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Sustainable Groundwater Management in the Arid Southwestern US: Coachella Valley, California

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Abstract Sustainable groundwater management requires approaches to assess the influence of climate and management actions on the evolution of groundwater systems. Traditional approaches that apply continuity to assess groundwater sustainability fail to capture the spatial variability of aquifer responses. To address this gap, our study evaluates groundwater elevation data from the Coachella Valley, California, within a groundwater sustainability framework given the adoption of integrative management strategies in the valley. Our study details an innovative approach employing traditional statistical methods to improve understanding of aquifer responses. In this analysis, we evaluate trends at individual groundwater observation wells and regional groundwater behaviors using field significance. Regional elevation trends identified no significant trends during periods of intense groundwater replenishment, active since 1973, despite spatial variability in individual well trends. Our results illustrate the spatially limited effects of groundwater replenishment occur against a setting of long-term groundwater depletion, raising concerns over the definition of sustainable groundwater management in aquifer systems employing integrative management strategies.

Keywords Sustainable groundwater management · Groundwater trends · Statistical analysis · California groundwater

1 Introduction and Background

Groundwater provides a critical freshwater resource for more than 2 billion people (Alley et al. 2002) and stores an estimated 90 % of nonfrozen freshwater (Koundouri 2004). Globally

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(Wada et al. 2010; Famiglietti and Rodell 2013) and within the United States (Konikow 2013), the documented unsustainable use has depleted groundwater storage, escalating concerns of groundwater resources to meet future water demands (Famiglietti 2014).

To evaluate groundwater availability, the concept of safe yield has been used, defined as the maximum amount of water produced from an aquifer and while maintaining aquifer storage (Lee 1915). Alley and Leake 2004 advanced aquifer sustainability, changing the focus from reliance of annual recharge and withdrawals to include the temporal patterns of withdrawals and groundwater behaviors. Alley and Taylor (2001) and Stoll et al. (2011) advocate that groundwater monitoring provide a means of measuring the impact of natural and anthropogenic influences on groundwater resources. An extensive network of observation wells in the Coachella Valley of California (Fig. 1) permits an evaluation of a complex and highly managed groundwater system to assess responses from natural and anthropogenic variability.

In California, groundwater depletion has been documented in regions of intense groundwater use (Famiglietti et al. 2011) with recognized impacts including land subsidence and aquifer compaction (Poland et al. 1972; Sneed et al. 2013). In the Coachella Valley, ten-fold increases in withdrawals between 1936 and 1967 resulted in observations of 30 m or more in aquifer elevation decline (Tyley 1974) with annual trends of 1.5 m per year near Palm Springs (Swain 1978) and subsidence of up to 6 mm/year (Sneed and Brandt 2013). Water agencies throughout the valley are working to effectively manage groundwater resources thus producing

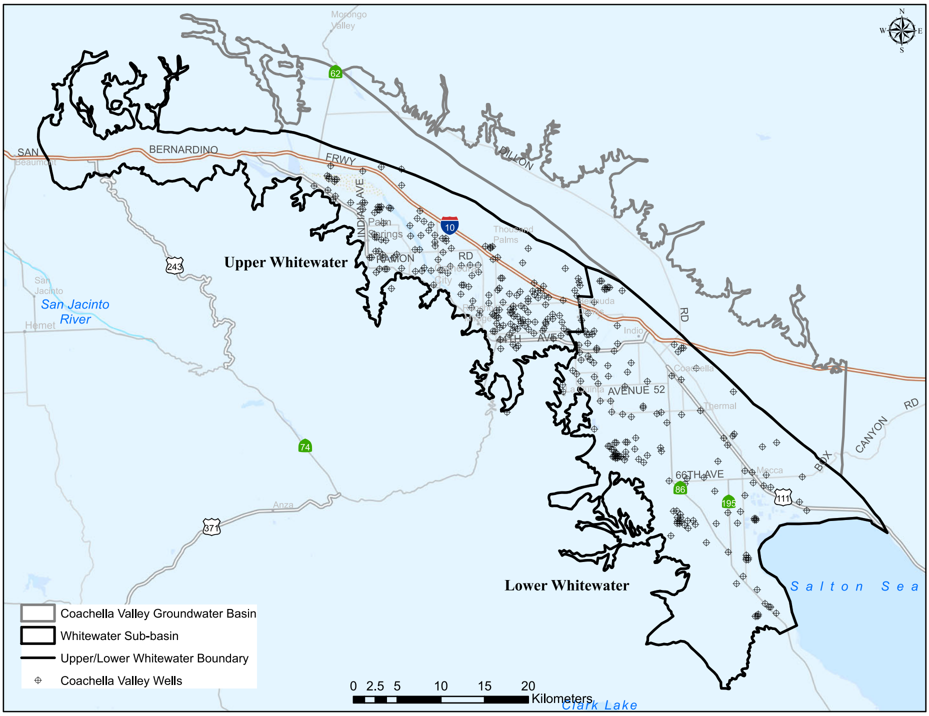

Fig. 1 Site map illustrating the Coachella Groundwater basin (in *grey*) with the Whitewater groundwater sub-basin (in *black*). A total of 336 groundwater observation wells are spatially distributed throughout the Whitewater basin

a complex arrangement of surface water allocations, groundwater withdrawals, water reuse and groundwater banking.

This study presents an analysis of historic groundwater elevations to characterize the influence of groundwater management and climate that have led to the behavior of the aquifer system. Previous studies have assessed regional aquifer behaviors using remote sensing observations (Famiglietti et al. 2011; Castle et al. 2014) without regard to local groundwater behavior. Our evaluation uses nonparametric trend analyses to assess individual and regional groundwater behaviors given that nonparametric approaches are ideal for non-normally distributed data often encountered in hydrologic time series (Helsel and Hirsch 2002). Panda et al. (2007) were the first to evaluate groundwater behaviors using nonparametric trend detection (Mann 1945; Kendall 1962; Helsel and Hirsch 2002; Weber and Perry 2006; Ghanbari and Bravo 2011; Bui et al. 2012; Machiwal and Jha 2014). Our analysis extends beyond these previous studies to evaluate regional groundwater elevation trends while accounting for cross-correlation of groundwater elevations. Our objectives to measure the performance of aquifer management are: (1) to investigate groundwater elevations trends to assess the impact of groundwater management and climate, (2) to evaluate regional groundwater behavior while accounting for spatial and serial correlation and (3) to examine the implications of our findings within a groundwater sustainability framework.

1.1 Site

The Coachella Valley is a northwest trending valley in southern California reaching from the San Bernardino Mountains to the north and the Salton Sea to the south (Fig. 1). The Salton Trough, a ridge-transform fault system (McKibben 1993), was filled by deltaic deposits from the Colorado River with reported depths up to 3700 m. The primary aquifer system is separated into an upper zone (45–90 m below grade) and a lower zone (90–180 m below grade) with semiconfining layers throughout the aquifer system (Sneed and Brandt 2013).

A combination of geologic controls and aquifer management by multiple water agencies creates a variable aquifer response across the valley. Structural geologic features including the San Andreas Fault Zone influence groundwater response by impeding flow (California Department of Water Resources 1964). Despite close interactions between the multiple water agencies, which include Coachella Valley Water District, Coachella Water Authority, Desert Water Agency, Indio Water Authority and Mission Springs Water District, each agency manages withdrawals differently. Previous groundwater evaluations (Tyley 1974; Swain 1978; Reichard and Meadows 1992) separated the region into the Upper Whitewater and Lower Whitewater basins representing where historical groundwater elevations were declining and rising since the completion of the Coachella Canal in 1949. Regional water plans (MWH 2012) continue to evaluate groundwater management by separating the Whitewater Basin into the Upper and Lower Whitewater; for the purpose of this study, groundwater behaviors were evaluated within the Whitewater Basin and by regions designated as the Upper and Lower Whitewater (Fig. 1) to fit within this existing management structure.

The basin hydroclimatology is typical of an arid region found throughout the southwestern United States. The arid valley averages 80–100 mm of annual precipitation on the valley floor with reported averages within mountain ranges of up to 800 mm

(Reichard and Meadows 1992; Sneed et al. 2002). Typical in arid groundwater systems (Gee and Hillel 1988), natural groundwater recharge is restricted to induced recharge from losing streams and valley-edge recharge. Mendenhall (1909) identified the source of groundwater recharge to the valley aquifer from precipitation and runoff events from the bordering mountains; Swain (1978) estimated a net annual natural recharge of 44.4×10^6 cubic meters per year (m^3/year) to the Whitewater Basin. By 1999, for comparison, total groundwater withdrawals were 463.8×10^6 m^3/year, or approximately 10 times that of estimated natural recharge. Population centers are concentrated in the Upper Whitewater, for example Palm Springs, and rely on groundwater to meet 92 % of total water demands. The Lower Whitewater is characterized as more agricultural, relying on groundwater to meet 36 % of total water demands. Artificial recharge to the Upper and Lower Whitewater basins via surface water imports obtained through transfers from the California State Water Project and through agreements to attain Colorado River allocations via the Quantification Settlement Agreement have been used to augment natural recharge since 1973.

2 Methods

2.1 Data

Groundwater elevations were recorded by the various water agencies at observation wells installed to survey changes in groundwater elevations (Fig. 1). Groundwater elevations were recorded approximately four times per year; however, as no formal observation plan was in effect, observations were temporally variable. We selected observations from 1960 to 2013 for our analysis, splitting data into decade periods starting with 1960. Individual groundwater well trend analysis was evaluated for wells with a combination of greater than 10 readings over a 5-year period for decadal analysis and greater than 30 readings over at least 25 years for the period of 1960 to 2013.

Precipitation data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) project (http://www.prism.oregonstate.edu/) was analyzed to evaluate annual precipitation data gridded at 4-km resolution over the study region (Fig. 2). For this analysis, data from 1910 to 2010 was analyzed to attribute average decadal precipitation behavior to observed trends in groundwater elevations.

2.2 Hypothesis Tests

An understanding of groundwater dynamics, which includes estimation of the temporal and spatial variability of groundwater behaviors as a response to both natural and anthropogenic influences, is a critical step to achieving sustainable groundwater management. Multiple approaches to evaluate groundwater dynamics, including time series analysis (Panda et al. 2007), groundwater flow simulation models (Faunt 2009) and remote sensing (e.g., Famiglietti et al. 2011; Castle et al. 2014) have been employed. Such approaches are restrictive due to their inability to evaluate local groundwater behavior. In this study, we employ the Mann-Kendall trend test to evaluate local groundwater behavior which can be up-scaled to evaluate regional groundwater trends using field significance.

2.2.1 Mann-Kendall Trend Test

Previous groundwater studies have sought to characterize changes in groundwater/surface water interactions (Rivard et al. 2009; Kustu et al. 2011) or to understand climate changes in groundwater systems (Stoll et al. 2011; Dudley and Hodgkins 2013). Use of the Mann-Kendall trend test for analysis of groundwater trends has historically been applied for water quality data (Broers and Grift 2004; Wahlin and Grimvall 2010) and only recently applied to groundwater elevations (Weber and Perry 2006; Panda et al. 2007; Ghanbari and Bravo 2011; Bui et al. 2012; Machiwal and Jha 2014). The use of nonparametric approaches are preferred for non-normally distributed data and avoids complications of correlated residuals in linear regression approaches, which could be corrected by various transformations akin to prewhitening, for example the Cochrane-Orcutt or Hildreth-Lu transformation (Johnston and DiNardo 1997).

The Mann-Kendall trend test is a nonparametric, rank-based method used to evaluate the presence of trends in time series data (Helsel and Hirsch 2002). The test proceeds by ranking data according to time and evaluating each successive data point. The test statistic, Kendall's S (Kendall 1962), is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{1}$$

where x is the data point at times i and j and sgn (x_j-x_i) is 1 if $x_j > x_i$, −1 if $x_j < x_i$ and 0 otherwise. For independent, identically-distributed random variables with large n,

$$E(S) = 0 \tag{2}$$

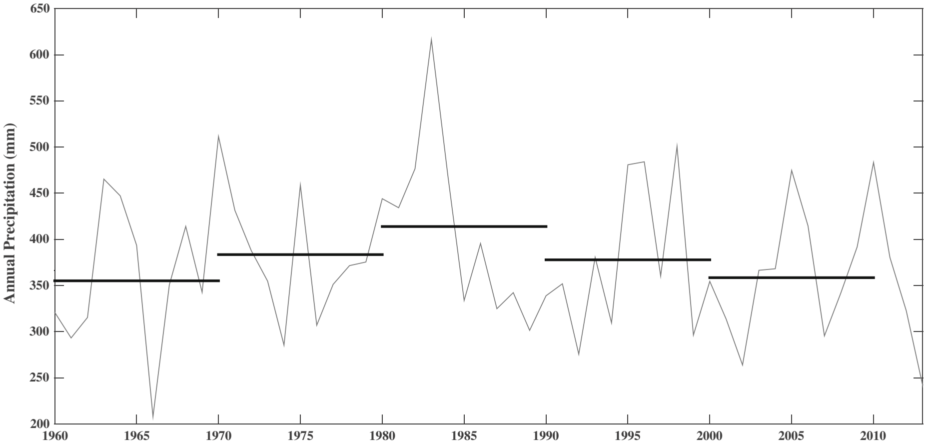

Fig. 2 PRISM annual precipitation data for the Coachella Valley. Decadal averages, shown as horizontal lines, are used as references to evaluate climatic controls to groundwater behaviors

When ties are considered (where $x_i = x_j$), we can calculate variance of S as

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(i)(i-1)(2i+5)\right] \tag{3}$$

where t_i represents the number of ties of extent i.

The magnitude of the trend is estimated using the Sen Slope estimator (b) given by

$$b = median\left(\frac{Y_j - Y_i}{X_j - X_i}\right) \forall j > i \tag{4}$$

where Y represents the observed groundwater elevation at time X (Helsel and Hirsch 2002).

2.2.2 Field Significance

Field significance, a term that represents the significance of regional behaviors, was used to evaluate decadal trends across the Coachella Valley. Previous approaches to assess regional groundwater behaviors used homogeneity tests (Panda et al. 2007; Machiwal and Jha 2014); such analysis provides spatial information to conglomerate at-site trends but fails to evaluate the statistical behavior of the entire aquifer system. The field significance test accounts for individual well behaviors to identify a regional trend; the results of the test are compared to trends that may result by chance, carried out here using a bootstrap approach. The procedure is influenced by serial correlation, the temporal correlation in individual groundwater observation time series, and spatial correlation, the spatial relation between groundwater observation wells resulting from the direct hydraulic connection between sites.

Spatial Correlation Lettenmaier et al. (1994) and Douglas et al. (2000) illustrate the importance of spatial correlation in interpretation of regional trends. Douglas et al. (2000) illustrate that correlation between sites violates independence assumptions when evaluating regional trend significance. As our study evaluates trends in groundwater observations that share a direct hydraulic connection between sites, we assume that at-site correlation requires other means to evaluate field significance.

Our assessment uses bootstrapping to evaluate field significance (Renard et al.; 2008). The bootstrapping method (Efron 1979) involves resampling to generate samples from which the statistical behavior of interest may be approximated. The bootstrapping approach employed here entailed the resampling of groundwater observations N times with replacement to estimate the statistical properties of the average Kendall's $S\left(\overline{S}_m\right)$ computed as

$$\overline{S}_m = \frac{1}{m}\sum_{k=1}^{m} S_k \tag{5}$$

where S_k is Kendall's S at the kth well in a region of m observation wells. A null hypothesis of no trend in spatially uncorrelated and independent estimates of S_k was employed; thus, $E\left(\overline{S}_m\right) = 0$. For the N bootstrap samples, we developed an empirical distribution function for $\overline{S}_m$ to determine the field significance. A total of 10,000 samples (N=10,000) were plotted using the Weibull plotting position (Cunnane 1978) such that

$$P\left(\overline{S}_m < S\right) = \frac{r}{N+1} \tag{6}$$

where r is the ordered rank of bootstrap results.

Spatial Correlation Hydrologic data often exhibit serial correlation which violates the assumption of serial independence and may result in the rejection of no trend when no trend exists. Von Storch (1995) recommended pre-whitening data to remove serial correlation in an individual time series. In the simplest approach, pre-whitening can be completed by removing the lag-1 autocorrelation which assumes the data were generated by an AR (1) process whereby

$$Y_t^* = Y_t - r_1 Y_{t-1} \tag{7}$$

where Y_t is the raw groundwater observation at time t and r_1 is the lag-1 autocorrelation (Yue and Wang 2004). Yue et al. (2003) illustrated that a pre-whitening process referred to as the "TFPW" approach exhibited higher power in evaluating trend significance. The method proceeds by estimating and removing the Sen Slope trend, removing the AR (1) relationship and reintroducing the slope trend estimates to the time series (Li et al. 2014). Other investigations employed a similar approach for streamflow trends (Wu et al. 2008; Rivard et al. 2009; Khaliq et al. 2009; Zhao et al. 2010; Birsan et al. 2013), precipitation trends (Deni et al. 2010; Burn et al. 2011) or evapotranspiration (Shadmani et al. 2012). It is not the purpose of this study to evaluate the performance of various pre-whitening approaches (Bayazit and Önöz 2007); instead, we evaluated the TFPW approach given previous studies findings for trend evaluation (Yue et al. 2003; Wu et al. 2008; Rivard et al. 2009; Zhao et al. 2010).

3 Results

3.1 Decade Trends

Results are presented for decade time periods (1960s to 2000s) in Fig. 3 where the magnitude of trend is estimated by the Sen Slope estimator (Eq. 4). To evaluate spatial behaviors of trends, individual well trend magnitudes were interpolated using ordinary kriging (Cressie 1990), a spatial estimation method that minimizes error variance. In our findings, we attribute observed decadal groundwater behaviors to historical information including surface water imports, groundwater use and precipitation. A statistical summary of decadal results illustrated in Fig. 3 are included in Table 1.

3.1.1 1960s

Negative trends were evident in the Upper Whitewater, a response attributed to increasing agricultural production (Riverside County Agriculture Crop Reports, 1960, 1970) and population growth, increases of 55 % in Palm Springs during the 1960s, potentially leading to increased groundwater withdrawals given the reliance of groundwater to meet water demands

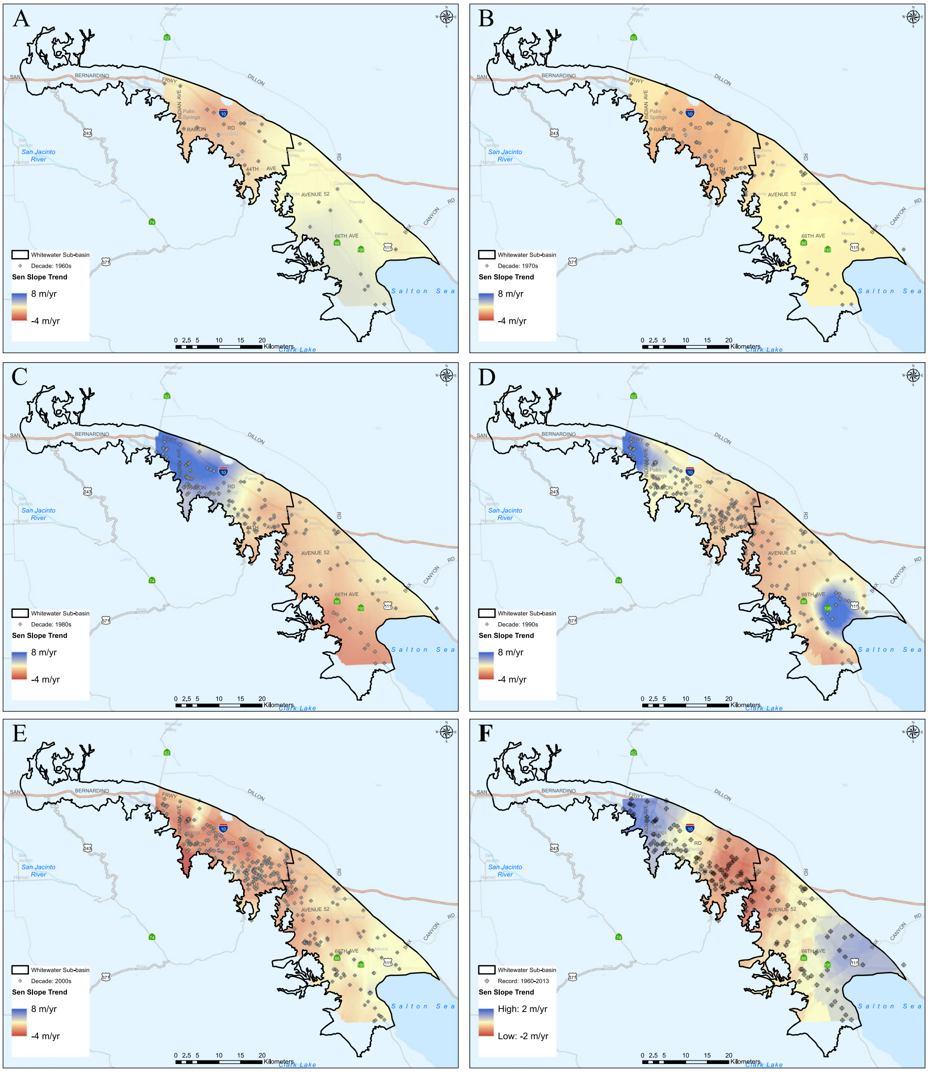

Fig. 3 At-site spatial interpolation for decadal trends including the 1960s (**a**), 1970s (**b**), 1980s (**c**), 1990s (**d**), 2000s (**e**) and 1960–2013 (**f**)

in the Upper Whitewater (Fig. 3a). Slight positive groundwater elevation trends were identified in the Lower Whitewater region near the Salton Sea. Completion of the Coachella Canal in 1949, which brought irrigation water to the Lower Whitewater from the Colorado River, offset the need to pump groundwater to meet water demands likely leading to the positive groundwater response.

3.1.2 1970s

Population growth and agricultural production increased rapidly in the 1970s (Riverside County Agriculture Crop Reports, 1970, 1980) contributing to the groundwater overdraft

Table 1 Summary statistics of decadal and record at-site trend analysis

Decade	Count	Mean m/year	Median m/year	Count (+/−)[a]	Mean (−) trend m/year	Median (−) trend m/year	Mean (+) trend m/year	Median (+) trend m/year
1960s	35	−0.34	−0.30	11/24	−0.62	−0.59	0.27	0.33
1970s	75	−0.41	−0.32	11/64	−0.53	−0.45	0.34	0.10
1980s	129	0.55	−0.25	51/78	−0.76	−0.61	2.55	1.85
1990s	202	−0.10	−0.54	48/154	−0.73	−0.69	1.89	0.69
2000s	272	−1.02	−1.06	21/251	−1.13	−1.12	0.29	0.25
60-2013	150	−0.46	−0.45	26/124	−0.68	−0.59	0.60	0.40

[a] (+/−) indicates positive groundwater elevation trends and negative groundwater elevation trends

(Fig. 3b). Across the valley, a majority of wells exhibited negative trends (85 %). The spatially interpolated trend magnitudes illustrated in Fig. 3b, however, depict a fraction of observation wells in the Lower Whitewater exhibiting neutral/slight positive trends (23 %). Groundwater recharge in the Upper Whitewater began in 1973 (MWH 2012) as the Whitewater River Spreading Basins recovered a combination of stormwater runoff and surface water allocations; replenishment rates for the system were minimal until 1979 which likely resulted in localized influences to groundwater elevations during the decade.

3.1.3 1980s

As the groundwater replenishment allocations increased in the Upper Whitewater, so did localized groundwater elevation trends (Fig. 3c). Almost 40 % of groundwater trends were positive throughout the valley where a majority of trends in the Upper Whitewater were positive (62 %). The increase of surface water allocations for groundwater replenishment in the Upper Whitewater likely resulted due to increased Colorado River allocations in addition to higher than normal precipitation during the decade (Fig. 2). The Lower Whitewater exhibited negative trends in groundwater elevations despite irrigation flows from the Coachella Canal.

3.1.4 1990s

Spatial trends illustrate the variability and limited effects of groundwater replenishment across the Coachella Valley (Fig. 3d). Increased surface water allocations for groundwater replenishment in the Upper Whitewater increased groundwater elevations in 28 % of observation wells. Further, pilot replenishment studies in the Lower Whitewater resulted in a positive aquifer response in the eastern portion of the valley where 16 % of observation wells exhibited positive trends. Throughout much of the valley, decreasing groundwater elevations are evident indicating high spatial variability in the groundwater overdraft.

3.1.5 2000s

The southwestern United States experienced prolonged drought during the 2000s (Fig. 2) which impacted the potential for natural recharge to the aquifer (Cayan et al. 2010). The drought also affected surface water diversions for groundwater replenishment (MWH 2012) and likely resulted in increased groundwater withdrawals to meet irrigation and urban water demands. The combination of climatic conditions and continued groundwater withdrawals resulted in groundwater overdraft during the decade (Fig. 3e).

3.1.6 1960–2013

In an effort to alleviate groundwater overdraft, the water agencies initiated groundwater replenishment in conjunction with water reuse and surface water diversions. Since 2009, agreements by Coachella Valley Water District through the Quantification Settlement Agreement have resulted in increased surface water allocations diverted to groundwater replenishment systems in the Upper Whitewater. The behavior of groundwater elevations from 1960 to 2013 illustrates the effect of artificial groundwater recharge to increase groundwater elevations (Fig. 3f). Fig. 3f clearly shows the limited spatial influence of groundwater replenishment given the dramatic declines in groundwater elevations, up to 2 m per year, in the central portion of the Valley.

3.2 Field Significance

An assessment of a regional trend allows us to identify an aquifer-based evaluation of sustainable groundwater management. Although decadal trends discussed in Section 3.1 provide compelling visual evidence of groundwater behaviors, we cannot test the significance of regional groundwater trends with such approaches. To address this concern, we evaluate the field significance of at-site hypothesis tests to identify the significance of a regional trend. For this analysis, our null hypothesis is that no regional trend exists with a significance level of 0.05.

Figure 4 illustrates the field significance for TFPW data following Yue et al. (2003) and Li et al. (2014) where the bars represent the probability of rejecting the null hypothesis. The results document insignificant trends throughout the 1960s, 1990s and during the entire study period of 1960–2013. Significant trends were identified across the Whitewater Basin in the

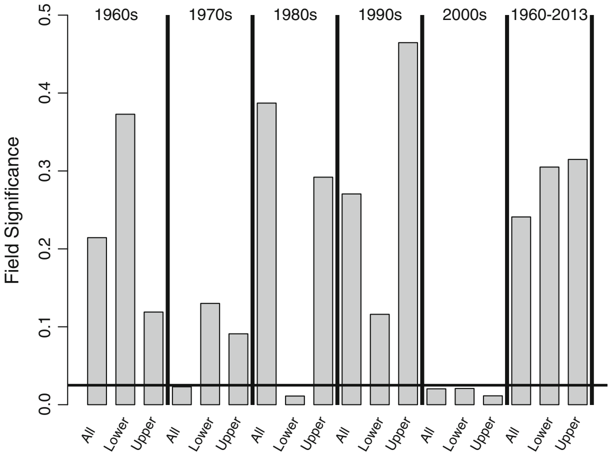

Fig. 4 Field significance of trend tests. The height of the bar represents the probability of rejecting the null hypothesis, meaning if the height of the bar is above the horizontal line representing our level of significance (0.025), then the regional trend is insignificant

1970s and 2000s, while significant trends were identified in the Lower Whitewater (1980s and 2000s) and Upper Whitewater (2000s). These results substantiate visual identification of aquifer behaviors illustrated in Fig. 3. For example, Lower Whitewater significant trends in the 1980s are clearly evident in Fig. 3c. The complex mix of positive groundwater elevation trends near the recharge facilities and negative groundwater elevation trends in the central portion of the Valley (Fig. 3) result in an insignificant trend during the entire study period (Fig. 3f), highlighting the complexity encountered in evaluating sustainable groundwater management.

The combination of spatial distribution of groundwater behaviors and the magnitude of trends as illustrated in Fig. 3 were found to influence regional trends. Consider, for example, the decade of the 1980s. In the Upper Whitewater, groundwater replenishment activities effectively increased groundwater elevations resulting in positive groundwater elevation trends in the northwestern portion of the aquifer while decreasing groundwater elevation trends were exhibited in the southwestern portion of the Upper Whitewater. The combination of increasing and decreasing trends in the Upper Whitewater resulted in no significant regional trend to be identified (Fig. 4). In the Lower Whitewater, negative trends were clearly evident across the region (Fig. 3c) and a significant regional trend was identified (Fig. 4). Similar results were found across the study period illustrating the influence of groundwater replenishment activities on observed groundwater behaviors.

4 Discussion

A long history of groundwater overdraft, reported as early as the 1910s, has existed across the Coachella Valley as groundwater withdrawals were used to meet regional water demands. Today, the region relies on a complex mix of groundwater withdrawals, surface water allocations from the Colorado River and water reuse to support an economy comprised of agricultural production, golf courses and tourism and population centers including Indio and Palm Springs.

Our results illustrate variable benefits of groundwater replenishment practices to alleviate the groundwater overdraft in the Valley; observations near the recharge facilities exhibited a change in groundwater elevation trends from negative to positive while other regions, specifically the groundwater elevations in the central portion of the Valley, continued to exhibit overdraft conditions (Fig. 3). The drought and reduced surface water allocations during the 2000s clearly impacted groundwater elevations with widespread negative groundwater elevation trends (Fig. 3e). Our field significance analysis (Fig. 4) identified a significant trend during the 2000s thus highlighting the reliance of regional groundwater management on groundwater replenishment via surface water allocations. In a statistical evaluation of the long-term groundwater trends, our results failed to identify significant trends; a result attributed to the effectiveness of groundwater replenishment to locally increase groundwater elevations.

To illustrate the behavior of groundwater elevations across the Coachella Valley, we average groundwater elevations per calendar year. For each region, we calculate an annual average groundwater elevation as the number of observations per well in addition to the number of groundwater wells being observed changed throughout the study period. As a reference, the average groundwater elevation is compared to the average elevation observed in 1960. In this analysis, we present a single average groundwater elevation; given results illustrated in Fig. 5, we recognize that a single number cannot represent the behavior of the groundwater elevation both spatially and temporally. However, this analysis permits a valuable comparison of average annual groundwater behavior to understand the evolution of the system due to both climate and regional water management impacts. Figure 5 includes records of annual groundwater replenishment volumes obtained from the Coachella Valley Water District (MWH 2012) and annual precipitation records for representative regions.

The behavior of average groundwater elevations in the Upper Whitewater illustrates a rapid depletion of groundwater storage between 1960 and 1980 (Fig. 5b); in contrast, the Lower Whitewater exhibited positive storage changes followed by declines in groundwater elevations until approximately 2010 (Fig. 5c). In the Upper Whitewater, the change in groundwater behaviors in 1980 likely resulted due to a combination of above-average precipitation (Fig. 2) and steadily increasing groundwater replenishment volumes in the Upper Whitewater (MWH 2012). In contrast, the Lower Whitewater exhibited declines in groundwater storage with a sharp decline observed in 2000 as a prolonged drought was recorded across the southwestern

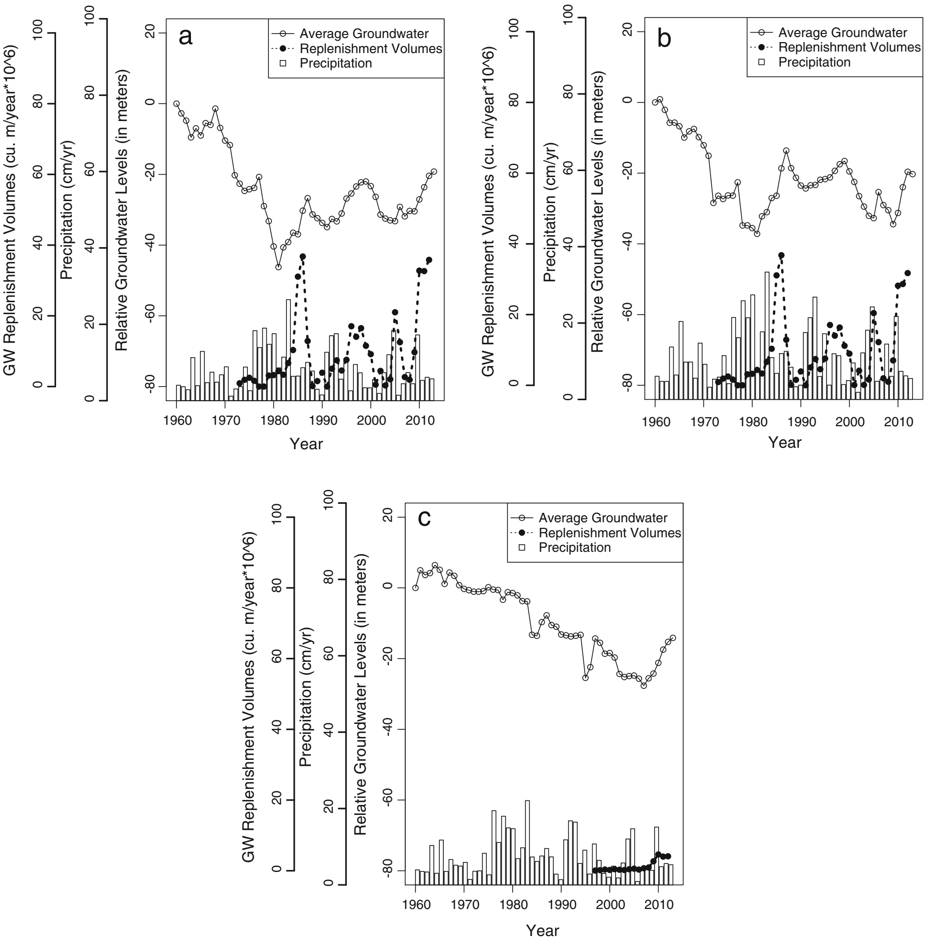

Fig. 5 Annual average groundwater elevation behaviors for the entire Whitewater sub-basin (**a**), the Upper Whitewater (**b**) and Lower Whitewater (**c**) illustrating the influence of groundwater replenishment volumes to average elevations

United States. A change in average groundwater behaviors were observed in approximately 2007 coincides with pilot groundwater replenishment in the region (MWH 2012); the pilot program led to the installation of a replenishment facility in the Lower Whitewater in 2009.

4.1 Sustainability Framework

Multiple water management decisions including agreements with water agencies outside the Valley have brought surface water allocations from the Colorado River to be used for groundwater replenishment and irrigation, alleviating the need for groundwater withdrawals to meet water demands. Further, conservation efforts including education and rebate programs have alleviated demands (MWH 2012). Despite these efforts, average groundwater elevations are approximately 19 m below 1960 levels (Fig. 5a).

Groundwater sustainability requires more than a “no-net withdrawal from the aquifer” condition as advocated by Bredehoeft (1997) and Alley and Leake (2004). Results in Fig. 3 provide evidence of groundwater overdraft with localized positive responses in groundwater elevations resulting from replenishment. Field significance results confirm the positive influence of groundwater replenishment activities; during decades with large replenishment volumes, no significant regional trend was identified. Conversely, our statistical evaluation identified significant regional behaviors during the 2000s which coincided with drought in the southwestern United States and reduced replenishment volumes (Fig. 4). In Fig. 5, we identify the effect of groundwater replenishment to suppress the decline of average groundwater elevations.

If we compare groundwater behavior during the 2000s, a decade when the region did not receive a large volume of surface water allocations, to the 1980s, a decade when the region received large volumes of surface water allocations, it becomes apparent that the spatially limited effect of groundwater replenishment occurs against a milieu of long-term groundwater depletion. As evidenced in both Figs. 3 and 4, unsustainable groundwater practices in the region resulted in groundwater declines with reduced surface water allocations. During periods when surface water freely flowed into the region, groundwater elevations rebounded and no significant regional groundwater trend was identified. The observed groundwater behaviors thus fail to exhibit characteristics of a resilient management strategy. The scenario of continued unsustainable groundwater use in a region that relies heavily on groundwater resources to meet water demands has important implications for the region, especially given the uncertainty in future climate changes and the likelihood of increased droughts (IPCC 2007) and the uncertainty of future allocations from the Colorado River (Barnett and Pierce 2009).

5 Conclusions

Gleeson et al. (2012) advocate for integrative water management, a goal already achieved in the Coachella Valley, which accounts for more than the “ins and outs” of a groundwater water budget (Bredehoeft 1997, 2002; Sophocleous 2000; Alley and Leake 2004). The results of our analysis can be used to assess the monitoring component of groundwater sustainability frameworks similar to Pandey et al. (2011) and Zhou (2009). The spatial and temporal analysis using at-site and regional Mann-Kendall approaches, which may have limited power in trend detection in groundwater time series, identified external factors including climate and water management decisions; in the case of Coachella Valley, these decisions include the introduction of Colorado River allocations for irrigation and groundwater replenishment. The simplicity of our approach permits knowledge dissemination to discuss groundwater behaviors and the impacts of groundwater management to facilitate evaluation and stakeholder involvement in an effort to achieve groundwater sustainability in the Valley. Further, our analysis provides transparent analyses for the identification of future groundwater sustainability actions by providing a temporal and spatial analysis using common hydrology approaches which account for management actions, climate and groundwater use to set long-term sustainable goals (Gleeson et al. 2012). Despite a legally complex mix of agreements to secure surface water allocations for groundwater replenishment and irrigation, the spatial patterns of overdraft remain evident.

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