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LETTER

Availability of high-magnitude streamflow for groundwater banking in the Central Valley, California

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Abstract
California’s climate is characterized by the largest precipitation and streamflow variability observed within the conterminous US. This, combined with chronic groundwater overdraft of 0.6–3.5 km³ yr⁻¹, creates the need to identify additional surface water sources available for groundwater recharge using methods such as agricultural groundwater banking, aquifer storage and recovery, and spreading basins. High-magnitude streamflow, i.e. flow above the 90th percentile, that exceeds environmental flow requirements and current surface water allocations under California water rights, could be a viable source of surface water for groundwater banking. Here, we present a comprehensive analysis of the magnitude, frequency, duration and timing of high-magnitude streamflow (HMF) for 93 stream gauges covering the Sacramento, San Joaquin and Tulare basins in California. The results show that in an average year with HMF approximately 3.2 km³ of high-magnitude flow is exported from the entire Central Valley to the Sacramento-San Joaquin Delta often at times when environmental flow requirements of the Delta and major rivers are exceeded. High-magnitude flow occurs, on average, during 7 and 4.7 out of 10 years in the Sacramento River and the San Joaquin-Tulare Basins, respectively, from just a few storm events (5–7 1-day peak events) lasting for 25–30 days between November and April. The results suggest that there is sufficient unmanaged surface water physically available to mitigate long-term groundwater overdraft in the Central Valley.

1. Introduction
California’s groundwater resources have been in decline since the early 1920s (Faunt 2009, USGS 2014). For most of the 20th century, statewide groundwater storage loss was estimated between 0.6 and 1.85 km³ yr⁻¹ (1960–2003) (Faunt 2009). More recent studies estimate annual losses to be between 1.4 and 3 km³ yr⁻¹ (DWR et al 2013), 8.9 km³ yr⁻¹ (2006–2010, Scanlon et al 2012) or even as high as 40 km³ (2012–2016, Xiao et al 2017). During the fourth year of the 2012–2016 drought, an additional 7.4 km³ of groundwater was pumped to balance the 10.7 km³ shortage in surface water supplies (Howitt et al 2014). As of 2017, California has 21 critically overdrafted groundwater basins (out of 515, which account for >80% of California’s annual groundwater pumping), 14 of which are located within the Central Valley (DWR 2016). These indicators of chronic groundwater overdraft highlight the need for groundwater recharge efforts in California and availability analyses to estimate surface water resources available for groundwater banking.

California’s depleted groundwater aquifers can provide ~44 km³ of storage capacity for groundwater banking (Scanlon et al 2016). Groundwater banking refers to approaches that intentionally place or retain more water in groundwater aquifers than would otherwise naturally occur. These approaches include conjunctive use (substituting surface water for groundwater to reduce groundwater use), in-lieu recharge (supply surface water to users who normally use groundwater), and managed aquifer recharge (MAR) (the active recharge of groundwater with...
surface water through infiltration basins or injection wells) (Scanlon et al 2016, DWR 2017). Increasing groundwater storage could enhance long-term drought resilience by facilitating multi-year storage and water markets. Another advantage of subsurface storage is reduced evaporation losses, which amount to over 2.0 km³ annually for the 24 largest lakes (Goodridge et al 1974) or about 8 m yr⁻¹ in California (Connell-Buck et al 2011). Large-scale MAR and aquifer storage and recovery (ASR) programs in California, including the Kern and Semitropic Groundwater Banks and the Arvin-Edison water storage district, currently account for only a small fraction (about 0.37 km³/year) of California’s water supply (DWR et al 2013, Christian-Smith 2013). However, with a median cost of $0.33 per m³ per year, groundwater recharge is a more cost-effective solution to water availability than seawater desalination ($1.54–$2.43 per m³) or reservoir expansion ($1.38–$2.27 per m³; BOR 2013) (Perrone and Merri Rohde 2016). A recent survey of 202 MAR applications submitted to DWR for funding identified that the most important factor influencing the average annual recharge volume for MAR projects is the availability of water for recharge and storage—highlighting the need for comprehensive assessment of additional water sources for groundwater recharge (Perrone and Merri Rohde 2016). Among the potential water sources identified by DWR (2017) for groundwater replenishment (e.g. stormwater, recycled water, desalination, water transfers, water conservation, and surface water) storm water and high-magnitude flows (i.e. flood flows) are likely the most accessible and largest sources of water for future expansion of groundwater banking (Harter and Dahlke 2014, Kocis et al 2016, Scanlon et al 2016).

1.1. Climate change induced challenges for water management

California’s highly variable climate, with known periods of both drought and abundant precipitation, and a strong north-south gradient in natural water availability, is a challenge to water resources management (Hanak et al 2011, Dettinger et al 2011). Over the past century, California’s water supply has relied upon more than 1400 surface water reservoirs and the Sierra Nevada snowpack to store water in the winter for use during the summer months (Hanak et al 2011). California’s surface water reservoirs have the capacity to store nearly 50% of the average annual statewide runoff (about 52.8 km³) but provide relatively limited storage in order to mitigate floods and to supply water during prolonged drought (Lettenmaier and Sheer 1991, Diffenbaugh et al 2015). California’s water managers are increasingly challenged by climate change related water supply uncertainty (e.g. increasing storm intensity, changes in flooding and droughts) and a variety of rapidly evolving social factors (e.g. population growth, water use patterns, technology) (Jacobs and Snow 2015).

Under climate change, California is predicted to experience longer, more frequent, and more spatially extensive heat waves and extended droughts (Tebaldi et al 2006, Lobell et al 2011), which can increase water demand (Chung et al 2009, Mirchi et al 2013). Increasing winter temperatures (Knowles et al 2006) are expected to result in a decrease in snowpack by 25%–40% over the next 50 years (Mote et al 2005). The majority of California’s climate is predicted to become increasingly arid, marked by more extremes (Cayan et al 2008, Seager et al 2007). Over the next few decades, total annual precipitation and precipitation frequency are expected to decrease (Pierce et al 2013, Dettinger et al 2011), while extreme events during wet years are expected to increase (Berg and Hall 2015). In particular, atmospheric rivers, which are narrow, intense bands with high water-vapor content that contribute 20%–50% of the state’s precipitation (Dettinger 2011) are expected to increase in intensity (Shields and Kiehl 2016). These changes in precipitation translate to pronounced changes in runoff, such as more frequent and more severe floods and droughts (Dettinger et al 2011, Das et al 2011, Das et al 2013), shifts in peak streamflow to winter and early spring away from summer and fall (Barnett et al 2005), and earlier spring snowmelt (Stewart et al 2005).

1.2. High-magnitude flows for on-farm recharge and groundwater banking

Early winter (December—February) floods in California generally result from atmospheric rivers—narrow jets of warm, moist air from the tropics near Hawaii. These events are projected to increase, over the next 100 years, in both duration (up to an additional 7.2 event days) and intensity (up to an 11% increase) (Dettinger 2011). The projected increase in storm duration and intensity during the early winter may increase winter flood risk, creating considerable challenges to existing flood control systems (Yu et al 2015). This, combined with earlier snowmelt and increased floodplain urbanization, is expected to increase flood risk and decrease surface water supply reliability in California (Hanak and Lund 2012). In order to adapt to these climate challenges, several studies have suggested moving much of California’s ‘drought’ water storage from surface reservoirs to groundwater aquifers, which can provide reliable multi-year storage (Tanaka et al 2006, Medellin-Azuara et al 2008, Connell 2009). With the passage of the new groundwater legislation in California, the Sustainable Groundwater Management Act (SGMA) in 2014, the focus on groundwater replenishment strategies has increased in an effort to bring critically overdrafted groundwater basins into balance (ACWA 2014, SGMA 2014). However, implementation is hampered by surface water availability for groundwater banking and lack of funds to cover costs of land, environmental compliance, and construction of recharge basins (Perrone and Merri Rohde 2016).
order to capture large amounts of excess surface water at minimal cost, on-farm recharge has emerged as a promising groundwater banking opportunity in California (Hamlin 1987, Bachand et al 2014, 2016). On-farm recharge is a form of MAR where farmland is flooded during the winter using surface water to recharge the underlying groundwater for later use when surface water supplies are limited. With 2.9 cents per m$^3$, the cost of on-farm recharge is much less than the cost for reservoir storage and dedicated recharge basins (Bachand et al 2016). On-farm recharge makes use of the irrigated agricultural landscape as spreading grounds (about 32,500 km$^2$ in California of which 13,000 km$^2$ are rated to have suitable soils for on-farm recharge (O’Geen et al 2015)) and transfers surface water via gravitational flow using existing irrigation infrastructure (Dahlke et al 2017). As such, on-farm recharge presents an ideal groundwater banking strategy in groundwater-dominated regions with large climate variability where large spreading grounds are needed to capture water from few storm events.

The use of winter flood flows is not limited to on-farm recharge and could be used in a variety of groundwater banking practices. Winter flood flows are an ideal source of surface water for groundwater banking because while most surface water in California is legally allocated, runoff from high-magnitude storm events during the winter is often not. The California State Water Resources Control Board does not currently consider flood flows for permanent water right/permit applications or water planning in California but instead uses the Rational Method and average flow conditions in water availability analyses (Kuichling 1889, SWRCB 2017a). In addition, during the winter, water demand from the agricultural sector is relatively low, and high-magnitude runoff is often not captured by surface water reservoirs to maintain storage space for flood protection (Hanak and Lund 2012, DWR 2017). Thus, flood flows that exceed environmental flow requirements could serve as an additional source of water to support expansion of groundwater recharge efforts through, for example, on-farm recharge and temporary water permits for groundwater banking/storage (Harter and Dahlke 2014, Scanlon et al 2016, SWRCB 2017b).

A recent report published by the California Department of Water Resources, Water Available for Replenishment, estimated the average amount of surface water available for groundwater replenishment for 10 regions using the WEAP model and monthly water supply and demand data. The report suggests that the average amount of surface water available per year under infrastructure capacity and environmental flow requirements is limited—totaling only 0.79 and 0.38 km$^3$/year in the Sacramento and San Joaquin-Tulare Basins, respectively (DWR 2017). However, instead of actual infrastructure capacity data the report considers the water right with the largest single point diversion capacity on a given stream as a proxy for diversion capacity, and further assumes that if no water right exists on a stream or the stream is fully appropriated, no water is available for that river. In other words, the report only estimates the amount of water available under existing water rights. This approach neither takes into account flood flows nor the possibility of future expansion in infrastructure and permanent or temporary water right permits (permits valid for 180 days that allow short-term diversion of surface water) and therefore largely underestimates the amount of surface water potentially available for groundwater recharge. The DWR (2017) report does provide a ‘maximum estimate’ based on unlimited diversion capacity (including flood flows) and estimates that the water available for replenishment is ∼5 and 1.1 km$^3$/year in the Sacramento and San Joaquin-Tulare Basins, respectively. However, these estimates are based on monthly outflow estimates determined with the WEAP model, which include only limited consideration of temporal dynamics (e.g. daily or inter-annual) in water availability and do not capture the availability of flood flows for groundwater recharge at time scales representative of storm events in adequate detail.

In complement to the report published by DWR (2017), the objective of this study is to assess the availability of flood flows, here termed high-magnitude flows (HMF), within the Central Valley, California for potential use for groundwater banking. This study is the first comprehensive analysis of historical streamflow records that assesses the magnitude, frequency, duration, and timing of high-magnitude flows for different regions (Sacramento, San Joaquin and Tulare basins), time periods (Nov–April, Dec–Feb etc.), and record periods (full record, post-impairment record) in the Central Valley, California. As such, this analysis provides unique insights into the physical and spatial distribution of surface water potentially available for expansion of groundwater banking. Our work builds on previous studies that evaluate the potential of conjunctive use and managed aquifer recharge in California (Purkey et al 1998, Hanak and Stryjewski 2012, Scanlon et al 2016). Various impediments to the use of high-magnitude flows for groundwater banking and particularly on-farm recharge are addressed in the discussion section. Results from this analysis should be valuable for water management, climate adaptation, flood risk mitigation, and conjunctive use of surface water and groundwater in many groundwater-dependent regions.

2. Data and method

2.1. Study area

The Central Valley (CV) (65,000 km$^2$) of California located between 35 and 41°N and 118 and 122°W is...
one of the most agricultural productive regions in the world, producing more than half of all fruits, vegetables, and nuts grown in the United States—on less than 0.5% of the total land area and just 1% of the total agricultural land (House Committee 2014, USDA 2012). The Central Valley has a Mediterranean climate with 125–510 mm of precipitation in the valley and over 1000 mm in the Sierra Nevada mountains (1961–1990, DWR 2003), most of which falls as rain or snow between November and April, and a mean annual temperature range of 17 °C–19.5 °C across the CV. Roughly 28 000 km² of the valley are irrigated with an extensive system of reservoirs, canals and aqueducts, as estimated from 1998–2005 (Hanak et al. 2011). The valley is comprised of two major drainage areas, the Sacramento River basin (SRB) and the San Joaquin Valley, the latter, which can be distinguished into two major basins, the San Joaquin River Basin and the Tulare Basin. The Sacramento River, the San Joaquin River, and their many tributaries contribute, on average, 22 km³ and 7.2 km³ of streamflow annually to the Sacramento—San Joaquin Delta (1966–2015, CDEC 2017)—the only natural outlet of the CV to the Pacific Ocean. Average annual evapotranspiration (1961–2003) in the Central Valley ranges from 1156 to 1422 mm yr⁻¹, with the highest rates in the San Joaquin-Tulare Basins (Faunt 2009).

2.2. Data sources
Historical daily streamflow data were used from the United States Geological Survey’s (USGS) Surface Water Data for the Nation website for sites within the Central Valley and associated watersheds (Hydrologic Unit Code 18) that had more than 50 years of recorded data (93 sites) (figure 1, table S1). Stream gauges were classified as impaired or unimpaired by cross-referencing the sites with the Hydro-Climatic Data Network (HCDN). The HCDN contains unimpaired streamflow sites which are preferred for trend studies (McCabe and Wolock 2002) because they are unaffected by artificial diversions, surface water storage, or other works of man (Slack et al. 1994). The HCDN-2009 dataset utilized in this study is considered a subset of the GAGES-II reference network, which has similar criteria for site selection. Of the 93 selected sites, the HCDN classifies 12 sites as unimpaired; one additional unimpaired site identified using dam and point of diversion data.

2.3. High-magnitude flow metrics
For each site, the 90th percentile was calculated for the full record of available data. Using the 90th percentile as a threshold for high-magnitude flows was motivated by the USGS and the environmental flow community to designate flows as ’much above normal’ or as ’high’ flows (Richards 1990, Clausen and Biggs 1997, Clausen and Biggs 2000, Olden and Poff 2003, Baker et al. 2004, Henriksen et al. 2006, Knaak et al. 2015, USGS 2016) and the frequent flood releases from surface water reservoirs during high flow events (Hayhoe et al. 2004).

Five metrics were used to assess high-magnitude flows: magnitude, duration, timing, intra-annual frequency, and inter-annual frequency (figure 1(b)). Magnitude is the total flow volume above the 90th percentile, duration is the number of days above the 90th percentile, timing is the day of the hydrologic year...
(DOHY) of the center of mass (COM) of flows above the 90th percentile, and intra-annual frequency is the count of 1-day peaks that occur over the 90th percentile. A 1-day peak event occurs on a day where the flow is higher than both the previous day and the next day. For each of these four metrics, the average metric value was calculated only over years with flows above the 90th percentile and years with a zero value (no flow above the 90th percentile) were removed (from here on referred this process is referred to as ‘zero-deflation’). To account for this zero-deflation of the data (the artificial lowering of the mean value due to the abundance of zeroes created by zeroing out flows below the 90th percentile), an inter-annual frequency, or the fraction of years with flow above the 90th percentile, was considered.

2.4. Calculation periods
Since stream alterations and impairments such as dams and diversions can severely alter the flow regime, the high-magnitude flow metrics were analyzed over two periods of record: the full record of available data and the record of data since the most recent impairment. For the post-impairment period the common year of all most recently constructed, significant dams within the watershed of each of the 93 gauges was determined using a GIS analysis. For the Sacramento River Basin and the San Joaquin Valley the post-impairment periods consisted of the years 1970–2014 and 1989–2014, respectively.

The analysis of the high-magnitude flow metrics was conducted for several time periods and five different water year types (critical [C], dry [D], below normal [BN], above normal [AN] and wet [W]) defined in the San Joaquin Valley Index and Sacramento Valley Index (SWRCB 1995, Null and Viers 2013) (see supplementary data available at stacks.iop.org/ERL/12/084009/mmedia). Each metric was determined for the hydrologic year (October 1 to September 30 the following year), for November to April, December to February, and each month between November and April. These time period estimates were then split by year type, zero-deflated, and averaged inter-annually over both the entire period of record and from the most recent impairment year to the present. The timing metric was considered only over the hydrologic year.

3. Results
The results are presented as estimates for each station within each basin and as a summary of the conditions at the outlets of each basin using two exemplary stream gauges that represent the integrated basin flow from the Sacramento River Basin (SRB) and the San Joaquin–Tulare Basins (SJTB), respectively. The two gauges are: (1) the USGS gauge 11447650 (55 040 km² catchment area): an impaired site near the outlet of the SRB near Freeport, CA with data available from 1906 present, and the most downstream gauge considered by this study on the Sacramento River, and (2) the USGS gauge 11303500 (35 066 km² catchment area) an impaired site near the outlet of the SJTB near Vernalis, CA with data available since 1923, and the most downstream gauge considered by this study on the San Joaquin River. Unless stated otherwise each metric is reported as an average, zero-deflated value of flow above the 90th percentile for the full record period across all year types considering only years in which flows above the 90th percentile occurred. Flow above the 90th percentile is abbreviated as high-magnitude flow or HMF.

3.1. Magnitude
For most stream gauges considered in this study, the annual HMF ranged between 0.005 and 0.10 km³. The long-term average annual fraction of HMF to total flow can range from 1% to 67% for sites across the Central Valley (outlet SRB 5%, SJTB 9%). Based on the outlet stream gauges at Freeport and Vernalis the SRB and SJTB contribute together over 3.9 km³ annually as HMF to the Delta across all year types (table S2). The SRB discharges about 54% (2.1 km³) of the total annual HMF, while the San Joaquin and Tulare Basins (SJTB) account for approximately 46% (1.8 km³). For the post-impairment periods the annual HMF at the outlets of the SRB (1970–2014) and SJTB (1989–2014) shift to 2.4 km³ and 1.6 km³ respectively indicating that since the 1970s a higher fraction of the HMF is stored in surface water reservoirs in the SRB and a lower fraction is stored in the SJTB.

The 3 month and 6 month winter periods produce the majority of the annual HMF (figure 2(a)). Approximately 95% (2.0 km³) of the total annual HMF in the SRB, and 67% (1.2 km³) in the SJTB, occur during the six-month winter period from November to April. Furthermore, about 62% (1.3 km³) of the total annual HMF in the SRB, and 30% (0.54 km³) in the SJTB, occur during the three-month winter period from December to February. During wet years the SRB and SJTB discharge about 3.5 km³ and 2.7 km³ as HMF, respectively (figure 2(d)). In a critically dry year (and also dry years for the SJTB), no flows above the 90th percentile are discharged from both basins. However, during dry years the SRB discharges about 0.16 km³ in HMF to the Delta from November to April.

3.2. Duration
The average annual duration of HMF varies from 37 to 90 days throughout the Central Valley (figure 2(b), table S3). For most watersheds considered in this study, annual duration of HMF is between 37 and 45 days during an average year. At the outlet of the SRB and SJTB, the annual duration of HMF across all year types is 51 and 80 days, respectively. Between
November and April, HMF occur, on average, for 46 days at the outlet of the SRB and 50 days at the outlet of the SJTB. Similar to the magnitude results, most HMF occur for 28 and 23 days at the outlet of the SRB and SJTB respectively, on average, for 46 days at the outlet of the SRB and 50 days at the outlet of the SJTB. Similar to the magnitude results, most HMF occur, on average, for 46 days at the outlet of the SRB and SJTB. Between November and April, HMF occur, on average, for 46 days at the outlet of the SRB and SJTB. The annual number of peak events ranges between 8 and 12 events. At the outlets of the SRB and SJTB, there are 6 and 8 peak events annually. Between November and April, the outlets of the SRB and SJTB record 6 and 5 peak events, respectively, on average, reflecting the late occurrence of HMF in the SJTB due to snowmelt events in May and June. During wet years the SRB exhibits, on average, 8 peak events between November and April, while the outlet of the SJTB averages 7 peak events (figure 2(f)). In a critical year, both outlets of the SRB and SJTB show no peak events. The average annual number of 1-day peak events does not change for the post-impairment period.

3.4. Inter-annual frequency
Recurrence of high-magnitude flow varies greatly from year to year (40%–99%) in the Central Valley (figure 3, table S5). The majority of watersheds had HMF occurring in 80% to 99% of the full record period (<1960–2014). At the outlet of the SRB approximately 73% of years showed HMF while the outlet of the SJTB had HMF only in 47% of all years. For the post-impairment period the outlets of the SRB and SJTB show HMF in approximately 64% and 36% of all years. The SRB shows overall the highest HMF reliability across all year types. For both the November–April and December–February period HMF were observed at the outlet of the SRB in 73% and 70% of all years since 1906. For the outlet of the SJTB these percentages drop to 44% and 38% for 1923–2014, respectively. Critically dry and dry years provide no HMF and approximately 25% of below normal years show HMF at the outlet of the SJTB.

3.3. Intra-annual frequency
The annual number of 1-day peak events with HMF varies from 4 to 14 events throughout the Central Valley (figure 2(e), table S4). For most watersheds considered in this study, the annual number of peak events ranges between 8 and 12 events. At the outlets of the SRB and SJTB, there are 6 and 8 peak events annually. Between November and April, the outlets of the SRB and SJTB record 6 and 5 peak events, respectively.
Even during wet years, only 88% of the wet years observed between 1923 and 2014 created HMF at the outlet of the SJTB.

3.5. Timing
The day of the hydrologic year (DOHY) on which the center of mass (COM) of HMF occurs varies from the 125 DOHY (early February) to the 283 DOHY (early July) across the Central Valley (figure 4, table S6). For most stream gauges, the COM is normally distributed between DOHY 123 and 251, but peak occurrences in COM DOHY fall between either the 130–140 DOHY (mid-February) or the 230–240 DOHY (mid-May). At the outlet of the Sacramento River Basin the COM of HMF occurs approximately 1.5 months earlier (DOHY 140, mid-February) than at the outlet of the SJTB, which is on the 187 DOHY (early April). At the outlet of the SRB the COM of high-magnitude flows does not change much across the different year types (e.g. 136–141 for below normal to wet years). In contrast, the COM observed at the outlet of the SJTB varies between the 192 DOHY (early April) in wet
years and the 241 DOHY (end of May) in below normal years.

4. Discussion

Our results indicate that over the 6-month winter period (November-April) an average year with HMF exports approximately 3.2 km³ (full record period) to 3.5 km³ (post-impairment period) of streamflow from the entire Central Valley to the Delta. Furthermore, wet years in the Sacramento Valley alone provide HMF of approximately 3.3 km³ from November to April. A comparison of these results to the long-term average groundwater overdraft in the Central Valley estimated by the California Department of Water Resources at 0.6–3.5 km³ yr⁻¹ (Faunt 2009, DWR et al 2013), with 80% of overdraft occurring in the San Joaquin-Tulare Basins (Famiglietti et al 2011), suggests that there is sufficient surface water physically available to mitigate long-term groundwater overdraft in the Central Valley.

The analysis of the HMF timing, duration and frequency exhibit geographical differences that could be important for utilizing HMF for groundwater banking. Year-to-year HMF reliability is greatest in the Sacramento Valley where HMF occurs, on average, during 7 out of 10 years. In contrast HMF reaches the outlet of the SJTB only during 4.7 out of 10 years but occurrence increases to an average of 7.2 out of 10 years for sites near the Sierra Nevada mountains, thus increasing HMF reliability for groundwater banking on the east side of the Central Valley. During the November-April period most of the HMF occurs over relatively short time periods, on average, 30 and 25 day for sites within the SRB and SJTB, respectively, and as the result of just a few storm events (5–7 1 day peak events). The latter is consistent with hydroclimatic studies of Neiman et al (2008) and Dettinger et al (2011) who estimated that 30%–50% of all the precipitation in California falls in only 5 to 10 days per year contributing up to 71% of annual streamflow. The few occurrences and short duration of HMF strongly suggest the need to coordinate efforts for the local-scale diversion of flood flows to actually utilize these flows.

For on-farm recharge, the timing of HMF is crucial since perennial crops and certain stages of crop growth do not tolerate flooded conditions (Visser et al 2003, Niu et al 2014). The center of mass of the HMF (i.e. date at which 50% of the annual HMF has passed) occurs in mid-February for the outlet of the SRB and at the end of April for the outlet of the STJB (figures 4 (b) and (d)). Early occurrence of HMF in the SRB could potentially promote its Central-Valley-wide use for groundwater banking, utilizing the State’s vast irrigation infrastructure (Georgakakos et al 2012, Hanak and Lund 2012). In contrast, most of the HMF in the SJTB originates from snowmelt late in the winter and spring season as indicated by the COM
results (Dettinger and Cayan 1995, Stewart et al 2004). The late occurrence of HMF in the SJTB will likely limit utilization of flood flows for on-farm recharge in the SJTB since onset of the growing season is shifting towards earlier dates in the southern Central Valley (e.g. early February) thus increasing the risk of crop damage (Feng and Hu 2004, Gutierrez et al 2006). However, HMF could be utilized more efficiently in the SJTB if reservoir operation policy would be changed such that more water from the conservation pool would be released for storage in groundwater aquifers allowing more space for flood management, as precipitation and runoff patterns are expected to change (Purkey et al 1998, Jenkins et al 2004, Maurer and Duffy 2005, Hanak and Lund 2012).

Although the high-magnitude flow metrics show overall little change when comparing the full to post-impairment period, the metrics for sites within both the SRB and the SJTB show a greater spatial variability in the post-impairment period indicated by the increased standard deviation on the metric average (figure 3(b), table S2). The most apparent change between the full and post-impairment records is a decrease in the average fraction of years with HMF between November and April, which decreased from 78% to 70% (10% loss) in the SRB and from 54% to 42% (22% loss) in the SJTB. This decrease in HMF occurrence is suggesting that the implementation of a wide variety of water management practices and impairments across the basin has had dampening effect on very high flows. Further, sites across both the SRB and the SJTB become and less temporally variable during years with flow above the 90th percentile (site-specific standard deviations are generally smaller) from the full record to the post-impairment record, suggesting that individual sites are becoming increasingly regulated over time. For water management, the post impairment period represents more closely the current state of the system and therefore may provide a more realistic estimate of current and future HMF metrics. In contrast, the full record encapsulates long-term climate variability within the Central Valley that is indeterminate from the post-impairment record, thus providing insights into the long-term variability of the HMF metrics.

4.1. Environmental (instream) flow considerations

The high-magnitude flow analysis naturally raises the question: how would the diversion of the estimated HMF influence the availability of environmental flows? HMFs are important for sediment transport, channel formation and scouring (Fisher 1983, Baron et al 2002, Lane et al 2016), maintaining riparian vegetation (Hupp and Osterkamp 1985, Sparks 1995), facilitating upstream and downstream dispersal of native riparian organisms (Meffe 1984, Moyle and Light 1996), and inducing spawning in native fishes (Baumgartner et al 2014). While diverting flood flows for groundwater recharge could provide potential benefits for flood risk mitigation (Hanak and Lund 2012), it could also impact the availability of environmental flows. However, in consideration of these impacts and in light of the increasing demand for surface water from a variety of sources, it might be possible to utilize HMF in a way that can maintain environmental flows. For example, Inman and Jenkins (1999) found that the majority of large sediment flux events (i.e. events that carried 20–30 times the amount of sediment of an average event) from the 20 largest streams entering the Pacific Ocean in California occurred at the beginning of the wet season following a longer dry period. In the context of groundwater recharge projects, this suggests that through careful management of HMF, the HMF events after a dry period could be reserved for channel formation or environmental flows, while later HMF events could be utilized for groundwater recharge with minimal impacts to overall sediment flux. This would also be consistent with operation and management practices commonly applied in MAR operations, which avoid the use of sediment-rich waters because of the risk of sediment accumulation, sediment penetration, or biofouling that could lower infiltration rates (Racz et al 2011).

To assess this potential risk for environmental flows, HMF at the outlets of the SRB and SJTB was compared to daily records of the hydrologic condition of the Sacramento-San Joaquin River Delta (available since 1976, USBR 2008), which regulates flows from the Central Valley Project and the State Water Project to meet environmental flow and water quality standards for native species in the Delta. Results indicate that for 99% of the days with HMF the Delta was in true excess condition. The Delta is declared as being in true excess conditions when flow exceeds the needs of the State Water Project and the Central Valley Project (i.e. surface water deliveries), the export to import ratio is met, and when flow exceeds the required flow and water quality for fish in the Delta (State of California and the United States of America 1985). Interestingly, during 41% of the days since 1976 the Delta has been in true excess conditions; of this percentage, on 19% and 22% of these days HMF occurred at the outlets of the SRB and SJTB (see figure S1 supplemental materials). This suggests that with careful planning HMF could be jointly utilized for both environmental flow and groundwater banking objectives. Finally, under the growing demand for water and a predicted decline in surface water resources resulting from climate change, trade-offs and reconciliation will have to be made within both environmental and societal demands for improved management of water resources.

4.2. Additional considerations for using HMF for groundwater banking

The use of HMF for groundwater banking should be considered with regard to the variety of physical,
institutional, and political constraints to implementing such projects. The results of this analysis suggest that a larger volume of HMF is available in the Sacramento Basin than in the San Joaquin-Tulare Basins; however, the majority of severe groundwater overdraft occurs in the Tulare Lake Basin (Faunt 2009, DWR 2015). This disparity between reliable water supply in the northern Central Valley and severely unmet water demand in the southern Central Valley is at the crux of California’s water management issues. Currently, Central Valley Project and State Water Project pump stations in the south Delta are not operated at full capacity due to environmental regulations (SWRCB 2006). Capacity of both projects to route water south is further impacted by land subsidence in the San Joaquin Valley, which has caused operational, maintenance, and construction-design problems for water-delivery and flood-control canals including the Delta-Mendota Canal and the California Aqueduct (Faunt et al 2016). However, both the planned Sites Reservoir (storage capacity of 2.2 km³), located on the west side of the Sacramento Valley near Maxwell, CA, and the proposed Delta Tunnel project (part of the Bay Delta Conservation Plan) would provide operational flexibility to the State’s water supply system that could be used to temporarily store water for slower release to groundwater recharge areas. As indicated in the DWR (2017) Water Available for Replenishment report, the irrigation infrastructure capacity (e.g. canals, diversions, ditches) is, at present, a limiting factor for full use of HMF for groundwater banking. However, based on the passage of SGMA, which encourages larger groundwater recharge efforts, and the $7.12 billion dollar California Water Quality, Supply, and Infrastructure Improvement Act of 2014, which dedicates $2.7 billion dollars for investments in water storage projects CA AB 1471 (2014), it is not unreasonable to assume that conveyance capacity of the surface water supply system will improve in the coming years. Because large-scale expansion of surface water storage is limited in California (Lund et al 2014), it is expected most investments will be made towards integrating storage operations.

Soil suitability for groundwater banking on agricultural land in California was analyzed by O’Geen et al (2015), who found that roughly 13,000 km² of agricultural land, primarily in the Central Valley, has excellent to moderately good suitability for groundwater banking using a combination of five factors: deep percolation, root zone residence time, chemical properties, topography, and surface conditions. A modified version of the soil agricultural groundwater banking index (SAGBI) on agricultural land was also studied by considering deep ripping in addition to the five factors above, which involves the process of breaking apart flow-restricting soil layers to improve deep percolation of water in the upper meter of the soil. Under the modified version, 22,500 km² of agricultural land were identified as having excellent to moderately good potential for groundwater banking. While soils are generally finer textured and sometimes saline in the Sacramento Basin and thus less suitable, the Sacramento Basin still provides about 3200 km² of soils rated excellent to moderately good.

Crop suitability experiments are currently underway (Kocis et al 2016, Dahlke et al 2017) including on-farm recharge experiments on alfalfa, almonds, pistachio and pecans. Dahlke et al (2017) tested variable amounts of winter water (1.2–8 m m⁻²) and different water application timings on old (>5 year) dormant alfalfa stands and found minimal yield loss, short-lived saturated conditions in the root-zone, and the majority (>90%) of the applied water going to groundwater storage. Other studies have assessed the suitability of table grapes (Dokoozlian et al 1987) and wine grapes (Bachand et al 2016) for winter-dormancy groundwater banking. In both studies, the grapes showed no adverse effects or yield declines in the following growing season. O’Geen et al (2015) provide an estimate of tolerance of common fruit and nut trees to saturation and identified pears, plums and almonds to be able to tolerate standing water for up to 2 weeks. However, since soils with high percolation rates are preferred for on-farm recharge, injury risk from anoxia in the root zone as a result of waterlogged conditions is likely reduced in these soils.

At present, groundwater recharge is not considered a beneficial use of surface water in the State of California. To use surface water for groundwater banking, a new water right permit or a change to an existing water right must be obtained, requiring a site-specific water availability analysis. As indicated in the DWR (2017) Water Available for Replenishment report, water available for groundwater replenishment on some rivers was estimated to be zero because the river is already fully appropriated. This is because in some parts of California, mainly the tributaries to the Sacramento and San Joaquin Rivers, water rights account for up to 1000% of natural surface water supplies (Grantham and Viers 2014). However, over-appropriation is, to some degree, an artifact of the water rights system; specifically, the difference between actual water use and the face-value of an appropriated water right. Often this difference is unknown, and water allocations are based only on average flow conditions. Thus, issuance of a temporary water permit, which could specifically target surface water diversions outside the growing season (e.g. in November–April) in anticipation of wet winters, might increase overall accessibility of surface water for groundwater banking and short-term (e.g. within the same water year) use of the banked water. However, without improvements or amendments to the water rights system, implementation of groundwater banking programs for multi-year storage of surface water in groundwater aquifers will likely remain a regulatory challenge.
5. Conclusions

We studied the magnitude, frequency, duration, and timing of high-magnitude flow (i.e. flow above the 90th percentile) in the Central Valley, California in order to assess the physical availability of surface water for groundwater banking. The focus on high-magnitude flow was motivated by the large streamflow variability in California, specifically storm events during wet years, which produce runoff volumes that often exceed the surface water storage capacity within the state and are frequently discharged to the Pacific Ocean as indicated by the observed high-magnitude flows at stream gauges downstream of major reservoirs. We estimate that in years with HMF the mean high-magnitude flow exported from the entire Central Valley to the Sacramento-San Joaquin Delta from November to April is 3.2 km$^3$, often at times when environmental flow requirements of the Delta and major rivers are exceeded. These HMFs could provide enough water to balance more than two times the annual groundwater overdraft. Similarly, wet years can provide over four times the average annual groundwater overdraft. During wet years, the SRB and SJTB discharge about 3.3 km$^3$ and 1.6 km$^3$ as HMF from November to April, respectively. High-magnitude flow occurs, on average, during 7 and 4.7 out of 10 years in the Sacramento River and the San Joaquin-Tulare Basins, respectively, from just a few storm events (5–7 1-day peak events) lasting for 25–30 days between November and April. These high-magnitude event flows could be managed more efficiently, involving conjunctive use of surface and groundwater resources and reservoir reoperation for controlled releases of these flows for groundwater banking. Expansion of surface water use to include HMF for groundwater recharge offer significant advantages for long-term water security in California but also requires addressing several regulatory challenges including the acknowledgement of groundwater recharge as beneficial use in California water law. However, the state’s increased emphasis on more sustainable groundwater management and the increasing willingness of farmers to adopt on-farm recharge practices should facilitate increased use of these underutilized flows.

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References

ACWA (Association of California Water Agencies) 2014 Sustainable Groundwater Management Act Fact Sheet (www.acwa.com/sites/default/files/post-groundwater/2014/04/2014-groundwater-fact-sheet.pdf) (Accessed: 21 April 2016)
CA A B 1471 2014–14 session of the California State Legislature (Water Quality, Supply, and Infrastructure Improvement Act of 2014)
Bachand P A, Roy S B, Choperena J, Cameron D and Horwath W R 2014 Implications of using on-farm flood flow capture to recharge groundwater and mitigate flood risks along the Kings River, CA Environ. Sci. Technol. 48 13601–9
Bachand P, Roy S, Stern N, Choperena J, Cameron D and Horwath W 2016 On-farm flood capture could reduce groundwater overdraft in Kings River Basin Calif. Agr. 70 2007–2011
Baker D B, Richards R P, Loftus T T and Kramer J W 2004 A new flashy index: characteristics and applications to midwestern rivers and streams J. Am. Water Resour. As. 40 503–22
Barnett T P, Adam J C and Lettenmaier D P 2005 Potential impacts of a warming climate on water availability in snow-dominated regions Nature 438 303–9
Baron J S, Poff N L, Angelmeier P L, Dahm C N, Gleick P H, Hairston N G, Jackson R B, Johnston C A, Richter B D and Steimann A D 2002 Meeting ecological and societal needs for freshwater Ecol. Appl. 12 1247–60
Baumgartner L J, Conallin J, Wooden I, Campbell B, Gee R, Robinson W A, and Mullen-Cooper M 2014 Using flow guilds of freshwater fish in an adaptive management framework to simplify environmental flow delivery for semiarid riverine systems Fish Fish. 15 410–27
Berg N and Hall A 2013 Increased interannual precipitation extremes over California under climate change J. Clim. 26 6324–34
BOR (Bureau of Reclamation) 2013 San Luis Reservoir Expansion Draft Appraisal Report 160 pp (www.usbr.gov/mp/sllpp/docs/2013_11_19_DRAFT_San_Luis_Expansion_Appraisal_Report.pdf)
Cayan D R, Maurer E P, Dettinger M D, Tyree M and Hayhoe K 2008 Climate change scenarios for the California region Clim. Change 87 21–42
CDEC (California Department of Water Resources) 2017 Chronological Reconstructed Sacramento and San Joaquin Valley, Water Year Hydrologic Classification Indices (http://cdexc.water.ca.gov/cgi-progs/iodr/wshist)
Christian-Smith J 2013 Improving Water Management through Groundwater Banking: Kern County and the Rosedale-Rio Bravo Water Storage District (California; Pacific Institute USA)
Chung F et al 2009 Using future climate projections to support water resources decision making in California California Energy Commission Technical Report CEC-500-2009-052 F
Clausen B and Biggs B 1997 Relationships between benthic biota and hydrological indices in New Zealand streams Freshwater Biol. 38 327–42
Clausen B and Biggs B 1997 Flow variables for ecological studies in temperate streams: groupings based on covariance J. Hydrol. 237 184–97

O RcID IDs

Tiffany N Kocis https://orcid.org/0000-0001-5889-5861
Helen E Dahlke https://orcid.org/0000-0001-8757-6982
Richards R P 1990 Measures of
Olden J D and Poff N L 2003 Redundancy and the choice of
Purkey D R, Thomas G A, Fullerton D K, Moench M and Pierce D W
et al
Mote P W, Hamlet A F, Clark M P and Lettenmaier D P 2005
Niu S, Luo Y, Li D, Cao S, Xia J, Li J and Smith M D 2014 Plant
Mirchi A, Madani K, Roos M and Watkins D W 2013 Climate
Meffe G K 1984 Effects of abiotic disturbance on coexistence of
McCabe G J and Wolock D M 2002 A step increase in
Neiman P J, Ralph F M, Wick G A, Lundquist J D and Dettinger
Environ. Res. Lett. ‘
Geen A et al
M, McGuire V L and McMahon P B 2012 Groundwater
16
River Res. Appl.
and managed aquifer recharge in California and Arizona
2016 Enhancing drought resilience with conjunctive use
during managed aquifer recharge, as quanti
Axelrad L 1998
Francisco Estuary and Watershed Science
11
Institute) (Berkeley, CA: The Natural Heritage
Groundwater Banking
Costs of managed aquifer recharge in California

Declining mountain snowpack in western North America
areas for groundwater banking on agricultural lands
Integrating storage in California
– 316
– 347
fl
86
75
– 88
– 348–1
fl
109
– 10
– 8
– 79
fl
11
– 75
fl
– 34
fl
– 62
fl
– 562–70
fl
50
– 107
fl
2
3
– 75–90
Ecosystem 65 1525–34
Meffe G K 1984 Effects of abiotic disturbance on coexistence of
predator-prey fish species Ecology 78 149–61
Neiman P J, Ralph F M, Wick G A, Lundquist J D and Dettinger
M D 2008 Meteorological characteristics and overland
precipitation impacts of atmospheric rivers affecting the
West Coast of North America based on eight years of
SSM/I satellite observations J. Hydrol. 9 22–47
Niu S, Luo Y, Li D, Cao S, Xia J, Li J and Smith M D 2014 Plant
growth and mortality under climatic extremes: an overview
Environ. Exp. Bot. 98 13–19
Null S E and Viets J H 2013 In bad waters: water year
classification in nonstationary climates Water Resour. Res.
49 1137–48
O’Geen A et al 2015 Soil suitability index identifies potential areas for groundwater banking on agricultural lands Calif. Agr. 69 75–84
Olden J D and Poff N L 2003 Redundancy and the choice of
hydrologic indices for characterizing streamflow regimes
River Res. Appl. 19 101–121
Perrone D and Merri Rohde M 2016 Benefits and economic
costs of managed aquifer recharge in California San
Francisco Estuary and Watershed Science 14 1–13
Pierce D W et al 2013 Probabilistic estimates of future changes in
California temperature and precipitation using statistical
dynamical downscaling Clim. Dyn. 40 839–856
Porkey D R, Thomas G A, Fullerton D K, Moench M and
Axelrad L 1998 Feasibility Study of a Maximal Program of
Groundwater Banking (Berkeley, CA: The Natural Heritage
Institute)
Racz A J, Fisher A T, Schmidt C L, Lockwood B and Los Huertos
M 2011 The spatial and temporal dynamics of infiltration
during managed aquifer recharge, as quantified using mass
balance and thermal methods Ground Water 50 562–70
Richards R P 1990 Measures of flow variability and a new
flow-based classification of Great Lakes tributaries J. Great
Lakes Res. 16 53–70
Scalon B R, Faunt C C, Longuevergne L, Reedy R C, Alley W
M, McGuire V L and McMahon P B 2012 Groundwater
depletion and sustainability of irrigation in the US high
plains and central valley Proc. Natl Acad. Sci. 109 9320–25
Scalon B R, Reedy R C, Faunt C C, Pool D and Uhlman K
2016 Enhancing drought resilience with conjunctive use
and managed aquifer recharge in California and Arizona
Environ. Res. Lett. 11 035011
Seager R et al 2007 Model projections of an imminent transition to
a more arid climate in southwestern North America
Science 316 1181–4
SGMA 2014 (Sustainable Groundwater Management Act), §§
346–1–10, §§ 347–1–23, §§ 348–1–3. State of California
Shields C A and Kiehl J T 2016 Atmospheric river landfall–
latitude changes in future climate simulations Geophys.
Res. Lett. 43 8775–82
Slack J R, Lamb A M, Landwehr J M and US Geological Survey
1994 Hydro-Climatic Data Network (HCDN)—A USGS
Streamflow Data Set for the US for the Study of Climate
Fluctuations (US Department of the Interior, US
Geological Survey)
Sparks R E 1995 Need for ecosystem management of large rivers
and their floodplains BioScience 45 168–82
State of California and United States of America 1985 Water
Project—Central Valley Project Coordinated Operation
Agreement. Department of the Interior, Bureau of
Reclamation
Stewart I T, Cayan D R and Dettinger M D 2004 Changes in
snowmelt runoff timing in western North America under a
business as usual climate change scenario Clim. Change 62
217–32
Stewart I T, Cayan D R and Dettinger M D 2005 Changes
toward earlier streamflow timing across western North
America J. Clim. 18 1136–55
SWRCB (State Water Resources Control Board) 1995 Water
Quality Control Plan for the San Francisco Bay/
Sacramento–San Joaquin Delta Estuary (www.waterboards.
ca.gov/waterrights/water_issues/programs/baydelta/
wq_control_plans/1995wqcp/docs/1995wqcpb.pdf)
(Accessed: 3 October 2016)
SWRCB (State Water Resources Control Board) 2006 Water
Quality Control Plan for the San Francisco Bay/
Sacramento–San Joaquin Delta Estuary (www.waterboards.
ca.gov/waterrights/water_issues/programs/baydelta/
wq_control_plans/2006wqcp/) (Accessed: 10 March 2017)
SWRCB (State Water Resources Control Board) 2017a Water
Availability information (www.waterboards.ca.gov/
waterrights/water_issues/programs/water_availability/)
(Accessed: 10 March 2017)
SWRCB (State Water Resources Control Board) 2017b Applications
for Groundwater Recharge/Storage (www.waterboards.ca.gov/
waterrights/water_issues/programs/applications/
groundwater_recharge/) (Accessed: 10 March 2017)
Tanaka S K, Zhu T J, Lund J R, Howitt R E, Jenkins M W,
Paludo M A, Tauber M, Ritzema R S and Ferreira I C 2006
Climate warming and water management adaptation for
California San Francisco Estuary Change 76 361–87
Tebaldi C, Hayhoe K, Arblaster J M and Meehl G A 2006 Going
to the extremes Clim. Change 79 185–211
USBR (United States Bureau of Reclamation) 2008 Central Valley
Project and State Water Project Operations Criteria and
Plan Biological Assessment. Report, 1016 p (www.usbr.
gov/mp/cvo/OCAP/docs/OCAP_BA_2008.pdf)
USDA (United States Department of Agriculture) 2012 Census of
Agriculture 2012 (US Department of Agriculture)
USGS (United States Geological Survey) 2014 Water Use in the
United States (US Department of the Interior, US
Geological Survey) (http://water.usgs.gov/watuse/index.
html)
USGS (United States Geological Survey) 2016 Daily Streamflow
Conditions, USGS Current Water Data for the Nation (US
Department of the Interior, US Geological Survey) (http://
waterdata.usgs.gov/nwis/rt)
Visser E J W, Voesenek, L A C I, Vartapetian B B and Jackson M
B 2003 Flooding and plant growth Ann. Bot. 91 107–109
Xiao M, Koppa A, Mekonnen Z, Pagán R B, Zhan S, Cao Q,
Aierken A, Lee H and Lettenmaier D P 2017 How much
groundwater did California’s Central Valley lose during the
2012–2016 drought? Geophys. Res. Lett. 44 1–8
Yu Z, Jiang P, Gautam M R, Zhang Y and Acharya K 2015
Changes of seasonal storm properties in California and
Nevada from an ensemble of climate projections I.
Geophys. Res. AtmoNo. 120 2676–88