost, quantity or quality are unacceptable
Managed solutions	Depletion (managed)	Fees, taxes, or transferable rights
	Reduce aquifer demands	Urban and agricultural water conservation policies Reallocation mechanisms (e.g. markets)
	Surface water substitution	Retaining local surface waters Importing surface water
	Conjunctive use	Drought cycling Seasonal cycling

exceed marginal water-use values or until poor water quality prevents further beneficial use. Where pumping is managed (by fees, taxes, or transferable rights) depletion arrives more slowly, with low-valued pumping uses ending earlier than with the unmanaged case, allowing longer use of some higher-valued groundwater.

Reducing water demands

A direct approach to counter a groundwater overdraft problem is to reduce withdrawals by decreasing water demands. Although an obvious solution, it is often the least likely to be implemented. Decreasing demand can occur by using less water and losing the associated productivity or by investing in agricultural and urban water-use efficiency practices, which often reduce recharge. Both represent a direct economic loss in the short-term and require institutional changes that may be more costly than the consequences of the overdraft itself. Convincing hundreds of pumpers to forego immediate direct economic benefits for collective long-term economic benefits remains a challenge. A more realistic alternative would be a progressive reallocation trend in which market-like mechanisms motivate the transfer of water from lower to higher valued users.

Surface-water substitution

Surface-water substitution is a common historical response to overdraft. Steadily declining groundwater levels raise fears of excessive pumping costs or exhaustion of groundwater supplies, motivating local water users and their governments to seek additional substitute surface water supplies. Two surface sources are often available, retained local surface waters and imported surface waters. Both sources require the construction and maintenance of a new local surface-water distribution system, along with institutions and finance for this new surface water system. Imported surface waters require additional capital expenditures, as well as a willingness and ability to appropriate water for importation, requiring additional capital, legal, and political resources. With pure surface water substitution, the new surface water sources replace groundwater use entirely. This can occur where new surface water sources, once built, provide water at a cost less than pumping groundwater. This situation arises from the greater economies of scale often seen in surface water, once developed, compared with economies of scale and sometimes greater operating costs for groundwater development. Complete elimination of groundwater use by surface water substitution can result in water-logging of soils, as deep percolation of applied surface waters exceeds aquifer discharge.

Conjunctive use

Conjunctive use is a common approach to mitigating groundwater over-abstraction. Llamas and Martínez-Santos (2005) note that groundwater overdraft frequently

occurs in a historical context as the first step in conjunctive use. Initially high water tables are taken advantage of as an inexpensive water source allowing a region to intensify agricultural development and accumulate capital to support later more sustainable water development. In addition to this macroeconomic advantage, early overdraft, by drawing down groundwater levels, makes space available for later storage of surface water. In regions where artificial recharge is hydrologically (i.e. sufficient natural and imported inflows) and hydrogeologically feasible, historical overdraft may be an effective means of underground reservoir construction.

Several conjunctive use approaches can be distinguished: drought cycling, seasonal cycling and continuous (Pulido-Velázquez et al. 2003). Drought cycling of groundwater storage and use relies on more surface water during wetter years and delivers more water from groundwater during drought years. This approach takes advantage of temporal changes in water availability (and cost) and is commonly desirable in regions with significant inter-annual variability of surface water where surface storage of wet-year surpluses is uneconomical, would suffer excessive evaporative losses, or would cause unacceptable environmental disruption. While such a system might seem to require institutional control of groundwater to limit groundwater use in wetter years, this is often not the case. Where the surface water-supply system has the financial ability to offer surface water at a price slightly less than the cost of pumping groundwater, most users will choose surface water when it is available, and resort to groundwater only in drier years (Vaux 1986; Jenkins 1991).

Seasonal cycling of groundwater storage and use employs the same logic as drought cycling of groundwater use, only on a shorter seasonal time-scale. Seasonal cycling responds to seasonal imbalances in water availability and demands. For example, California's Kern groundwater bank artificially recharges via percolation basins throughout the winter and employs extraction wells from March until July (KFMC 2005). Continuous conjunctive use is often employed in coastal areas, using surface or reclaimed water to prevent seawater intrusion into aquifers. Many actual water resource and groundwater problems lend themselves to mixed conjunctive use strategies, drawing on an appropriate combination of these methods.

Economic aspects of overdraft

Most groundwater pumping and overdraft is for economic purposes. Individual farmers or agencies use groundwater because it is less expensive and more available (physically, economically or legally) than other sources for their purposes. In an overdraft regime, groundwater pumping continues until the marginal cost of pumping begins to exceed the value of the pumped water for economic production. At this point, farmers can reduce production, implement more efficient irrigation or switch to higher value crops. Efficient irrigation decreases pumping costs because less is extracted but may not cause groundwater

levels to stabilize or rise if prior irrigation methods provided significant recharge (Kendy 2003). If alternative surface water sources are available for a similar or lower cost, farmers can switch entirely to the new source or combine surface and groundwater use (conjunctive use).

As an alternative to hydrology-based definitions, aquifer overexploitation can be defined by its economic suboptimality. Economic overexploitation begins when extraction exceeds the pumping rate at which present value of net benefit is maximized (Gardner 1979; Young 1992). From this perspective, overdraft is “bad” only if the net return on the least profitable crop is less than the present value of all future pumping costs savings (Howitt 1979). This statement excludes consideration of environmental externalities and other groundwater services discussed later.

Figure 1 graphically represents the economics of over-extraction (Gardner 1979; Young 1992), with various simplifying assumptions, including that the aquifer is homogenous and drawdown spreads quickly throughout the basin (“bathtub” model). The annual pumping rate (x-axis) is considered constant over several years. Present value of agricultural returns from irrigation (“Benefit”) are concave because irrigation water increases crop yield at a decreasing rate until too much water is applied and yields decline. The private cost of pumping is slightly convex if a pumper recognizes that today’s extraction will increase his own future pumping costs. The private cost of pumping also includes a “user cost” (or “scarcity rent”), i.e., the present value of future benefits lost by present extraction. User cost reflects the opportunity costs (profits that could have been made) from water at higher levels unavailable in the future. The social cost curve (NRC 1997) includes reciprocal and unidirectional externalities and buffer and option values. Reciprocal externalities describe how any one pumper’s extraction imposes a cost on all aquifer pumpers. Unidirectional externalities include costs imposed by pumpers on non-pumpers, such as from environmental degradation, land subsidence or seawater intrusion. Buffer value includes the services of in situ groundwater against various types of uncertainty (Bredehoeft and Young 1983; Tsur 1990; Tsur and Graham-Tomasi 1991). Finally, option value is the benefit

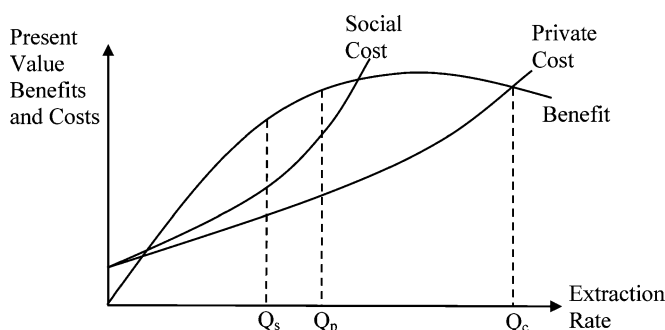


Fig. 1 Benefits and costs of groundwater extraction—adapted from Gardner (1979) and Young (1992). Competitive common pool pumping rate (Q_c), optimal pumping considering private costs (Q_p), optimal pumping considering private and social costs (Q_s)

of conservative extraction rates when water managers know that irreversible consequences of overdrafting (e.g. seawater intrusion or land subsidence) could occur (Tsur and Zemel 1995). The loss of buffer value or option value can be described as a risk externality (Provencher and Burt 1993).

In Fig. 1 optimal pumping occurs where the benefit curve minus the cost curve is greatest, maximizing net benefit. Considering only private costs, this occurs at Q_p (where benefit and private cost slopes are identical), while socially optimal extraction would limit pumping to Q_s . In many aquifers pumping approaches Q_c (where net benefits are zero) because groundwater is a common pool resource in which usually property rights are ill-defined and access nonexclusive. A rule of capture ensues where operators own only the water they pump, leaving unextracted water to other farms (Provencher and Burt 1993). Since individual farmers do not benefit from their conservation efforts, the incentive is to keep pumping while there are any profits to be made.

This result has led many researchers to attempt quantifying economic gains from regional groundwater management. Extraction from most aquifers is unregulated, leading to the question of whether gains from regional groundwater management suggested by optimization models are enough to warrant the institutional costs of groundwater management (Gisser and Sanchez 1980; Knapp and Vaux 1982; Feinerman and Knapp 1983; Reichard 1987; Brill and Burness 1994; Knapp and Olson 1995). Several authors show that gains from management are small and regulation should be approached with skepticism (Gisser 1983; Bredehoeft et al. 1995). However, Koundouri (2004a, b) suggests this result stems from simplified assumptions found in many economic models of groundwater use.

The constant optimal extraction rate described illustrates economic concepts involved but remains a static analysis. In practice, dynamic models are mostly used to analyze groundwater management to suggest how optimal extraction rates change over time and can adapt to changing technologies and prices (Burt 1964; Brown and Deacon 1972). Dynamic economic models commonly suggest initially overdrafting aquifers (Howitt 1979; Vaux 1985; Young 1992). Extraction steadily decreases as pumping costs increase, finally reaching an optimal steady-state pumping rate.

Dynamic economic models are effective at evaluating trade-offs between present extraction and future costs but they have been less effective at incorporating more complex physical and spatial consequences of groundwater use (Bredehoeft and Young 1970). However, recent papers show renewed interest in more realistically representing hydrogeologic spatial realities (Moreaux and Reynaud 2004; Reinelt 2005; Brozovic et al. 2006). In the effort to study the economics of groundwater use within a water-resource-system context, others have investigated the economics of the conjunctive use of surface water and groundwater resources (e.g. Noel et al. 1980; Noel and Howitt 1982; O'mara and Duloy 1984; Provencher and Burt 1994; Knapp and Olson 1995).

Models with economic objective functions that focus on representation of the engineered hydrologic system including groundwater include Young and Bredehoeft (1972), Reichard (1987), Draper et al. (2003), Cai et al. (2003), and Pulido-Velazquez et al. (2006) among many others. Modeling studies that consider the economics of groundwater management in relation to water transfers include McCarl et al. (1999) and Knapp et al. (2003).

Economic-engineering analysis of ending overdraft in the Tulare Basin

Next, a hydro-economic optimization model is used to study how a region with an irrigation based economy can adapt to a no overdraft policy. California's Tulare Basin (44,000 km², population 2 million) is featured in the case study. The model's groundwater component is simpler than the economic models discussed above because pumping costs are fixed to maintain model linearity (private cost is linear and social cost non-existent in Fig. 1). The preceding discussion on groundwater economics is provided to justify why ceasing overdraft is considered for the Tulare Basin (see "Regional groundwater levels" section below); it does not describe the modeling work presented in the following.

This study assumes a decision was made to stop overdrafting groundwater. This choice could be imposed by an agency or court order, it could be based on localized negative hydrogeological and environmental effects of overdraft, and it could be supported by dynamic economic models that suggest optimal regional groundwater depths have been achieved or surpassed. The latter two reasons are relevant for the Tulare Basin. Government or court intervention is not currently envisaged. Adopting a sustainable regional groundwater policy would most likely occur progressively and involve changing water-use incentives within the context of water and water storage markets currently active in the region. A model is used to investigate the economic and water-management effects of ending overdraft. In particular, the value of new conjunctive-use infrastructure built by groundwater banks between 1990 and 2005 is investigated. The model identifies the combination of water demand reduction, surface water substitution, and conjunctive use solutions (Table 1) that allow the system to adapt at the lowest cost to a no overdraft policy.

Tulare Basin, California

The Tulare Lake Hydrologic Region is a closed hydrologic basin comprising the southern portion of California's Central Valley. The valley is underlain by a series of interconnected mostly unconfined aquifers of area 21,500 km² and average depth of 1.3 km. These aquifers have been historically overexploited, resulting in low piezometric levels and high land-subsidence in some locations (Planert and Williams 1995).

The Tulare Basin is one of California's most productive agricultural regions. Water consumption is high (circa 16,000

million m³/year) but natural inflows are limited. The Tulare Basin is the state's greatest water-importing region, importing annually between 4,000 and 7,000 million m³ (Mm³). Major water imports arrive from the San Joaquin River (through Friant-Kern Canal) and Northern California (from the California Aqueduct; see Fig. 2). Since the 1990s, some imported water is stored during wet periods by artificial recharge in groundwater banks managed by local irrigation districts (e.g. Semi-tropic, Kern, Arvin-Edison). Despite the water imports, overdraft continues in the basin. Annual change in groundwater storage varies widely depending on rainfall; in 1998 it was estimated at +1,000 Mm³ but at -5,000 Mm³ in 2001 (CDWR 2005). Average annual groundwater overdraft was estimated at 380 Mm³ (USBR 1997) for the period 1921–1993.

Regional groundwater levels

Pumping lifts have increased since 1945 when intensive exploitation began from, in some cases, artesian conditions to present lifts that can exceed 100 m (KFMC 2005; CDWR 2005). Table 2 provides average regional pumping heads and other regional groundwater basin data from the early 1990s (initial storage estimated for 1920). Pumping heads listed include effects of local drawdown and well losses. Interseasonal variability of piezometric head ranges from approximately 15 m for unconfined aquifers to 50 m for confined layers (KFMC 2005; T. Haslebach, Kern County Water Agency, personal communication, 2006). Piezometric head under the regions' groundwater banks can be much higher than regional levels.

Several studies have considered groundwater management in the southern Central Valley using dynamic economic models (Howitt 1979; Knapp and Vaux 1982; Feinerman and Knapp 1983; Knapp and Olson 1995; Schuck and Green 2002; Knapp et al. 2003). Howitt (1979) published a preliminary estimate of optimal depth to groundwater for three sub-basins within the northern Tulare Basin (Kings, Kaweah, Tule,) averaging 57 m (62, 51, 60 m respectively). Feinerman and Knapp (1983) and Knapp and Olson (1995) estimate benefits of optimal control for Kern County and recommended pumping depths. Their first study estimates regional steady-state pumping lifts at 169 and 127 m under competition and optimal control regimes respectively.

Both studies for which steady-state pumping depths are given above used a pumping cost of 0.045 \$/kWh and a 5% discount rate. Results were sensitive to both discount rate and energy cost, with recommended pumping depths increasing with higher discount rates and decreasing with higher energy costs. These results suggest levels during the early 1990s were at or approaching their economic optimums. Groundwater levels in most areas not covered by groundwater banks have since further decreased.

A decision-maker with a strong interest in regional sustainability (e.g., 3% discount rate) could argue that groundwater depths have passed their optimal levels. Besides the economic optimality of regional groundwater depth, environmental and political factors would most

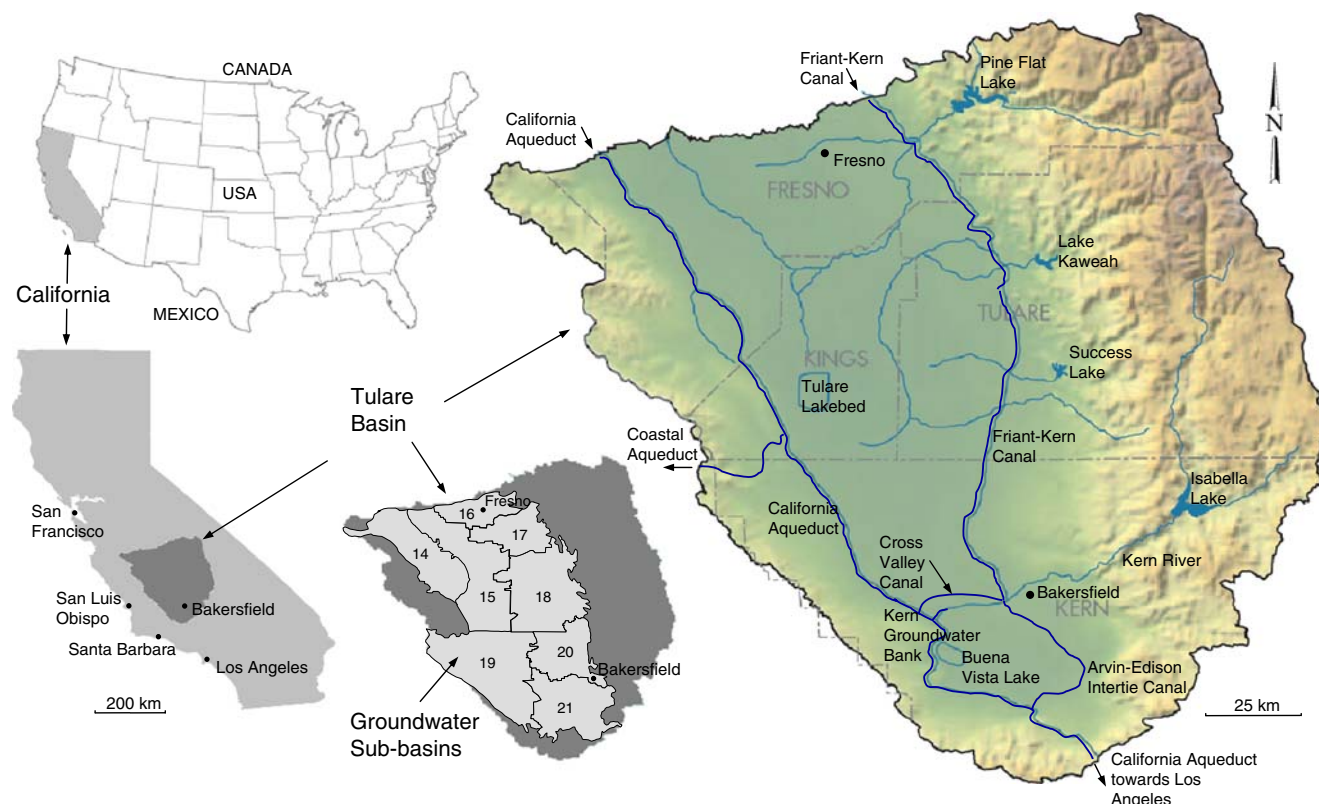


Fig. 2 The Tulare Basin is a closed hydrological basin in the southern part of California's Central Valley (modified from CDWR 2005). The small Tulare *outline map* shows the extent of Tulare groundwater sub-basins. The *large map* shows major canals and natural watercourses on a background of topography. Counties are written in *uppercase*

likely influence this decision. This position is the starting point of this study and opens a new question: How should system operation best adapt to a new sustainable groundwater use policy? Because economics motivates most water use in the region and was a key factor in deciding to halt overdraft, economic considerations should also influence how the system is newly operated. This is the working hypothesis of the model runs presented in the next section where economic water demands drive operations and allocations.

Method

A sustainable groundwater use policy is analyzed using a portion of an economic-engineering optimization model of California's water-supply system. The model named CALVIN (California Value Integrated Network; Jenkins et al. 2001; Draper et al. 2003) provides time series of optimal surface and groundwater monthly operations, water use and allocations to maximize statewide net economic benefits. This includes changing surface and groundwater operations and reallocating or marketing

Table 2 Pumping and storage data for each groundwater sub-basin

Groundwater sub-basins	Pumping head (m)	Pumping cost (\$/m ³)	Pumping capacity (Mm ³)	Initial storage (Mm ³)	Ending storage (Mm ³)	Overdraft (Mm ³)
Westside (basin 14)	116	0.062	411	63,001	56,449	6,552
Tulare Lake (basin 15)	71	0.038	503	86,954	86,857	97
Fresno (basin 16)	45	0.024	75	7,844	0	7,844
Kings River (basin 17)	48	0.026	188	9,018	8,641	377
Tule-Kaweah (basin 18)	69	0.037	430	50,296	41,874	8,422
W Kern (basin 19)	105	0.055	211	53,145	53,148	-2
NE Kern (basin 20)	102	0.054	133	27,914	28,868	-953
S Kern (basin 21)	106	0.056	282	63,642	58,700	4,943
Total overdraft (Mm ³) over 72 year period:						27,280

Source: Pumping heads from CDWR (1994), initial and ending storage from USBR (1997), data and costs discussed further in Jenkins et al. (2001). Pumping capacity in Mm³ is per month

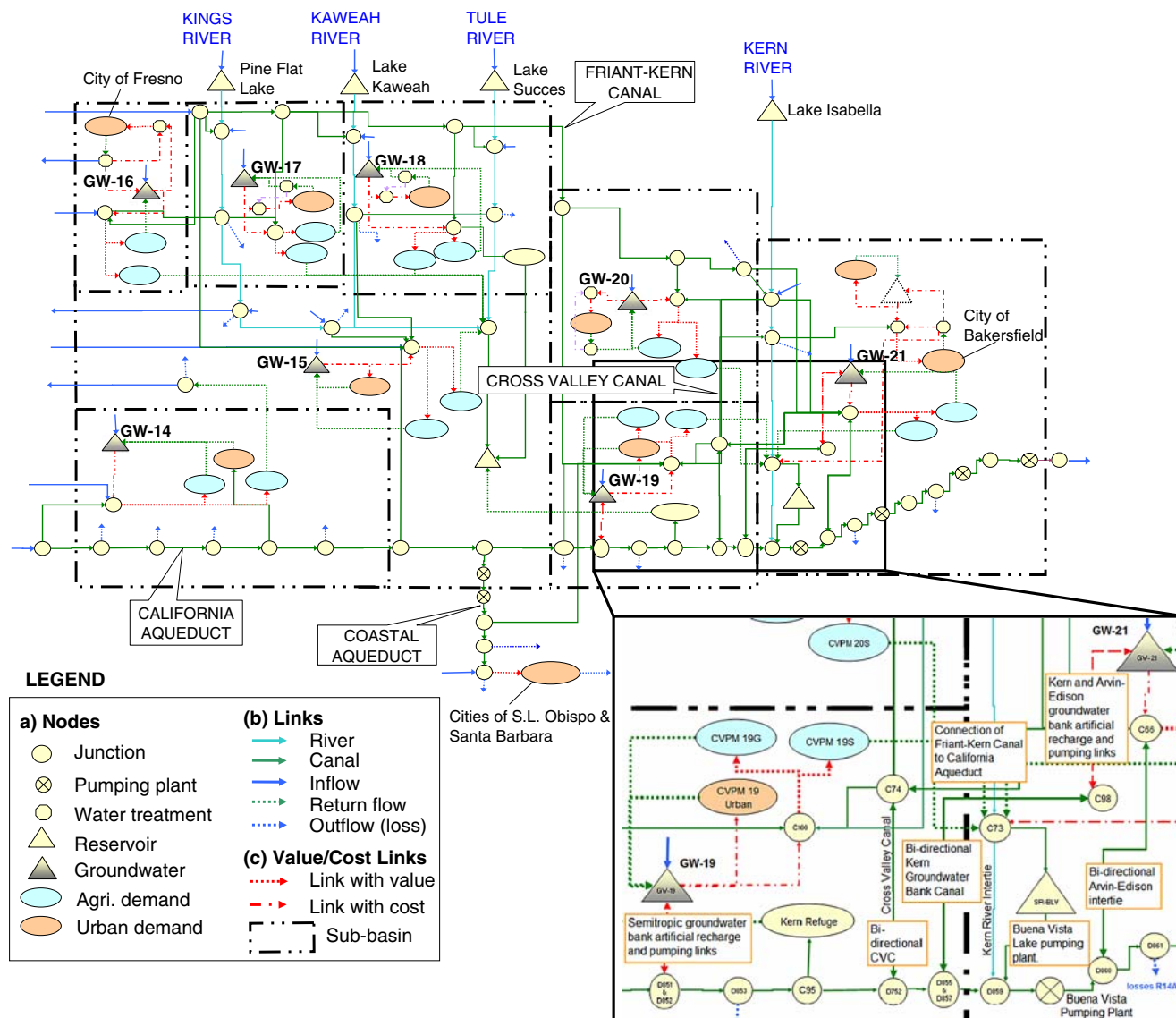


Fig. 3 Schematic of Tulare Basin CALVIN model network. Modeled conjunctive use infrastructure enhancements from 1990 to 2005 are labeled in the *zoom box*. A fully labeled network is found in the section [Electronic supplementary material](#)

water to maximize regional economic net benefits within environmental flow constraints. The model employs all available water-management options to economically adapt to the presence or absence of groundwater overdraft. Because CALVIN's objective function is economic, time series of shadow values provide the monetary value of relaxing model constraints throughout the network.

The model optimizes over a 72-year historical hydrologic record (1921–1993) for a particular level of infrastructure, population and land-use development (projected to the year 2020 in this case). Conjunctive use infrastructure is modeled at 1990 and 2005 levels. Water demands are represented as economic penalty functions, based on agricultural and urban demand curves for water. Agricultural demand curves were derived using the Statewide Water Agricultural Production (SWAP) model (Howitt et al. 2001) and urban demand curves were taken from published sources (Jenkins et al. 2001, see Appendix

B). Operating costs for pumping, artificial recharge, desalination and water treatment also are represented. CALVIN employs the HEC-PRM (USACE 1999) Prescriptive Reservoir Model software as its computational and organizational core. HEC-PRM uses a computationally efficient generalized network flow linear optimization formulation that represents the system as a network of

Table 3 Four modeled scenarios

Scenario	Description
ODCU–	Overdraft (OD) with less (1990 level) conjunctive use infrastructure (CU–)
ODCU+	Overdraft (OD) with more (2005 level) conjunctive use infrastructure (CU+)
NoODCU–	No Overdraft (NoOD) with less conjunctive use infrastructure (CU–)
NoODCU+	No Overdraft (NoOD) with more conjunctive use infrastructure (CU+)

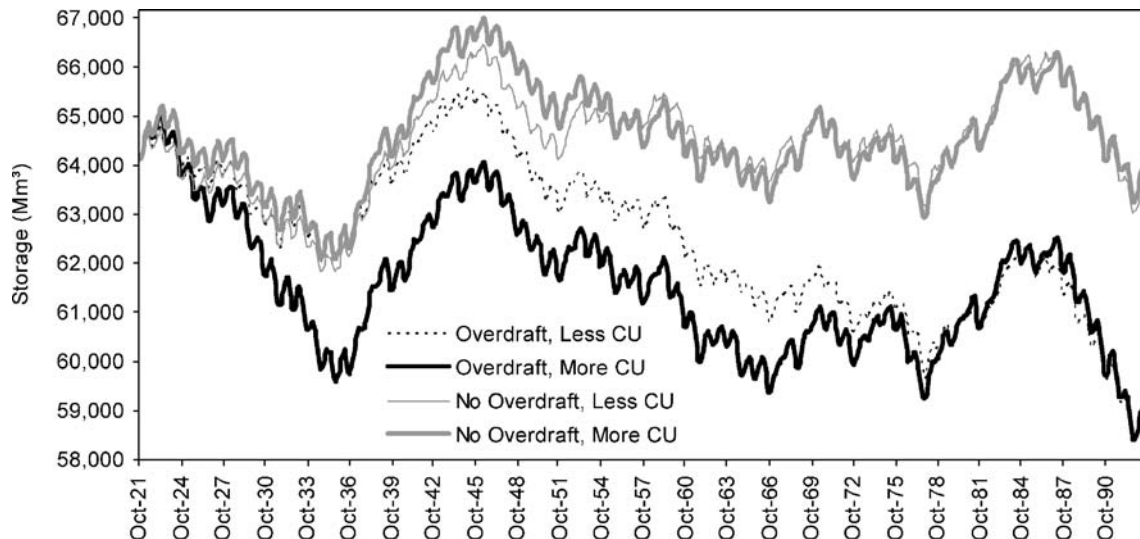


Fig. 4 Groundwater storage (million m^3) in southern Kern County (sub-basin 21) for the four management scenarios. *Less CU* refers to the less conjunctive use infrastructure (1990 level) and *More CU* refers to 2005 levels

nodes and links. “Generalized” refers to the possibility of including gain/loss multipliers on network flows. Use of a linear model guarantees a unique globally optimal solution while use of the network flow algorithm offers more than a 10-fold increase in solution speed relative to a standard linear program solver (Labadie 2004). The model minimizes costs subject to flow continuity at nodes and capacity constraints on links; it can be written “Min” $\sum \sum c_{ij} X_{ij}$ subject to $\sum_i X_{ij} = \sum_j a_{ij} X_{ij} + b_j \forall j$, $X_{ij} \leq u_{ij} \forall ij$, $X_{ij} \geq l_{ij} \forall ij$, where X_{ij} is flow leaving node i towards node j (link ij), c_{ij} = costs of flow through link ij (scarcity costs or operational costs), b_j = external inflows to node j , a_{ij} = gain/loss coefficient on flows in link ij , u_{ij} = upper bound (capacity) on link ij , and l_{ij} = lower bound on link ij . This restricted network flow formulation precludes including other constraints such as groundwater response equations. The number of links (1,617) multiplied by the number of time periods (864) gives the number of X_{ij} decision variables (1,397,088). The full CALVIN model solves in approximately 12 h using an initial solution on a 2 GHz PC.

For this study, the California-wide model has been reduced to the Tulare Basin region (292,896 decisions). Inter-regional boundary conditions include fixed inflow time series (San Joaquin River diversion and the California Aqueduct in the north) and fixed outflows (California Aqueduct deliveries to southern California). These regional boundary flows are marked in Fig. 2. The Tulare Basin is divided into eight water demand areas, each with agricultural and urban water demands. Each water

demand area overlies one of eight semi-interconnected groundwater sub-basins. The eight sub-basins of the Tulare Basin as well as the water storage and conveyance network appear in Figs. 2 and 3.

As a large-scale regional economic-engineering model, CALVIN tracks groundwater volume in each sub-basin and does not represent the piezometric surface (groundwater level) as would a spatially distributed groundwater model. These limitations are discussed in Jenkins et al. (2001, see Appendix J) and Pulido-Velázquez et al. (2004). Pumping lifts are constant for each sub-basin and based on averaged water levels from the 1990s. The model does not dynamically represent groundwater flow within and between the groundwater sub-basins or stream-aquifer interactions. Instead, it uses fixed series of flows between sub-basins derived from simulation of the historical period by a spatially distributed groundwater model: the Central Valley Groundwater-Surface Water Model (CVGSM; USBR 1997). Groundwater recharge time series also are taken from the CVGSM model, although deep percolation of irrigation water is dynamically modeled.

Modeling scenarios

Initial groundwater storage of the Tulare Basin was estimated at 362,000 Mm^3 (USBR 1997). A representative overdraft rate for each groundwater sub-basin was set based on extraction rates estimated during the 1990s

Table 4 Summary values for scarcity and scarcity costs in the Tulare Basin under the four scenarios

	Average annual water scarcity (Mm^3)		Annual scarcity cost (million US \$)	
	CU+ ^a	CU–	CU+	CU–
Overdraft	318	779	17	59
No overdraft	728	1241	48	118

^a CU+ more (2005 level) conjunctive use infrastructure, CU– less (1990 level) conjunctive use infrastructure

Table 5 Average deliveries, scarcities, and scarcity costs for economic water demand areas for each modeled scenario

	Target (Mm ³)		Delivery (Mm ³)		NoOD		Scarcity (Mm ³)		Scarcity cost (1,000 \$/year)		NoOD	
	CU ^a	CU ⁺	CU ^a	CU ⁺	CU ⁻	CU ⁺	CU ⁻	CU ⁺	CU ⁻	CU ⁺	CU ⁻	CU ⁺
Agricultural demands^b												
Westside (14)	1,845	1,681	1,836	1,681	1,704	1,704	164	9	19,569	2,064	19,572	13,709
Tulare Lake (15)	2,457	2,375	2,457	2,320	2,366	2,366	82	0	3,235	0	8,791	3,609
Fresno (16)	611	605	605	583	605	605	6	6	149	149	2,383	173
Kings River (17)	1,030	1,012	1,012	979	983	983	17	17	445	445	3,839	3,435
Tule-Kaweah (18)	2,664	2,291	2,462	2,216	2,360	2,360	374	203	39,684	12,470	51,498	28,396
W Kern (19)	1,180	1,120	1,161	1,023	1,119	1,119	60	19	3,939	1,253	20,443	3,980
NE Kern (20)	835	787	797	722	787	787	47	38	3,465	2,771	16,631	3,522
S Kern (21)	1,433	1,405	1,407	1,289	1,404	1,404	28	27	1,755	1,640	21,848	1,784
Total agricultural demands	12,055	11,276	11,737	10,814	11,327	11,327	779	318	72,242	20,792	145,004	58,608
Urban demands												
Fresno	469	469	469	469	469	469	0	0	0	0	0	0
Bakersfield	321	321	321	321	321	321	0	0	0	0	0	0
Santa Barbara, San L. O.	171	171	171	171	171	171	0	0	0	0	0	0
Total urban demands	961	961	961	961	961	961	0	0	0	0	0	0
Total water demands	13,017	12,238	12,698	11,775	12,289	12,289	779	318	72,242	20,792	145,004	58,608

^a Scenarios: OD overdraft, NoOD no overdraft, CU⁺ more (2005 level) conjunctive use infrastructure, CU⁻ less (1990 level) conjunctive use infrastructure

^b Agricultural demand sub-basin numbers are in parentheses

(USBR 1997). This resulted in an estimated annual overdraft rate of 380 Mm³ for the entire basin. Applied over the 72-year modeled period, the modeled overdraft leads to 335,000 Mm³ of ending storage for the entire basin.

The model is run under four scenarios (Table 3), all with projected year 2020 water demands and using 72 years of historical monthly time series of inflows to represent hydrologic variability. “No overdraft” runs constrain ending groundwater basin storages to equal initial storage volumes. Model runs also contrast the conjunctive use infrastructure present in the early 1990s with current expanded infrastructure capacities. (Fig. 3). These include the Kern, Arvin-Edison and Semitropic irrigation district water banks and new conveyance links to the California Aqueduct (west-ward flow of the Cross Valley canal, Buena Vista Lake Pumping facility, and the Arvin-Edison Intertie; SAIC 2003). Figure 3 shows the framework of such infrastructure; more detail is given in the section [Electronic supplementary material](#)

Model Results

The combination of model runs permits examination of the effects of overdraft policies on water scarcity (shortages), water-scarcity costs, water users’ willingness-to-pay for additional water, and the value of conjunctive use facilities (artificial recharge and pumping) within the region. Preliminary results of this study were described by Harou and Lund (2007).

Groundwater storage

For each management alternative, groundwater storage in the Tulare Basin varies on seasonal and drought time scales. Figure 4 shows groundwater storage for southern Kern County. In addition to long-term trends of overdraft, there are also significant changes in recharge and withdrawal over seasonal and drought time-scales. Drier periods have steep decreases in storage. The time span of drought-related drawdown and refill cycles is commonly a decade or longer (Lettenmaier and Burges 1982; Pulido-Velázquez et al. 2004). For all sub-basins, cyclical

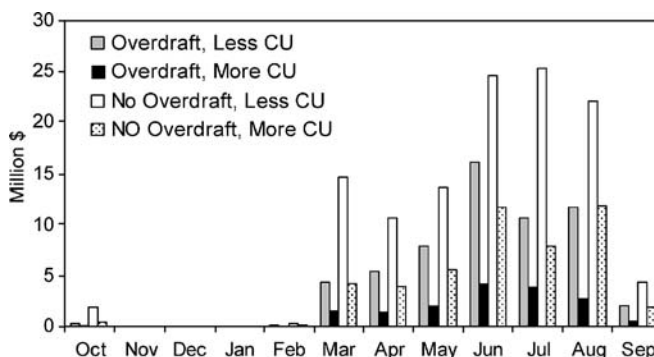


Fig. 5 Average monthly agricultural water scarcity costs (US dollars)

Table 6 Monthly average and 72-year maximum marginal willingness to pay for additional water at water demand sites

	Average marginal WTP (\$/m ³)				Maximum marginal WTP (\$/m ³)			
	OD CU– ^a	OD CU+	NoOD CU–	NoOD CU+	OD CU–	OD CU+	NoOD CU–	NoOD CU+
Agricultural demands^b								
Westside (14)	0.05	0	0.05	0.04	0.45	0.45	0.45	0.45
Tulare Lake (15)	0.02	0	0.04	0.02	0.03	0	0.09	0.03
Fresno (16)	0.01	0.01	0.05	0.01	0.02	0.02	0.08	0.08
Kings River (17)	0.02	0.01	0.06	0.05	0.03	0.03	0.08	0.08
Tule-Kaweah (18)	0.06	0.03	0.08	0.05	0.13	0.05	0.13	0.13
W Kern (19)	0.03	0.01	0.09	0.04	0.05	0.05	0.14	0.05
NE Kern (20)	0.04	0.03	0.10	0.04	0.14	0.06	0.18	0.08
S Kern (21)	0.03	0.03	0.09	0.03	0.05	0.05	0.14	0.05
Urban demands								
Fresno	0	0	0	0	0	0	0	0
Bakersfield	0	0	0	0	0	0	0	0
Santa Barbara, San L Obispo	0	0	0	0	0	0	0	0

^a Scenarios: *OD* overdraft, *NoOD* no overdraft, *CU+* more (2005 level) conjunctive use infrastructure, *CU–* less (1990 level) conjunctive use infrastructure

^b Agricultural demand sub-basin numbers are in parentheses

patterns of groundwater storage follow similar trends with and without conjunctive use infrastructure. However, conjunctive use operations have a greater role for off-setting agricultural water scarcity as demonstrated in the next section.

Scarcity and its costs

The model provides time series of optimal flows at each location in the network. The economic penalties used in the optimization imply a water-supply target for each demand and economic costs of not providing a full target delivery. Because available water is limited and less than the region's full demands, any physically feasible water allocation will cause water scarcity to some water users. The cost of this scarcity is evaluated using the economic penalties.

Overall scarcity results from the four optimized alternatives are summarized in Table 4. The scarcity cost from ending an overdraft of 380 Mm³/year in the Tulare Basin would be roughly US \$31 million/year (48 minus 17 in Table 4) with current conjunctive use infrastructure and \$59 million/year with 1990 infrastructure levels. Both estimates assume the best-case economically optimal operations from CALVIN. Dividing those costs by 380 Mm³ gives the average supplemental cost incurred per cubic meter not used due to the no overdraft policy; it is 0.08 \$/m³ with current conjunctive use infrastructure and 0.16 \$/m³ with less infrastructure. Assuming optimal

operations which take most advantage of the new infrastructure, the average cost of reducing each cubic meter of overdraft is half of what it would be without the expanded conjunctive use infrastructure.

Deliveries, water scarcity and scarcity costs of individual water demand areas are summarized in Table 5. The urban areas of Fresno, Bakersfield and Santa Barbara suffer no water scarcity; their high willingness-to-pay for water and relatively low water use allow them to purchase enough water to avoid shortages. The ability to purchase water from agricultural areas eliminates the need for expensive desalination (at a conservative cost of \$1.1/m³). Agricultural water-right holders sell or lease part of their water to farmers or cities with higher willingness-to-pay. Agricultural sector water scarcities roughly double without overdraft.

Water scarcity and scarcity-cost estimates are available at each location on the network for each monthly time step. Water scarcity and scarcity cost vary seasonally, following seasonal patterns of local water demands and availability (Fig. 5). As seen in Table 4, the no overdraft with current conjunctive-use scenario (NoODCU+) faces scarcity costs similar to the scenario allowing overdraft but with less conjunctive use (ODCU–).

Willingness-to-pay for more water

Water demand areas that experience water scarcity would economically benefit from additional supplies. Marginal

Table 7 Average value (\$/m³) of additional imported water at the northern boundaries of the Tulare Basin

	ODCU– ^a	ODCU+	NoODCU–	NoODCU+
Friant Kern Canal	0.10	0.04	0.14	0.10
California Aqueduct (Westlands)	0.10	0.02	0.13	0.07

^a Scenarios: *OD* overdraft, *NoOD* no overdraft, *CU+* more (2005 level) conjunctive use infrastructure, *CU–* less (1990 level) conjunctive use infrastructure

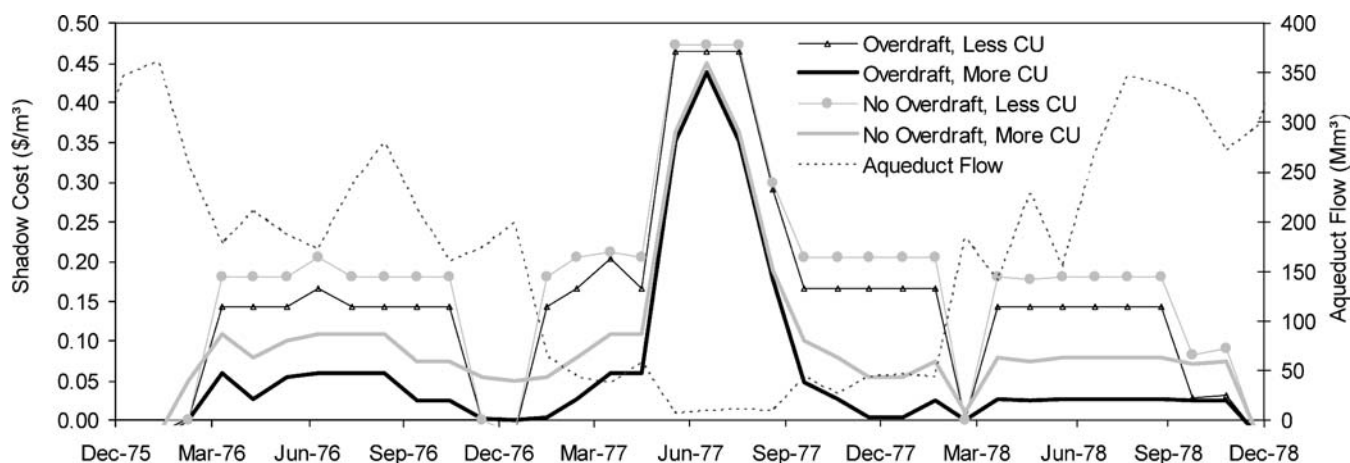


Fig. 6 Marginal value of additional imports from the California Aqueduct (beyond historical deliveries) based on economic water demands in the Tulare Basin and historic deliveries to southern California during the period of the 1976–77 drought

willingness-to-pay (WTP) reflects what demand areas would be willing to pay for an extra m^3 given their current allocation in each model run. Marginal WTP is estimated as the slope of the economic benefit function at the delivered water quantity. If the delivery falls on a discontinuity in the piece-wise linear benefit function, the lower slope is taken so values represent a lower bound on the WTP for an additional unit of water. Demand areas receiving full deliveries have no scarcity (in this case the urban demands) and no marginal WTP (Table 6).

Table 7 provides average monthly values for additional water imports at the northern boundary of the Tulare Basin. These values are the shadow values of mass-balance constraints at border nodes which receive the fixed inflows. Water is worth slightly more in the eastern Friant-Kern canal system due to its proximity to water-demand areas and lower pumping costs. Average marginal WTP (Table 6) is slightly less than the marginal value of additional surface-water imports (Table 7) because of the way it is estimated. In both cases, additional water is worth more when less conjunctive use infrastructure is available because there is less opportunity to store and convey water within the basin. Conjunctive use infrastructure decreases the value of additional imported supplies because it allows the basin to store more water in wet periods for use within the basin in dry periods.

Figure 6 focuses on the value of additional California Aqueduct imports during the 1976–1977 drought. At the

height of the drought, historic aqueduct flow was at its lowest and all alternatives show similar economic values for further imports. During more normal years, 1976 and 1978, differences in the value of additional supplies returns to those in Table 7.

Value of capacity expansion

Shadow values on constraints pertaining to water storage and conveyance capacities provide estimates of the value of augmenting both storage and conveyance capacities. Table 8 shows average and maximum annual marginal value of added surface water storage capacity at the four major reservoirs in the Tulare Basin. These values could help identify promising locations for reservoir enlargement; the smaller reservoirs Kaweah and Success show the highest expansion benefits. Conjunctive use infrastructure added in the basin over the last 15 years decreases the value of increasing reservoir capacity, replacing it with better use of groundwater storage.

Recharge capacity is usually more valuable than pumping capacity in the region's two modeled groundwater banks (Fig. 7). This is because groundwater banking infrastructure is connected to the California Aqueduct, which in the model contains on its southern border a fixed historic outflow time series. Southern California, if represented economically as in the statewide CALVIN model, would increase the shadow value on groundwater

Table 8 Average of maximum monthly shadow values of each hydrologic year (\$/tcm)

Current summer max. capacity (Mm^3)		Average annual maximum monthly shadow values (\$/tcm ^a)			
		ODCU ^b –	ODCU+	NoODCU–	NoODCU+
Pine Flat Lake	1,230	0.6	0.5	1.7	1.5
Lake Kaweah	179	173	55	203	119
Lake Success	102	152	51	192	117
Lake Isabella	693	25	10	32	11

^a tcm: thousand cubic meter

^b Scenarios: *OD* overdraft, *NoOD* no overdraft, *CU+* more (2005 level) conjunctive use infrastructure, *CU–* less (1990 level) conjunctive use infrastructure

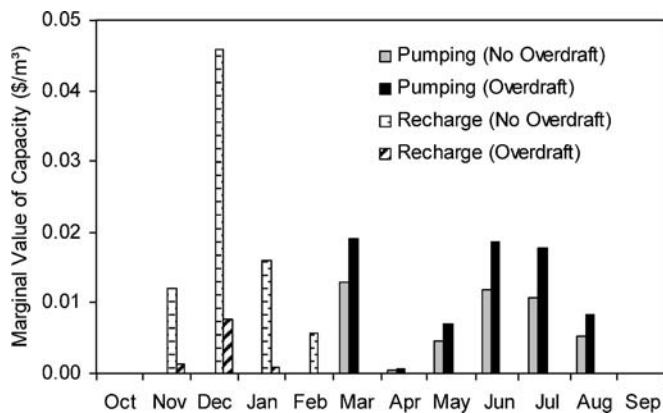


Fig. 7 Shadow values showing the monthly economic value of more artificial groundwater recharge and groundwater pumping capacity in the Kern and Arvin-Edison groundwater banks (groundwater sub-basin 21)

bank pumping capacities, better reflecting the value of the Tulare Basin as California's conjunctive use hub. Recharged groundwater in CALVIN can be used for regional export or to satisfy local economic or fixed water demands. This double function explains the high value of expanding percolation facilities, especially without overdraft.

The value of artificial recharge varies seasonally (Fig. 7) and annually (Fig. 8). In dry years, percolation basins have little value. Both figures show that prohibiting overdraft often more than triples the economic value of additional recharge capacity. Although the value of further recharge is strongly affected by existence of overdraft, actual operations are not. Figure 8 shows that the system is constrained enough by water demands and fixed exports that actual recharge rates recommended by the model are similar. Slightly less recharge occurs with overdraft since these alternatives have more water available for deliveries.

Modeling limitations and discussion of results

Several key assumptions and limitations of the model and its application are useful in interpreting its results. CALVIN, as a multi-period optimization model, suggests water allocations, operations and costs that reflect perfect hydrologic foresight. In systems with significant over-year storage such as the Tulare Basin, the sequence of storages will differ from those obtained with a simulation model and performance for some years will be optimistic (Draper 2001).

In CALVIN both groundwater levels and flows between sub-basins are fixed based on historic simulation results from an outside groundwater model. The more basin-scale groundwater volumes differ from historical storages, the more inaccurate the historical inter-basin flows will be. Groundwater pumping costs are static and do not vary with storage. Thus the model does not provide insights into one major benefit of ending overdraft—stabilizing pumping costs. The effect of pumping costs on optimal system management could be investigated by examining sensitivity to different fixed regional groundwater levels but results would remain tempered by the static nature of the analysis. A spatially lumped but dynamic treatment of groundwater effects for Kern County considering water transfers is given by Knapp et al. (2003).

Finally, all model runs portray perfectly optimized operations without institutional constraints. They represent an economic-engineering ideal, which might be difficult to achieve institutionally. Results, including operations and economic information should therefore be considered a best-case. The model assumes perfect operation for minimizing economic penalties. CALVIN's limitations are discussed by Draper et al. (2003).

For the specific application of CALVIN to the Tulare Basin, an important limitation is the fixed historic boundary flows. The Tulare Basin is a major hub for

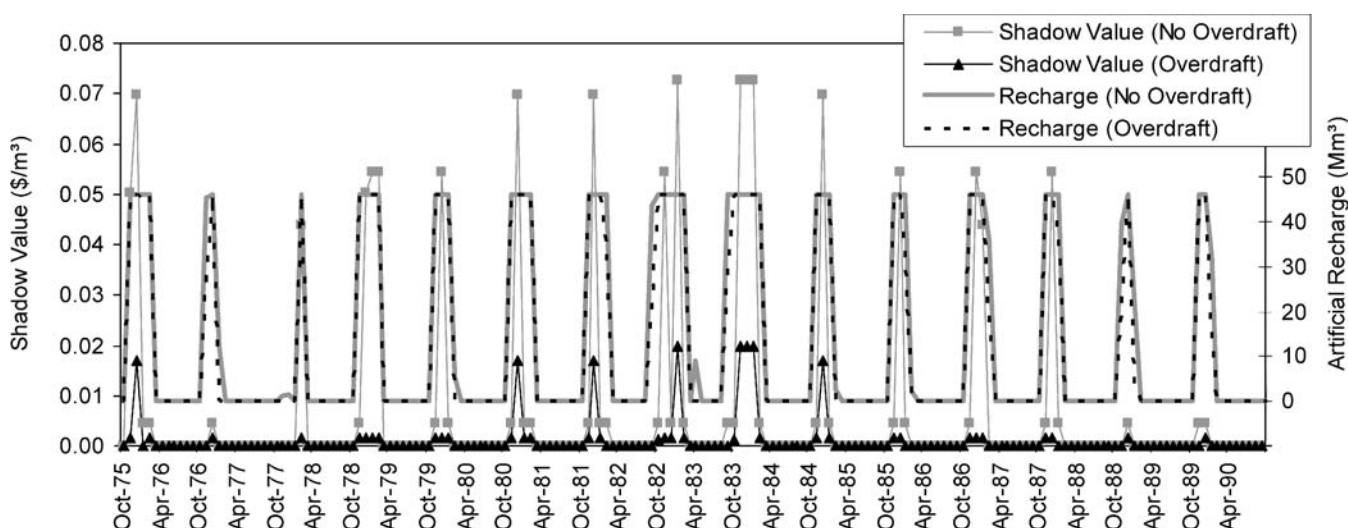


Fig. 8 Artificial groundwater recharge flows and shadow values from 1975–1990 for the aggregated Kern and Arvin Edison groundwater bank (sub-basin 21) with 2005 level conjunctive use infrastructure

inter-regional water transfers and storage in California's statewide water system. Tulare Basin operations are strongly influenced by the boundary inflows and outflows. If California were to manage water resources as suggested by the statewide CALVIN model, inflows and outflows of the Tulare Basin region would probably differ from historical flows. More importantly, a fixed historical Tulare Basin export to southern California does not represent water demands in southern California economically. Because the Tulare Basin will increasingly be called to serve as a groundwater bank for southern California, this simplified representation of southern California demands understates the value of Tulare Basin water supplies and infrastructure. An easy way to correct this would be to simply extend this study to all of central and southern California. Apart from increasing run times and the complexity and quantity of interpretable results, this further study would be feasible using the full state CALVIN model in its present form. A benefit of the current case study is that fixed boundary flows reduce the effects of the model's perfect hydrologic foresight.

Another modeling issue is the scale of groundwater analysis: the existence and extent of overdraft varies throughout the Tulare Basin; the large modeled sub-basins cannot capture this spatial variability. Figure 9 shows the observed evolution of depth to groundwater in 330 Kern County wells from 1990 to 2006. This plot reveals long-term changes in groundwater level vary widely throughout the region. Also of interest is that groundwater levels rose in 59% of wells, probably due to increased recharge from groundwater banks. This observation supports the claim made that the most realistic institutional solution for ending overdraft in the Tulare Basin would be the increasing incentives brought about by the ability to store and sell water.

In some parts of the Tulare Basin, recommended steady-state levels have not been reached, which questions why these areas should be lumped in with those with a graver overdraft problem. Knapp and Olson (1995) consider conjunctive use with stochastic surface flows and produce

a probability distribution of optimal steady state pumping lifts for Kern County centered on 145 or 178 m (optimal control or common property regime respectively). These steady-state depths are 9–17 m greater than those suggested by Feinerman and Knapp (1983) when not considering conjunctive use. Since these depths are 40–70 m more than the current regional depth to groundwater, perhaps some areas (e.g. in Kern County) should not reduce pumping? These remarks point to the relevance of spatial variation when managing aquifer overexploitation. However, to analyze the Tulare Basin as a whole and evaluate different strategies, a coarse level of spatial aggregation is used here (groundwater sub-basins average 3,000 km²).

Having noted key limitations and simplifications, the study does provide a best-case cost estimate of enforcing a sustainable groundwater yield in a region with intensive groundwater use. The study underlines the importance of considering groundwater overdraft, and policies for reversing it, within the context of diverse system-wide water management activities and objectives. Overdraft is not easily reversed by considering groundwater management alone; for many semi-arid basins, this would be unrealistic. Results of the model help provide a perspective on how to end groundwater overdraft in a larger water-management context. An example is given in the next paragraph.

Because the historical record for the Tulare Basin begins and ends in drought periods, the optimal trajectory of groundwater storage with no long-term depletion stays mostly well above current storage levels (Fig. 4). This provides a specific case where initial drawdown of aquifers creates storage capacity that enables later conjunctive use. Initially overdrafting to make space for later flexible operations may be the optimal management strategy for some water-resource systems. Whether this is the best option in practice will depend on existence of sources of water for recharge, institutional feasibility, ecological effects, hydrogeological characteristics and water quality.

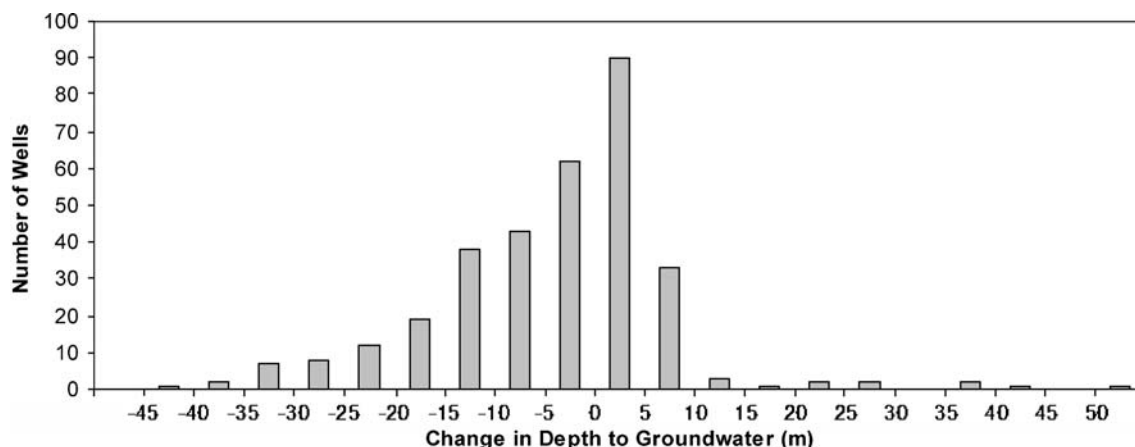


Fig. 9 Change in depth to groundwater in 330 wells of Kern county from 1990 to 2006 (CDWR 2006). *Negative values indicate rising groundwater levels (e.g. 62 well levels rose between 0 and 5m during the 16-year period)*

Conclusions

While some groundwater overdraft may be beneficial depending on its hydrologic, environmental and economic consequences, its timing and duration, and on one's perspective, all overdraft must inevitably end. This can occur through inaction, with variable results, or by way of managed solutions. Sustainable managed solutions for renewable aquifers typically involve a combination of reduction of water demands, surface-water substitution, and conjunctive use. In some situations, temporary overexploitation may provide important economic benefits for the over-lying society and engineering functions such as water-quality protection and storage for conjunctive use schemes.

California's Tulare Basin has relied on overpumping groundwater for irrigation but will be faced with potential water-quality problems, subsidence and inefficient pumping costs. A hydro-economic optimization model examined how the region could adapt if it chooses to forego overdrafting. Results showed ceasing groundwater overdraft with current conjunctive-use infrastructure would increase water scarcity by approximately 410 Mm³/year at an annual supplemental cost of \$31 million. These are best-case figures since the model assumes economically optimal operations and perfect hydrologic foresight. This cost is two orders of magnitude less than the annual agricultural revenue generated by the counties of the Tulare Basin (\$8,000 million). Seen in this light, costs incurred to end over-abstraction are significant but not catastrophic. However, if the inability to trade water during droughts led to urban or industrial water shortages, economic damage could be much larger. Water scarcity caused by ceasing overdraft was similar to the scarcity already present circa 1990 when basins were overexploited but had less conjunctive use infrastructure. Conjunctive use infrastructure built during the last 15 years greatly reduces the costs of ceasing to overdraft the region's aquifers. This suggests that system operation and in particular conjunctive use have a major role in making sustainable groundwater use policies a success. The methodology and findings of this study, although representative of areas in California's southern Central Valley, are less relevant to regions where water trades are impossible, surface water imports non-existent, or where groundwater basins are nonrenewable (limited possibility of artificial recharge). The study demonstrates groundwater overdraft problems can most effectively be addressed by considering them within the context of their hydrologic, economic and engineered water resource systems.

Acknowledgements Funding was provided by the California Energy Commission while the first author was a graduate student at the University of California at Davis. The authors thank C. Brush, B. Wagner, V. Kretsinger and an anonymous reviewer for comments that improved the paper. T. Haslebach is thanked for providing information and insights on local hydrogeology. We also thank G. Marques, M. Pulido-Velázquez, M. Jenkins, and S. Tanaka for useful discussions on conjunctive use and help with modeling conjunctive use for the Tulare Basin.

References

- Andrews ES, Chung FI, Lund JR (1992) Multilayered, priority-based simulation of conjunctive facilities. *J Water Resour Plan Manage* 118:32–53
- Blomquist W, Schlager E, Heikkilä T (2004) Common waters, diverging streams, linking institutions and water management in Arizona, California, and Colorado. Resources for the Future Press, Washington, DC
- Bredehoeft JD (1997) Safe yield and the water budget myth. *Ground Water* 35:929
- Bredehoeft JD (2002) The water budget myth revisited: Why hydrogeologists model. *Ground Water* 40:340–345
- Bredehoeft JD, Young RA (1970) The temporal allocation of ground water: a simulation approach. *Water Resour Res* 6:3–21
- Bredehoeft JD, Young RA (1983) Conjunctive use of groundwater and surface-water for irrigated agriculture: risk-aversion. *Water Resour Res* 19:1111–1121
- Bredehoeft JD, Papadopoulos SS, Cooper Jr HH (1982) The water budget myth, scientific basis of water resource management. National Academy Press, Washington, DC, pp 51–57
- Bredehoeft JD, Reichard EG, Gorelick SM (1995) If it works, don't fix it: benefits from regional groundwater management. In: El-Kadi AI (ed) *Groundwater models for resources analysis and management*. CRC, Boca Raton, FL, pp 103–124
- Brill TC, Burness HS (1994) Planning versus competitive rates of groundwater pumping. *Water Resour Res* 30:1873–1880
- Brown G, Deacon R (1972) Economic optimization of a single-cell aquifer. *Water Resour Res* 8:557–564
- Brozovic N, Sunding D, Zilberman D (2006) Optimal management of groundwater over space and time. In: Goetz R, Berga D (eds) *Frontiers in water resource economics*. Springer, Berlin, pp 109–136
- Burt O (1964) Optimal resource use over time with an application to ground water. *Manage Sci* 11:80–93
- Cai XM, McKinney DC, Lasdon LS (2003) Integrated hydrologic-agronomic-economic model for river basin management. *J Water Resour Plan Manage* 129:4–17
- CDWR (California Department of Water Resources) (1994) The California water plan update, 1993, Bulletin 160-93, CDWR, Sacramento, CA
- CDWR (California Department of Water Resources) (2005) California water plan update, vol 3, chapter 8, Tulare Lake Hydrologic Region, CDWR, Sacramento, CA
- CDWR (California Department of Water Resources) (2006) Planning and local assistance: groundwater level data. CDWR, Sacramento, CA. <http://wdl.water.ca.gov/gw/>. Cited 10 Dec 2006
- Custodio E (2002) Aquifer overexploitation: What does it mean? *Hydrogeol J* 10:254–277
- Custodio E, Llamas R (2003) Intensive use of groundwater: introductory considerations. In: Llamas R, Custodio E (eds) *Intensive use of groundwater*. Swets, Lisse, The Netherlands
- Draper AJ (2001) Implicit stochastic optimization with limited foresight for reservoir systems, PhD Thesis, Dept. Civil and Env. Eng., University of California at Davis, USA
- Draper AJ, Jenkins MW, Kirby KW, Lund JR, Howitt RE (2003) Economic-engineering optimization for California water management. *J Water Resour Plan Manage* 129:155–164
- Feinerman E, Knapp KC (1983) Benefits from groundwater-management: magnitude, sensitivity, and distribution. *Am J Agric Econ* 65:703–710
- Gardner DB (1979) Economic issues of groundwater management. Proceedings of the 12th Biennial Conference on Ground Water, Report no. 45, California Water Resources Center, Riverside, CA, pp 163–169
- Gisser M (1983) Groundwater: focusing on the real issue. *J Polit Econ* 91:1001–1027
- Gisser M, Sanchez DA (1980) Competition versus optimal-control in groundwater pumping. *Water Resour Res* 16:638–642
- Harou JJ, Lund JR (2007) Economic and water management effects of a no overdraft policy: California's Tulare Basin. In: Ragone

- S, Hernández-Mora N, de la Hera A, Bergkamp G, McKay J (eds) The global importance of groundwater in the 21st Century: proceedings of the International Symposium on Groundwater Sustainability. National Groundwater Association, Westerville, Ohio, USA
- Hottelling H (1931) The economics of exhaustible resources. *J Polit Econ* 39:137–175
- Howitt RE (1979) Is overdraft always bad? Proceedings of the 12th Biennial Conference on Ground Water. Report no. 45, California Water Resources Center, Riverside, CA, pp 50–61
- Howitt RE, Ward KB, Msangi SM (2001) Appendix A: statewide water and agricultural production model. In: Jenkins MW et al. (eds) Improving California water management: optimizing value and flexibility. Report No. 01-1, Center for Environmental and Water Resources Engineering, University of California at Davis, CA
- Jenkins MW (1991) Yolo county, California's water supply system, conjunctive use without management, MSc degree project, University of California at Davis, USA
- Jenkins MW, Howitt RE, Lund JR, Draper AJ, Tanaka SK, Ritzema RS, Marques GF, Msangi SM, Newlin BD, Van Lienden BJ, Davis MD, Ward KB (2001) Improving California water management, optimizing value and flexibility. Report no. 01-1, Center for Environmental and Water Resources Engineering, University of California at Davis, CA
- Johnston RH (1997) Sources of water supplying pumpage from regional aquifer systems of the United States. *Hydrogeol J* 5:54–63
- Kendy E (2003) The false promise of sustainable pumping rates. *Ground Water* 41:2–4
- KFMC (Kern Fan Monitoring Committee) (2005) The 2001 Kern Fan area operations and monitoring report, KFMC, Bakersfield, CA
- Knapp KC, Olson LJ (1995) The Economics of conjunctive groundwater-management with stochastic surface supplies. *J Environ Econ Manage* 28:340–356
- Knapp K, Vaux HJ (1982) Barriers to effective groundwater-management: the California case. *Ground Water* 20:61–66
- Knapp KC, Weinberg M, Howitt R, Posnikoff JF (2003) Water transfers, agriculture, and groundwater management: a dynamic economic analysis. *J Environ Manage* 67:291–301
- Konikow LF, Kendy E (2005) Groundwater depletion: a global problem. *Hydrogeol J* 13:317–320
- Koundouri P (2004a) Potential for groundwater management, Gisser-Sanchez effect reconsidered. *Water Resour Res* 40:13
- Koundouri P (2004b) Current issues in the economics of groundwater resource management. *J Econ Surv* 18:703–740
- Kretsinger V, Narasimhan TN (2006) California's evolution toward integrated regional water management: a long-term view. *Hydrogeol J* 14:407–423
- Labadie JW (2004) Optimal operation of multireservoir systems: state-of-the-art review. *J Water Resour Plan Manage* 130(2):93–111
- Lettenmaier DP, Burges SJ (1982) Cyclic-storage: a preliminary assessment. *Ground Water* 20:278–288
- Llamas R, Custodio E (2003) Intensive use of groundwater, a new situation which demands proactive action. In: Llamas R, Custodio E (eds) Intensive use of groundwater. Swets, Lisse, The Netherlands
- Llamas MR, Martinez-Santos P (2005) Intensive groundwater use, silent revolution and potential source of social conflicts. *J Water Resour Plan Manage* 131:337–341
- McCarl BA, Dillon CR, Keplinger KO, Williams RL (1999) Limiting pumping from the Edwards Aquifer: an economic investigation of proposals, water markets, and spring flow guarantees. *Water Resour Res* 35:1257–1268
- Meillier LM, Clark JF, Loaiciga H (2001) Hydrogeological study and modeling of the Kern Water Bank, University of California Water Resources Center, University of California at Davis, CA
- Molle F (2003) Development trajectories of river basins, a conceptual framework. Research Report 72, International Water Management Institute, Battaramulla, Sri Lanka
- Moreaux M, Reynaud A (2004) Optimal joint management of a coastal aquifer and a substitute resource. *Water Resour Res* 40:10
- Nishikawa T, Densmore JN, Martin P, Matti J (2003) Evaluation of the source and transport of high nitrate concentrations in ground water, Warren Subbasin, California. US Geol Surv Water-Resour Invest Rep 03-4009
- Noel JE, Howitt RE (1982) Conjunctive multibasin management: an optimal-control approach. *Water Resour Res* 18:753–763
- Noel JE, Gardner BD, Moore CV (1980) Optimal regional conjunctive water management. *Am J Agric Econ* 62:489–498
- NRC - National Research Council (1997) Valuing groundwater, economic concepts and approaches. National Academy Press, Washington, DC
- O'mara GT, Duloy JH (1984) Modeling efficient water allocation in a conjunctive use regime: the Indus Basin of Pakistan. *Water Resour Res* 20(11):1489–1498
- Planert M, Williams JS (1995) Groundwater atlas of the United States, California, Nevada. HA 730-B, US Geological Survey, Reston, VA
- Provencher B, Burt O (1993) The externalities associated with the common property exploitation of groundwater. *J Environ Econ Manage* 24:139–158
- Provencher B, Burt O (1994) Approximating the optimal groundwater pumping policy in a multiaquifer stochastic conjunctive use setting. *Water Resour Res* 30:833–843
- Pulido-Velázquez M, Marques GF, Jenkins MW, Lund JR (2003) Conjunctive use of ground and surface waters: classical approaches and California's examples. Proceedings of the XI World Water Congress, CD-ROM, Madrid, Spain, October 2003
- Pulido-Velazquez M, Jenkins MW, Lund JR (2004) Economic values for conjunctive use and water banking in southern California. *Water Resour Res* 40(3), W03401
- Pulido-Velazquez M, Andreu J, Sahuquillo A (2006) Economic optimization of conjunctive use of surface water and groundwater at the basin scale. *J Water Resour Plan Manage* 132:454–467
- Reichard EG (1987) Hydrologic influences on the potential benefits of basinwide groundwater-management. *Water Resour Res* 23:77–91
- Reinelt P (2005) Seawater intrusion policy analysis with a numerical spatially heterogeneous dynamic optimization model. *Water Resour Res* 41(5)
- SAIC (2003) Existing west (east) side conveyance and exchange facilities, technical memorandum for task 806 (807), Prepared for Friant Water User Authority, SAIC, Santa Barbara, CA
- Schuck EC, Green GP (2002) Supply-based water pricing in a conjunctive use system: implications for resource and energy use. *Resour Energy Econ* 24:175–192
- Sophocleous M (2003) Environmental implications of intensive groundwater use with special regard to streams and wetlands. In: Llamas R, Custodio E (eds) Intensive use of groundwater. Swets, Lisse, The Netherlands
- Theis CV (1940) The source of water derived from wells, essential factors controlling the response of an aquifer to development. *Civil Eng* 10:277–280
- Tsur Y (1990) The stabilization role of groundwater when surface-water supplies are uncertain: the implications for groundwater development. *Water Resour Res* 26:811–818
- Tsur Y, Graham-Tomasi T (1991) The buffer value of groundwater with stochastic surface-water supplies. *J Environ Econ Manage* 21:201–224
- Tsur Y, Zemel A (1995) Uncertainty and irreversibility in groundwater resource-management. *J Environ Econ Manage* 29:149–161
- USBR (US Department of the Interior, Bureau of Reclamation) (1997) Central Valley Project Improvement Act, Draft Programmatic Environmental Impact Statement. Documents and Model Runs (2 CD-ROMs). USBR, Sacramento, CA
- USACE (US Army Corps of Engineers) (1999) HEC-PRM Package. Hydrologic Engineering Center, Davis, CA

- Vaux HJ (1985) Economic aspects of groundwater recharge. In: Asano T (ed) Artificial recharge of groundwater. Butterworth, Boston, MA, pp 703–718
- Vaux HJ (1986) Water scarcity and gains from trade in Kern county, California. In: Frederick K (ed) Scarce water and institutional change. Resources for the Future, Washington, DC
- Young RA (1992) Managing aquifer over-exploitation: economics and policies. In: Simmers I, Villarroya F, Rebollo LF (eds) Selected papers on aquifer overexploitation. Heise, Hannover, Germany, pp 199–222
- Young RA, Bredehoeft JD (1972) Digital-computer simulation for solving management problems of conjunctive groundwater and surface water systems. *Water Resour Res* 8:533–548
- Zektser S, Loaiciga HA, Wolf JT (2005) Environmental impacts of groundwater overdraft: selected case studies in the southwestern United States. *Environ Geol* 47:396–404