

100 years of California's water rights system: patterns, trends and uncertainty

Theodore E Grantham¹ and Joshua H Viers²

¹ Center for Watershed Sciences, University of California, 1 Shields Avenue, Davis, CA 95616, USA

² School of Engineering, University of California, 5200N. Lake Road, Merced, CA 95343, USA

E-mail: tgrantham@ucdavis.edu and jviers@ucmerced.edu


Received 26 February 2014, revised 19 June 2014

Accepted for publication 18 July 2014

Published 19 August 2014

Abstract

For 100 years, California's State Water Resources Control Board and its predecessors have been responsible for allocating available water supplies to beneficial uses, but inaccurate and incomplete accounting of water rights has made the state ill-equipped to satisfy growing societal demands for water supply reliability and healthy ecosystems. Here, we present the first comprehensive evaluation of appropriative water rights to identify where, and to what extent, water has been dedicated to human uses relative to natural supplies. The results show that water right allocations total 400 billion cubic meters, approximately five times the state's mean annual runoff. In the state's major river basins, water rights account for up to 1000% of natural surface water supplies, with the greatest degree of appropriation observed in tributaries to the Sacramento and San Joaquin Rivers and in coastal streams in southern California. Comparisons with water supplies and estimates of actual use indicate substantial uncertainty in how water rights are exercised. In arid regions such as California, over-allocation of surface water coupled with trends of decreasing supply suggest that new water demands will be met by re-allocation from existing uses. Without improvements to the water rights system, growing human and environmental demands portend an intensification of regional water scarcity and social conflict. California's legal framework for managing its water resources is largely compatible with needed reforms, but additional public investment is required to enhance the capacity of the state's water management institutions to effectively track and regulate water rights.

 Online supplementary data available from stacks.iop.org/ERL/9/084012/mmedia

Keywords: water rights, water resources management, surface water, rivers

1. Introduction

Recent droughts and increasing hydroclimatic volatility in western USA are testing the ability of water managers to meet diverse and growing demands for supply reliability, improved water quality, and healthy ecosystems (Gleick and Chalecki 1999, Christensen *et al* 2004, Wilhite *et al* 2007). Despite evidence that human water demands have begun to stabilize, decreasing surface water availability has caused high levels of water stress throughout much of the western

USA (Averyt *et al* 2013). Climate models predict that much of arid and semi-arid western North America is likely to become warmer and perhaps drier in the future (Stewart *et al* 2005, Westerling *et al* 2006, Barnett *et al* 2008), suggesting that major changes in water use and allocation patterns will be required. In California, for example, projections of decreasing snowpack and population growth will make it difficult to meet growing urban demands while maintaining agricultural deliveries and needed water for the environment (Hayhoe *et al* 2004, Tanaka *et al* 2006, Medellín-Azuara *et al* 2008). These trends are commensurate with global projections for other regions with semi-arid or Mediterranean-type climates (Klausmeyer and Shaw 2009), which are characterized by extremes in seasonal and interannual variability in precipitation, large scale development of irrigated



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](http://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

agriculture, and higher human population density (Grantham *et al* 2013).

Emerging water management challenges in semi-arid regions of the world are typified by California—the world’s tenth largest economy—which must satisfy water demands for 38 million people, a US\$40 billion agricultural economy, and freshwater ecosystems (DWR 2009). Recent studies indicate that the state is ill-prepared to adopt measures required for the sustainable management of water resources (Hanak *et al* 2011, California Natural Resources Agency 2014). For example, California’s water rights system is the primary regulatory framework under which surface water is allocated yet the amount of water actually used by water rights holders is poorly tracked and highly uncertain (Little Hoover Commission 2010). The lack of accurate accounting thus represents a critical challenge to the allocation of water among competing users in a cost-efficient and sustainable manner.

California’s water rights administration system was legislatively established in 1914 with the creation of a Water Commission, which later would become the State Water Resources Control Board (Water Board) (Littleworth and Garner 2007). The Water Board administers the water rights system and is responsible for allocating available water supplies for beneficial uses in an orderly manner (Water Board 2014b). However, since its establishment a century ago, the Water Board has issued water rights that amount to over five times the state’s average annual supply (Little Hoover Commission 2010). Today, over-allocation of available supplies, coupled with uncertain water use by individual water right holders, has become a significant handicap for water policy and management reform (Hanak *et al* 2011). As regional drought and growth reduce available supplies, inaccurate water use accounting has also intensified conflicts over water (Wines 2014, Dearen and Burke 2014) and made it difficult to secure adequate water allocations for freshwater ecosystems (Gillilan and Brown 1997, Water Board 2014c). Consequently, the water rights system has been identified by water managers as one of the state’s most important long-term water problems (Null *et al* 2012).

Accurate quantification of water supply and use is an essential first step towards sustainable water management. Yet, a comprehensive assessment of surface water allocations of the state’s rivers and streams has not been conducted. Furthermore, the extent to which water right allocations approach, or exceed, natural surface-water supplies has not been systematically evaluated in rivers throughout the state. Here, we analyze the state’s water rights database to estimate the degree of water appropriation in approximately 4000 catchments in California by comparing water rights allocation volumes with modeled predictions of unimpaired, surface water availability. The water right holder, intended uses, and dates of water rights records are also examined to compare allocations among ownership and use-classes and to examine trends in water allocation volumes from 1914 to 2013. Finally, we analyze county-level water use data to quantify the disparity between water rights allocations and estimated surface water withdrawals. These analyses highlight

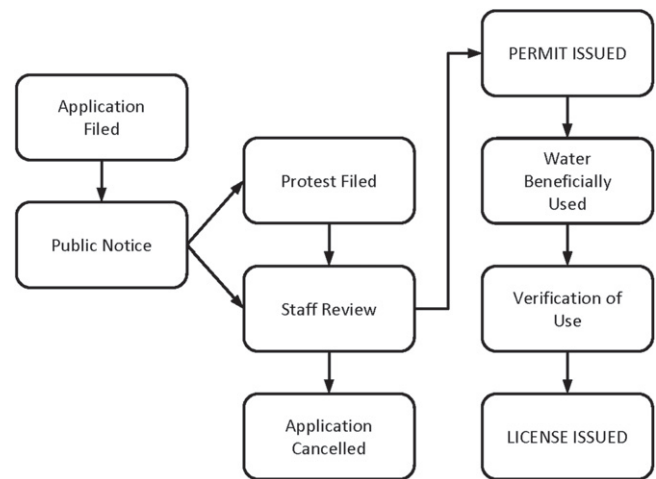


Figure 1. Simplified diagram of appropriative water rights review process by the State Water Board, modified from permitting and licensing flow charts (Water Board 2014b).

deficiencies in the water rights system that should be addressed as part of state water management reforms (e.g., California Natural Resources Agency 2014) and can be used to identify river basins where inaccuracies in water rights records may impede local efforts to efficiently and sustainably manage water resources.

2. Background and methods

2.1. California’s water rights system

California water management is a highly complex amalgamation of laws, policies and institutions derived from Roman, Spanish, English and indigenous governance systems, which has been described in detail by others (e.g., Hundley 2001, Hanak *et al* 2011). Here, we provide a brief overview of the state water rights system, summarized from Littleworth and Garner (2007) and Water Board documents (2014b). California’s modern water rights system began to take form in the mid 19th century and early 20th century with the influx of settlers from the eastern USA. Initially, competing claims for water in the water scarce state were settled through litigation and court decisions. But as the number of claims and scale of water projects grew, a more comprehensive system for regulating water rights was required. In 1914, the state legislature established a Water Commission, which would later become the Water Board. Because of political pressures, several types of water rights including groundwater, riparian and pre-1914 appropriations were excluded from the Water Board’s authority. However, the Water Board was given primary responsibility for administering post 1914 appropriative water rights, which were required for the state’s major agricultural and water supply systems developed in the 20th century. In addition, the Water Board retains broad authority in enforcing the state’s reasonable use and public trust doctrines (Littleworth and Garner 2007).

Any person or entity wishing to appropriate surface water must file an application with the Water Board, which initiates a permit review process (Water Board 2014b) (figure 1). Decisions to issue a water right permit are based on availability of water, satisfaction of reasonable use requirements, and preservation of environmental uses (e.g., fish and wildlife resources). Once an application is approved, the right must be exercised according to permit terms and conditions, which may include a maximum seasonal or annual allocation volume, limits on timing and rates of diversion, specifications on where the water can be used, and other measures to minimize environmental impacts. The ‘face value’ amount of water granted by a permit is an estimate of the maximum possible volume required by the applicant; actual amounts used vary by year but may be significantly less than the face value (Littleworth and Garner 2007).

Following a monitoring period, typically ten or more years, the Water Board confirms terms and conditions of the permitted water use, and may issue a license to the appropriator (figure 1). The Water Board has limited authority over non-appropriative water rights (Littleworth and Garner 2007). However, in 2009, the Board implemented new reporting requirements for groundwater, riparian and pre-1914 surface water rights, with penalties for failing to file statements of use (California Water Code section 5101). This has led to an increase in water use reporting, although reports are not systematically audited for accuracy and have been filed only for a small fraction of non-appropriative water users (personal correspondence with Phil Crader, Division of Water Rights, 28 June 2013).

2.2. Analysis of water rights database

The Water Board maintains a public water rights database, the electronic Water Rights Management System (eWRIMS), to track and share water rights information (Water Board 2014a). The database contains information on water rights and statements of use and is the basis for our assessment, focusing on all active, appropriative water rights records. These are the most common types of surface water right in the database and account for the greatest allocation volumes. The records used in our analysis consisted of pending, permitted and licensed water rights filed since 1914, and included information on face-value allocations, year of filing, right holder, use types, and geographic location. We did not consider statements of use, which have been filed for some riparian and pre-1914 water rights claims because the data are incomplete and of uncertain quality.

Based on the water rights records, appropriative water rights holders were classified into private and public entities. For privately held rights, individuals were distinguished from corporate entities (e.g., corporations, associations, private power utilities, and partnerships). Public water rights holders included federal, state, and municipal agencies and irrigation and reclamation districts. Purpose of use was also evaluated, based on use-designations for individual water rights (e.g., hydropower, agriculture, domestic, industrial, recreation, and environmental).

2.3. Assessment of spatial allocation patterns

Locations of surface water diversions have been mapped in a Geographic Information System (GIS) by the Water Board. Water rights may have multiple points of diversion (PODs), which collectively divert an annual volume up to the face value of the permit or license. Because diversion volumes are not reported for individual PODs, we selected a single POD for each water right and attributed the entire face value to that location. Next, total face-value allocations were calculated at the 12-digit Hydrologic Unit (HUC12) scale (USGS 2012) for 4108 catchments in California. Finally, water allocations were accumulated downstream to determine the cumulative annual water allocation for each catchment. To visualize the HUC12 drainage network, line segments were created between HUC12 centroids to represent directional flow paths to receiving catchments. Because most of the Colorado River basin occurs outside of California, we did not evaluate allocation volumes for the Colorado River.

To evaluate water right allocation volumes in relation to water availability, we used an empirical modeling approach to predict mean annual flows for California’s HUC12 catchments. Models were developed using Random Forests (RF) (Breiman 2001), a statistical approach used for prediction and classification. Following methods described in Carlisle *et al* (2010), a RF model to predict expected (E), annual natural flow was trained with data from 180 USGS reference gages (e.g., those minimally affected by land- and water-management activities) and catchment predictor variables (e.g., climate, topography, soils and geology) in the Gages-II database (Falcone 2011). The RF model was implemented in *R* with the randomForest package (Liaw and Wiener 2002).

Model performance was assessed by comparing predictions with randomized subsets of observed data (O) withheld during RF model development. Several performance metrics were calculated (Moriassi *et al* 2007), including coefficient of determination (r^2), Nash–Sutcliffe coefficient, and percent bias. In addition, predictive performance was assessed in a jack-knife technique by sequentially excluding individual reference gages and re-running the model to evaluate observed against predicted (O/E) values at the omitted site. To predict monthly flows at un-gaged HUC12 catchments, the same set of catchment predictor variables used in model training was calculated for each HUC12 catchment including the upstream drainage area. The trained RF model was then used to predict expected mean annual flows in each catchment from 1950 to 2010, from which a long-term average was calculated and compared with water rights allocation volumes.

2.4. Comparison of water rights allocations with surface water withdrawals

To compare water rights allocations with actual water use, total face value water right volumes were calculated at the county level and compared with estimates of actual surface water withdrawals. Water rights used exclusively for hydro-power generation were excluded from the face-value

Table 1. Summary of active surface water right records in State Water Rights Database (Water Board 2014a).

| Water Rights type | Count | Face-value total (10 ⁶ m ³) |
|-------------------------------------|---------------|--|
| Appropriative | | |
| Licensed | 10 810 | 123 517 |
| Permitted | 1 466 | 263 647 |
| Pending | 345 | 11 038 |
| Subtotal | 12 621 | 398 202 |
| Statements of Diversion and Use | 10 885 | 40 571 |
| State & Federal Filings | 2152 | 15 986 |
| Stockpond | 5613 | 7 |
| Small Domestic | 611 | 3 |
| Adjudicated (pre-1914 and Riparian) | 8 | 0.3 |
| Total | 31 890 | 454 770 |

calculations. Gross water use estimates were obtained from US Geological Survey Water Use Data for California, 1985–2005 (USGS 2014). Average, county-level use was calculated by the sum of reported self-supplied, surface water withdrawals for public supply, domestic, industrial, livestock, and irrigation purposes.

3. Results

3.1. Appropriative water right allocations

We obtained 31 890 active, surface water rights records from the eWRIMS database (Water Board 2014a), representing approximately 450 000 million cubic meters (Mm³) (table 1). Records included 12 621 active appropriative water rights, accounting for 398 202 Mm³ of water. Most (85%) appropriative water rights are licensed, although permitted water rights account for two-thirds of the volume allocated. In addition, most water is granted to a relatively small number of appropriative water rights (figure 2(a)). For example, of the top 1% water rights by count account for over 80% of the total water volume allocated.

Based on the water rights records analyzed in this study, the volume of water allocated per right has declined since the early 20th century (figure 2(b)). Ten-year average volumetric water allocations peaked in the early 1930s (>120 Mm³ per right), but has fluctuated between 5 and 40 Mm³ per right since the 1950s. However, the number of water rights filed has steadily increased over time (figure 3(a)). Following a period of relatively slow growth in the early 1900s, the number of rights filed accelerated in the late 1940s. The rate of water rights filings slowed in the 1990s, but has remained stable at approximately 60 water rights filed per year. Since the 1970s, most new water rights have been issued to individuals and private entities, while holdings by federal, state and other public agencies has not appreciably changed (figure 3(a)).

Although private entities hold the vast majority (78%) of water rights filed, most water by volume is allocated to public

entities (figure 3(b)). Notable increases in water allocation volumes occurred in 1927, when the appropriative water rights were filed for major federal dam projects on the Sacramento River (Shasta Dam) and Trinity River (Trinity Dam), and in 1933, when water rights were filed by the Imperial Irrigation District to divert water from the Colorado River. Currently, over 80% of the water rights issued by volume are held by federal (32%), state (10%), municipal (15%) and other public entities (24%). Private corporations hold approximately 18% of all water allocated, while individuals hold rights to less than 1% of water by volume.

Of 12 621 appropriative water rights in the eWRIMS database, nearly 70% have PODs with agricultural use designations (figure 4). Other common designations were domestic (35%) and recreation (27%) uses. Approximately 3% of applications are designated for hydropower, although they account for 68% of total water right allocations by volume. Other uses associated with high water allocation volumes are domestic (42%), agricultural (34%), and recreation (26%).

3.2. Spatial distribution of water rights

To quantify the spatial distribution of water right allocations, local and cumulative face value totals were calculated at the HUC12 watershed scale. Trends in the extent and intensity of water allocations were also evaluated by mapping water allocations to catchments since 1914 (figure S1). Currently, face value allocation volumes are greatest for the Sacramento and San Joaquin Rivers and their major tributaries (figure 5(a)). When water rights used exclusively for hydropower generation are excluded (because hydropower is a non-consumptive use), allocation volumes significantly decrease (figure 5(b)). Excluding hydropower water allocations, the total volume allocated to appropriative water rights in the Sacramento-San Joaquin Delta is 109 000 Mm³, approximately three times the average unimpaired outflow of the system (35 000 Mm³) (DWR 2007).

Cumulative water allocation volumes were evaluated relative to predicted, unimpaired surface water availability for all HUC12 catchments (figure S2). The model performed well in predicting mean annual flow based on several performance metrics ($r^2 = 0.95$, NSE = 0.94, PBIAS = 1.2). Assessment of predictive performance using jack-knife removal of individual reference gages yielded a mean O/E ratio of 0.94, suggesting high accuracy in predicting unimpaired annual flow (a value of 1.0 indicates perfect model performance).

Water right allocations exceed average local surface water supplies in much of the drainage network (figure S3 and figure 6) and allocation percentages increase with river size. Among catchments with annual runoff of less than 100 Mm³ ($n = 685$), mean allocation is 1% and nearly three-quarters of the small catchments have allocations levels below 10%. In contrast, catchments with runoff greater than 1000 Mm³ and 5000 Mm³ are predominately allocated at levels above 100%. Excluding water allocations for hydropower (figure 6), catchments with annual runoff of 500–1000 Mm³, 1000–5000 Mm³ and greater than 5000 Mm³ have mean allocation values of 41%, 107%, and 158%, respectively.

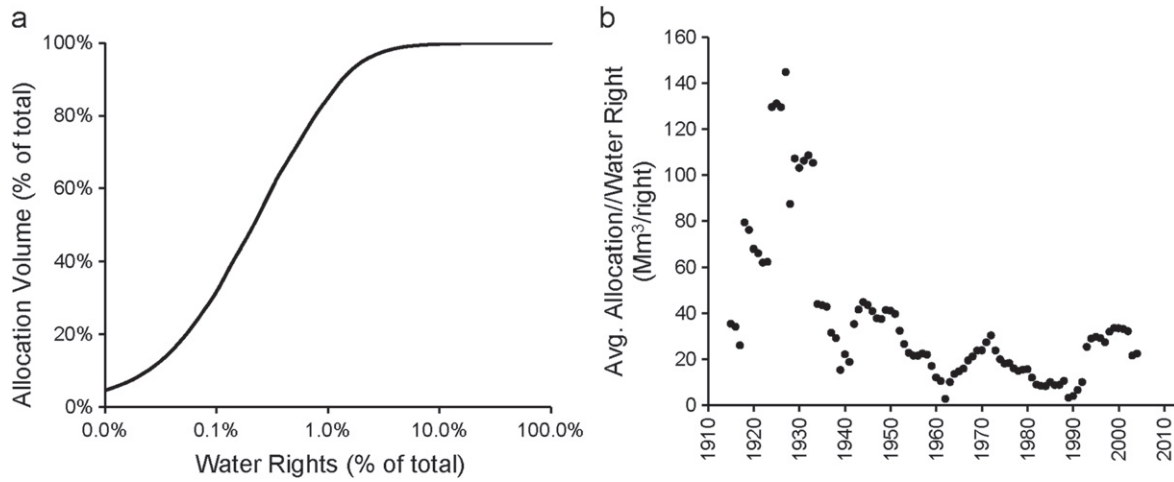


Figure 2. Water allocation volumes (a) by water right count and (b) over time (10-year rolling average), based on appropriative water rights records (Water Board 2014a).

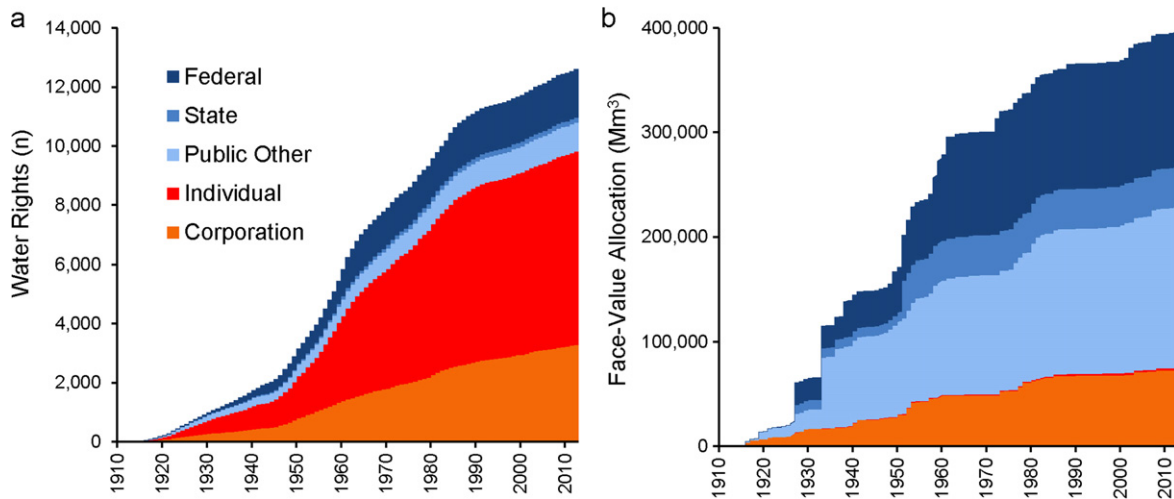


Figure 3. (a) Water rights and (b) face value allocation volumes issued to public and private entities since 1915, based on appropriative water rights records (Water Board 2014a). Note, volumetric allocations to water rights held by individuals (in (b)) is negligible.

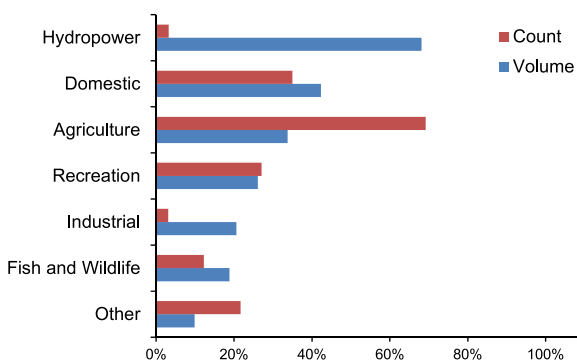


Figure 4. Water rights use designations, expressed as percentage of total water right count and volumetric water allocation.

Excluding hydropower water rights, catchments with the highest water allocation levels are the San Joaquin River (861%), Salton Sea basin (705%), Putah Creek (673%), Kern River (631%) and Stanislaus River (391%). Large river basins with relatively low allocation levels are the Smith River (<1%) and Cottonwood Creek (2%). The Owens River basin, which is a primary water supply source for the City of Los Angeles, has a low water allocation percentage (4%). However, when water rights associated with hydropower use are included, allocation percentage increases to 224%, indicating that water rights designated for hydropower are used for water supply. Public entities hold nearly all of the water allocated by appropriative water rights in California’s major river basins (table 2).

Most of California’s major river basins have water rights allocations that exceed their natural, unimpaired annual supply (table 2; figure S4). Among 27 major rivers, 16 had allocation levels greater than 100% of natural supplies.

3.3. Comparison of water rights allocations with surface water use

Face value allocations (excluding hydropower use) were compared with estimates of annual surface water withdrawals

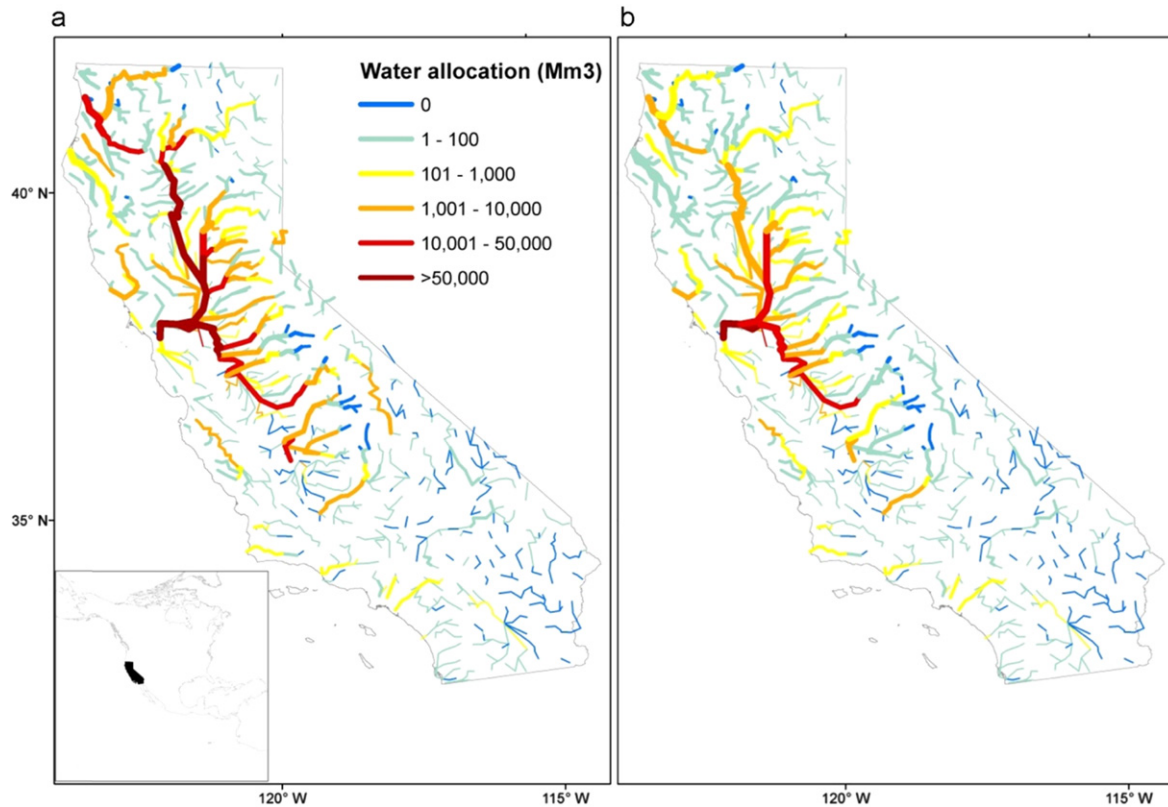


Figure 5. Cumulative water allocation volumes (a) for all water rights and (b) excluding water rights used exclusively for hydropower generation.

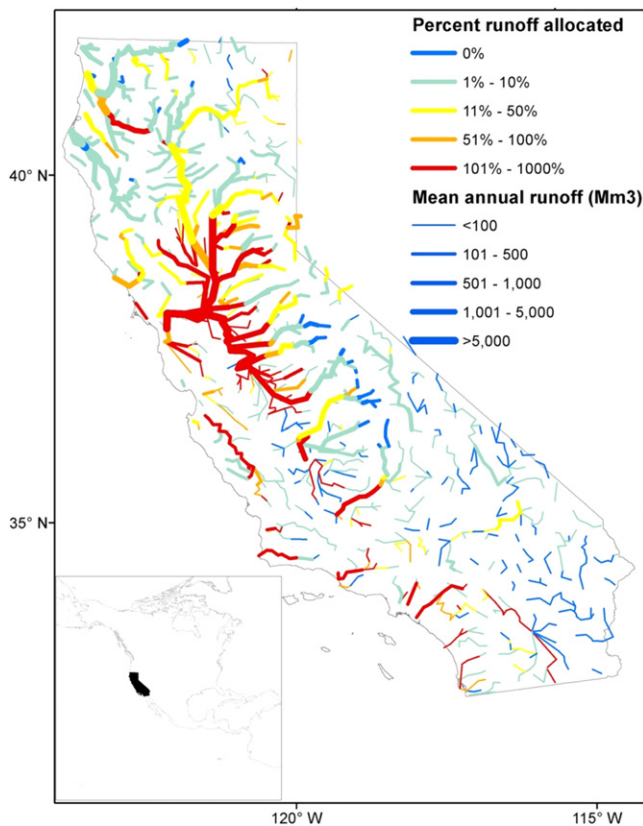


Figure 6. Cumulative water right allocations relative to mean annual runoff, excluding water rights for hydropower generation.

at the state and county scale (USGS 2014). Statewide, appropriate water rights filed for consumptive uses (totaling 149 400 Mm³) are approximately five times greater than estimated annual surface water withdrawals (30 350 Mm³). At the county scale, volumetric allocations of water rights are poorly correlated with ($r=0.16$) and generally over-predict surface water withdrawals (figure 7). This, in part, is explained by differences in water diversion locations and place of use. For example, major intake facilities for the State Water Project and Central Valley Project are located Contra Costa County and are associated with water rights exceeding 40 000 Mm³. Nearly all of the water diverted at this location is delivered south of Contra Costa County. The discrepancy between local water rights allocations and use is compounded by the fact that the water projects are known to deliver a small fraction of their entitlements (Littleworth and Garner 2007). Although water rights allocations generally exceed estimated annual surface water use, there are several counties that use more water than their local water right entitlement. These include counties in southern California that import significant volumes of water for agricultural production (e.g., Tulare and Fresno) and urban water supply (e.g., San Diego and Los Angeles) (figure 7; figure S5).

4. Discussion

This assessment indicates that water allocated through the state appropriate water rights system exceeds overall mean

Table 2. Water allocation volumes for California’s major rivers. See figure S4 for river locations.

| River | Drainage area (km ²) | Annual natural runoff (Mm ³) ^a | Water rights allocation ^b (Mm ³) | Percent runoff allocated | Percent allocated to public ^c |
|-------------------|----------------------------------|---|---|--------------------------|--|
| Smith River | 1864 | 3659 | 8 | 0.2% (0.2%) | 82% |
| Klamath River | 31 402 | 18 213 | 5833 ^d | 32% (100%) ^d | 99% |
| Trinity River | 7692 | 6006 | 5635 | 94% (250%) | 100% |
| Eel River | 9536 | 8330 | 42 | 1% (2.6%) | 31% |
| Russian River | 3846 | 2194 | 1141 | 52% (113%) | 89% |
| Salinas River | 11 082 | 431 | 1032 | 239% (343%) | 99% |
| Sacramento River | 67 830 | 23 282 | 35 336 | 152% (655%) | 92% |
| Pit River | 14 220 | 3454 | 217 | 6% (500%) | 62% |
| Cottonwood Creek | 2444 | 702 | 11 | 2% (2%) | 57% |
| Stony Creek | 2012 | 494 | 268 | 54% (484%) | 98% |
| Feather River | 15 350 | 9027 | 16 934 | 188% (633%) | 98% |
| Yuba River | 3483 | 2966 | 3613 | 122% (431%) | 97% |
| Cache Creek | 2971 | 714 | 1149 | 161% (213%) | 98% |
| Putah Creek | 1694 | 471 | 3171 | 673% (886%) | 98% |
| San Joaquin River | 45 877 | 7949 | 68 473 | 861% (1585%) | 97% |
| Mokelumne River | 5157 | 1646 | 2335 | 142% (436%) | 96% |
| Consumnes River | 2460 | 576 | 304 | 53% (53%) | 88% |
| Stanislaus River | 3100 | 1342 | 5246 | 391% (1787%) | 99% |
| Tuolumne River | 4851 | 2022 | 3273 | 162% (438%) | 99% |
| Merced River | 3288 | 1170 | 1285 | 110% (583%) | 99% |
| Kings River | 5046 | 1799 | 1412 | 78% (520%) | 0% |
| Kern River | 6322 | 801 | 5057 | 631% (1185%) | 100% |
| Owens River | 9004 | 539 | 19 | 4% (224%) | 34% |
| Salton Sea | 15 219 | 227 | 1601 | 705% (710%) | 96% |
| Santa Ynez | 2322 | 249 | 831 | 334% (334%) | 99% |
| Santa Clara River | 4165 | 264 | 417 | 158% (196%) | 99% |
| Santa Ana River | 6370 | 306 | 559 | 183% (183%) | 85% |

^a Mean annual runoff at outlet, predicted from statistical model (1951–2010 average).

^b Water right allocations percentages, excluding water rights for hydropower. Allocations levels including hydropower shown in parentheses.

^c Proportion of cumulative water right allocation (excluding hydropower), that are held by public entities including federal, state, and municipal agencies.

^d Klamath River water rights calculations do not account for water allocations in upper river basin located in the State of Oregon.

water supplies by approximately five times. Our findings also highlight river basins where significant over-allocation of surface water supplies is likely to lead to conflicts among water users, particularly during periods of water scarcity when insufficient water is available to satisfy all face-value water right demands. For example, the results underscore the challenge of balancing human and ecosystem water needs in the Sacramento-San Joaquin Delta, the hub of California’s water management system and source of its greatest vulnerability (Hanak *et al* 2011), where cumulative rights allocations are approximately three times greater than average natural supplies. Allocation levels tend to increase with river size, although many small rivers, particularly on the south coast, are also subject to high water demands. In recent years, new water rights applications have been concentrated in small river basins (figure S1), suggesting that appropriation levels will continue to intensify throughout the river network.

The face values of appropriative water rights reflect the degree to which surface water supplies have been allocated, but must be interpreted with caution. For example, the appropriative water rights system incentivizes permit holders to over-report water use to protect the face-value amount of their water right and therefore represents a generous estimate of actual water use. In addition, return flow (e.g., from irrigation runoff or canal leakage) can be re-used by downstream appropriators, allowing for ‘double-counting’ of the same volume of water. Nevertheless, the large magnitude of water right allocation volumes relative to natural supplies and poor correlation between county-level allocations and estimates of actual use provide strong evidence that the state has over-allocated water in many, if not most, river basins. Furthermore, allocation volumes only account for post-1914 appropriative water rights; other types of water rights (e.g., riparian claims) make the total amount of surface water allocated significantly higher than estimates provided here.

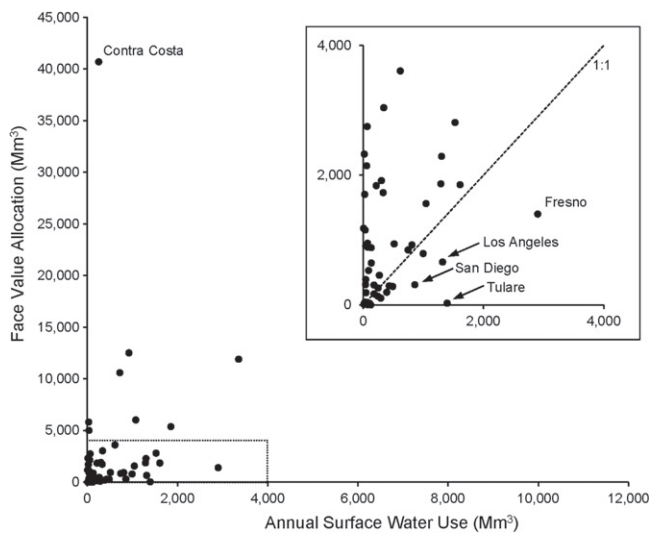


Figure 7. Total face-value allocations for California counties ($n = 58$) compared with mean annual surface-water withdrawals (USGS 2014).

In a well-functioning appropriative water rights system in which allocation volumes are accurately tracked and verified, over-allocation of water supplies is not necessarily a problem. During periods of water scarcity, junior appropriators have to forego their entitlement, but when water is abundant, most water rights holders should be able to exercise their claims. However, inaccurate accounting threatens the value and security of water right entitlements, particularly when curtailments are required during times of scarcity. For example, the current drought in California has led the Water Board to issue emergency curtailments of all water users in specific watersheds to protect fishery resources (Water Board 2014c). Such blanket curtailments would not be necessary if the Water Board had accurate water-use information, which could potentially be used to target specific water users and develop cooperative strategies to reduce water diversion impacts on environmental flows.

In over-allocated systems, water to satisfy new demands will likely require re-allocation of existing water rights. While modification of water rights represents a potential threat to right holders, the disproportionate control of the state’s water supply by state and federal agencies indicates that impacts to private water rights will be limited. This is because improvements in water rights accounting will have a much greater effect on large, publically held entitlements (that are probably over-prescribed) than on relatively small entitlements held by individuals. Furthermore, most dedicated water by volume is held as water rights permits (not licenses) by state and federal agencies, and thus could be curtailed to better reflect actual use through the licensing process. Therefore, there is significant flexibility in the current water rights system to support re-allocation of water to uses that support the public interest.

California water law also authorizes the re-allocation of water rights to address evolving societal needs and changing environmental conditions (Shupe *et al* 1989, Littleworth and

Garner 2007). For example, the public trust doctrine establishes that the government has an ongoing duty to safeguard the long-term preservation of natural resources (Frank 2012). In California, Fish and Game Code 5937 is an expression of the public trust doctrine, which requires that flows be provided below dams to maintain fish in good condition, and has been used to limit water rights in order to preserve environmental resources (Börk *et al* 2012). In addition, the state’s reasonable use doctrine requires that all water rights be exercised in a reasonable manner, which is determined in the context of broader public interest in water supply reliability, ecosystem health, and other public trust values (Littleworth and Garner 2007).

Improving the scope and implementation of the state’s water rights system is one of many challenges that California must overcome to adapt its water management system to 21st century conditions (Hanak *et al* 2011). Foremost, efforts to reform surface water rights administration must be coupled with improved monitoring and quantification of riparian and pre-1914 appropriative rights. In addition, the archaic separation of surface and groundwater rights and absence of state-level groundwater regulation prevents the development of conjunctive-use schemes (e.g., groundwater banking and water marketing), while contributing to overdraft of the state’s major groundwater basins (Faunt 2009). Dysfunctional groundwater management also threatens surface water supplies and freshwater ecosystems in many of the state’s rivers (Zektser *et al* 2005, Howard and Merrifield 2010).

Chronic under-funding of state regulatory agencies is a critical constraint to modernizing the state water rights system. Water rights administration has long suffered from low levels of staffing, contributing to decades-long backlogs in processing water rights applications (Little Hoover Commission 2010). Underfunding, in part, reflects political opposition to action by those who benefit from lax enforcement. However, population growth, hydroclimatic volatility, and changing societal values are expected to disrupt state water management and to be potential catalysts for policy innovation, as has occurred in other Mediterranean-climate regions of the world. In Australia, for example, an unprecedented 13-year dry period led government to undertake major water reforms in the 1990s, which included restructuring the national water rights system. Under the new policy, water rights were separated from land title, quantified, and restricted to ‘environmentally sustainable levels of extraction’ (2004 National Water Initiative). A similar overhaul of the water rights system occurred in South Africa in the 1990s (Backeberg 2005). In California, the legal framework for managing water resources is largely compatible with needed reforms, as described above, and significant legislative actions is probably not necessary. Rather, political will and sufficient funding are the essential elements for improving the state’s capacity to perform its water rights administrative, monitoring and enforcement functions.

After 100 years since its establishment, California’s water rights system is struggling to adapt to 21st century realities of increasing water stress, changing climate, and societal demands for water supply security and a healthy

environment. Innovative solutions have been proposed to address these challenges, including market schemes, institutional reforms, and new approaches to ecosystem management (Renwick and Green 2000, Gleick 2003, Hanak *et al* 2011). However, the effectiveness of these strategies fundamentally relies on our ability to accurately measure and track water availability, movement, and uses. Recognizing that addressing deficiencies in the water right system will not alone be sufficient for ensuring reform, without improved quantification and regulation of water rights, such reform will be impossible. To date, the state simply does not have accurate knowledge of how much water is being used by most water rights holders. As such, it is nearly impossible to curtail or re-allocate water in an equitable manner among water users and to effectively manage for environmental water needs. Quantifying spatial patterns and uncertainty in the water rights allocations is an important first step for developing strategies to reconcile and sustainably manage competing water demands in a water-stressed region. California's legal framework for managing water resources is largely compatible with needed reforms, but without additional public investment, the capacity of the state's water management institutions to effectively regulate water rights will remain weak. This is a situation that urgently needs correcting to meet water management challenges arising from drought, population growth and climate change.

Acknowledgements

We greatly appreciate support and feedback from Jeanette Howard, Leo Winternitz, Laci Videmsky, Chacha Sikes, Phil Crader, Sam Boland and State Water Resources Control Board staff. Jay Lund provided helpful comments on an earlier draft of this manuscript. We also thank Daren Carlisle, David Wolock, Eric Holmes, Kurt Fessenmyer and Nick Santos for data analysis and modeling assistance. This research was supported by funding from the S D Bechtel, Jr Foundation.

References

- Averyt K, Meldrum J, Caldwell P, Sun G, McNulty S, Huber-Lee A and Madden N 2013 Sectoral contributions to surface water stress in the coterminous US *Environ. Res. Lett.* **8** 035046
- Backeberg G R 2005 Water institutional reforms in South Africa *Water Policy* **7** 107–23
- Barnett T P, Pierce D W, Hidalgo H G, Bonfils C, Santer B D, Das T, Bala G, Wood A W, Nozawa T and Mirin A A 2008 Human-induced changes in the hydrology of the western US *Science* **319** 1080–3
- Börk K S, Krovvoza J F, Katz J V and Moyle P B 2012 The rebirth of Cal. fish & game code 5937: water for fish *UC Davis Law Rev.* **45** 809–913
- Breiman L 2001 Random forests *Mach. Learn.* **45** 5–32
- California Natural Resources Agency 2014 California water action plan. (accessed 3 June 2014 at http://resources.ca.gov/california_water_action_plan)
- Carlisle D M, Falcone J, Wolock D M, Meador M and Norris R H 2010 Predicting the natural flow regime: models for assessing hydrological alteration in streams *River Res. Appl.* **26** 118–36
- Christensen N, Wood A, Voisin N, Lettenmaier D and Palmer R 2004 The effects of climate change on the hydrology and water resources of the Colorado river basin *Clim. Change* **62** 337–63
- Dearen J and Burke G 2014 California's flawed water system can't track usage. May 27, 2014 Associated Press. (accessed 1 June 2014 at <http://bigstory.ap.org/article/californias-flawed-water-system-cant-track-usage>)
- Department of Water Resources (DWR) 2007 *California Central Valley, Unimpaired Flow Data* 4th edn (Sacramento, CA: Bay-Delta Office)
- Department of Water Resources (DWR) 2009 *California Water Plan, 2009 update*. Bulletin 160–09 (Sacramento, CA: Department of Water Resources)
- Falcone J A 2011 GAGES-II: Geospatial attributes of gages for evaluating streamflow (digital spatial data set retrieved from http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesll_Sept2011.xml)
- Faunt C C (ed) 2009 *Groundwater Availability of the Central Valley Aquifer, California* (Reston, VA: US Geological Survey)
- Frank R M 2012 The public trust doctrine: assessing its recent past and charting its future *UC Davis Law Rev.* **45** 665–92
- Gillilan D M and Brown T C 1997 *Instream Flow Protection: Seeking a Balance in Western Water use* (Washington DC: Island Press)
- Gleick P H 2003 Global freshwater resources: soft-path solutions for the 21st century *Science* **302** 1524–8
- Gleick P H and Chalecki E L 1999 The impacts of climatic changes for water resources of the Colorado and Sacramento-San Joaquin river basins *J. Am. Water Resour. Assoc.* **35** 1429–41
- Grantham T, Figueroa R and Prat N 2013 Water management in mediterranean river basins: a comparison of management frameworks, physical impacts, and ecological responses *Hydrobiologia* **719** 451–82
- Hanak E, Lund J, Dinar A, Gray B, Howitt R, Mount J, Moyle P and Thompson B B 2011 *Managing California's Water: From Conflict to Reconciliation* (San Francisco, CA: Public Policy Institute of California)
- Hayhoe K *et al* 2004 Emissions pathways, climate change, and impacts on California *Proc. Natl. Acad. Sci. USA* **101** 12422–7
- Howard J and Merrifield M 2010 Mapping groundwater dependent ecosystems in California *PLoS One* **5** e11249
- Hundley N 2001 *The Great Thirst: Californians and Water—A History* (Berkeley, CA: University of California Press)
- Klausmeyer K R and Shaw M 2009 Climate change, habitat loss, protected areas and the climate adaptation potential of species in mediterranean ecosystems worldwide *PLoS One* **4** e6392–6392
- Liaw A and Wiener M 2002 Classification and regression by randomforest *R News* **2** 18–22
- Little Hoover Commission 2010 *Managing for Change: Modernizing California's Water governance* (Sacramento, CA: Little Hoover Commission)
- Littleworth A L and Garner E L 2007 *California Water II* (Point Arena, CA: Solano Press Books)
- Medellín-Azuara J, Harou J J, Olivares M A, Madani K, Lund J, Howitt R E, Tanaka S K, Jenkins M W and Zhu T 2008 Adaptability and adaptations of California's water supply system to dry climate warming *Clim. Change* **87** 75–90
- Moriassi D, Arnold J, Van Liew M, Bingner R, Harmel R and Veith T 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations *Trans. ASABE* **50** 885–900
- Null S E, Bartolomeo E, Lund Jr and Hanak E 2012 Managing California's water: insights from interviews with water policy experts *San Francisco Estuary Watershed Sci.* **10** 1–24

- Renwick M E and Green R D 2000 Do residential water demand side management policies measure up? an analysis of eight California water agencies *J. Environ. Econ. Manage.* **40** 37–55
- Shupe S J, Weatherford G D and Checchio E 1989 Western water rights: the era of reallocation *Nat. Resour. J.* **29** 413–34
- Stewart I T, Cayan D and Dettinger M D 2005 Changes toward earlier streamflow timing across western north America *J. Clim.* **18** 1136–55
- Tanaka S K, Zhu T, Lund Jr, Howitt R E, Jenkins M W, Pulido M A, Tauber M, Ritzema R S and Ferreira I C 2006 Climate warming and water management adaptation for California *Clim. Change* **76** 361–87
- United States Geological Survey (USGS) 2012 Hydrologic unit maps. (accessed 16 January 2014 at <http://water.usgs.gov/GIS/huc.html>)
- United States Geological Survey (USGS) 2014 USGS water use data for California. (accessed 17 January 2014 at <http://waterdata.usgs.gov/ca/nwis/wu>)
- Water Board (State Water Resources Control Board) 2014a eWRIMS - Electronic water rights information management system (accessed 3 January 2014 at waterboards.ca.gov/waterrights/water_issues/programs/ewrims/index.shtml)
- Water Board (State Water Resources Control Board) 2014b The water rights process (accessed 15 January 2014 at waterboards.ca.gov/waterrights/board_info/water_rights_process.shtml)
- Water Board (State Water Resources Control Board) 2014c Emergency curtailment of diversions based on insufficient flow to meet all needs on Mill and Deer Creeks. (accessed 15 June 2014 at waterboards.ca.gov/waterrights/water_issues/programs/drought/docs/mill_deer_antelope_creeks/2014_0523_05e.pdf)
- Westerling A L, Hidalgo H G, Cayan D and Swetnam T W 2006 Warming and earlier spring increase western US forest wildfire activity *Science* **313** 940–3
- Wilhite D A, Diodato D M, Jacobs K, Palmer R, Raucher B, Redmond K, Sada D, Helm-Smith K, Warwick J and Wilhelmi O 2007 *Managing Drought: A Roadmap for Change in the United States (Conf. Proc. 18–20 September 2006)* (Longmont, CO: Geological Society of America)
- Wines M 2014 West's drought and growth intensify conflict over water rights. 16 March 2014 New York Times (accessed 17 March 2014 at <http://nyti.ms/1gJZSC3>)
- Zektser S, Loáiciga H A and Wolf J T 2005 Environmental impacts of groundwater overdraft: selected case studies in the southwestern US *Environ. Geol.* **47** 396–404