Journal of Hydrology 519 (2014) 131–147

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Analysis of projected water availability with current basin management plan, Pajaro Valley, California

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ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form 2 July 2014
Accepted 4 July 2014
Available online 15 July 2014
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Groundwater
Climate
Management
Integrated hydrologic models
Water allocation
Water recycling

SUMMARY

The projection and analysis of the Pajaro Valley Hydrologic Model (PVHM) 34 years into the future using MODFLOW with the Farm Process (MF-FMP) facilitates assessment of potential future water availability. The projection is facilitated by the integrated hydrologic model, MF-FMP that fully couples the simulation of the use and movement of water from precipitation, streamflow, runoff, groundwater flow, and consumption by natural and agricultural vegetation throughout the hydrologic system at all times. MF-FMP allows for more complete analysis of conjunctive-use water-resource systems than previously possible with MODFLOW by combining relevant aspects of the landscape with the groundwater and surface-water components. This analysis is accomplished using distributed cell-by-cell supply-constrained and demand-driven components across the landscape within "water-balance subregions" (WBS) comprised of one or more model cells that can represent a single farm, a group of farms, watersheds, or other hydrologic or geopolitical entities. Analysis of conjunctive use would be difficult without embedding the fully coupled supply-and-demand into a fully coupled simulation, and are difficult to estimate a priori.

The analysis of projected supply and demand for the Pajaro Valley indicate that the current water supply facilities constructed to provide alternative local sources of supplemental water to replace coastal groundwater pumpage, but may not completely eliminate additional overdraft. The simulation of the coastal distribution system (CDS) replicates: 20 miles of conveyance pipeline, managed aquifer recharge and recovery (MARR) system that captures local runoff, and recycled-water treatment facility (RWF) from urban wastewater, along with the use of other blend water supplies, provide partial relief and substitution for coastal pumpage (aka in-lieu recharge). The effects of these Basin Management Plan (BMP) projects were analyzed subject to historical climate variations and assumptions of 2009 urban water demand and land use. Water supplied directly from precipitation, and indirectly from reuse, captured local runoff, and groundwater is necessary but inadequate to satisfy agricultural demand without coastal and regional storage depletion that facilitates seawater intrusion. These facilities reduce potential seawater intrusion by about 45% with groundwater levels in the four regions served by the CDS projected to recover to levels a few feet above sea level. The projected recoveries are not high enough to prevent additional seawater intrusion during dry-year periods or in the deeper aquifers where pumpage is greater. While these facilities could reduce coastal pumpage by about 55% of the historical 2000–2009 pumpage for these regions, and some of the water is delivered in excess of demand, other coastal regions continue to create demands on coastal pumpage that will need to be replaced to reduce seawater intrusion. In addition, inland urban and agricultural demands continue to sustain water levels below sea level causing regional landward gradients that also drive seawater intrusion. Seawater intrusion is reduced by about 45% but it supplies about 55% of the recovery of groundwater levels in the coastal regions served by the CDS. If economically feasible, water from summer agricultural runoff and tile-drain returnflows could be another potential local source of water that, if captured and reused, could offset the imbalance between supply and demand as well as reducing discharge of agricultural runoff into the National Marine Sanctuary of Monterey Bay. A BMP update (2012) identifies projects and programs that will fund a conservation program and will provide additional, alternative water sources to reduce or replace coastal and inland pumpage, and to replenish the aquifers with managed aquifer recharge in an inland portion of the Pajaro Valley.

Published by Elsevier B.V.

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http://dx.doi.org/10.1016/j.jhydrol.2014.07.005
0022-1694/Published by Elsevier B.V.

1. Introduction

The availability and sustainability of water resources is subject to changing demands and supplies that are integrated through movement of all the water resources within a watershed, and the conjunctive use of these waters. Conjunctive use of water is the joint use and management of surface-water, recycled water, and groundwater resources to sustain a reliable supply and minimize damage to the quantity or quality of the resource. The use and movement of water resources also are constrained by infrastructure and other circumstances such as climate variability and agricultural practices. Sustaining current agricultural productivity affects the local economy, resulting in prosperity, growth, and further transformation of agri-business to more dynamic and intensive farming with higher profit crops, multiple plantings or harvests and multiple growing seasons. This growth depends on a reliable source of water which may be quantified through a systematic, basin-wide water budget. Such budgets assess the water supply from precipitation, surface water, and groundwater and water demands of agriculture, urban, and environmental uses. The groundwater, surface-water and landscape budgets from an integrated hydrologic model (IHM) also can be used to assess the potential effect of climate variations or climate change on sustainable water supplies. Hydrologic budgets for complex systems are best assessed with an IHM that simulates all the physically-based components of interest because they are fully integrated and coupled flows that provide the "one-water" analysis needed for conjunctive use (Hanson and Schmid, 2013). Thus, an IHM that fully links the movement and use of demand-driven and supply-constrained components of a hydrologic system provides the means for analyzing and understanding conjunctive use and sustainable BMP projects. PVHM uses MF-FMP (Hanson and Schmid, 2013; Hanson et al., 2010) to provide this fully coupled, cell-by-cell distributed, fully iterative simulation of supply-constrained and demand-driven conjunctive use and movement of water from natural and anthropogenic sources (Hanson et al., 2014).

This paper describes the analysis of water resources for a 34-year projection of current agricultural and urban supply and demand by the U.S. Geological Survey and Pajaro Valley Water Management Agency (PVWMA). This projection uses historical climate and hydrology back to the severe 2-year drought of 1976–1977. A "base case" analysis was used to evaluate the efficacy of the current facilities implemented as part of a broader BMP that has been developed and is being updated by PVWMA. The updated BMP includes the evaluation and development of additional alternative local water supplies, aquifer replenishment through managed aquifer recharge (MAR), and demand management in Pajaro Valley of coastal Monterey Bay, California (Fig. 1). Conjunctive use for agriculture that was historically, predominantly irrigated with groundwater is combined with water supply facilities that replace coastal groundwater pumpage with supplement supplies including local surface-water from aquifer storage and recovery (ASR), recycled water and other blend supplies. Thus BMP components are trying to implement local solutions that include capture and reuse of local runoff, recycled water, and transferred groundwater as well as conservation through managed aquifer recharge and reduced demand through additional efficiency or alignment of supply and demand. The analysis of the simulated potential performance of these combined facilities will provide a basis to refine their use and to develop other components to help bring supply and demand back into balance, help restore the depleted aquifers, reduce seawater intrusion, and sustain the water resources needed for agricultural, environmental, and urban supply.

1.1. Pajaro Valley

The Pajaro Valley is located about 129 km (80 miles) south of San Francisco, CA in the central part of coastal Monterey Bay, north of the Monterey Submarine Canyon and Elkhorn Slough (Fig. 1). PVWMA stewards the water resources over an area of about 31,080 ha (120 mi^2), about half of which is farmland that relies almost exclusively on groundwater to supply irrigation water. The valley consists of about 10,927 ha (27,000 acres) irrigated agriculture that yields an annual value of more than $800 million of high value fruit, vegetable row crops, orchards, and vineyards in 2011. (Table 1, PVWMA, 2012). The distribution of water-balance subregions used for the water-availability analysis are a mixture of municipal and agricultural service areas that also separate the regions served by the CDS (Fig. 2A). The distribution of crops from 2009 were used for this analysis and assumed to remain constant over the projection period (fig. 2B). This map shows the wide variety and complexity of crops that have been mapped down onto individual model cells of PVHM that each represents about 6.1 ha (15 acres).

Growth in population and cultivation have increased the demand for available water supplies (groundwater, captured surface water, and recycled water) within the Pajaro Valley (Hanson, 2003a, 2003b). Decades of exploitation of the groundwater resources have resulted in storage depletion (overdraft), increased streamflow infiltration, and seawater intrusion. Seawater intrusion was identified in the late 1940s (CWRCB, 1953) and has continued to jeopardize the use of groundwater in the coastal regions of Pajaro Valley. Because Pajaro Valley is bounded by the San Andreas Fault along the foothills of the Santa Cruz Mountains, large surface-water storage facilities are not feasible (Fig. 1). Although PVWMA had a right to importation of water from the state water project the cost of transmission infrastructure and lack of public support has precluded this option. Thus, PVWMA with the help of local urban and agricultural users has focused on developing local supplies, reuse, replenishment, and conservation through increasing efficiency of use. Increased irrigation efficiency through drip irrigation, night irrigation, and water reuse would increase conservation throughout the valley, but were not evaluated in this analysis.

As a first step toward developing a more comprehensive BMP, PVWMA is providing additional local supplies to replace coastal pumpage, and thereby attempt to limit or reduce seawater intrusion (PVWMA, 2007; Hanson et al., 2008, 2010). The BMP was updated in 2012 with new potential projects to optimize existing facilities and develop new supplies that include a new ASR project utilizing storm water from Watsonville Slough; the reuse of reclaimed water College Lake water with the RWF, a managed aquifer recharge project using Pajaro River water, and development of an irrigation efficiency program. The latter program, for example, could include evaluation of irrigation efficiencies for current practices, recommendations for alternative irrigation methods, or related scheduling practices that maximize use of CDS deliveries. The projects and programs described in the BMP Update will provide a more comprehensive and basin-wide suite of projects and policies to reduce overdraft and seawater intrusion, and promote sustainability.

Mitigating the dependence on groundwater was partially supplemented through the construction of additional infrastructure to help reduce overdraft and seawater intrusion through alternative water supplies that reduce coastal pumpage. The Harkins Slough Project (HSP) includes the first ASR system in the coastal Sunset Dunes region, and is part of a potentially broader managed aquifer recharge and recovery (MARR) program. The HSP-ASR provides a new supply of water for irrigation that diverts local winter

Table 1
Agricultural land use and crop values.[a]

Land Use Type	2009 acres	2011 acres	2012 acres	Dollar[b] value per acre	2012 crop Dollar[b] value
Fallow	2767	2364	2600	–	–
Vegetable row crops (Lettuce, Celery, Zucchini, Artichokes, etc.)	6498	7679	8914	$7690	$68,575,461
Strawberries	7068	9120	7251	$51,058	$370,207,734
Raspberries, Blackberries	3655	4295	4888	$47,166	$230,303,765
Blueberries	NA[c]	39	41	$38,188	$1,566,292
Vines/Grapes	27	147	129	$2495	$321,189
Deciduous (Apple Orchards)	1530	2318	2128	$5282	$11,239,654
Nurseries/Flower/Subtropical Plants	1397	1378	1404	$93,873	$131,789,364
Other	788	918	997	–	–
Unknown agricultural use	4569	6	11	–	–
Total acreage/Dollars	28,299	28,264	28,363	$245,702	$814,003,459

[a] Land use and crop values from Santa Cruz County Agricultural Commissioner 2011 Crop Report (PVWMA, 2012). Although the Pajaro Valley includes portions of both Santa Cruz and Monterey Counties, Santa Cruz County crop values were assumed to be more reflective of the Pajaro Valley since Monterey County crop values may be heavily influenced by the production in the Salinas Valley.
[b] Dollars are in United States Dollars.
[c] Reported acreage was not available.

runoff from Harkins Slough and stores it underground through infiltration in the Sunset Dunes recharge pond where it can be recovered and supplied to coastal agriculture. The CDS system is a 20 mile pipeline network that distributes water from this ASR, as well as inland supplemental City water-supply wells, and the RWF (Fig. 3) to replace coastal groundwater pumpage (Fig. 2). The ASR system was initially implemented in 2002 with the ability to deliver about 1.4 million m^3 (1150 acre-ft) water to farms in the areas subsequently defined as WBS 8, 16, and 17 for the PVHM model (Fig. 2). The water delivered is a mixture of groundwater and local runoff diverted when available from Harkins Slough that is recharged in the first five months of the year at the ASR pond (Fig. 2). The diversion supplied 6.9 million m^3 (5560 ac-ft) of metered water deliveries to the ASR operation between 2002 and 2009 (Fig. 4A) while the ASR recovery wells have supplied about 1.6 million m^3 (1290 ac-ft) of water to the CDS between 2002 and 2009 (Fig. 4A). Thus, not all recharge water is being delivered to the CDS and some local recharge occurred from water not directly recaptured by the ASR operation. In 2007, the CDS was extended to also include some of the agriculture in coastal Monterey County south of the Pajaro River in the Springfield Terrace region (WBS 9) (Fig. 2), bringing the area capable of being served by the CDS to about 7000 acres. Deliveries from supplemental wells and City Blend wells contributed another 6.1 million m^3 (4940 ac-ft) to the CDS. The Recycled Water Facility (RWF) was completed in 2009 and combines treated disinfected, tertiary treated wastewater blended with groundwater supplied by City of Watsonville wells and PVWMA blend wells (Fig. 2). In 2009, the RWF provided 1.7 million m^3 (1340 ac ft) to the CDS. From all of these sources, the CDS delivered from 0.2 million m^3 (167 ac-ft) in 2002 up to 3.0 million m^3 (2406 ac-ft) in 2009 for a total of 9.3 million m^3 (7567 ac-ft) for the initial eight years of operation. The CDS has the potential to deliver up to about 8.8 million m^3 (7150 acre-ft) water per year to most of the coastal farms within the Pajaro Valley given existing facilities, and the design capacity to deliver much more. This could represent up to 15% of the 59.6 million m^3 (48,300 acre-ft) average agricultural pumpage for the period 2004–2009.

1.2. Pajaro Valley hydrologic model

A fully integrated hydrologic model was developed for Pajaro Valley using MF-FMP (Harbaugh, 2005; Schmid, 2004; Schmid et al., 2006; Schmid and Hanson, 2009). The Pajaro Valley Hydrologic Model (PVHM) was calibrated for the period 1963–2009 (Hanson et al., 2008, 2010, 2014). While precipitation supplies some water for agriculture, groundwater pumpage has been the main source of water for irrigation. The number of agricultural wells has grown from just over 100 in 1960s to more than 850 by 2009 which almost doubled the collective pumping capacity of the basin in 46 years. The total number of wells and related pumpage capacity for delivery of groundwater far exceeds the sustainable limits of the resources, with over 2000 wells for domestic, agricultural and drinking water supply (Hanson et al., 2014).

The supply components used to simulate the replacement of coastal pumpage included water delivered by the CDS to four coastal subregions (Fig. 2) from the RWF, HSP-ASR recovery pumpage, potable water from the City of Watsonville distribution system used to blend with the RWF deliveries that help maintain reduced salinities needed for production of fruit and vegetable crops, and supplemental water from PVWMA blend wells. The highest priority delivery is recycled water. The RWF was assumed to deliver its full operational capacity of 4.9 million m^3 (4000 ac-ft) from March through November with no operation between December and February (a period of lower agricultural irrigation demand when maintenance is typically performed). Recycled water is blended with 1.2 million m^3/yr (1000 ac-ft/yr) of potable water from the City of Watsonville's distribution system derived from related inland wells. The next highest priority delivery is the ASR recovery well pumpage of about 0.19 million m^3/yr (150 ac-ft/yr). Additional demand is also met with the limited contribution of a supplemental supply well that is located near the inland part of the CDS of up to about 1.2 million m^3/yr (1000 ac-ft/yr).

The PVHM historical simulation and this base-case projection were developed to analyze the BMP project components as the water supply is partially converted from a predominantly groundwater system to a system that also relies on managed aquifer recharge of captured runoff and on reuse of reclaimed water. The PVHM simulates the diversion, storage, and redistribution of water from water supply sources to multiple farms with a hierarchy of priority of supply sources specified on a monthly basis. The operation of the CDS was simulated as part of the historical simulation with PVHM for the 8-year period 2002–2009 to evaluate the potential effects of conjunctive use in lieu of pumpage for WBS 8, 9, 16, and 17 (Fig. 2A) (Hanson et al., 2008, 2010, 2014).

The simulation of the HSP includes of the diversion of local runoff at Harkins Slough, infiltration at the ASR recharge pond (Sunset Dunes recharge pond), pumpage with the ASR recovery well and two supplemental wells that are each simulated by one-cell WBS's (Fig. 2). Water captured by Harkins Slough is simulated as local runoff from precipitation and irrigation. The MAR system is a form of aquifer-storage-and-recovery system (ASR) that is supplied by the diversion of flow in Harkins Slough to the ASR. When local

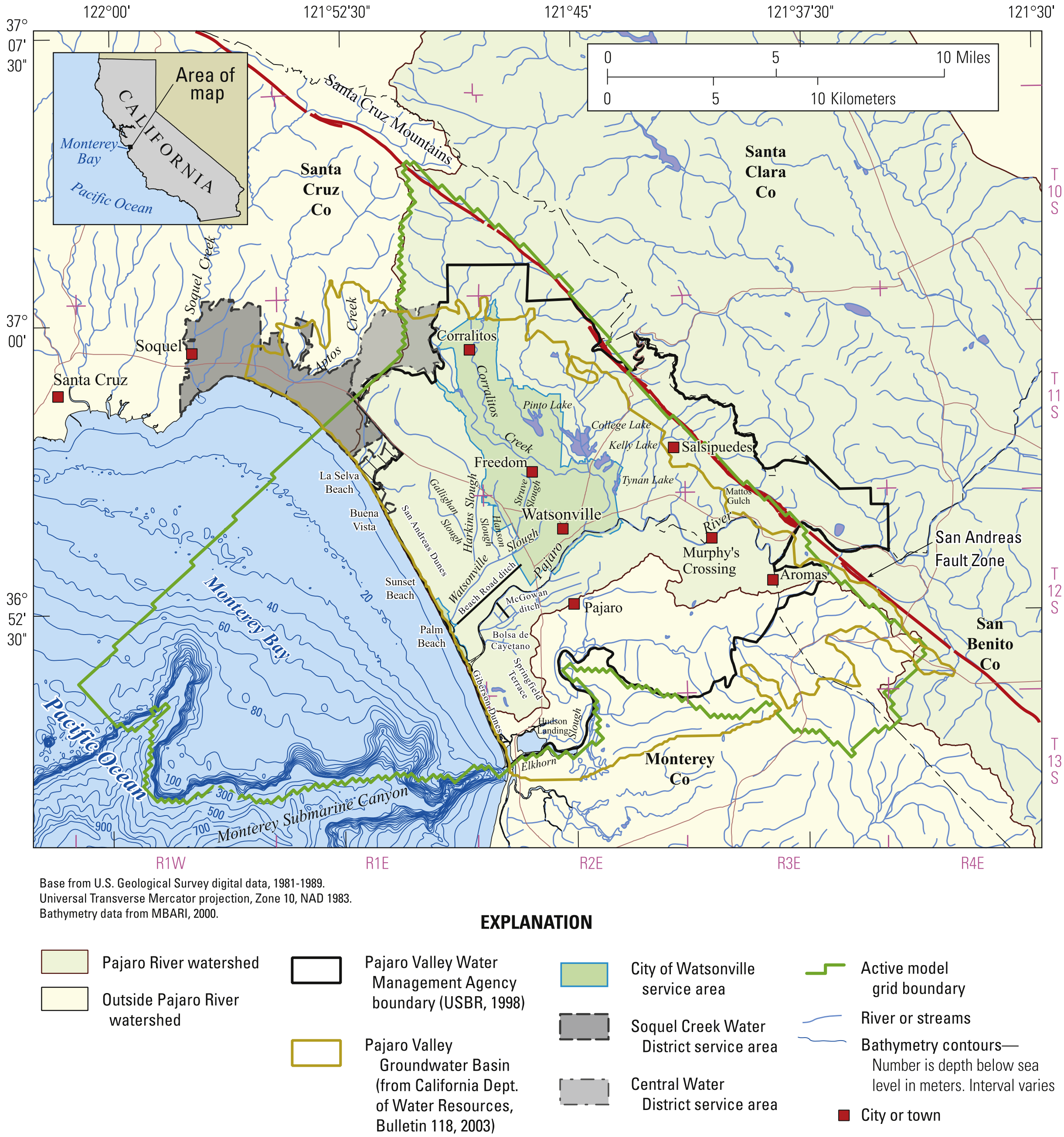

Fig. 1. Map showing Pajaro Valley in Monterey Bay region of California (Hanson et al., 2014).

runoff that collects in the slough is available, it is simulated as a diversion of flow from the Slough using the SFR package linked to FMP within MF-FMP during the months of January through May up to the capacity of the diversion facility. The PVWMA water right allows up to about 2.5 million m^3/yr (2000 ac-ft/yr) to be potentially diverted from Harkins Slough to the Sunset Dunes recharge pond from November through May. However, the diversion of the full water right has not been achieved due to a combination of water availability and water quality limitations on the slough side.

The routed surface-water flows of the Harkins Slough that represent local runoff are diverted at the Harkins Slough Diversion and supplied to the infiltration pond. The simulation of the ASR demand for recharge water is formulated as a percolation requirement. In MF-FMP input, the monthly percolation rate is entered as a water demand for the one-cell ASR pond using virtual crop coefficients that drive the historical distribution of monthly infiltration rates (Schmidt et al., 2009). Infiltration issues (clogging) at the recharge basin has also limited the volume of diverted water. For example, there are dry winter periods such as 2007 or dry springs such as 2003 when runoff is limited or not available for some months of diversions. The water delivered to the ASR is progressively reduced during the recharge months (simulated as January–May) based on measured reduction in the infiltration rates that are aligned with estimated historical infiltration rates (Schmidt et al., 2009). This results in a more realistic representation of recharge and does not allow delivering water to the ASR that cannot be infiltrated. This approach to ASR deliveries constrains the supply of groundwater recharge that is available through the ASR operation. Water from the ASR site is recovered through shallow pumping and delivered through the CDS throughout the year to support multiple cropping periods. The recovery

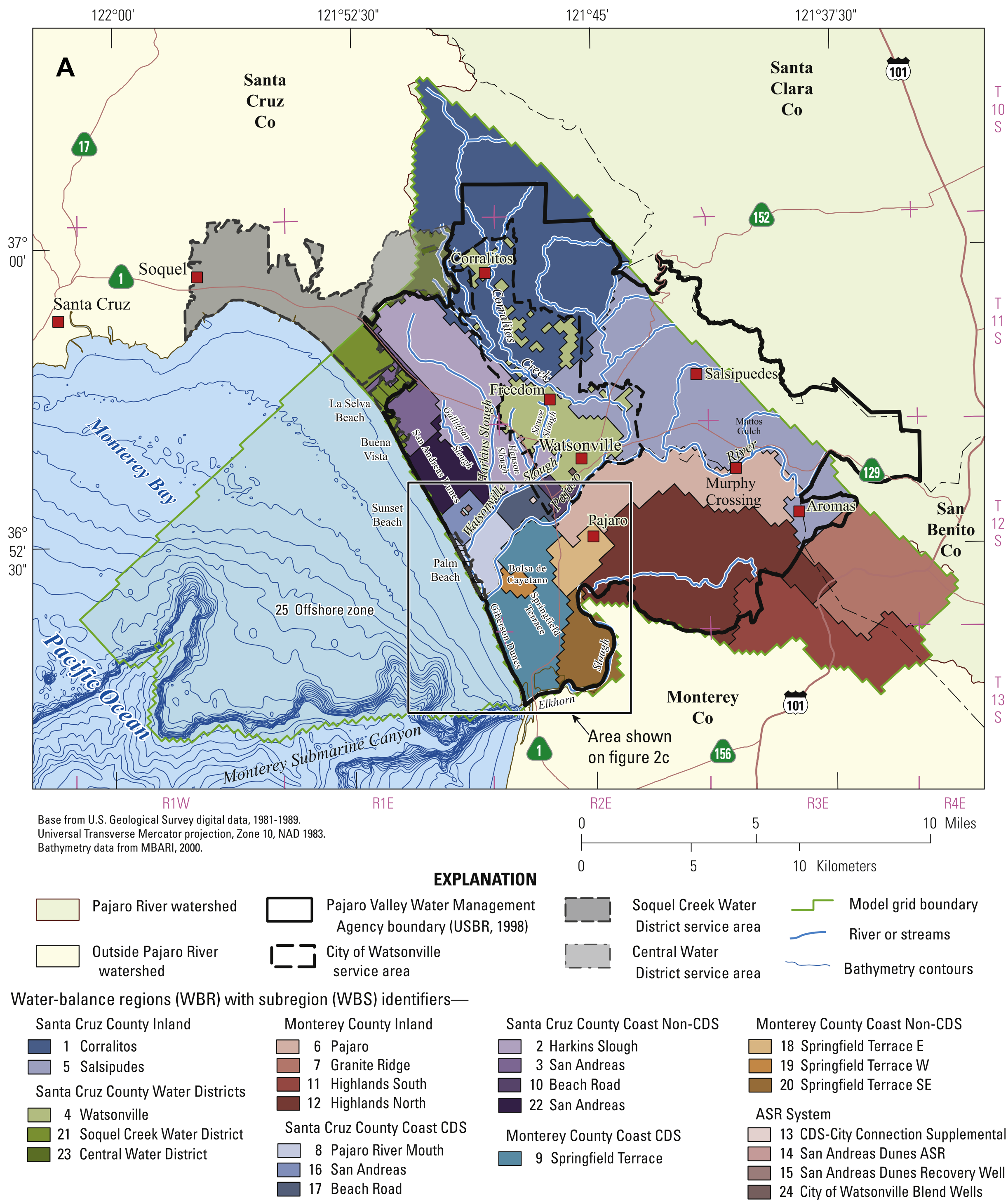

Fig. 2. Maps showing selected (A) Water-balance subregions used to in PVHM to assess conjunctive use, coastal pumpage, and related seawater intrusion, (B) 2009 model equivalent land-use (virtual crop) groups discretized to model grid, and pie chart of percentage of total land use over entire model area , and (C) Close-up view of coastal region with the Coastal Distribution System, ASR, recycled water and supplemental groundwater supplies used to analyze conjunctive use and alternative supplies in Pajaro Valley, California (Hanson et al., 2008, 2010, 2014).

pumpage is further limited by the pumping capacity of the recovery well and a calibrated head limit for the recovery well.

Another source of water is needed to provide deliveries during temporary shortages or periods when the RWF is offline. Since there is no in-line storage in the CDS, shortages in delivery demand are currently addressed by augmenting the RWF and ASR deliveries with pumpage from supplemental blend wells and a connection to the delivery system of the City of Watsonville. Additional demand is ultimately met with pumpage from local coastal wells (Fig. 2B).

The priorities for water delivered to WBSs, from highest to lowest, are (1) ASR, (2) recycled water, (3) remote supplemental wells, and (4) local coastal farm wells (Fig. 3B). With the RWF connected, the CDS now receives the majority of its water from recycled treated wastewater, which is blended with additional groundwater supplied by City of Watsonville wells through a city distribution connection (Figs. 2B and 3A). The crop water demand in the WBSs governs the demand for delivery required from the local supply sources (Fig. 3A, B). The fractions of the total CDS delivery to each

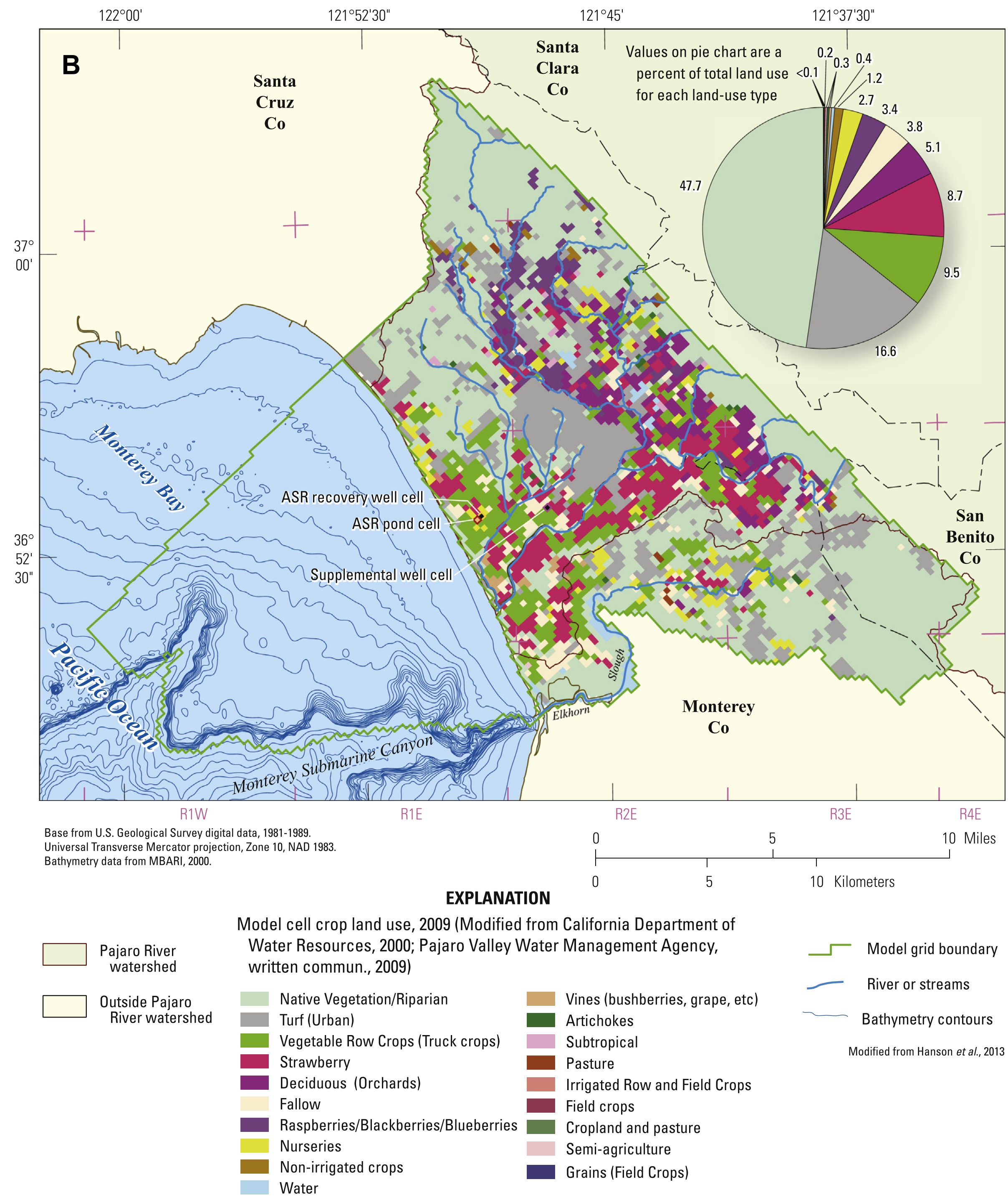

Fig. 2 (*continued*)

of the four WBS subregions are based on the potential delivery capacity of all turnouts within each WBS as a fraction of the of total delivery capacity of all turnouts. The user-specified order of simulated sources for deliveries used with MF-FMP is defined by priorities set by PVWMA. Groundwater pumpage is constrained by the pumping capacity of each CDS supply well (Schmid and Hanson, 2009) and by well-by-well water-level limits defined in the MNW package within MF-FMP (Halford and Hanson, 2002) that were determined during model calibration to historical deliveries (Fig. 4B).

Results from the PVHM historical simulation of conjunctive use (Hanson et al., 2014) demonstrate how MF-FMP can simulate a complex demand-driven and supply-constrained conjunctive-use plan with climatically variable sources, variable priority of sources, and an agricultural demand that can varies on a monthly basis (Fig. 4A and B). However, actual deliveries can also be subject to other factors such as variable pumping rates and hours of delivery operations that may control the reported deliveries along with estimated demand. This is exemplified for the months of August through October, 2004 when the supplemental well deliveries that were simple demand-based deliveries overestimate actual deliveries that were reduced for reasons other than demand (Fig. 4B). In addition, the simulated supply priorities can be changed on a monthly basis, which enables evaluation of different delivery sce-

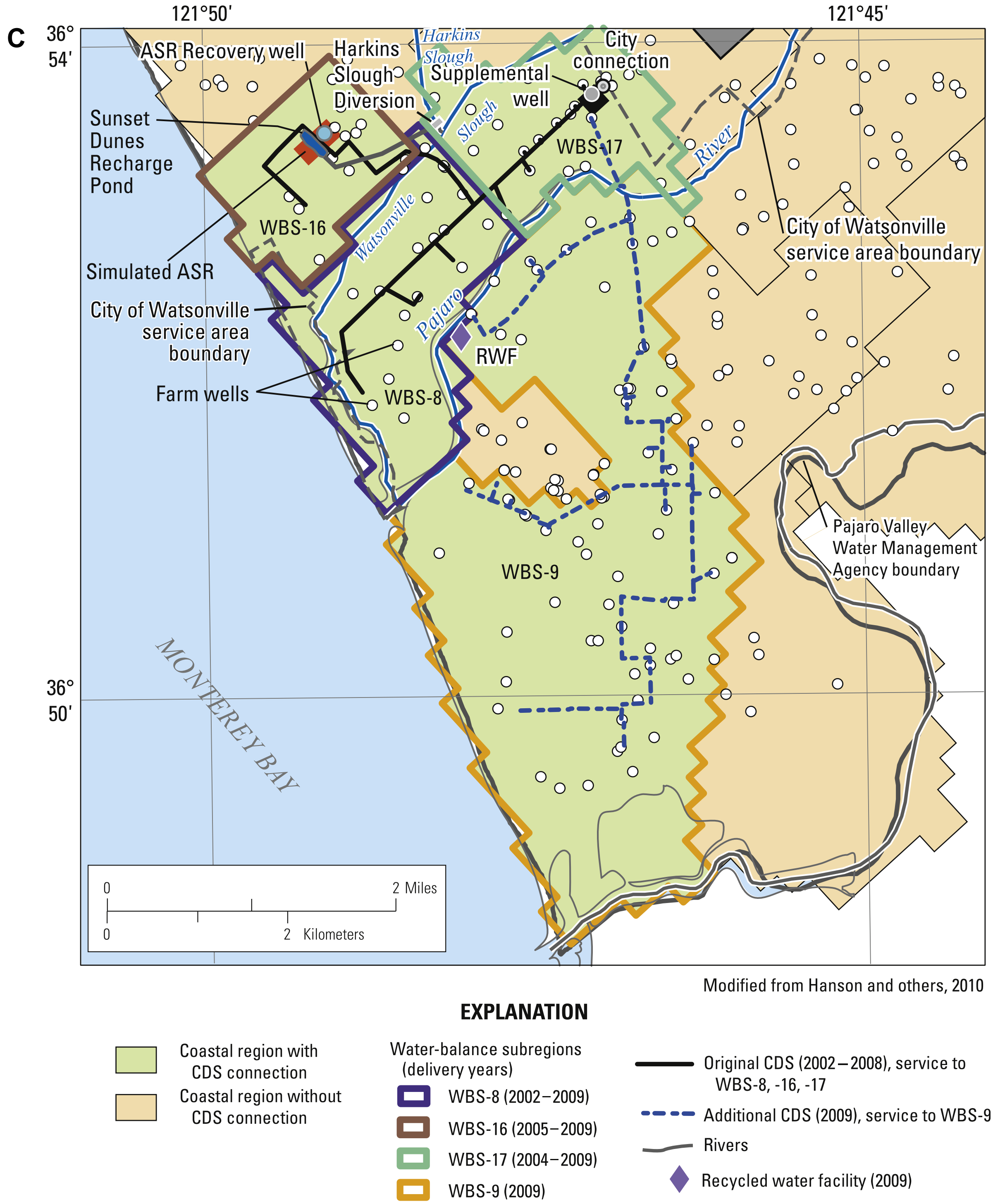

Fig. 2 (*continued*)

narios as was done for this simulation for selected months when the ASR recovery wells were out of service and during the regular maintenance of the RWF that is offline from December through February. On the basis of the initial eight years of operation, the PVHM successfully simulates the delivery components to the four coastal subregions (Fig. 4C).

The PVHM MF-FMP model is used to assess the adequacy of the existing infrastructure BMP projects under different climatic conditions, including wet periods and droughts, and to test the efficacy of CDS deliveries for coastal irrigation. The model will help PVWMA managers assess the effects of additional BMP components to further reduce coastal pumpage and seawater intrusion. Thus the base case provides a framework for systematic analysis and comparison for exploring additional components, climate change, and other supply-and-demand stressors that collectively affect sustainable use of the water resources. The distribution and dynamics of supply and demand would be difficult to analyze without embedding them in an integrated simulation and are difficult to estimate a priori. Without the coupling of the supply and demand components modeling provided by MF-FMP this analysis would be impractical if not impossible. Additional components of surface storage and other MAR projects can easily be added to

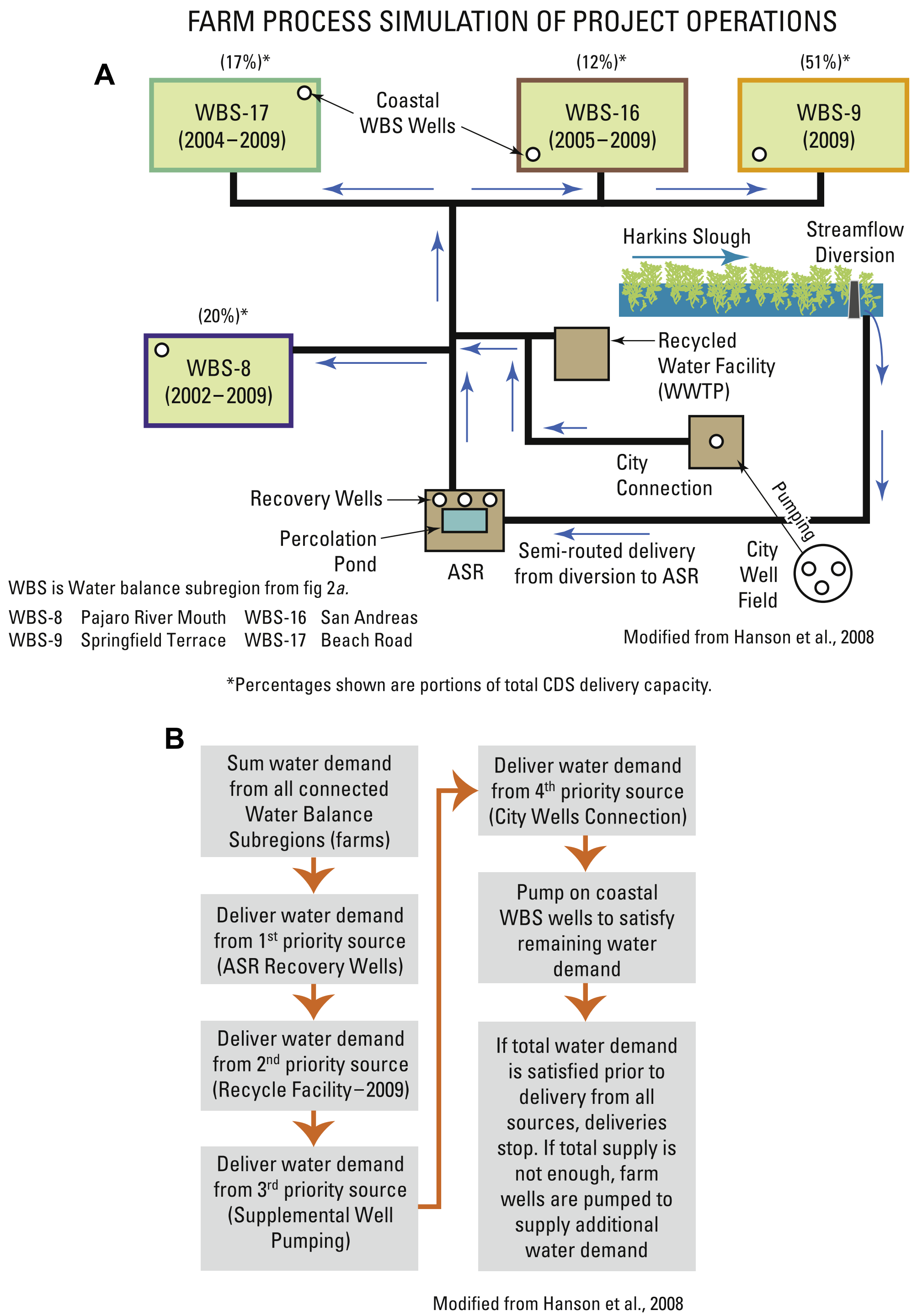

Fig. 3. Diagram showing (A) structure of the local deliveries and (B) the hierarchy of order of operation of the ASR and CDS deliveries as part of the conjunctive use simulated by MODFLOW with the Farm Process within the Pajaro Valley, California (Hanson et al., 2014).

the base-case simulation. For example, simulation of surface storage of additional water as surplus deliveries from the RWF or additional wet-year runoff could be stored in the Slough behind the tidal gates or in the proposed College Lake impoundment as lakes or canals. Additional coastal or inland MAR or ASR sites can be added and tested for their effect on recharge and reduced pumpage. Finally, this framework also provides a vehicle for future optimization analysis with MF-FMP coupled to the Groundwater Management Package (Ahlfeld et al., 2005) to better resolve the proportions and limits of BMP projects that would further refine the feasibility of timing and flow options that also are subject to other environmental, hydrologic, agricultural, or engineering constraints. Optimization analysis of the BMP options will provide a systematic estimate of the optimal allocations for the final suite of BMP projects and policies as well as provide the potential trade-off costs for choices that are less than optimal.

2. Base-case projection

The calibrated PVHM model was used to analyze a base-case projection for a 34-year period beyond 2009 (2010–2044) using

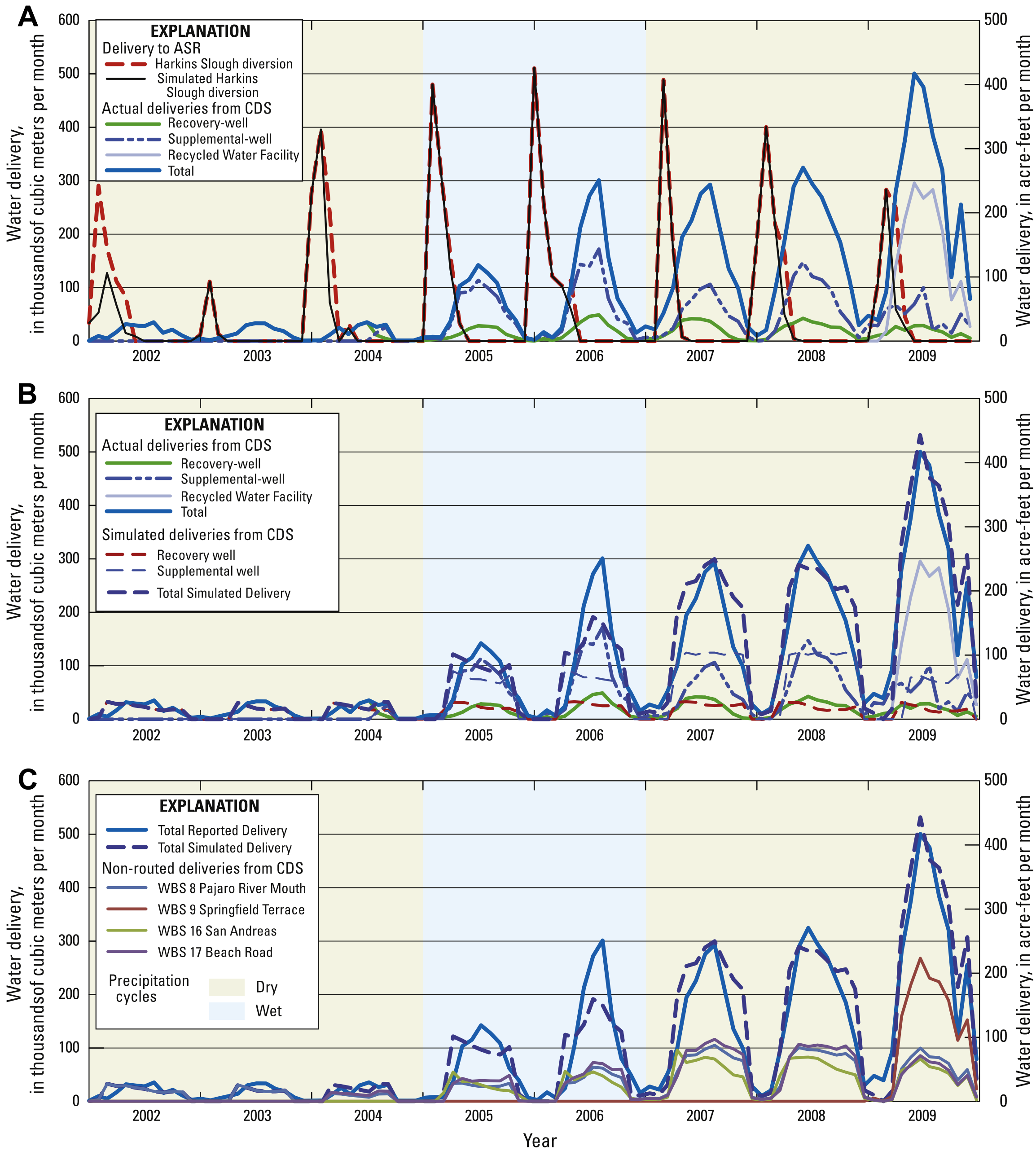

Fig. 4. Graphs showing the historical operation of the ASR components with (A) the capture of local runoff at Harkins Slough, and (B) the multiple farm driven demand for the combined simulation of the aquifer-storage-and-recovery system and Coastal Delivery System as part of the conjunctive use simulated by MODFLOW with the Farm Process within the Pajaro Valley, California (Hanson et al., 2014).

historical climatology, current land use, water-use and water supply infrastructure. The historical climatology represents the use of precipitation, potential evapotranspiration, and streamflow by incrementing the months of the year within decrementing the calendar years from 2009 to 1976 to create a projection from 2010 (2009) to 2043 (1976). This provides the historical climate variability and related wet and dry periods that affect the supply and demand components of water use and movement with the projection ending on the severe drought of 1976–1977. In concert with this historical climate variation, sea-level changes from the San Francisco Tidal gage (NOAA, 2012) were also implemented in the annual order of monthly values for the historical period. While this approach does not include the additional potential effects of climate change and related sea-level rise, the modeling framework is capable of addressing these additional issues in future studies as was done using MF-FMP for the Central Valley (Hanson et al., 2012). The projection assumes that land use and cropping cycles that are used by MF-FMP to simulate agricultural irrigation demand along with climate data were held to the 2009 distributions. This includes the multiple planting and harvesting of selected fruit and vegetable row crops during a single year.

The base-case projection also includes the assumption of no growth in the demand for water supply for urban or rural residential use, which does not represent the small local population growth and related increase in urban water demand. Thus groundwater pumpage from municipal, rural residential, and City of Watsonville wells were assumed to repeat the usage of the months of 2009. Similarly, the diversion of streamflow on Corralitos and Brown's Creeks for City of Watsonville drinking-water supply were assumed to represent the monthly average potential diversions for the historical period of record used for the projection (1976–2009). The potential diversions of 2.5 million m^3/yr (2000 ac-ft/yr) at the base of Harkins Slough that supports the ASR was assumed to represent the full water right the PVWMA can execute for delivery of water to the HSP recharge pond between January and May of each year. Similarly, the northern and southern onshore and offshore boundary heads used to drive the groundwater inflows and outflows along the northern and southern landward boundaries of the model were held to the monthly values of boundary water levels during 2006. These simplifications provide a "base case" scenario that allows for the assessment of the current agricultural demand, effects of new sources of water replacing some coastal pumpage for irrigation, and climate variability over a significant time period that includes major wet periods and droughts that generally cover the last major climate cycle of the Pacific Decadal Oscillation (1977–1999) and several cycles of climate variability that occur at 2 to 19-year periods that are typical for Pajaro Valley (Hanson, 2003b) and other California coastal watersheds (Hanson et al., 2009).

The CDS system was simulated to deliver the maximum potential water based on the production of the various sources and the capacity of the CDS pipeline network. The CDS system is simulated in MF-FMP as nonrouted deliveries with specified demands from the RWF and City connection and demand estimated deliveries for the ASR and supplemental wells. Thus the actual conveyance network of the pipelines is not simulated but instead the water is delivered to meet irrigation demand prior to the estimation of supplemental coastal pumpage if needed. It was assumed that all of this water is delivered even if it exceeds demand. All water from the RWF and City connection were proportionally delivered to the four coastal regions regardless of demand and were supplemented with deliveries of demand driven from the HSP-ASR and supplemental blend well. The HSP diversion was assumed to potentially divert up to the full 2.5 million m^3/yr (2000 ac-ft/yr) but is limited by the current amount of water flowing through Harkins Slough that is available for diversion based on current climate-driven runoff. This represents one aspect of the supply-constrained and demand-driven coupling of MF-FMP. If CDS water delivered is in excess of demand, the water in excess of local demand becomes runoff as semi-routed returnflows to the mouth of the Pajaro River at Monterey Bay that represent some of the outflows from Beach Road and McGowan Ditches and from Watsonville Slough. Thus, the CDS is simulated to deliver about 8.8 million m^3/yr (7150 ac-ft/yr) to partly replace coastal groundwater pumpage for irrigation in four of the eleven coastal subregions (Fig. 2A and B).

3. Results

The supply-and-demand analysis of the base-case projection indicates several important results that characterize the potential performance of the existing BMP infrastructure and potential opportunities. This analysis includes the source and disposition of delivered waters and reductions in coastal pumpage. The potential effects of these projects includes the distribution of coastal groundwater-level recoveries, the nature of reduced seawater intrusion, the sources of water that supply the recovery, and continuation of overdraft conditions that vary with climate. Finally, the analysis includes a summary of excess water deliveries and potential other local sources of water that may be captured, stored, and reused. While model projections are subject to considerable uncertainty in future land and water use and climate, they provide a systematic framework for testing and ultimately optimizing the group of projects and proportions of water that would be needed to curtail overdraft and seawater intrusion, identify the limits of use of groundwater, provide a BMP that promotes sustainable water resources, diversification of sources and replenishment that may even yield some long-term recovery of the aquifers of Pajaro Valley. The analysis of existing infrastructure does not represent a complete analysis of other potential components, changing conditions of use and supply, or optimal distributions of feasible supply and demand that are subject to various constraints. These additional analyses are the subject of ongoing studies by PVWMA and the USGS.

The simulated projected deliveries from the CDS vary from year to year and averaged about 8.1 million m^3/yr (6550 ac-ft/yr) with small increases in demanded deliveries from the ASR and supplemental wells. This simulated increase in pumpage was partly an artifact of recovered groundwater levels rising above the pumping-head limits placed on these wells that allowed more pumpage than occurred historically (2002–2009). The small decrease in CDS deliveries is partly from some direct uptake of groundwater to satisfy ET for crop and natural vegetation that represents an additional 1100 ac-ft. The regions that are located in the coastal region of Monterey County that are not receiving water from the CDS (non-CDS) show a pumpage of 1600 ac-ft/yr that is comparable to the 2004–2009 rate of about 1800 ac-ft/yr and little change in the direct uptake of groundwater for ET. Additional CDS deliveries to these regions could further reduce potential overdraft and seawater intrusion of the coastal regions.

The projected CDS deliveries result in an overall reduction in agricultural pumpage of about 11% and a reduction of 55% for the CDS regions. This is combined with a projected 45% reduction in the average rate of seawater intrusion. However, an analysis of the water budget shows an average deficit (groundwater inflows less outflows) of approximately 12,000 acre-feet per year (Hanson et al., 2014).While the projections indicate that the CDS could deliver between 60% and 120% of the total annual demand of the four coastal subregions served by the CDS, disparities still occur for monthly supply and demand with coastal pumpage still required in all four subregions. Annual CDS deliveries appear to completely replace pumpage (96–100%) for Springfield Terrace (WBS 9), San Andreas (WBS 16), and Beach Road (WBS 17), yet there is still a demand for coastal pumpage that occurs during the peak irrigation months of May through October which is largest during the dry years (Fig. 5A). Thus coastal pumpage still represents about half of the CDS delivery capacity and ranges annually from 29% to 59% (WBS 9), 41% to 63% (WBS16), and 19% to 52% (WBS 17) of the local total farm irrigation delivery requirement (TFDR) of each subregion, respectively (Fig. 5A). Similarly, overall annual deliveries could potentially replace from 59% to 89% of the pumpage for the Pajaro River Mouth (WBS 8) but demand for coastal pumpage still represents 8–40% of the local TFDR that occurs in the peak irrigation months and drier years (Fig. 5A). The mismatch between supply and demand also results in overall annual potential deliveries exceeding demand for Pajaro River Mouth (WBS 8) by up to 43% and exceed annual demand for Beach Road (WBS 17) by up to 10% of the annual deliveries (Fig. 5B) even though there is still monthly requirements for coastal pumpage in these regions.

Modest water-levels recoveries occur throughout the central coastal parts of the valley where the CDS is projected to be in operation (Fig. 6). This is exemplified by some of the projected water levels at wells in the coastal region where water levels start to approach or exceed mean sea level (Fig. 2A). Equivalent freshwater heads for the alluvium and Aromas Aquifers will require water levels a few feet above mean sea level (Hanson, 2003b). Water-level recoveries are probably constrained in the alluvial aquifer by the tile-drain fields in the central coastal regions of Pajaro Valley but projected water level recoveries in the Springfield Terrace region do recover to adequate levels during wet and dry-year periods. Recovery in the central coastal region occurs with less climatic var-

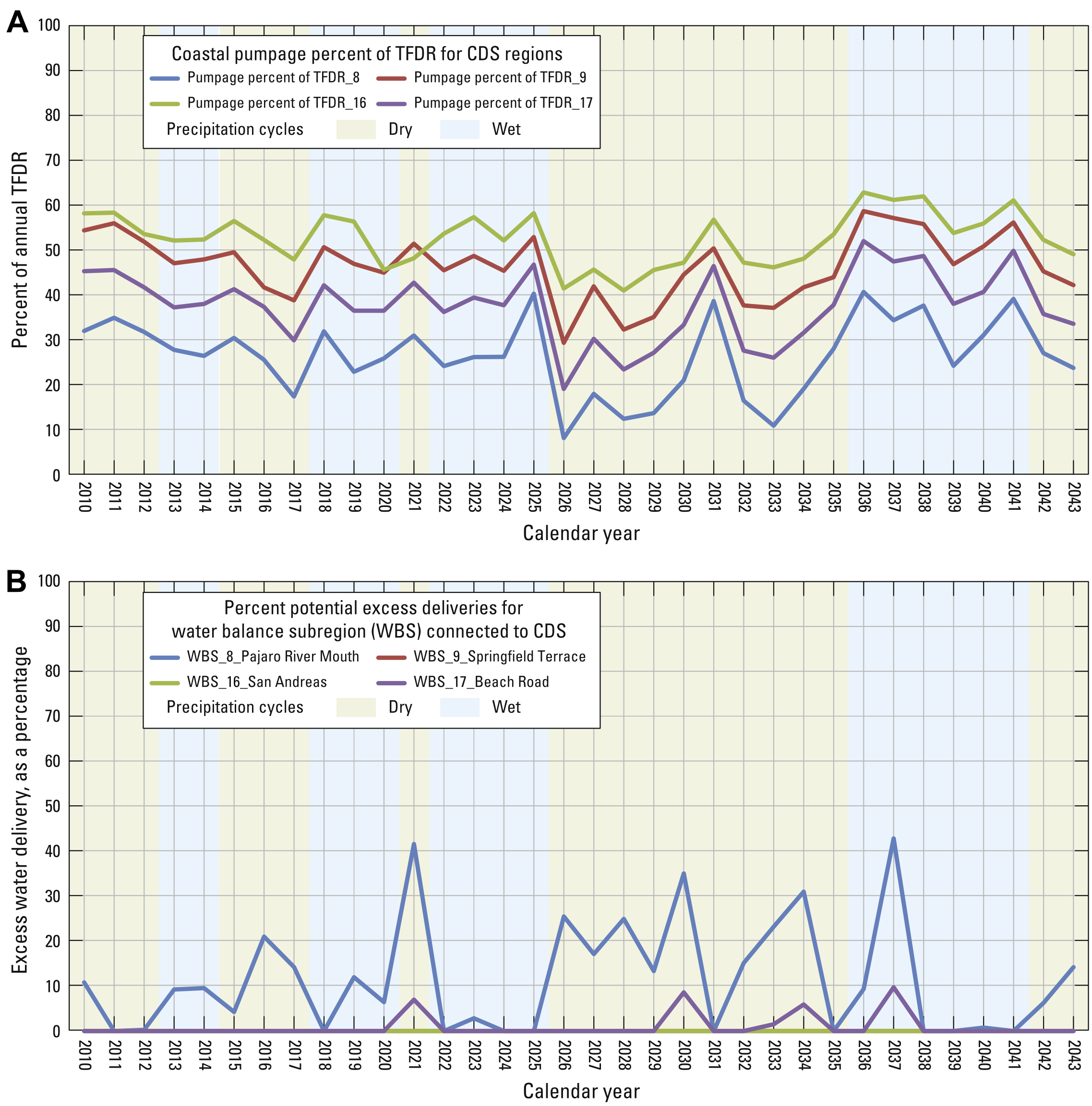

Fig. 5. Graphs showing the (A) percentage of irrigation requirement (TFDR) delivered by CDS, and (B) percentage of water delivered in excess of the irrigation requirement for the coastal subregions served by the CDS in Pajaro Valley, California.

iability but remains below sea level (Fig. 6B). Thus groundwater-level recoveries will be more evident in the Aromas where pumpage reductions are largest and the aquifers are confined and not constrained by tile drain fields. This is exemplified in the central coastal region where recoveries (Fig. 6B) in the Aromas are above the 4 ft of equivalent fresh water head needed to prevent seawater intrusion (Hanson, 2003b). However, in the inland regions where agricultural and municipal pumpage is sustained at historical levels, water levels do not recover or continue to show water-level declines below sea level that are sustaining the long-term regional cone of depression (Fig. 8A) that contributes to seawater intrusion for the entire valley and limits coastal recovery with fresh water (Fig. 6B). This is exemplified by the projection of water levels at municipal wells such as WW-10 (Fig. 6D) and for water levels that are responding to projected the agricultural pumpage in the inland subregions of Corralitos and Salsipuedes (Fig. 6C).

On average, there is a decline in seawater intrusion as coastal inflow but seawater continues to intrude the freshwater aquifers with projected water-level declines below sea level throughout the south-central part of the valley (Fig. 7A). The majority of the coastal region that was identified with seawater intrusion in 2001 (Lear, 2001) is still near or below sea level and below the equivalent freshwater heads needed to prevent landward flow of seawater (Fig. 7A). This is especially apparent during the projection of the drought during the 1980s and the severe 1976–1977 drought at the end of the projection (Figs. 7B and 8). About 55% of the water that is driving the simulated recovery of the four CDS regions from reduced pumpage is flowing in from the ocean-ward side of the four CDS subregions. This is partly the result of the sustained depressed groundwater levels on the landward side of these coastal regions where municipal and inland demands are not curtailed or supplemented. While the relief from some coastal pumpage is significant and helpful, basin overdraft of potable water is still estimated to occur at an average rate of about 12.3 million m^3/yr (10,000 ac-ft/yr) for the entire PVWMA region. This diminished but sustained overdraft is not only driven by cyclic agricultural demand but also by sustained municipal demand inland from the coastal agriculture and further exacerbated by droughts within the climate cycles. The municipal demand tends to sustain regional landward gradients from regional cones of

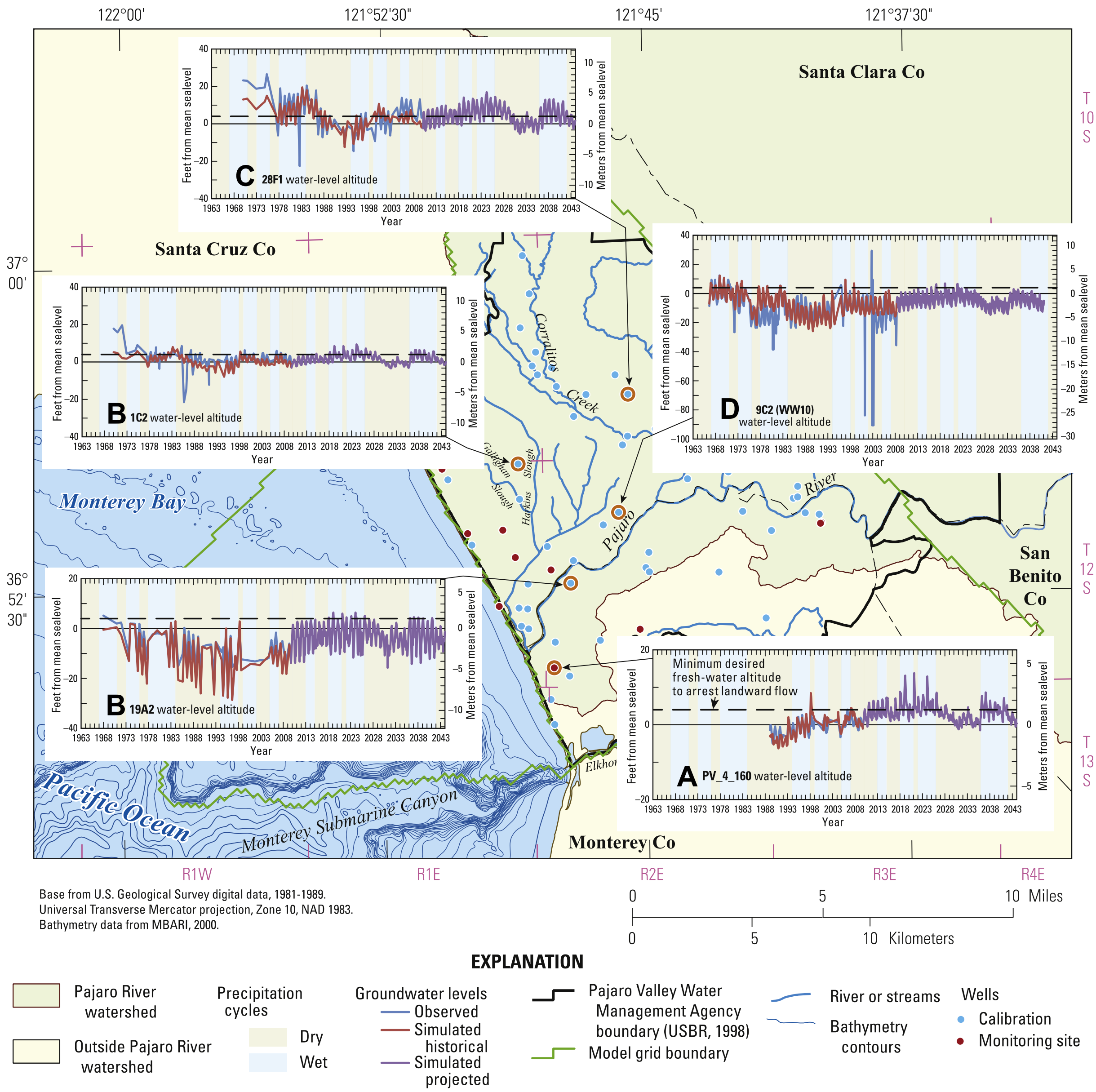

Fig. 6. Graphs of historical and projected future water levels for selected wells in (A) the coastal region where CDS deliveries are occurring, and (B) coastal regions that are not receiving supplemental water from the CDS, (C) inland regions that are subject to agricultural, and (D) inland regions subject to municipal pumpage in Pajaro Valley, California.

depression coincident with municipal wells supplying the City of Watsonville (Figs. 1 and 2). A variety of mitigation measures could help to reduce overdraft including increased irrigation efficiencies, development of additional local sources of water for both agriculture and municipal demand, additional storage to buffer the disparities between climate-driven supply and market/climate driven agricultural demand at annual to multi-year periods, additional coastal and inland ASR sites, and additional managed aquifer recharge that can create additional replenishment and dampen the effects of multi-year droughts. Other sources of water may include projects added to the BMP that could capture additional recharge in coastal and inland regions such as along from the Pajaro River near Murphy Crossing, develop capture, treatment and reuse of inefficient irrigation losses, develop alternate sources of municipal supplies such as more winter streamflow diversions, or find additional uses of treated wastewater for industry and urban landscape irrigation. Managed aquifer recharge could help with a more dispersed and sustained replenishment of groundwater and reduction of the effects of overdraft throughout the basin. While groundwater will remain the predominant source of water for municipal supply and irrigation, extractions from the shallower aquifers that are more connected to recharge and additional managed aquifer recharge will provide a better connection between local runoff and groundwater. Managed aquifer recharge that actually reaches the deeper aquifers may only be possible with surface applications in regions where the alluvial confining layer is absent or through some form of coastal injection in unused irrigation wells.

The simulated demand for irrigation as part of the total CDS deliveries results in some excess water that could become inefficient losses as runoff discharged to Monterey Bay through the Pajaro River, sloughs, and agricultural drains. In addition to these inefficient losses, the water potentially captured by the regions of tile drains represents 53% of the total annual irrigation requirement for the four CDS subregions. These potential tile-drain flows represent water rising from recovered groundwater levels in the alluvial aquifer and from deep percolation of water in excess of

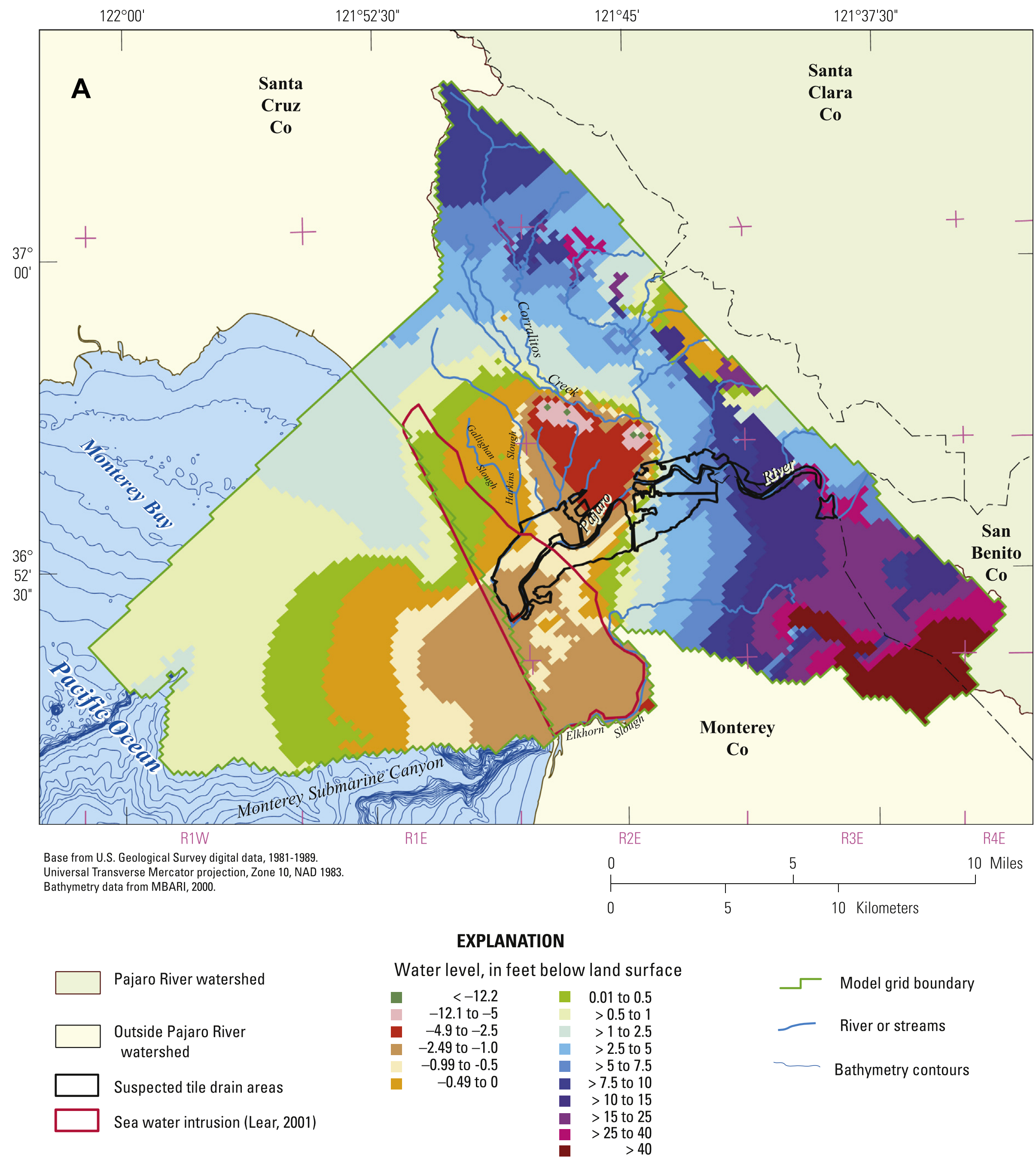

Fig. 7. Maps showing distribution of simulated (A) groundwater levels and (B) change in groundwater levels for the base-case projection to December, 2043 in Pajaro Valley, California.

ET consumption of precipitation and irrigation from irrigation inefficiencies. The collective tile-drain outflows represent between 37% and 305% of the remaining annual pumpage simulated within the CDS subregions and between 18% and 104% of the annual TFDR (Fig. 9A). The total water discharged from the tile drains ranges from 4% to 20% of the annual TFDR for the entire basin. This water averages about 8% of the total agricultural pumpage for 2009 and represents about 70% of the average overdraft for the projection period. Additional distribution, storage, and reuse of these waters to replace the remaining coastal agricultural pumpage indicates that the tile drain returnflows could satisfy from 20% to 62% of the average total annual simulated agricultural pumpage and the additional simulated returnflows could satisfy from 8% to 90% of the agricultural coastal pumpage for the other seven non-CDS coastal subregions. Combined with the inefficient losses these collectively represent between 50% and 350% of the total annual simulated agricultural pumpage of all coastal regions for the projection period (Fig. 9B). Some of these supplementary waters are more available during the droughts because of the additional irrigation and could especially be useful in buffering the effects of increased demand during these periods. These percentages are not exact and do not represent the potential mismatch between monthly supply and demand or the additional infrastructure that would be required for storage and transmission. The percentages of available reusable water also would be reduced because of treatment, blending, and a reduction in amount because they are coupled to the coastal pumpage which could be less if these others waters provide additional irrigation water. However, they clearly

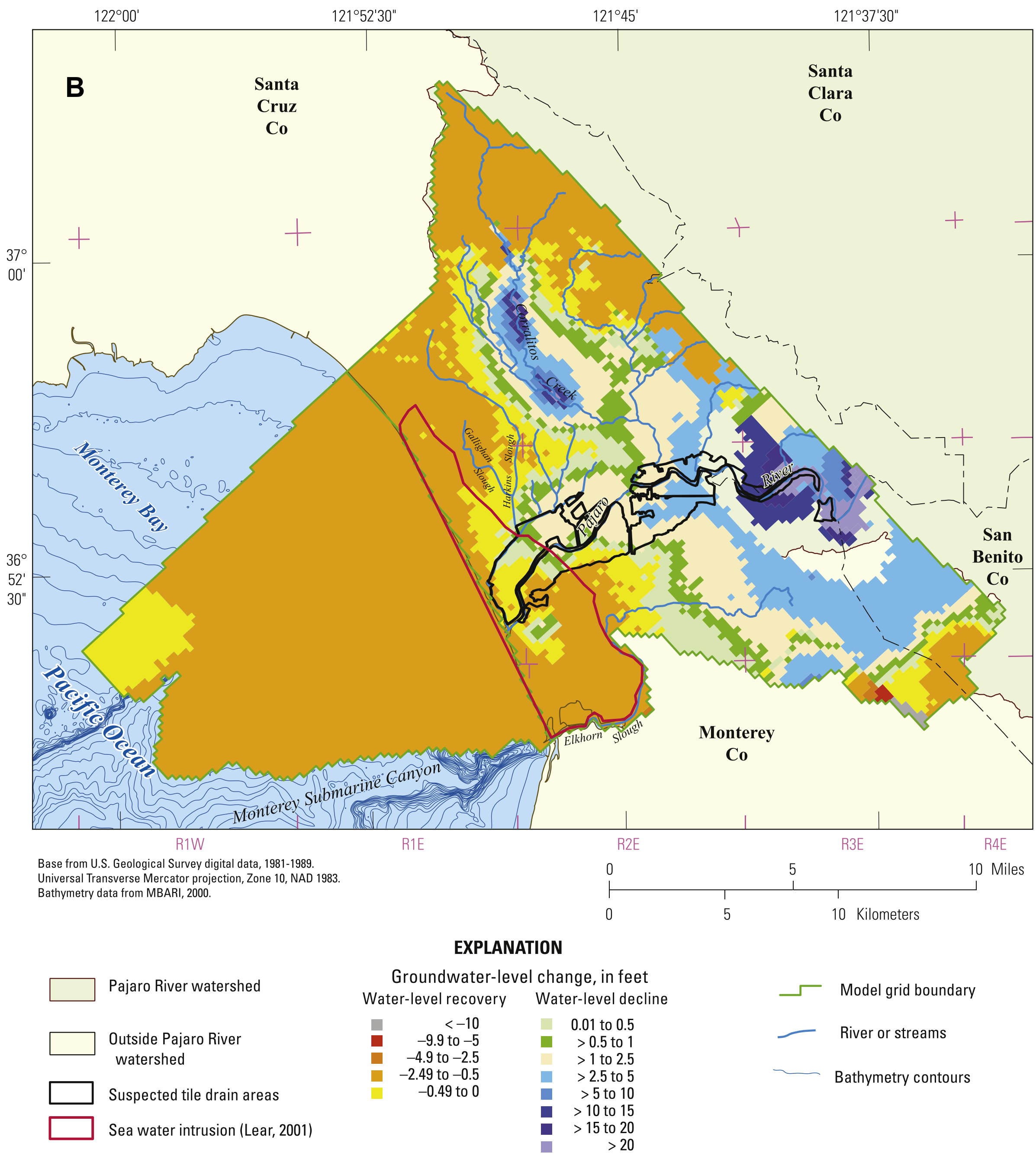

Fig. 7 (*continued*)

indicate that the reuse from these two other sources of water could significantly contribute to reduced groundwater extractions, seawater intrusion, and basin overdraft and they could be another potential BMP component of local alternatives. A more quantified and systematic estimate of their potential contribution coupled to potentially reduced groundwater pumpage and other projects with optimization modeling could be used to assess the final suite of local supply, storage, and replenishment projects being developed by PVWMA for the updated BMP.

Interception, treatment, and reuse of these agricultural return-flow and drain waters also could have other benefits toward the management of the fate and transport of salts and nutrients within Pajaro Valley. These waters contain nutrients such as nitrates, salts, herbicides, and pesticides that are discharged into the National Marine Sanctuary of Monterey Bay at the mouth of the Pajaro River, Watsonville and Harkins Sloughs, and the Beach Road and McGowan Ditches (CRWQCB, 2006, 2011; US_EPA, 2005). Blooms of Pseudo-nitzschia in central California have alternately been linked to river discharge and/or upwelling processes; a recently published model for toxigenic Pseudo-nitzschia blooms in Monterey Bay, CA suggests resolution of these viewpoints through the consideration of seasonality (Lane et al., 2009). The Pajaro River introduces disproportionately large nitrate loads on a highly seasonal basis, and is frequently paired with nitrate contributions to changing regional water quality. Nitrate concentration in the Pajaro River have risen from <0.1 mM in the 1950s to levels that regularly exceed the drinking-water standard of 0.714 mM (Ruehl et al., 2007). This also was confirmed by analysis of nutrients from summer samples of agricultural drain water from the Beach Road Ditch and Watsonville Slough (Hanson et al., 2003a) and more

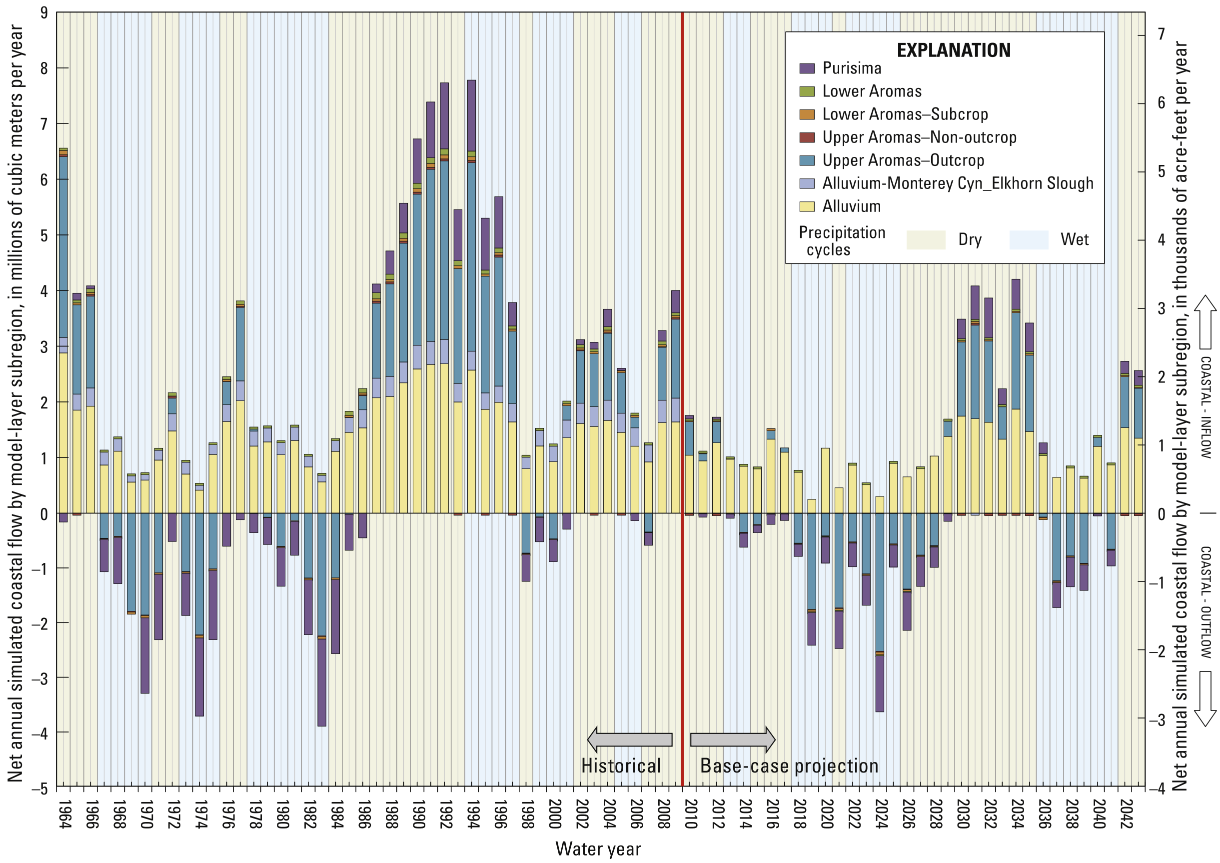

Fig. 8. Graph showing temporal distribution of coastal inflows and outflows for the simulated historical and projected hydrologic conditions in Pajaro Valley, California (modified from Hanson et al., 2014).

recently by the California Regional Water Quality Control Board analysis of impacted reaches of the Pajaro River and agricultural drains such as the Beach Road and McGowan Ditches (CRWQCB, 2006). Thus, capture, treatment, and reuse of these waters could provide an additional source of water for irrigation reuse or artificial recharge, and also could reduce discharges that may contribute to algal blooms that are toxic to the fisheries of Monterey Bay National Marine Sanctuary.

4. Discussion

The Pajaro Valley application demonstrates how MF-FMP can facilitate the simulation of a complex conjunctive-use plan with a climatically variable source, changing sources of alternate water supply, and agricultural demand that varies monthly. Unlike other decoupled and volumetric-based allocation schemes such as WEAP (Sieber and Purkey, 2011), MF-FMP can respond to water-level and rate limited supply-and-demand relations that represent coupled flow-dependent flows. Thus rates and volumes are part of the analysis in a demand-driven and supply-constrained and physically-based modeling framework. This analysis of sustainability and potential recovery of the coastal aquifers is centered on several key questions. What is the percentage of replacement of water from coastal pumpage with deliveries through the CDS for the four regions served by the CDS? Where is coastal recovery occurring and what is providing the water for this groundwater recovery? Is the entire basin recovering and, if not, where are conditions still indicating persistent storage depletion? How large are the additional outflows that occur during the recovery such as additional runoff from tile-drain waters and irrigation runoff or as coastal submarine outflows? The potential percentage of TFDR that is supplanted by surface deliveries is about 56% for the four regions serviced by the CDS. If the other coastal non-CDS regions were included the excess water from recycled water and reuse of drain and runoff waters could potentially reduce the additional average 12.3 million m^3/yr (10,000 ac-ft/yr) of coastal pumpage for the region of known seawater intrusion, which is a potential 27% reduction in the total average groundwater deficit relative to the historical period 1964–2009 (Hanson et al., 2014). However, the recovery of coastal groundwater levels and aquifer storage is driven by additional coastal inflow of saline underflow of seawater with about 55% coastal inflow contributing to the total groundwater inflow into the CDS regions.

Water supplied directly from precipitation, and indirectly from reuse, captured local runoff, and groundwater is necessary but inadequate to satisfy agricultural demand without coastal pumpage and regional storage depletion that sustains seawater intrusion. These facilities reduce potential seawater intrusion by about 45% with groundwater levels in the four regions served by the CDS projected to recover to levels a few feet above sea level. The projected groundwater level recoveries are not high enough to prevent additional seawater intrusion during dry-year periods or in the Aromas aquifers where pumpage is relatively greatest. These results could be further exacerbated if the urban demand for water supply was increasing as was demonstrated within our similar analysis of urban demand and climate change for the Central Valley (Hanson et al., 2012).

Planning for periods longer than the 43-year projection that will be subject to additional demands driven by climate change, sustained urbanization, and expanded agriculture, as well as additional environmental issues that may become important stressors

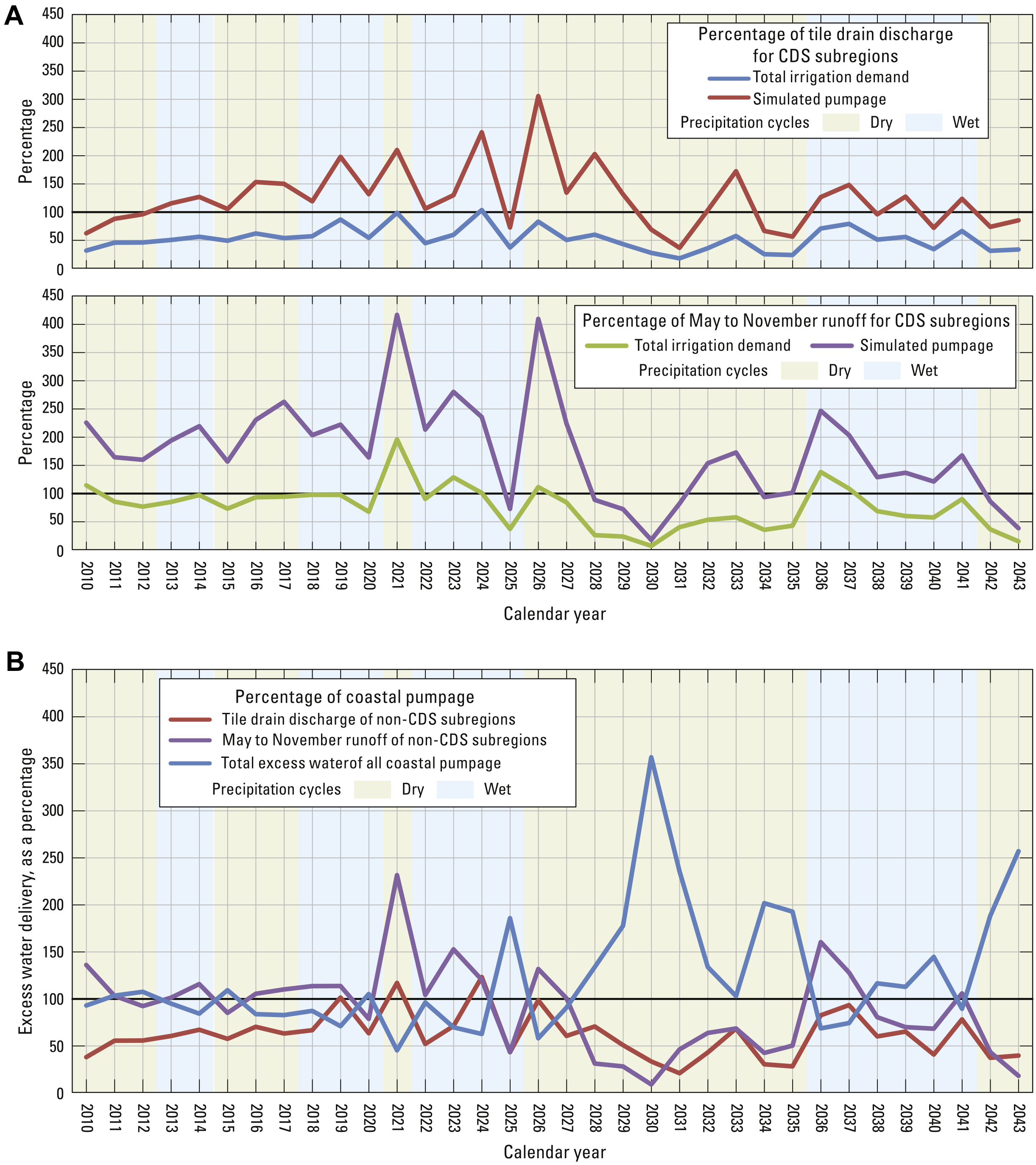

Fig. 9. Graphs showing the percentage of annual irrigation requirement (TFDR) and residual coastal pumpage represented by total surface discharge from tile-drain and May–November CDS region runoff for (A) CDS regions, and (B) for additional non-CDS coastal regions adjacent to CDS regions and total coastal pumpage demand in Pajaro Valley, California.

on supply and demand, respectively. The coastal inflows could be further exacerbated by the potential increase in sea-level rise that would increase the required equivalent freshwater heads on the ocean boundary by as much as an additional meter based on the projections from climate change analysis (Cayan et al., 2008, 2009). These increased sea levels will, in turn, require even higher coastal groundwater levels to help prevent additional seawater intrusion. These higher sea-levels combined with seasonal high tides and storm surges could also promote additional surface inundation of low-lying coastal regions that could even exceed the tidal gates that protect Harkins Slough and other regions that could be used to capture local runoff or store recycled water. Thus some limitations from the uncertainties of future conditions along with uncertainties in crop and land-use properties allow this information to be used in a comparative context relative to other scenarios or different conditions but do not represent a specific future outcome of the movement and use of water.

5. Conclusions

While the simulated facilities demonstrate that they could reduce coastal pumpage, coastal pumpage is still required in all subregions to meet demand. Thus the existing hydrologic infrastructure is necessary but not sufficient to abate overdraft and related seawater intrusion with existing land and water use and historical climate variability. Some of the supplemental water that is delivered in excess of demand may be available for use in adjacent coastal regions that continue to create demands on coastal pumpage. To allow recovery of groundwater levels that will reduce seawater intrusion and basin-wide overdraft alternative local sources and replenishment will need to occur throughout the basin to help reduce municipal and agricultural demand for groundwater. This includes managing inland urban and agricultural supplies and demands that continue to sustain water levels below sea level and, therefore, regional landward gradients that contribute to overdraft and seawater intrusion. In this projection, the recovery of groundwater levels in the coastal regions served by the CDS is actually half supplied by additional seawater intrusion. Water from runoff and tile-drain returnflows is a local source of water that could be captured and reused to offset the imbalance between supply and demand.

A holistic approach to a basin wide set of supply-and-demand components of the new BMP will facilitate more sustainable water resources. While other California coastal regions such as the Los Angeles Basin have implemented expensive barrier injection systems supplied with imported water, these systems still suffer from additional seawater intrusion due, in part, to the sustained inland groundwater demand that make these mitigation projects an inland replenishment system and not a coastal barrier system. This is evidenced in the Los Angeles Basin example by the landward flow of the barrier injection water (Newhouse and Hanson, 2000). Thus, the reduction of demand along with additional reuse and replenishment can help create a more complete solution to sustainable water resources.

The supply-and-demand framework of MF-FMP that is used in PVHM allows for the analysis of coupled flows that would be difficult or impossible to estimate through other means. This analysis was limited to a set of specific conditions that represent an initial base-case and framework for BMP analysis. A broader analysis, additional projects identified through the BMP review process can be combined with these facilities and analyzed collectively with optimization modeling of the projection simulation of PVHM using the Groundwater Management Process (Ahlfeld et al., 2005) with MF-FMP. This type of analysis would include not only other projects, and sources of water, but would also include constraints such as minimal streamflows, coastal water levels, volumes of agricultural extraction, increased irrigation efficiencies, limited increase in urban demand, or selected climate cycles that could be used to better define the feasible range of a more complete ensemble of projects and policies, optimal distribution of these components, and the trade-off costs for demands exceeding supply.

Acknowledgements

The authors would like to acknowledge the reviewers Derek Ryter (USGS) as well as the journal reviews from the anonymous reviewers and Paul Misut of the USGS. The authors would also like to thank Larry Schneider for the illustrations. This work was co-funded by Pajaro Valley Water Management Agency and the U.S. Geological Survey Cooperative Water Program.

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