California's evolution toward integrated regional water management: a long-term view

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Abstract Water resources sustainability hinges on interrelated physical, chemical, biological, and human processes, all of which may affect the quantity and quality of available water supplies. California's decades-long transition process from intensive and often unmanaged groundwater development toward more effective, sustainable integrated water resources management has resulted in important lessons. The process offers insights to other countries that seek to achieve sustainability. Long-term systematic groundwater and surface water monitoring programs and ongoing assessment of regional groundwater systems are an integral part of management. On local to global scales, the need for fundamental data, regional resources assessments, and increased support for scientific and technological advances is becoming increasingly apparent. The scientific community must enhance society's understanding of the essential links between basic data needs and the advancement and application of scientific approaches for effective water management. Correspondingly, scientific and political communities must coordinate common interests in endeavors toward sustainable management. Public outreach is a necessary complement to achieve sustainability goals and garner support for the programs needed to develop water policies based on sound science, manage water resources, and meet future water demands while avoiding unacceptable impacts.

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Résumé La durabilité des ressources en eau est à la charnière de processus physiques, chimiques, biologiques et humains, tous inter-reliés et à même d'affecter la quantité et la qualité de la disponibilité en eau d'alimentation. Les processus de transition décadaires en Californie, entre un développement intensif et non contrôlé des eaux souterraines, à un système plus rentable et durable de gestion intégrée des ressources en eau, a permis de conclure sur d'importantes leçons. Ce processus offre, en effet, des perspicacités à d'autres pays qui cherchent à concrétiser la durabilité. Les programmes systématiques de surveillance des eaux souterraines et de surface, sur le long terme, font parti intégrant de ce type de gestion. De l'échelle locale à l'échelle globale, la nécessité de données fondamentales, de bilans régionaux des ressources, et d'un support croissant aux avancées scientifiques et techniques, est devenu de plus en plus apparent. La communauté scientifique doit améliorer la compréhension de la société, en ce qui concerne les liens essentiels entre le besoin de données et l'avancement et l'application des approches scientifiques pour une gestion efficace de l'eau. De la même manière, les communautés scientifiques et politiques doivent coordonner leurs intérêts communs en se démenant pour une gestion durable. La mobilisation du publique est un complément nécessaire pour accomplir les objectifs de la durabilité, et rassembler le support aux besoins des programmes, de manière à développer des politiques de l'eau basées sur une science juste, à gérer les ressources en eau et satisfaire les futures demandes tout en évitant des impacts non acceptables.

Resumen La sostenibilidad de los recursos hídricos gira sobre procesos interrelacionados físicos, químicos, biológicos y humanos, todos los cuales pueden afectar la cantidad y calidad de fuentes disponibles de agua. El proceso de transición de varias décadas que ha experimentado California, a partir de un desarrollo intensivo y frecuentemente carente de gestión de aguas subterráneas, hacia una gestión más efectiva, sostenible e integrada de recursos hídricos ha dado por resultado lecciones importantes. Este proceso ofrece alternativas para otros países que buscan alcanzar sostenibilidad. Los programas de monitoreo sistemático a largo plazo de agua superficial y agua subterránea, y las evaluaciones actuales de sistemas regionales de agua subterránea constituyen una parte integral de la

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gestión. Se hace cada vez más evidente, a escala global y local, la necesidad de datos básicos, evaluaciones regionales de recursos, y apoyo creciente para avances científicos y tecnológicos. La comunidad científica tiene que estimular el entendimiento de la sociedad de las relaciones fundamentales entre las necesidades de datos básicos y los avances y aplicación de enfoques científicos para un manejo efectivo del agua. Del mismo modo, las comunidades científicas y políticas tienen que coordinar intereses comunes en los esfuerzos hacia una gestión sostenible. El involucramiento del público es un complemento necesario para alcanzar los objetivos de sostenibilidad y obtener apoyo para los programas necesarios que permitan desarrollar políticas hídricas basadas en ciencia sana, gestión de recursos hídricos, y alcanzar las demandas futuras de agua mientras se evitan impactos inaceptables.

Keywords Groundwater management · Groundwater monitoring · Sustainability · Integrated resources management · Water policy

Introduction

Groundwater constitutes 30.1% of the earth's freshwater resources (Leap 1999) and is a critical component of global water supplies. Many factors contribute to the importance of groundwater resources, including population growth, climate variability, source water quality, and uncertain surface water availability. Groundwater is integral to the hydrologic system, and plays a vital role in the functioning of ecosystems and biological habitats.

In California (Fig. 1), groundwater has contributed greatly to economic prosperity for over a century, facilitated by groundwater laws that have been largely judiciary and minimally statutory. However, the need for groundwater statutes has gradually grown with time. Consequently, the history of groundwater development and evolving groundwater management strategies in California provide an instructive example of the state's adaptation to the constraints of natural resource systems.

Fig. 1 California's counties and adjoining states

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Table 1 California water balance summary (km^3)

	Water year (% of normal precipitation)		
	1998 (171%)	2000 (97%)	2001 (72%)
Water entering State			
Precipitation	407	232	172
Inflow from Oregon/Mexico	2.84	2.10	1.36
Inflow from Colorado River	6.17	6.54	6.41
Imports from other regions	N/A	N/A	N/A
Total	416	240	179
Water leaving State			
Consumptive use of applied water[a]	27.8	34.4	34.2
Outflow to Oregon/Nevada/Mexico	1.85	1.11	0.86
Exports to other regions	N/A	N/A	N/A
Statutory required outflow to salt sink[b]	59.0	38.7	21.1
Additional outflow to salt sink	90.0	45.9	22.0
Other outflows[c]	230	127	119
Total	408	247	197
Storage changes in State[d,e]			
Change in surface reservoir storage	8.88	−1.60	−5.67
Change in groundwater storage[f]	−1.73	−5.55	−12.0
Total	7.15	−7.15	−17.6
Applied water	41.8	51.6	50.7

Source: DWR (in press)

N/A Used to identify areas where data are not available

[a]Definition: consumptive use is the amount of applied water (agricultural, municipal, irrigation, wetlands) used and no longer available as a source of supply. Applied water is greater than consumptive use because it includes consumptive use, reuse, and outflows

[b]Salt sinks include the Salton Sea (located in Imperial and Riverside Counties), the Pacific Ocean, and saline aquifers

[c]Evaporation, evapotranspiration of native vegetation, groundwater subsurface outflows, natural and incidental runoff, agricultural effective precipitation (annual precipitation used by crops planted in developed irrigated land areas), and other outflows

[d]Storage changes in State corresponds to water entering State minus the water leaving State

[e](+) Water added to storage, (−) Water removed from storage

[f]Change in groundwater storage is based upon best available information. Basins in the north part of the State (North Coast, San Francisco, Sacramento River and North Lahontan Regions and parts of Central Coast and San Joaquin River Regions) have been modeled – Spring 1997 to Spring 1998 for the 1998 water year and Spring 1999 to Spring 2000 for the 2000 water year. All other regions and year 2001 were calculated using the following equation:

Change in groundwater storage = intentional recharge + deep percolation of applied water + conveyance deep percolation − withdrawals

This equation does not include the unknown factors such as natural recharge and subsurface inflow and outflow

Table 2 Annual agricultural and municipal water demands met by groundwater

Hydrologic region	Total demand volume (km^3)	Demand met by groundwater (km^3)	Demand met by groundwater (%)
North coast	1.31	0.32	25
San Francisco Bay	1.67	0.08	5
Central coast	1.56	1.29	83
South coast	6.32	1.45	23
Sacramento River	10.76	3.30	31
San Joaquin River	9.08	2.71	30
Tulare Lake	13.02	5.35	41
North Lahontan	0.70	0.19	28
South Lahontan	0.59	0.29	50
Colorado River	5.51	0.42	8

Source: DWR (1998)

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California's groundwater resources are widespread and diverse. There are 431 presently delineated basins in ten hydrologic regions (Fig. 2) that underlie 40% of California (California Department of Water Resources, DWR 2003). In an average year, groundwater supplies about 30% of the state's overall water demands; in drought years, it may be 40% or greater (DWR 2003). In 2000, California accounted for approximately 18% of the total groundwater withdrawals in the United States (Hutson et al. 2004). Population projections estimate growth to about 48 million people in 2020, an increase of about 16 million people since 1995 (DWR 1998). DWR (1998) reported total water needs in 1995 (for an average year) of 98.1 cubic kilometers (km^3), while for 2020 it forecasted needs of 14.6 km^3 for urban use, 38.6 km^3 for agricultural use, and 45.6 km^3 for environmental use, or a total of 98.8 km^3. Table 1 summarizes California's total statewide sources of water and estimated water use, including water use by natural processes such as evaporation and evapotranspiration (DWR in press). During a dry year, such as 2001, there is a significant reduction in storage, particularly groundwater storage. Notably, however, DWR (in press) reports that values in Table 1 were developed by estimation techniques since measured data are "not available on a statewide basis." Table 2 summarizes average year agricultural and municipal supplies in each of California's ten hydrologic regions (DWR 1998). As shown in this table, some regions rely heavily on groundwater resources to meet local needs.

Populous areas are inversely related to the location of water supplies, and this complicates solutions for addressing future water resources demands. Groundwater overdraft is currently estimated to occur at the rate of about 1.2–2.5 km^3/year (DWR 2003). Additionally, urban and other land uses, and also elevated concentrations of naturally occurring physical and chemical constituents, contribute to other stresses on the available supply. There are also concerns about the development of additional water supplies in areas of pre-existing water quality problems. Thus, the available water supply may be reduced unless treated. Desalination technologies will also be increasingly important to restore groundwater that has become impaired through seawater intrusion or historical land use, or to develop and use naturally occurring brackish water. As described in this paper, a comprehensive assessment of overdraft in the state of California has not been conducted since 1980. Moreover, future groundwater availability in the state is not well understood. In many basins, information is insufficient to assess or quantify overdraft.

California has slowly moved toward improving water resources management approaches on a statewide scale. Recently, legislative and other initiatives have increased partly in response to public awareness and concern. However, are these initiatives being coordinated and are they meeting the State's long-term needs? Continued initiatives need to be carefully based on relevant scientific input. The long-term goal is to implement integrated regional water management that achieves sustainable water resources.

This paper illustrates California's evolution from an early era of intensive exploitation toward integrated water resources management. This evolution is characterized by a growing awareness that groundwater is a renewable but finite resource that needs to be managed locally and regionally so available resources will also satisfy the needs of future generations. California's water history and experience weave a remarkable case history of a society seeking to prosper from its bountiful natural resources. The fundamental lesson learned is that society must adapt to the constraints of finite natural systems. Such adaptation entails scientific understanding of nature, as well as the development of appropriate institutions and policies. The California experience, including its struggle and progress toward sustainable management of its groundwater resources provides insights to others in the world that seek sustained use of groundwater resources while protecting the natural function of ecohydrologic systems.

This paper is broadly divided into three parts: "The past," covering the period from California's statehood to the late 1980s, "The transition," from the 1990s to the present, and "The future," looking ahead to the next few decades. Important events in California's water history are summarized in Table 3. Table 4 lists acronyms used in this paper.

The past

Early groundwater development

California attained statehood in 1850. Its early settlers used the abundant natural resources, including water, for prosperity. Early governmental attitude was one of encouraging economic progress through minimal regulation. Within a few decades, surface water and groundwater were being developed at rates exceeding those of natural replenishment, and water was often wasted through inefficient

Fig. 2 California's 10 hydrologic regions, DWR (2003)

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Table 3 Chronology of important dates

Date	Notable actions, events and activities
1878	Constitutional Convention resolves that the use of all appropriated water in California is for public use, subject to the regulation and control of the state
1878	John Wesley Powell submits *Report on the Lands of the Arid Region of the United States* to the United States Congress
1903	In the case Katz vs. Walkinshaw, the California Supreme Court rejected the British common law doctrine of landowners owning everything beneath their land. So landowners have overlying rights for reasonable and beneficial use; these rights are correlative to other overlying rights in a groundwater basin
1910	Introduction of deep well turbine pump in the Santa Clara Valley
1911	Civil Code establishes that water in the State is the property of the people of the State
1914	Water Commission Act requires surface water appropriators to comply with permit process
1921	State declares that the people have a paramount interest in the use of all water of the State, including surface and underground, and that the State determines what water can be converted to public use or controlled for public protection
1928	State Constitutional amendment declares water resources are to be put to reasonable and beneficial use
1931	First reported case of land subsidence due to groundwater abstraction in the vicinity of San Jose
1961–62	Interim Assembly Committee examined groundwater problems but deferred recommendations
1976–78	Governor's Commission formed to review water rights law; report prepared, including recommendations for groundwater management
1983	Passage of Urban Water Management Planning Act; facilitates long-term resource planning and analyses to ensure adequate water supplies
1991	AB 255 authorized local agencies overlying basins subject to critical conditions of overdraft to establish programs for groundwater management
1992	Passage of AB 3030, the Groundwater Management Act; encourages development of local groundwater management plans
1999	California Budget Act directed DWR to provide a statewide update of the inventory of groundwater basins, develop a model groundwater management ordinance; and develop guidelines for evaluating local groundwater management plans
2000	Passage of AB 303, the Local Groundwater Management Assistance Act; assists local entities with efforts to conduct groundwater studies or implement monitoring and management
2001	Passage of SB 221 and SB 610; requires water suppliers to demonstrate sufficient water supplies are available for planned development projects
2001	Passage of AB 599, the Groundwater Quality Monitoring Act; focuses on coordinating monitoring efforts and developing a statewide monitoring approach
2002	Passage of SB 1938; amends the Groundwater Management Act to add more comprehensive monitoring and other requirements
2003	Passage of SB 1672, the Integrated Regional Water Management Planning Act; encourages local agencies to cooperatively manage water supplies
2003	Voters approve Proposition 50; provides more than $3.4 billion US dollars, subject to appropriation, for many land and water quality and quantity management activities
2004	DWR develops guidance for Integrated Regional Water Management plans

use. In 1878, the First California Constitutional Convention recognized the negative consequences of exploitation of water resources without associated responsibilities. It declared by resolution that the use of *all* water appropriated was declared to be a public use, subject to the regulation and control of the state. This resolution was later incorporated in California's Constitution as Article 10, Section 5.

John Wesley Powell: early visionary

John Wesley Powell, geologist, geographer, linguist, explorer and second director of the United States Geological Survey (USGS) from 1881 to 1894, understood over a century ago the interconnections among climate, physiography, soils, and water. He also recognized the need for new and imaginative approaches to harness the natural resources of the arid regions of the American west. Powell's landmark

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Report on the Lands of the Arid Region of the United States (Powell 1878), submitted to the United States Congress the same year as the First California Constitutional Convention, deserves greater recognition of its enduring significance. In his report, which preceded the formation of the USGS and the availability of topographic maps, he synthesized analyses of such diverse subjects as climate, geography, land use, and land law into an integrated vision of conditions in the west. Powell perceived the inherent complexity of natural forces and the physical system; more importantly, he understood the necessity for society to adapt to its physical environment in a manner that preserves the benefits of the land and results in shared benefits for its people. Accordingly, he integrated knowledge across disciplinary fields. DeBuys (2001) comments that "it was the habit of his mind always to fit new data into the pattern of the whole, to build continually the mosaic of a total view."

The crux of Powell's revolutionary conceptualization came in 1890 when he authored a series of articles published in the *Century Magazine*. In these articles, he argued for local institutional control and management and also the development of an interface between humankind and physical forces of nature (deBuys 2001). Powell's enduring vision remains relevant today; his recommendations embraced the following concepts:

- Organize a local body with interdependent and unified interests and values for an entire hydrographic basin that is segregated by well-defined boundaries
- Establish local self-government by hydrographic basin to create broad, diverse management units that perform effective responsible water resource management with an appreciation for the interdependence between the resources and local interests and where interlocking interests act as checks against detrimental effects on resources
- Develop local institutions and plans for water conservation and management that recognize the present value of water, the value of water in perpetuity, and the means for distributing such commonwealth
- Develop public support and understanding of long-term management needs.

Early investigators, scientific advances, and groundwater terms

Fundamental hydrologic principles began to be established before and throughout the 20th century and continue to evolve today. Renowned early investigators include H. Darcy in 1856, Dupuit in 1863, G. Theim in 1906, O.E. Meinzer in 1923, C.V. Theis in 1935, C.E. Jacob in 1940, and M. K. Hubbert in 1940 (Leap 1999). Even so, there remains a challenge for applying scientific advances to local, state, national, and global needs to better quantify and effectively manage water resources. Subsequent to the formation of the USGS in 1879, early investigators, including W. C. Mendenhall (1908) and C. H. Lee (1914) evaluated the response of the State's aquifer systems in San Bernardino County, the San Joaquin Valley (which extends across portions of 11 counties from the southern portion of Sacramento County to Kern County), and the Owens Valley (located in Inyo and Mono Counties). The term "overdraft" was first applied to groundwater basins by Mendenhall (1908), who used it to describe steadily declining groundwater levels during a period of high precipitation that was otherwise conducive to groundwater level recovery. Overdraft is most often defined in terms of safe yield. Safe yield was first introduced by Lee (1914) to describe the net annual supply of groundwater that may be developed without persistent lowering of groundwater levels. Although dissatisfaction with the term "safe yield" has been expressed (Thomas 1951; Kazmann 1956; Mann 1961), particularly with the furtherance of sustainable resource concepts (Sophocleous 1997, 1998; Alley et al. 1999; Custodio 2002; Alley and Leake 2004), this term is often used interchangeably with other terms such as perennial or sustainable yield. All these expressions commonly convey the same concept or intent, i.e., development and use of groundwater at a rate that is renewable (Mann 1961). The generally accepted legal definition of safe yield was first delineated in a report by the State Water Rights Board (1962):

> The safe yield of the ground water reservoir ... is the maximum average annual pumping draft which can be continually withdrawn for useful purposes under a given set of conditions without causing an undesired result.

Table 4 Acronyms

AB 303	Assembly Bill 303, Local Groundwater Management Assistance Act
AB 3030	Assembly Bill 3030, the Groundwater Management Act
AB 599	Assembly Bill 599, Groundwater Quality Monitoring Act of 2001
Commission	Governor's Commission
DWR	California Department of Water Resources
GWR	Groundwater Replenishment System
IRWM	Integrated Regional Water Management
MWD	Metropolitan Water District
NGWA	National Ground Water Association
NSTC	National Science and Technology Council
OCWD	Orange County Water District
SB 1672	Senate Bill 1672, the Integrated Regional Water Management Planning Act of 2002
SB 1938	Senate Bill 1938, the Groundwater Management Act of 2002
SB 221	Senate Bill 221
SB 610	Senate Bill 610
SB 901	Senate Bill 901
SCVWD	Santa Clara Valley Water District
SWRCB	State Water Resources Control Board
US	United States
USGS	United States Geological Survey
UWMP	Urban Water Management Plan
Water Code	California Water Code

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An "undesired result" is commonly interpreted to mean a progressive lowering of groundwater levels leading eventually to depletion of the supply. Undesired results also include long-term depletion of groundwater storage, inducement of seawater intrusion or other degraded water quality, or land subsidence (Mann 1961; Todd 1980).

Based on the definition of safe yield, overdraft has been legally defined in California as a condition when extractions exceed safe yield plus temporary surplus; temporary surplus is the amount of water that can be pumped from a basin to provide storage space for surface water that would be wasted during wet years if it could not be stored in the basin (City of Los Angeles vs. San Fernando 1975, 14 Cal.3d 199, 280, 537). Many recent papers have contributed to expanded discussion of intensive groundwater use, overdraft, and groundwater depletion, including Alley et al. (2002), Custodio (2002), Llamas and Custodio (2003), Konikow and Kendy (2005), Custodio et al. (2005).

Basic groundwater laws

In contrast with a number of other semi-arid states or countries, groundwater development has been mostly unregulated in California. Though regulation has been broached in the Legislature several times, groundwater management remains a voluntary local activity, or it is regulated in adjudicated groundwater basins.

As California's agricultural economy and urban centers grew at the turn of the 20th century, the State government initiated efforts to conserve water resources. The Civil Code of 1911 and the Water Commission Act of 1914 established principles for beneficial use of the State's water resources. Specifically, the Civil Code stated that all water within the State is the property of the people of the State, and that the right to use water may be acquired, as prescribed by law. The Water Commission Act required surface water appropriators to comply with a permitting process. In 1921, a State law passed, declaring that the people have a paramount interest in the use of all water of the State, including surface and underground, and that the State determines (Water Code Section 104) what water can be converted to public use or controlled for public protection (California Water Code 2005). Despite the progressive steps taken during 1911 and 1914, riparian owners of water (i.e., landowners with property situated along a watercourse) continued to waste surface water. In 1928, a referendum passed (and was later incorporated in California's Constitution) declaring that the water resources of the State be put to reasonable and beneficial use, regardless of whether a user had riparian or appropriative rights.

Under the public trust doctrine, originating in early Roman law, resources such as air, running water, the sea, and the lands adjoining the sea are available to all humankind by "natural law." This doctrine is part of the constitution of California; it also corresponds to the concept of public dominion in Roman and European legislation. In California, the State is responsible for ensuring that water is beneficially, and not wastefully, used. Legally, public trust applies only to navigable waters and tidelands; thus, the scope of public trust is restricted to surface water resources. However, from declarations in 1911 and 1921 that were later incorporated in the Water Code, groundwater falls within the realm of public trust, if not within its legal fold (Narasimhan and Kretsinger 2003).

Groundwater rights in California include overlying rights, appropriative rights, and prescriptive rights. In a 1903 case, Katz vs. Walkinshaw, the California Supreme Court rejected the British common law doctrine of landowners owning everything beneath their land (Schneider 1977). The court modified the common law precedent so landowners have overlying rights for reasonable and beneficial use. These rights are correlative to other overlying rights in a groundwater basin, i.e., when water shortages occur, all overlying users share the common supply. Groundwater that is surplus to overlying owner's needs can be withdrawn and used on non-overlying lands; this constitutes an appropriation of groundwater. This use is inferior in priority to overlying uses. Between appropriators, priority is governed by the principle "first in time, first in right" (City of Los Angeles vs. City of San Fernando (1975) 14 Cal.3d 199, 241).

Prescriptive rights can be established through the adverse use of another's water (i.e., pumping of non-surplus water) where the use is actual, open and notorious, hostile, and adverse to the original owner, and also continuous and uninterrupted for five consecutive years, under claim of right (City of Pasadena vs. City of Alhambra (1949) 33 Cal.2d, 208, 926, 207). Pumping from an overdrafted groundwater basin is generally determined to be adverse to other users; this is an example of a situation where rights may be gained or lost through prescription.

Groundwater management approaches

Groundwater management began to occur in California long before it became formally recognized through state legislative initiatives. Groundwater management may be defined as the ongoing performance of coordinated actions related to groundwater withdrawal and replenishment to achieve long-term sustainability of the resource without detrimental effects on other resources. Preferably, such management programs are a local responsibility, conducted in coordination with other entities (including cooperative monitoring programs), and regularly evaluated to ensure consistency with basin-wide management objectives.

Sustainability has many different meanings; perhaps the most globally espoused view is the continued productivity of commodities to maintain economic growth. The scientific community, however, has defined groundwater resources sustainability in prior publications (Sophocleous 1997, 1998; Alley et al. 1999; Narasimhan and Kretsinger 2003; Alley and Leake 2004). In a White Paper on groundwater management, sustainability was approached based on the physical laws that govern the behavior of earth systems and was defined as (Narasimhan and Kretsinger 2003):

Sustainability encompasses the beneficial use of groundwater to support present and future generations, while simultaneously ensuring that unacceptable consequences do not result from such use.

This view of sustainability entails four premises (Kretsinger and Narasimhan 2005):

– Surface water and groundwater constitute a single resource
– Groundwater is a finite resource and a component of a larger natural resources system. Actions on one or more system components generally affect the long-term balance of the whole system
– Groundwater replenishment is strongly influenced by climate variability, as well as natural and enhanced recharge processes. Consequently, groundwater resources development must adapt to the system's varying capacity for renewal
– Communities need to share and manage groundwater resources so the natural resources system retains its integrity for the future.

Examples of early management actions

Examples of decades-long groundwater-management actions include those implemented by the Santa Clara Valley Water District (SCVWD) and Orange County Water District (OCWD) beginning in about 1919 and 1933, respectively. These cases, which represent only two of the 431 basins in California, provide excellent illustrations of dynamic management approaches where surface water and groundwater are conjunctively managed. The summary below describes the management programs first initiated by these districts and how these programs have evolved to manage resources today.

Santa Clara Valley Water District

Water has played an important role in the history and development of Santa Clara County (Fig. 1) since at least the 1850s when the first well was drilled in San Jose, a city that now thrives on a population of about 925,000. By 1865, nearly 500 artesian wells served the needs of farmers and others (Reymers and Hemmeter 2001). Droughts and increased water demands resulted in more drilling. The introduction of the deep-well turbine pump in 1910 led to an explosive increase in groundwater withdrawal; and, by 1913, farmers were confronted with escalating costs of pumping due to lowered water levels. In 1919, an association of farm owners and operators prepared a resolution to the County Board of Supervisors that opposed wasteful use of water. In 1920, the Water Conservation Committee charged Fred Tibbetts, a civil engineer, with the task of conducting a comprehensive water survey of the valley as a prelude to forming a water district for integrated water management (Reynolds 2000). Subsequently, Tibbetts and Kieffer (1921) produced an integrated water plan for the Santa Clara Valley watershed, comprising 17 surface water impoundments, complemented by carefully distributed artificial recharge facilities, and pumping stations for groundwater abstraction. After two failed referendums, area voters approved formation of the Santa Clara Valley Water Conservation District in 1929 for the purpose of integrated water management (Reymers and Hemmeter 2001). Later, this district (located in Santa Clara County, Fig. 1) evolved into what is now the SCVWD, which was formed through the consolidation and annexation of other county flood control and water districts. Notably, in 1929, without economic leveraging by state or federal initiatives, the public approved formation of the institution that, ahead of its time, facilitated integrated water management.

After much political debate, a scaled-down version of the Tibbetts-Kieffer plan of 1921 was implemented by the SCVWD between 1936 and the early 1950s with very encouraging results. However, the growth of the electronic industry during the 1950s inevitably led to surface water importation from outside the Santa Clara Valley watershed. The SCVWD is now a water resource management agency for the entire county and provides water at wholesale rates to 13 private and public water retailers that serve more than 1.7 million residents. In 2000, total water use was 0.5 km^3, where groundwater supplied from three basins was about 0.2 km^3 (Reymers and Hemmeter 2001). Conjunctive management of surface water and groundwater resources has been an integral part of the SCVWD's comprehensive water resources management efforts to "ensure that groundwater resources are sustained and protected" (Reymers and Hemmeter 2001). The water supply infrastructure includes reservoirs, treatment plants, and 18 major recharge systems that include a combination of off-stream and in-stream facilities.

Historically, a total of 4 m of inelastic subsidence occurred due to intensive groundwater production and persistent groundwater level decline. Over 0.9 m of subsidence was discovered in downtown San Jose in 1931 and was later confirmed by releveling in 1932 (Rappleye 1933). Presently, subsidence occurs at a rate of < 3 mm/year. Through continued management of its water resources, the SCVWD has curtailed subsidence.

Orange County Water District

The OCWD (located in Orange County, Fig. 1) was formed by a Special District Act in 1933, and through this Act became empowered to fulfill its mandate to protect the groundwater basin from depletion and irreparable damage (OCWD 1993). A California special district is a separate local government that delivers public services to a particular area. From the mid-1940s to the 1960s, groundwater levels declined in the OCWD and seawater intrusion was observed. In 1948, the OCWD began using imported water from the Metropolitan Water District (MWD) of southern California for artificial recharge. The MWD service area includes portions of Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Ventura Counties (Fig. 1). In 1953, the District Act was amended to allow pumpers (or producers) to be charged a pump tax and to report

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abstraction quantities. These requirements allowed the OCWD to improve estimates of the amount of imported water needed to offset pumpage and, thus, also created a mechanism to reverse trends toward groundwater depletion.

In 1965, the OCWD began to actively manage groundwater conditions at the coast to mitigate seawater intrusion. By 1969, the OCWD further modified its management approach with the adoption of a conjunctive use policy (OCWD 1993). A full-scale intrusion control project was approved in 1971, and the OCWD implemented intrusion control with two barriers created through extensive injection well networks. The Alamitos Barrier uses 100% imported potable water for injection; the Talbert Barrier consists of 28 injection wells and has been in operation since 1975. At the Talbert Barrier, 30–60% of the injectate is recycled water from a treatment facility called Water Factory 21; the remainder is groundwater abstracted from a deep aquifer that is blended with the recycled water. The OCWD is moving toward completing new treatment facilities, the Groundwater Replenishment System (GWR), by 2007 (DWR 2003). The GWR is designed to meet future needs for intrusion control and will include eight new injection wells and increase the amount of injected water from 57 to 152 thousand m^3/day. Treated water from the new facilities will be of high quality resulting from multiple treatment processes in an advanced purification system that includes microfiltration, reverse osmosis, and ultraviolet light with hydrogen peroxide.

The OCWD uses integrated water management practices to manage the groundwater in its basins and also develop reserves for drought conditions (DWR 2003). Currently, the OCWD serves a population of about 2 million. Whereas in 1933 about 86% of the groundwater was pumped for agricultural purposes, now, due to urban development, less than 4% is used for that purpose. The OCWD actively engages in public outreach, including free water education classes to teach residents about local, state, and global water issues; how water affects health; conservation methods; and solutions to alleviate future water shortages.

California's management methods

In addition to the groundwater rights categorized above, California's groundwater is managed through other means, including statutory authority; groundwater management districts or agencies; groundwater management plans; city and county ordinances; and groundwater basin adjudication. Formal groundwater management plans and local ordinances mostly came later and are discussed below under "Groundwater management: next steps."

More than 20 types of local districts or agencies have statutory authority to provide water for beneficial uses. The total number of such agencies that have general powers to manage some aspect of groundwater within their boundaries is uncertain (DWR 2003). However, thirteen Special Act districts (formed between 1933 and 1993 by the State Legislature to meet the unique water needs of a specific area) regulate or limit abstraction; seven agencies adopted plans under Water Code Section 10750, the portion of the Water Code detailing provisions for groundwater management (California Water Code 2005).

Another means of groundwater management that is generally considered as a last resort is court adjudication of the basin where the court determines groundwater abstraction rights for each user. A single groundwater user can initiate basin adjudication. All or most groundwater users must be joined in the adjudication to be bound by the judgment. Adjudications are typically very costly and lengthy. The first basin-wide adjudication occurred in the Raymond Basin in Los Angeles County (Fig. 1); this was first filed in court in 1937, and the final decision occurred in 1944 (DWR 2003). Nineteen adjudications have occurred in California with most of these occurring in southern California.

Groundwater problems examined

An Assembly Interim Committee, formed in 1961–1962 to examine groundwater problems in California, foresaw that problems in such areas as the San Joaquin Valley "will probably become worse and in a few instances become critical before public attention will be focused on them sufficiently to stimulate local expenditures for necessary programs" (Governor's Commission 1978). The committee, however, deferred any recommended actions by concluding (Assembly Interim Committee 1962):

> If in the future, there are indications of major failure in any of the local groundwater management programs, and it can be determined that local negligence or inaction was the cause, the Legislature would then have a basis to take major corrective action.

Along with the 1976–1977 drought, "undesired results" in their various forms (including lowered groundwater levels leading to eventual depletion of groundwater supplies, seawater intrusion, and land subsidence), as especially observed in some coastal areas and the San Joaquin Valley, became a more widespread concern. In 1976, the Governor appointed a commission to review California water rights law in part to address groundwater problems (Governor's Commission 1978). The Commission noted serious questions about the future availability of new surface supplies and showed concern for expanding demands that were aggravating already serious overdraft problems (Peters 1982).

In response to severe and extensive groundwater problems in the state, the Commission prepared a report that contained recommendations for future rules pertaining to the comprehensive management of surface and groundwater. Specifically, relating to groundwater issues, the Commission recommended that legislation be enacted on groundwater management, the adjudication of groundwater rights, and conjunctive use of surface and groundwater resources. At the time of the Commission's report, however, the political system lacked the will to modify the existing legal standards that then formed the jurisdictional framework in California, thus no action was taken.

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Urban water management plans

In 1983, the California Legislature enacted the Urban Water Management Planning Act (Water Code Sections 10610–10657) to facilitate long-term resource planning and ensure adequate water supplies to meet existing and future water demands. The Act states that every urban water supplier that provides water to 3,000 or more customers, or that provides over 3.7 million m^3 of water annually, should make efforts to ensure that water supplies are sufficient to meet the needs of its various categories of customers during normal, dry, and multiple-dry years. The Act specifies the contents of the Urban Water Management Plans (UWMPs) and describes how urban water suppliers should adopt and implement the plans. When this Act was first adopted in 1983, groundwater was not explicitly addressed. The Act has, however, subsequently been amended by 18 bills. With legislation passed in 2001, groundwater reliability finally became incorporated in the Act as a required component of UWMPs.

The transition

Groundwater management: next steps

The first legislative actions taken by California to broadly address groundwater management occurred in 1991 and 1992. In 1991, an Assembly bill, AB 255, authorized local agencies overlying basins subject to critical conditions of overdraft to establish programs for groundwater management within their service area (DWR 2003).

In 1992, an attempt was made to revisit the recommendations made by the Governor's Commission (1978) for comprehensive groundwater management. The 1992 legislation passed (AB 3030, the Groundwater Management Act) and was considered a breakthrough for groundwater management at the local level. The initially proposed legislation, however, was substantially weakened. Although voluntary plans for groundwater management as prescribed by AB 3030 could be developed and implemented at the local level, significant groundwater management issues (e.g., overdraft, subsidence, and seawater intrusion) that have long-existed in California are generally being addressed outside of the purview of this legislation. Upon passage of AB 3030, AB 255 was repealed.

Ordinances adopted by city and county local governments are also a relatively recent means of managing groundwater, with 24 out of 27 existing ordinances adopted since 1990. Others are being considered. The main purpose of many of these ordinances is to limit groundwater export from the county or from certain groundwater basins or areas within the county. Only one county has included a more comprehensive approach that includes establishing basin management objectives. The full nature of the authority of cities and counties to regulate groundwater is uncertain. On the heels of these independent local efforts, DWR (2003) prepared a "model ordinance" to further encourage local entities to actively engage in groundwater management. While well intended, the model could result in overlapping and potentially conflicting efforts by local governments and water agencies. The formula-oriented model may also detract from its use or result in more time and cost devoted to unnecessary actions and less attention to locally specific management needs.

Recent strides in groundwater management

From 1992 to about 2000, many water agencies and suppliers embraced the notion of formal, yet still volunteered, groundwater management plans. Beginning about 2001, however, heightened interest by state water agencies, state and local governments, and others concerned about future planning and management strategies needed to address California's growing water demands resulted in a plethora of legislative and other initiatives. Recently adopted legislation and state guidance documents resulted in land-use planning coordinated with water supply sufficiency assessments; expanded groundwater management plans and monitoring programs; funding programs that encourage integrated regional strategies for water resources management; and a guidance document for minimum standards for integrated regional water management plans.

Basin conditions, supply sufficiency, and quality

In 2001, land use became more directly linked to the analysis of water supply sufficiency with the passage of two Senate bills (SB 221 and SB 610) that prohibit approval of urban housing projects of a defined magnitude unless the water supplier verifies that sufficient water supplies are available for the planned development project (Government Code Section 66473.7 and Water Code Section 10910) (California Government Code 2005; California Water Code 2005). To address sufficiency of supply, public water suppliers are required to describe the total available water supplies (e.g., surface water and groundwater) during various climatic conditions to meet 20-year projected water demands. Additionally, rights to abstract additional groundwater, if used for the project, must be substantiated. When groundwater is identified as a source of supply, the supplier must assess the future sufficiency of not only the groundwater source supplying the proposed project but also existing and planned future pumping occurring by the supplier and also other pumpers. Another bill adopted in 2001, SB 901, requires urban suppliers to also include information in UWMPs relating to the quality of available water sources and the manner in which water quality affects water management strategies and supply (DWR 2003).

The Groundwater Quality Monitoring Act of 2001 (AB 599) focuses on coordinating state agency monitoring efforts under the State Water Resources Control Board (SWRCB) to develop a comprehensive statewide groundwater monitoring approach. It is also directed toward integrating data and making those data more accessible, including increasing the availability of groundwater quality information to the public. Efforts to implement the bill and program resulted in two reports, including the

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report to the Governor and Legislature (SWRCB 2003) and the report prepared by the USGS in cooperation with the SWRCB titled "Framework for a Ground-Water Quality Monitoring and Assessment Program for California" (Belitz et al. 2003). The statewide program recommendations prioritized monitoring efforts according to basins that rely most heavily on groundwater for drinking water.

SB 1938, the Groundwater Management Act adopted in 2002, amends and expands AB 3030 groundwater management plans. The law now also requires public agencies seeking state funds administered through DWR for the construction of groundwater projects or groundwater quality projects to prepare and implement a groundwater management plan with certain required components (Water Code Section 10753.7). Previously, all plans were voluntary, and there were no required plan components. The requirements now include establishing basin management objectives, preparing a plan to involve other local agencies in the basin in a cooperative planning effort, and more comprehensive monitoring programs (including groundwater levels and quality; surface water flows and quality; and inelastic land surface subsidence for basins where it is identified as a potential concern) to assess changes in basin conditions and "generate information that promotes efficient and effective groundwater management" (Water Code Section 10753.7). The amended Water Code does not require groundwater management and monitoring by all local entities, but moves the State further toward addressing the many issues and questions about the future of groundwater management in California that were brought forth by the staff of the Governor's Commission on Water Rights Law (Schneider 1977).

In 2002, days after SB 1938 passed, the Legislature enacted SB 1672, the Integrated Regional Water Management Planning Act of 2002, to encourage local agencies to work cooperatively to manage available local and imported water supplies. The Act facilitates development of integrated regional water management plans that coordinate local programs and projects to improve source water quality; provide water supply reliability; augment agricultural, domestic, or environmental water supply; and improve the quality or quantity of groundwater. The enacted legislation contained no specific guidance for regional plans. However, California voters approved a proposition (Proposition 50) in 2002 that provides more than \$3.4 billion US dollars of funding, subject to appropriation, for many land and water quality and quantity management activities. There is a specifically designated Integrated Regional Water Management (IRWM) portion of this program for projects that provide for drought protection, protect and improve water quality, and improve local water reliability by reducing dependence on imported water. Eligibility for funding from this program hinges on applicants having completed (or preparing based on a set schedule) an AB 3030 or IRWM plan depending on the type of project proposed. Since there was no set guidance for the latter, DWR subsequently developed a guidance document that delineates minimum standards for IRWM plans (DWR and SWRCB 2004).

Various state funding vehicles have been approved by the Legislature or the State's voters for programs to improve groundwater management. As of 2003, DWR awarded \$15 million US dollars through AB 303 (the Local Groundwater Management Assistance Act passed by the State's voters in 2000) to fund 71 projects dealing with groundwater investigation, monitoring, or management. By 2003, under Proposition 13 funding (approved by the State's voters in 2000), DWR awarded more than \$170 million US dollars in loans and grants for groundwater recharge and storage studies and other local agency projects. However, not until 2002, when SB 1938 was passed and groundwater management plans became required to be eligible for state funds, and in 2004, when the minimum guidelines for IRWM project eligibility for Proposition 50 funds were developed, were there mechanisms that provided additional eligibility criteria for using state funds for groundwater management-related projects. Consequently, until recently, many entities enjoyed the opportunity to use the funds with minimal eligibility criteria.

Measure of success?

Although other states, and also some water agencies in California, heeded John Wesley Powell's recommendations some time ago, California has largely just begun planning on a basin-wide context, incorporating basin-wide management objectives, working cooperatively with other entities that overlie the basin, and expanding data collection efforts.

More than 200 agencies have developed AB 3030 Plans, over 60 agencies have adopted plans under other statutory authority, and at least 20 coordinated plans were prepared as of 2003, involving nearly 120 agencies. However, how successful have management efforts been with these plans? DWR (2003) comments:

- There are no reporting requirements when plans are implemented, so a comprehensive assessment of local planning efforts is not possible
- Some plans are simply brief recitations about continuing the agency's programs
- Not all agencies are actively implementing enacted programs.

Will the Water Code amended in 2003 with the passage of SB 1938 result in more effective groundwater management planning? Will monitoring data be better used to understand conditions and effectiveness of management actions? Will data sharing among local entities become better coordinated? Even though a measure of effectiveness is yet to be determined, DWR (2003) views the existence of these plans as "giant strides forward" considering the previous lack of management on a broad scale.

The 1999 California Budget Act directed DWR to develop criteria for evaluating groundwater management plans and also to develop a model groundwater management ordinance. In 2003, both these directed tasks were completed. DWR (2003), with input from the Groundwater Committee of the Association of California Water Agencies, prepared a summary of "Recommended and Required

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Components of Local Groundwater Management Plans." These components include the Water Code requirements, Section 10750 et seq., and also additional components that are not directly captured in the Water Code but are considered important aspects of any groundwater management plan. The objective of the summary is to ensure groundwater management plans are prepared and implemented to achieve the global goals of a "long-term, sustainable, reliable, good quality groundwater supply" (DWR 2003). An example of a recommended component is the periodic reporting of groundwater basin conditions and groundwater management activities. Additionally, a model groundwater management ordinance has been prepared for purposes of accomplishing the same global goals. The plan components and model ordinance are included as Appendices C and D, respectively, of the DWR (2003) bulletin, *California's Groundwater*.

Nearly concurrent efforts by DWR to facilitate effective groundwater management and develop the new IRWM plan standards (DWR and SWRCB 2004) "raise the bar" for means of achieving global water resources management goals. New questions arise, however. While the new level of guidance and legislation is intended to be beneficial, will the new laws or requirements potentially create redundant, bureaucratically layered, or burdensome approaches to groundwater management? The recent actions described above now result in: local groundwater management plans (Water Code Section 10753.7); model ordinances; specified management strategies that must be included in IRWMs; and a designated regional agency or regional group if project funding necessitates an "eligible" IRWM. Could management decisions and activities by local agencies be thwarted because there is too much management being shepherded by entities other than the local agencies? Recent actions move local entities and governments closer to "full" groundwater management where water agencies bring water supply and use into long-term balance (Peters 1982). However, much remains to be done.

Rather than sustainability, "sufficiency" is the term presently used in California's Water Code in association with land use and water supply assessments. While consideration of historical groundwater conditions and whether a basin has been reported to be in overdraft are required as part of water supply sufficiency analyses, future supply sufficiency is left to broad interpretation. A determination of future supply sufficiency is influenced by many variables, including the future reliability of the source of supply (e.g., groundwater, surface water, and recycled water); methods used to optimize the available source of supply (e.g., conjunctive surface and groundwater management, conservation, recycled water use, desalination, or other strategies); climatic variability; and water quality issues. Another factor that complicates the determination of future supply sufficiency is the stage of basin development. Particularly, an increase in the level of utilization of basin-wide water resources compounded by estimated increased water demands for multiple future uses increases the complexity of the determination.

Recent state documents more often incorporate the term sustainable (e.g., DWR 2003 and DWR and SWRCB 2004). This may subtly reflect the State's evolution toward a more holistic view of resource management. Sustainable, when referring to sustainable yield, is tending to supplant use of the term safe yield, perhaps because of the heightened attention to its broader implications. The overall sustainable concept varies primarily in that the overarching sustainability objectives connote greater consideration for balancing the beneficial use of components of whole systems while avoiding long-term detriment to any part.

The future

Setting priorities for effective resource management

On global, national, state, and local scales, the need to conduct regional resources assessments, improve fundamental analyses, and elevate support for scientific and technological advances is becoming increasingly apparent. To achieve sustainable resources goals, decision makers need improved information to assess and manage water resources (National Science and Technology Council (NSTC) 2004).

While DWR (2003) estimates groundwater overdraft is occurring at the rate of 1.2–2.5 km^3 per year, it also reports that a comprehensive assessment of overdraft in the State's groundwater basins has not been conducted since 1980. Overdraft estimates are being updated for California's water plan (DWR 1998; DWR in press). However, DWR (2003) concurrently reports "information is insufficient in many basins to quantify overdraft that has occurred, project future impacts on groundwater in storage, and effectively manage groundwater".

Scientists are aware, and water managers and others are beginning to recognize, that there is a distinct need for better data and better utilization of that data. These needs, though, generally exceed the financial capacity of local entities to effectively address them. Additionally, state, federal, and global support garnered to address wide-reaching technological and research needs are vital to develop the best possible science and management strategies that keep pace with the human stresses imposed on Earth's systems and also to better prepare for catastrophic natural processes. Therefore, the challenge is to communicate to decision makers and legislators that presently available information must be significantly enhanced to accomplish sustainability goals. Particularly, fundamental data, ongoing monitoring programs, data standards, data coordination and sharing, and regional aquifer characterization are core requirements for more effective management.

Monitoring: an integral part of management

Earth scientists are gaining a broadened appreciation of the complex behavior of Earth systems on spatial and time scales relevant to society. However, the subsurface still poses access and characterization difficulties, and it

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is intricately linked to external forces that are difficult or impossible to predict. With the expanding availability of sophisticated data acquisition systems and powerful computers, scientists continue to strive to predict or control the behavior of Earth systems. As a result of scientific advances and increased understanding of the complexity of whole systems, though, this has also led to recognition of the limitations of these analyses. Consequently, the importance of monitoring and comprehensive conceptual models is receiving greater attention.

Long-term systematic groundwater and surface water monitoring programs are necessary to continuously observe Earth systems and detect potentially unacceptable short or longer-term changes in the response of Earth systems. Physical and quality data also need to address the three-dimensional nature of groundwater flow to accurately represent the hydrologic system. Correspondingly, such monitoring programs need to become an integral part of water resources management programs to distinguish trends from short-term fluctuations, anticipate unintended consequences due to changes in resource utilization, identify emerging issues, and design improved water resources management strategies. Systematic groundwater data collection is particularly important due to the slow response of aquifers to changes in natural and imposed system stresses (Alley et al. 2002). Long-term data derived from programs designed to evaluate specific monitoring objectives allow for improved assessments of local and basin-scale processes. Other programs that form the essential core of local and regional analyses include geological mapping programs and regional aquifer characterization efforts that result in sufficient detail to understand the historical response of major aquifer systems due to natural or imposed stresses. Social and economic factors are also essential for the implementation of optimal water resources management programs.

Models have become an essential tool for analyzing complexly managed basins. Models applied to simulate historical conditions and evaluate future water resources management strategies require comprehensive, long-term hydrologic data sets (including climatic, water level, quality, stream flows, pumpage, and other water usage) and other information that provide an adequate representation of the physical system and also a historical hydrologic record suitable to distinguish trends due to varying stresses. In California, particularly in the southern part of the state, there are an ever-increasing number of basins where factors in addition to groundwater withdrawal and natural recharge necessitate consideration when analyzing groundwater conditions. Particularly, water banking, artificial recharge, water quality issues, ecosystem habitat, and potential inelastic subsidence are but a few components that significantly affect the overall system response or define the variables that enhance or constrain future management alternatives. Periodic updating of groundwater conditions using expanded historical data records, improved data sources, new methods of evaluation, and applied research should be recognized as indispensable. Additionally, area-specific economic and social factors influence preferences for some management strategies over others. Thus, communication between scientists and policy makers becomes an important aspect for implementing optimal solutions.

The needs

From a California perspective, DWR (2003) recognizes that there are data and analysis limitations for accurately assessing long-term groundwater storage changes and understanding future groundwater availability. In the same spirit, the USGS recommends periodic assessments of changes in aquifer storage and analyses extending beyond groundwater level and trend assessments (Taylor and Alley 2001; USGS 2002). In addition, there is need for improved understanding of hydrologic characteristics, including sources and rates of recharge, runoff, and consumption (NSTC 2004). Future needs include coordinated efforts for research, monitoring, and data sharing and coordination among federal, state, and local agencies (NSTC 2004). Support for such efforts correspondingly results in identification of data gaps, improved data sources (i.e., data that best represent the data collection objectives), and better definition of analysis needs.

The above-mentioned data limitations help stress the importance of fundamental data and information on aquifer characteristics to water planning and management statewide and locally. The degree of data availability generally corresponds to the level of groundwater development that has occurred in California's basins. Since 2003, the State's basin information has been made much more publicly accessible on its web site. A dynamic web-based information sharing system replaces what was formerly provided in hard copy format. Information sharing systems are progressively improved through implementation of technological innovations and periodic updating of current information.

A countywide groundwater-level monitoring program in Yolo County (Fig. 1) provides an illustration of some of the limitations of the water level data gathered from a network of more than 400 wells monitored by DWR, the Yolo County Flood Control and Water Conservation District, and others. Of these wells, 90 wells lack construction information. Thus, even though data have been gathered for more than 70 years from some network wells, the information is lacking to understand the aquifer conditions that those data represent. Most often, water levels are measured semi-annually; only 25 are measured monthly. Understanding stream-aquifer interactions and replenishment to the deep aquifer system (formations to depths of about 610 m) are of strong interest for future water supply planning and management. Consequently, although there are many monitoring facilities, the lack of information on what the data represent limits the ability to fully address important resource planning and assessment needs. Through the support of an AB 303 grant program administered by DWR, a countywide assessment of groundwater-level and quality monitoring programs occurred, and recommendations

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have been made for the long-term improvement of the program (Luhdorff and Scalmanini, Consulting Engineer 2004; Kretsinger et al. 2004). California's grant programs have been invaluable in facilitating water management efforts by local entities, and furtherance of such efforts necessitates continued state and national support.

Although DWR (2003) has estimated overdraft on a statewide basis, limitations exist for estimating long-term changes in storage. In many basins, the information is insufficient to quantify the overdraft that has occurred. Computation of change in storage entails determination of the average change in groundwater elevation over the basin (preferably from spring to spring for an appropriate hydrologic period) multiplied by the area overlying the basin and the average specific yield (or storage coefficient for confined aquifers) (DWR 2003). This approach appropriately recognizes consideration for confined aquifers and the compressible component of storage. However, in many basins, except where intensive groundwater development has been accompanied by corresponding comprehensive investigations, the data are typically limited in one or more of the following ways: aquifer characteristics are not defined for all developed formations, long-term groundwater level measurements may be available but are not necessarily adequately distributed in time (including frequency) or space (i.e., limited distribution among formations, wells may be of unknown completion, or are lacking in areal distribution, including proximity to natural or engineered sources of recharge). Correspondingly, the implication of loss of storage due to inelastic compaction of aquitards is not well understood on a basin-wide scale.

There exist opportunities for improved subsurface data collection (examples include geophysical log data, aquifer properties, and geochemical and isotope data) that have been applied by some. Exploration of the subsurface is generally costly, and the quality and utility of the data could be greatly enhanced through standardization of the form of such data (e.g., consistency in textural descriptions of subsurface materials using standard nomenclature rather than inexact descriptors). Electronic technology should be extended to subsurface information to provide greater accessibility to the information pivotal to improving the physical conceptualization of the subsurface such that complex issues affecting water resources can be more effectively analyzed and addressed.

Data and analysis limitations can result in misinterpretation of groundwater conditions, primarily due to the use of an inadequate conceptual model. The State monitors nearly 14,000 wells, and these data are largely available online for use by water agencies and others. These data, however, are not always appropriately used. For example, water levels representing different formations have been contoured in aggregate; as a result, declining water levels in one area or one formation of the basin may bias actual conditions or may be misinterpreted to connote a condition occurring on a broader scale. Without the availability or better understanding of fundamental data, it remains difficult to address such important questions as how much water is withdrawn from a formation(s) and the rates of replenishment of formations from which that withdrawal occurs (NSTC 2004). If overdraft estimates are based on simplified assumptions (i.e., specific yield times groundwater level decline) that do not consider water levels in the context of the aquifer system (i.e., confined or unconfined and the formation(s) that the levels represent), such rough estimates will not be very useful for future water resources planning. Nevertheless, these estimates have been used on a statewide planning and policy basis for decades.

In summary, there is a clear need for improved data collection on local to global levels to better estimate groundwater conditions, including long-term changes in storage by aquifer and for an appropriate hydrologic study period, and for understanding future water availability. Scientists and policy makers must recognize their mutual dependence and cooperate to assure that the best scientific information is made available for formulating the most effective groundwater management policies. As a corollary, it needs to be recognized that long-term, systematic monitoring and assessment programs are integral to sustainable, adaptive groundwater management.

Linking Earth, social, and political sciences

In response to critical water issues and increased awareness of the need to better understand future water requirements and supply availability, water resources management is receiving more attention by institutions at all levels. Water institutions are evolving along with changing social objectives, economic development, technology, and the degree of depletion of the resource (NSTC 2004). Some states have moved toward water resources management sooner than others. Albeit hesitantly, California also has arrived at the place John Wesley Powell envisioned more than a century ago. The State has progressed from unconstrained groundwater development to integrated water resources management approaches that consider interrelated responses and constraints of natural systems. This progress has been facilitated by important social decisions starting with the Constitutional Convention in 1878, then in 1978 recommending groundwater management actions, transitioning in 1992 to groundwater management plans and programs formally referred to as AB 3030 plans, and moving in late 2004 to minimum standards for integrated regional water management. Consistent with Powell's foresight and recommendations, California's groundwater management programs and strategies now include:

– Consideration of groundwater basin conditions (Water Code amendments in 2001 and 2002)
– Responsibility of local governments to implement groundwater management and monitoring programs
– Establishment of codes and guidance documents that require coordination among the many stakeholders in groundwater basins
– Outreach programs that inform the public and increase cooperation among public entities.

California's progress toward integrated resources management through local and regional institutions in the

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context of basin-wide considerations is laudable. However, local efforts have been escalated largely through statewide initiatives and leverages incorporated into laws and guidance documents that require actions for local entities to be eligible for state funding. Questions remain, though, about the future effectiveness of this financial leveraging. Will the State provide local governments the opportunity and flexibility to assess the role of local interests and values and to use that understanding to develop water management and conservation programs that balance the present value of water with the water needed for future societal interests? Or, alternatively, are initiatives increasing at a pace where the State exerts more control through embedded mechanisms to ensure management efforts are adequate? Can a local institution adequately determine what actions will have detrimental effects on resources? Will funding or subsidies resulting from initiatives with economic leverages be better utilized as a result of the criteria added for applicants to demonstrate regional cooperation and preparation and implementation of a qualified groundwater management plan? Or, will a lack of data collection, analysis, or development of appropriate conceptual models obscure potential long-term consequences?

Social and Earth sciences are inherently intertwined in all water resources management and sustainability endeavors. However, while planning and management requirements are being propelled forward, the necessary data and programs to synthesize those data are clearly lacking. Effective policies require good science. Recent efforts by the National Ground Water Association (NGWA) to conduct a survey of groundwater data needs (Reimer 2005) and the NSTC's (2004) recommendations related to the information, research, and technological advances needed to address questions concerning freshwater availability provide examples of outreach that facilitates cooperation between policy makers and scientists. Coordinated efforts among scientists and decision makers, along with public outreach, lead to more effective water resources management approaches and sustainability.

Perhaps as a result of increased public and political awareness of water issues and concerns, the necessity for the scientific community, including academia, researchers and consultants, to effectively communicate data, research, and technology needs to other segments of society has correspondingly increased. In California, local entities must now produce groundwater or integrated water resources management plans to be eligible for funds needed to build water-related projects. Thus, there is a "top down" economic leveraging that provides state level influence. This approach has had overall beneficial effects as management programs have increased while still maintaining control at the local level. At the same time, there is no clear mechanism to ensure that: (1) ongoing monitoring programs are adequately designed and sustained to address management objectives, and (2) long-understood scientific principles are more broadly and effectively applied. The scientific community needs to continue to advance mechanisms that link the need for fundamental data, continued research and application of that research, and improved scientific approaches to the social actions being taken to address the local, statewide, national, and global water resource issues. The general public and policy makers may not readily understand why "more data are needed" when at the same time already supported programs involve data from hundreds to thousands or even tens of thousands of wells.

Essentially, state and federal programs (such as those conducted by DWR and the USGS) designed to provide long-term basic hydrologic data collection and advances in the understanding and analysis of hydrologic systems require a greater level of support and funding or subsidies to address future national and global water issues. The scientific community needs to develop relevant science initiatives that respond to sustainability objectives and long-term water resources management and monitoring needs. The long-term economic value of such initiatives is often not apparent in a timely manner to policy makers or the public. Therefore, the scientific community plays a very important role in communicating the need for these initiatives.

Future water resources management considerations will necessarily involve more complex analyses, especially where groundwater provides a major component of the water supply. Earth science problems reflect the interaction of processes across many disciplines. Undoubtedly, cross-disciplinary efforts promise expanded opportunities to resolve future water resources problems. While preserving the core integrity of individual disciplines, scientific advances will accelerate if future water resources assessments, including consideration of the sustained integrity of ecohydrologic systems, encourage interdisciplinary contributions to discovery and problem resolution. Notably, the need for improved water management of shared resources requires that analyses once based on traditional disciplines such as hydrology, geology, soil science, and ecology be redirected toward understanding the complex interactions among the hydrological, geochemical, erosional, and nutritional cycles. Economic and social sciences also play an integral role in water resources management.

Models facilitate whole hydrologic systems analysis and will become increasingly relevant. Since models represent interpretive tools that correspondingly evolve with knowledge and data, continued research and scientific advances are necessary to update modeling applications and the representation of complex Earth systems and processes. Specifically, periodic reanalysis and updates of conceptual models and regional system flow and transport models will likely become increasingly important. Early modeling applications are often limited by available data. Models historically developed for regional or basin-wide analyses served useful purposes, including identification of data and information gaps. Pending model applications to address broader resources objectives or analyses, review and update of the systems represented could lead to very different results and future insights than suggested from initial simulations.

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Conclusions

Water resources sustainability hinges on interrelated physical, chemical, biological, and human processes, all of which may affect the quantity and also quality of available water supplies, including groundwater. As countries around the world strive to achieve sustainable management of their groundwater resources, much can be learned from California's experiences.

California's water experiences are unique. A century and a half ago, a vast land with abundant natural resources became occupied with an expanding population that has benefited through the years from scientific advancement. Along with growth and prosperity has come the recognition that utilization of the State's water resources requires attention to the limitations imposed by the behavior of natural systems. More than a century following Powell's revolutionary conceptualization of local resource management, California has progressed in spurts toward more effective water resources management. Gradual realization of the need for better management has been accompanied by the gradual development of social policies and institutions to facilitate sustainable use of groundwater for future generations.

Although groundwater management plans have proliferated in California in the last decade, their effectiveness is not yet fully known. The success of existing and new programs is partly related to how committed local entities are to ensuring that the plans are actively implemented and accomplish their purpose, including long-term sustainability of shared groundwater resources without detrimental effects on other resources.

Concerns arise, especially from California's local entities, that the explosion of interest in water issues and corresponding initiatives without adequate input are apt to result in unclear, redundant, and conflicting legislation and new guidelines that may unduly constrain local management. The preferred management approach involves continued local control; however, this approach appears subject to tests of the effectiveness of local efforts embodied in recent legislative actions and initiatives.

On local to global scales, the need to conduct regional resources assessments, improve fundamental analyses, and increase support for scientific and technological advances is becoming increasingly apparent. Hydrologic and Earth sciences advances over the last century provided tools to evaluate water resources systems. However, local and state institutions do not, as a whole, use these tools effectively. There is a clear need for improved data collection to better estimate groundwater conditions and understand future water availability. The scientific community must continue educational outreach and advance mechanisms that link the need for fundamental data, continued research and application of that research, and improved scientific approaches to the social actions being taken to address the local, statewide, national, and global water resources issues. Cross-disciplinary cooperative efforts should be encouraged as multi-systems processes inherently complicate issues involving sustainability. Envisioning the future mosaic requires that society recognize the multi-disciplined initiatives necessary to allow scientific advances and breakthroughs to new solutions. Essentially, coordinated efforts between decision makers and interdisciplinary scientists (including economic, social, and political scientists) are needed to improve information used to assess and manage common water resources.

Expanded public outreach efforts also result in greater awareness of sustainable resource concepts and the funding needed to support the monitoring and assessment programs that allow suppliers to balance common water supplies with future demands for long-term benefit while minimizing consequences. Ultimately, scientific and political communities must merge mutual interests and forge a coordinated plan that is understood and embraced by the public to ensure long-term resources sustainability. California's progress towards sustainable use of its groundwater resources continues, and much remains to be accomplished. The lessons that California has learned in the process (scientific, economic, social, institutional, and legal) offer insights to others in the world that seek to formulate sustainable water management programs.

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