Title

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Permalink
https://escholarship.org/uc/item/40h334w8

Journal
Journal of Water Resources Planning and Management, 145(12)

ISSN
0733-9496

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Publication Date
2019-12-01

DOI
10.1061/(asce)wr.1943-5452.0001117

Peer reviewed

Case Study

Land-Use Optimization for Sustainable Agricultural Water Management in Pajaro Valley, California

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Abstract: The uncertainty of water resources availability is a growing problem in California as agricultural industrialization, population growth, and climate change affect water resources. The intense manipulation of the hydrological regime has led to the depletion of the water resources in the state and the subsequent use of various adaptive management strategies to cope with environmental conditions and social concerns. The historical imbalance between water pumping and replenishment in Pajaro Valley has led to overdrafted aquifers, seawater intrusion, and salinization. The objective of this study is to estimate the sustainable carrying capacity of agricultural land in Pajaro Valley while preventing groundwater overdraft. A groundwater box model was built and calibrated using historical data to represent current and future hydrology and water management strategies. An optimization model maximized the economic profit using the agricultural acreage as the decision variable with a set of constraints aimed at determining the sustainable carrying capacity of the groundwater basin. Model constraints include total land and water availability, crop acreage, agricultural water use, and historical demand. In the Pajaro Valley, agricultural operations must use less water more efficiently, which means changes in crop types, size of activities, and fallowing land in parts of the basin. Results of the optimal scenario over 25 years show a 15% reduction of total agricultural acreage, 8.5% reduction in food production, average profit loss of 4%, and a 79% reduction in aquifer depletion. This study provides an overall vision of what can be accomplished with coordinated land use planning using strategies that harmonize individual decisions and shared natural resources. **DOI: 10.1061/(ASCE)WR.1943-5452.0001117.** *© 2019 American Society of Civil Engineers.*

Author keywords: Water management; Groundwater; Agriculture; Simulation-optimization model; Aquifer storage; Sustainability.

Introduction

Freshwater scarcity is a global problem with local solutions. The connections between water supply, demand, and quality must be carefully examined at a local scale to understand and respond to water shortages. Balanced solutions that require the cooperation of water managers and users can address deficits that threaten households, major economies, and endangered ecosystems. The culminating effects of global climate change and variability, such as changes in precipitation, drought persistence, and shrinking rivers, impact both surface and groundwater systems (Mani et al. 2016).

Furthermore, population growth, urbanization, economic development, and the industrialization of food production have intensified water management challenges worldwide (Cosgrove and Loucks 2015; Garrote 2017; Hanjra et al. 2012). These challenges are well illustrated in California, where the water landscape has been manipulated to meet human demand; wetlands were drained, land use was modified, rivers were re-engineered, and entire ecosystems were endangered (Watt 2016). The complex network of water reservoirs, aqueducts, and transfers have allowed for the state's expansive growth of the industry, agriculture, and population (Hanak et al. 2011).

California's water demand continues to grow due to the agriculture's expansion and shift from annual to perennial crops, although supply has become less reliable, in quantity and quality, due to climate change, droughts, and environmental demands

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Note. This manuscript was submitted on March 9, 2018; approved on March 19, 2019; published online on September 24, 2019. Discussion period open until February 24, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496.

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J. Water Resour. Plann. Manage., 2019, 145(12): 05019018

(Tamara et al. 2016). At the same time, there is a new focus on the state's natural river systems, and instream flow requirements are being established to protect and restore riparian ecosystems. While less water enters the hydrologic system as snow and precipitation, and a larger amount of water is allocated to environmental flows, irrigated agriculture continues to expand (Jägermeyr et al. 2017). Insufficient surface water supplies have led to the exploitation of groundwater throughout the state to meet urban and agricultural demands (Howitt et al. 2014, 2015; Larsen et al. 2014).

Agriculture is an important economic sector and water user in California. This industry produces half of the nation's fruits and vegetables, including many high-value crops, and accounts for the largest source of freshwater demand (Minor and Bond 2017; Mount et al. 2014). Currently, over 400 crops grow on almost 4 million ha of mostly irrigated cropland (USDA-NASS 2012). This industry was able to flourish in arid parts of the state due to skillfully engineered water transfers from the north and unregulated groundwater pumping statewide (Hanak et al. 2011). Groundwater is valued highly for irrigation because of its superior quality, ease of accessibility, and reliability. However, sustainable and continual reliance on groundwater depends on management activities and local practices (Rudestam et al. 2015). Demand for high-quality groundwater was exacerbated by the most recent multiyear drought that depleted surface water supplies throughout the state.

As farmers in California increase their reliance on groundwater, the natural infiltration of rainfall, streamflow, and percolation of irrigation water can become insufficient to maintain supplies. Furthermore, groundwater basins are being stressed as a result of disproportionate water withdrawal. This ongoing imbalance has severe consequences, namely basin depletion, which can cause loss of storage or seawater intrusion on the coast, both of which produce an unreliable water supply (Hoogesteger and Wester 2015).

The culmination of climate change increased demands, and mostly unregulated groundwater use has led to severe water shortages in California. The state legislature addressed these concerns with the passage of the Sustainable Groundwater Management Act (SGMA) in 2014. SGMA mandates the implementation of sustainable groundwater management plans in critically overdrafted basins by 2020, defined by the California Department of Water Resources (CADWR 2016). Agriculture is a central point of discussion on how to improve groundwater management because of its future hinges on sustainable groundwater management, which requires mitigation of overdraft. Agricultural water management research is necessary to address the needs of current and future farmers and water users.

The goal of this case study is to identify the sustainable carrying capacity of a single groundwater basin in California that maximizes the agricultural profit in the region to address both environmental and social sustainability. For this study, sustainable carrying capacity refers to the land use that will result in the maximum amount of water that can be withdrawn without overdrafting the aquifer. First, a groundwater box model (GBM) was built and calibrated, in comparison to results of the simulation model used by water managers in the Pajaro Valley to represent hydrology, water use, and groundwater storage (Hanson et al. 2014). Second, an optimization model was built to determine crop acreages that maximized agricultural profit given water and land use constraints. Third, results from the optimization model (i.e., crop acreage) were used as inputs into the groundwater box model to calculate the aquifer storage and assess the sustainable carrying capacity of the Pajaro Valley groundwater basin. Even though the location of the case of study is in California, this methodology can be applied to any groundwater-dependent agricultural region. This study shows a practical and innovative approach for the sustainable management of agricultural groundwater basins that emphasizes the interdependence of water and land use planning.

Study Area

Pajaro Valley (Fig. 1) is located within the central coast region of California and comprises southern Santa Cruz, northern Monterey, and a small part of San Benito counties. Watsonville is the principal city where residential, industrial, and commercial land uses predominate. The Pajaro Valley groundwater basin is bounded to the San Andreas Fault to the east and connected to Monterey Bay in the west, covering a surface area of 311 km^2 (120 mi^2) and with a total storage capacity of 9,584 million m^3 (CADWR 2006). The basin recharges through rainfall, irrigation water, and streamflow seepage from Pajaro River and its tributaries, and it includes unconfined and confined aquifers and semiconfined transition zones. This region is an ideal case study location because of its unique and threatened water supply, historical use of water management strategies, and the lucrative agricultural industry. Water supplies for the area include 2,700 groundwater wells, recycled water supplied by the Central Distribution System (CDS) (Fig. 1), and in a small portion, water from Pajaro River. Over 90% of agricultural and municipal water demands are met with groundwater resources because surface water supplies are insufficient and the area is not connected to the federal or state water projects. Reliance on groundwater has repercussions, including the lowering of the groundwater levels that has caused saltwater intrusion from the adjacent Monterey Bay since the 1950s (PVWMA 2014). The Pajaro Valley Water Management Agency (PVWMA) formed in 1984 to manage existing and supplemental water supplies within the basin.

PVWMA has implemented policies and an assortment of strategies to address groundwater overdraft while maintaining agricultural productivity and meeting water demands in the area, which have risen steadily in the past 50 years along with population, agricultural acreage, and groundwater extraction, with pumpage rising from 7.5 million m^3 in 1964 to 13.5 million m^3 in 2009 (Hanson et al. 2014). Agricultural land predominates in the valley and was estimated at 10,000 ha in 2006, compared to 5,000 ha for urban and rural municipalities (PVWMA 2014). Crops include berries, vegetable row crops, grapes, apples, and cut flowers, and production has developed into a multimillion dollar agricultural sector with crop yields valued at over $800 million in 2011, and the region ranks fifth for total agricultural production in California (PVWMA 2014). Large corporations, such as Driscoll's, California Giant, and Martinelli's & Company helped the area to become one of the top-ranked farming cities in the country, and this agroindustrial pressure creates a unique economic environment worth studying, which includes high-value crops, a recycled water system, and an aquifer recharge basin.

Land use distribution in Pajaro Valley has complex and dynamic crop patterns. Although crops shift yearly due to numerous factors such as traditions, preference, economic profit, etc., the total area of agricultural land has remained consistent since 1989 (PVWMA 2014). Agricultural demand for Pajaro Valley was divided into inland and coastal regions. Given the extent of the historic seawater intrusion and coastal access, agricultural demand for Pajaro Valley was divided into inland and coastal regions that are delineated by the CDS and Highway 1 (Fig. 1). This study defined inland crops as strawberries, vegetables (head and leaf lettuce), bush berries (raspberries and blackberries), vine grapes, artichokes, apple trees, cut flowers, and other crops (broccoli, cauliflower, onions, beans, and kale) and coastal crops as strawberries, vegetables, artichokes, cut flowers, and a small number of other crops. These crop assignments

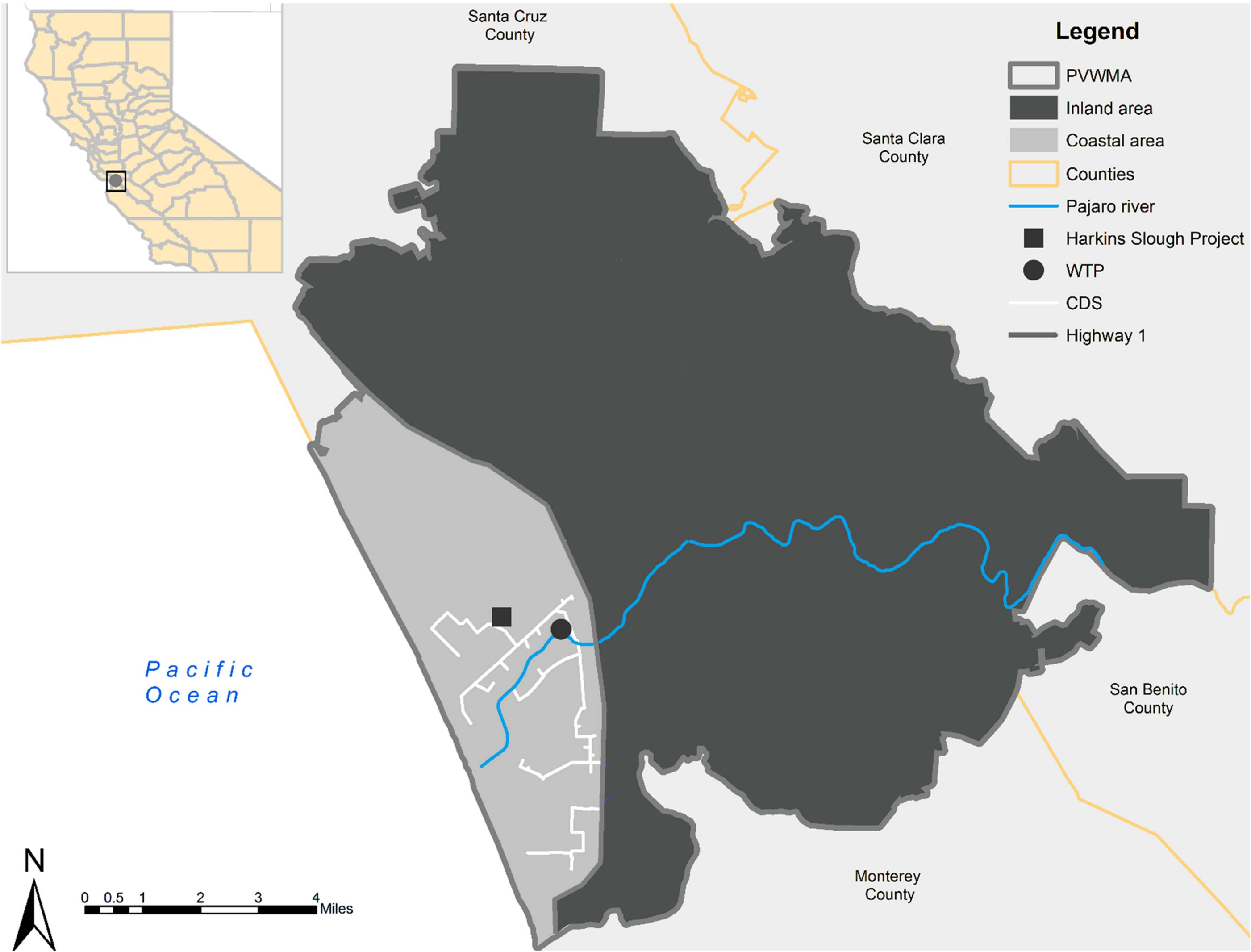

Fig. 1. Extent of Pajaro Valley study area. Main geographic and water management related features: Pajaro River, Harkins Slough Project, water treatment plant (WTP), coastal distribution system (CDS), and Highway 1.

were adapted from the 2012 PVWMA data in the *Basin Management Plan Update* (PVWMA 2014).

Overdraft of the Pajaro Valley groundwater basin has depleted the aquifer storage and led to saltwater intrusion from Monterey Bay into freshwater aquifers, causing water quality degradation and unsustainable storage levels. Seawater intrusion has been observed up to 4.8 km (3 mi) inland and could potentially reach farther if overextractions continue (Martin 2014). PVWMA is executing several measures as part of a Basin Management Plan to address the imbalance of water demands and supplies. The CDS was implemented in 2009 to supply irrigation water to farms in coastal areas with compromised groundwater supplies. Water from the CDS serves in lieu of local groundwater and helps to reduce coastal seawater intrusion by reducing groundwater pumping near the coast through the delivery of a mixture of groundwater from farther inland in the basin, water recovered from a locally managed recharge system, and wastewater from the Watsonville Area Water Recycling Project. This facility and its conveyance system can produce ~4.934 million m^3/year (4,000 acre-ft/year), which includes recycled water, Harkin Slough recovery wells, and blend wells. PVWMA also increased groundwater supplies through the Harkins Slough Project, a managed aquifer recharge and recovery basin. The project aims to replenish a shallow aquifer by infiltrating water diverted from the Harkins Slough in the winter to provide an alternative solution to the overuse of groundwater.

Water demand and supply challenges of this area provide a unique opportunity to develop strategies for improved water allocation and conservation. This study uses the coupling of a simulation and optimization model to provide a unique approach to sustainable groundwater management and could be integrated into future decision-making processes and groundwater sustainability plans.

Methods

A GBM was built and calibrated to represent the water supply, water use, and groundwater storage of Pajaro Valley groundwater basin. An optimization model was built to determine crop acreages that maximize agricultural profit given water availability constraints. The models were coupled to estimate the aquifer storage and assess the sustainable carrying capacity of Pajaro Valley groundwater basin by using the outputs from the optimization model (i.e., crop acreage) as inputs into the groundwater box model.

Groundwater Box Model

A GBM of aquifer storage in Pajaro Valley was built in the water evaluation and planning (WEAP) simulation modeling platform. WEAP is a software tool that operates on the basic principle of a water balance and can be applied to municipal and agricultural systems as an integrated water resources planning system (Yates et al. 2005). The GBM was built with historical agricultural and municipal water use data from 1966 to 2009. The groundwater system was represented with the mass balance equation [Eq. (1)] where ΔS_i was the change in storage; I_i was the inflows; and O_i was the outflows of the system. All variables were set in a yearly basis i

$$\Delta S_i = I_i - O_i \tag{1}$$

Inflows into the model were precipitation and irrigation recharge, which represent the percolation of water into the aquifer after evapotranspiration (ET) was satisfied. Another inflow was recharge from the Harkin Slough project. Outflows of the model were agriculture and municipal water demands, and blend wells for the Watsonville water treatment plant (Fig. S1). Although these are not the only inflows and outflows in the study region, other water sources are omitted for the simplicity of this model (i.e., section hydrologic flow analysis) (Hanson et al. 2014). The construction of the GBM followed the protocols described in Engel et al. (2007): (1) data collection of inflows and outflows; (2) agriculture water use estimation and calibration; and (3) calculation of the mass balance equation and model performance validation.

Data Collection

Data sources for inflows included land use data and Harkin Slough recharge inflows obtained from PVWMA and precipitation and reference evapotranspiration (ET_o) obtained from the California Irrigation Management Information System. An estimate of evapotranspiration (ET_h) was developed based on data from the National Solar Radiation Database and the Hargreaves-Samani equation whenever ET_o data was unavailable (Hargreaves and Allen 2003). Monthly crop coefficients values (k_c) were obtained from Hanson et al. (2014). In this study, the agriculture water demand (AWD_{ij}) was estimated using potential evapotranspiration, which can differ from the actual evapotranspiration. The application efficiency (AE) (a criterion that expresses how well an irrigation system performs during an irrigation event) was assumed to be spatially uniform throughout the valley. The percentage of irrigation use (SU) for gravity, sprinkler, drip, and other methods were obtained from the California Department of Water Resources (DWR 2011) and average application efficiencies (E) were obtained from Sandoval-Solis et al. (2013).

Data sources for outflows include population data for the City of Watsonville, and rural municipalities that were retrieved from the US Census Bureau (2014), and water use per capita (WUPC) for indoor and outdoor consumer water use from 1999 to 2015 was obtained from Cahill et al. (2013). WUPC from 1966 to 1999, was assumed as the fixed value of the 1999 WUPC. Similarly, WUPC from 2016 to 2040 was assumed to be the same value as in the year 2015. Rural WUPC was estimated to be 29% of the City of Watsonville, based on the urban-rural population ratio. The acreage factors and acreage share percentage were obtained from Lin et al. (2013). Well production data for the City of Watsonville, agricultural wells (referred to as PVWMA wells) and recycled water was provided by PVWMA. Linear regression models were used to fill gaps when input data for specific periods were missing. Table S1 shows the model equations.

Agricultural Water Use, Estimation, and Calibration

The agricultural water demand (AWD_{ijk}) was estimated using the equations described in Table S1 and compared to results obtained by Hanson et al. (2014), denoted as PVHM. First, a sensitivity analysis was performed, which revealed that E was the most sensitive parameter because it significantly modified the estimation of the application efficiency (AE_{ik}) that affected AWD_{ijk}. Efficiencies are the most uncertain variables because their values depend on the type of irrigation system, the sagacity of irrigators to operate the irrigation system, and the percentage of use of each irrigation system, which changed through time. Second, the calibration process was performed by adjusting AE values. PVWMA (2015b) provided AE values for each crop in Santa Cruz County for the years 2001 and 2010. The AE values for the year 2001 were used from 1995 to 2005, and the AE values for the year 2010 were used from 2006 to 2015. These values were later adjusted within a range of ±0.14 for both periods. Table 1 shows a comparison of PVWMA (2015b) and the calibrated AE values for each period. Lastly, a comparison of the water demand for agriculture between PVHM and GBM was performed [Fig. 2(a)]. Both models were assessed using the statistical analysis from Moriasi et al. (2007). The goodness of fit criteria used in this study were the coefficient of determination (R^2), index of agreement (d), Nash-Sutcliffe efficiency (NSE), and percent bias ($PBIAS$). The GBM performance was acceptable ($R^2 = 0.907$, $d = 0.892$, $NSE = 0.559$) and very good ($PBIAS = -2.32$) based on the evaluation criteria in the study of da Silva et al. (2015). Also, an invalidation test for predictive models was performed with a null hypothesis of no predictive ability (p-value less than 0.05) rejecting the null hypothesis (Bardsley and Purdie 2007).

Calculation of the Mass Balance Equation and Model Performance

Based on Eq. (1), at a given time, a groundwater basin has a certain amount of water that might increase or decrease based on the change of storage. If the total inflows are greater than the total outflows, the positive change will increase the groundwater storage. Conversely, if the outflows exceed the inflows, then the negative change will result in the decrease in groundwater storage. In this study, net groundwater storage is defined as the average change of storage for a determined period, and the change of storage is calculated every year by subtracting the inflows minus the outflows. GBM inflows ranged from 24.6 to 96.6 million $\mathrm{m^3/year}$, and outflows ranged from 40.7 to 98.6 million $\mathrm{m^3/year}$. In contrast, PVHM inflows ranged from 16 to 103 million $\mathrm{m^3/year}$, and outflows ranged from 30.8 to 90 million $\mathrm{m^3/year}$. Groundwater pumpage is dominated by agricultural use and was 13.5 times greater than urban and rural water demands. Recharge to the aquifer from precipitation is 6.2 times greater than recharge due to excess

Table 1. Application efficiencies of irrigation used to calibrate groundwater box model (GBM)

Crop	Period[a]	PVWMA[b]	Calibrated
Truck crops[c]	A	0.798	0.808
	B	0.755	0.770
Deciduous	A	0.676	0.623
	B	0.772	0.788
Vineyard	A	—	0.817
	B	0.850	0.788

[a] Period A: 1999–2005; and Period B: 2006–2015.

[b] PVWMA values from PVWMA (2015b).

[c] Truck crops are defined by the DWR and PVWMA as strawberries, vegetables, bush berries, artichokes, cut flowers, and other.

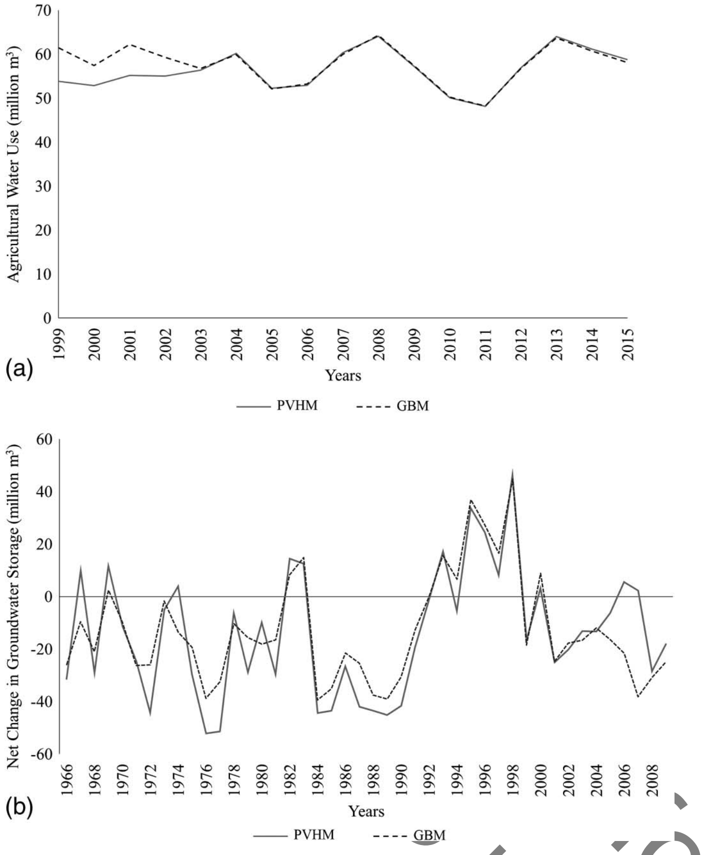

Fig. 2. Comparison between Pajaro Valley hydrologic model (PVHM) from Hansen et al. (2014) and the groundwater box model (GBM): (a) agricultural water demand (million m^3); and (b) net change in groundwater storage (million m^3).

irrigation. Fig. 2(b) shows the net change in groundwater storage of the GBM and PVHM.

The net groundwater storage of GBM was estimated (-14.8 million m^3/year) and compared to PVHM (-15.9 million m^3/year) from 1996 to 2009. Statistical analysis of the GBM parameters was performed ($R^2 = 0.945$, $d = 0.932$, $NSE = 0.699$, and $PBIAS = 5.4$) and the statistical criterion for NSE and $PBIAS$ showed good and very good performance, respectively (da Silva et al. 2015). These results validated the further use of the GBM and its inputs.

Optimization Model

The optimization problem under consideration was to identify the optimal annual land use by using limited water resources to grow eight types of crops in two irrigation regions, coastal and inland, to maximize agricultural benefit. Eq. (2) shows the objective function of the optimization problem

$$\text{Max } F = \sum_{i=1}^{8}[B_i^n A_i^n - (A_i^n \times AWD_i)CW_i] + \sum_{c=1}^{5}[B_c^n A_c^n - (A_c^n \times AWD_c)CW_c] \tag{2}$$

where B_i^n and A_i^n represent the benefit and allocated acreage of crop i (inland) in year n, respectively; AWD_i = agricultural water demand per inland crop; CW_{in} = cost of water for inland users; B_c^n and A_c^n represent the benefit and allocated acreage of crop c (coastal) in year n, respectively; AWD_c = agricultural water demand per coastal crop; and CW_c = cost of water for coastal areas. The first term of Eq. (2) captures the net benefit of inland agriculture, while the latter represents the net benefit of coastal agriculture.

Equations defined the optimization model in a linear programming procedure and were solved by the interior point method provided in the optimization toolbox of MATLAB (Fig. S2). Table S2 lists supportive equations, and Fig. S2 shows the conceptual optimization model. The constraints for the objective function were as follows:

- Minimum and maximum acreage: The acreage of each crop should be greater than or equal to the minimum historical value and less than or equal to the maximum historical acreage.
- Land availability: There are limitations on total available inland and coastal cultivable fields.
- Available water: The maximum amount of water that can be withdrawn from the groundwater basin was a time series constraint based on results from Hanson et al. (2014).
- Demand constraint: Based on historical data, the acreage of vegetables was constrained to be 40% greater than the acreage of strawberries.

Economic Inputs

The optimization model was built to estimate a series of optimal acreages that maximize economic profits. Profits were estimated as yearly benefits ($B_{i/c}^n$), which were the difference between crop revenue and the costs of production (COP) for that crop. All prices were adjusted using the consumer price index for 2015.

Crop revenues were calculated based on crop incomes from crop reports and economic contributions of Monterey County from 1966 to 2014 and the annual crop and livestock reports of Santa Cruz County base. COP components of the model were obtained from budgets published through current cost and return studies from the University of California Cooperative Extension (UCCE). These budgets were used to determine annual costs per acre for each crop including operational, cultural, and overhead costs that covered land preparation, plant establishment, fertilization, pest management, harvest, labor, equipment costs, property taxes, irrigation, sanitation, and management salaries. The price of water was removed from each budget because it was included separately in the optimization equation for specific circumstances in Pajaro Valley.

COP budgets for crops grown in the California central coast region were used for strawberries, vegetables, bush berries, artichokes, and apple trees, while the COP budget for grapes grown in the upper San Joaquin Valley was used for vinegrapes. The UCCE has not published a COP budget for cut flowers in California; therefore estimates were made based on COP budgets developed by the Cooperative Extension at Penn State University. Based on budget availability, each crop was treated slightly differently. The COP for strawberries was found by taking the average of two budgets, one for each year of production (Bolda et al. 2010, 2011). The COP for vegetables was determined based on budgets for various types of lettuce grown in this region because lettuce is commonly used in rotation with strawberries (Smith et al. 2009; Tourte et al. 2015). The COP for bush berries was calculated through consideration of the budgets for raspberries and blackberries, including an establishment year, the first year of reduced production, and four subsequent years of steady production (Bolda et al. 2012, 2013). The COP for artichokes was based on a single production year (Meister 2004). The COPs for apples and vinegrapes were based on a 25-year life of an apple orchard and vineyard, respectively (Klonsky and Stewart 2014; Verdegaal et al. 2012). The first year of establishment for

Table 2. Cost of production and revenue figures for the optimization model by crop type

Crop	COP per acre ($)	Income per acre ($)
Strawberries	46,270	69,351
Vegetables	7,425	31,404
Bushberries	34,723	59,823
Vinegrapes	5,652	4,535
Artichokes	5,558	9,235
Apples	3,838	5,796
Cut flowers	93,079	186,790
Other	11,439	26,509

Note: Figures adjusted to 2015 US dollars based on the consumer price index from the Bureau of Labor Statistics (2015).

vineyards is the most expensive, with subsequent years costing one-third of the initial price. The COP of the other crop group was based on the budgets of alfalfa, wheat, and beans (Long et al. 2014; Putnam et al. 2014; Wright et al. 2013).

Table 2 shows the COP budgets and revenue figures. All crops show economic benefit except for vinegrapes, for which revenue remains below the break-even point. From the year 2000 to 2010 vinegrapes had economic benefits, but not from 2010 to 2015 where COP exceeded revenues. Vinegrapes have become less economically viable in recent years because of inexpensive imports from Australia, competition from corporate farms in other regions of California, and the fact that harvest standards often change in harvest time, hang time, and Brix standards (Cline 2011).

The cost of water (*CW*) in Pajaro Valley was defined by the price of water and the energetic cost for pumping. Annual rates published by the City of Watsonville and PVWMA set water prices, which differ based on user location (growers outside or inside the metered area) and water source (growers who receive delivered water, urban users, and residential users). Water prices ranged from \$101 to \$338 per acre-ft and increased with an average yearly rate from 3% to 9.5% (Table 3). The energetic cost of pumping was estimated to range from \$0.18 to \$0.20 kWh for an average well depth of ~90 m (297 ft) for domestic wells, and ~131 m (431 ft) for municipal wells (Sandoval-Solis et al. 2015).

Coupling of Models

The model coupling component of this study aimed to integrate optimal crop acreage into the GBM. The GBM was evaluated from 2016 to 2040 under two future scenarios: baseline and optimized. Each scenario started with an initially available water supply of 64.1 million $\mathrm{m}^3/\mathrm{year}$. The baseline scenario follows the business-as-usual trend and shows a future projection without any additional water or land use management. The optimized scenario included optimized crop acreages as inputs to represent a sustainable groundwater management approach. For the optimized scenario, available water was restricted to 4.9 million $\mathrm{m}^3/\mathrm{year}$ less every 5 years starting in 2016 until reaching a minimum of 49.3 million $\mathrm{m}^3/\mathrm{year}$ by 2030, which was maintained until 2040. The total decrease in available water matched the overdraft estimation by Hanson et al. (2014) of 14.8 million $\mathrm{m}^3/\mathrm{year}$, which is the rationale for the available water constraint. In the GBM, historical climate data (1966–2015) repeats after year-2015. Fifty 25-year sequences of historical climate input data were defined (1966–1990, 1967–1991, …, 2016–2040) and evaluated for each scenario to capture the climate variability and seasonality of the system. The total processing time was 30 min.

Table 3. Costs per acre-ft of water service rates

Year	Urban residential	Rural residential	Delivered water	Coastal irrigation	Inland irrigation
2015	\$179	\$101	\$338	\$215	\$179
2016	\$191	\$92	\$348	\$235	\$191
2017	\$203	\$97	\$359	\$258	\$203
2018	\$217	\$103	\$369	\$282	\$217
2019	\$231	\$109	\$380	\$309	\$231
2020	\$246	\$115	\$395	\$338	\$246
Average increase (%)	6.6	6.0	3.0	9.5	9.5

Source: Data from PVWMA (2015a).

Results and Discussion

Crop Pattern, Economic, and Food Production

The coupled model determined the optimal crop pattern by maximizing net economic benefits while constraining agricultural water and land use, which decreased groundwater overdraft. Both scenarios began in the year 2000 with approximately ~8,000 ha (20,000 acres) and 62.5 million $\mathrm{m}^3/\mathrm{year}$ of water use. For the next 15 years, the trend increased to ~8,500 ha (21,000 acres) and 64.1 million $\mathrm{m}^3/\mathrm{year}$ for the baseline scenario and these values were maintained until 2040. The optimized scenario decreased water use to 49.3 million $\mathrm{m}^3/\mathrm{year}$ for ~6,315 ha (15,606 acres). The crop acreages that gained the most economic revenue and water use were bush berries, cut flowers, strawberries, and vegetables. These crops were allocated within their maximum allowable acres. The lowest crop revenues were for apple trees, vinegrapes, artichokes, and others, reflecting their minimized acreages. The optimal land use had a total acreage reduction of 15%.

The objective function was to maximize the net revenue from agricultural production while determining the optimal crop pattern for the available water. A similar objective function is observed in other studies. Mainuddin et al. (1997) determined the irrigation plan by optimal crop area allocation and groundwater requirement by maximizing the net economic benefit in Thailand. Benli and Kodal (2003) developed a linear model that allocates optimally available resources, rearranges crop patterns, and maximize economic crop revenue. These studies showed a decrease in available water corresponded to the upper limits of acreages of higher values crops, which is consistent with the finding from this study that crop acreages increase or decrease relative to the change in their economic profit.

Regarding economic benefit, the baseline scenario showed total revenue of \$274 million, which increased to \$289 million in the optimized scenario using the same allotment of water (64.1 million $\mathrm{m}^3/\mathrm{year}$). The net difference between the optimized and baseline scenario is shown in Table 4, where the pattern of higher revenue for the optimized scenario is observed even when the available water was reduced to 60 million m^3. However, if available water is reduced to 50 million m^3, revenue is reduced to ~\$239 million. In general, annual revenue decreased by 2.4% on average, which translates to ~\$5 million loss per reduction of 1.2 million m^3 (1,000 acre-ft) of available water.

Food production, defined as the total yield of crops measured in tons, started at 3.4 million tons in 2000 for both scenarios, decreased to 1.9 million tons in 2009, and then increased to 2.9 million tons in 2015. For the future projections, from 2016 to 2020, the optimized scenario delivered more food than the baseline given the available land, but the baseline scenario showed steadily higher

Table 4. Economic results from the groundwater box model (GBM) scenarios

Agriculture water use (million m^3)	Optimized—Baseline revenue ($ million)
64	$15.4
62	$10.5
61	$5.7
60	$0.8
58	−$4.1
57	−$9.1
56	−$14.1
54	−$19.1
53	−$24.2
51	−$29.3
50	−$34.4

amounts of food production from 2022 to 2040 due to the fixed acreages and available water in that scenario. Food production decreased 8.5% (428,000 t) under the optimization scenario.

Groundwater Projections

Groundwater has been overdrafted in Pajaro Valley for decades (Muir 1972; California State Water Resources Board 1953). The modeling results from this study illustrate aquifer depletion, where 49 years of historical annual time series of inflows (precipitation and irrigation recharge) and outflows (agricultural, urban/rural, and supplementary water demands) are estimated through a GBM and compared to PVHM (i.e., section hydrologic flow analysis) (Hanson et al. 2014). GBM results show an estimated annual average overdraft of -14.8 million m^3/year from 1966 to 2009, close to the PVHM result of -15.9 million m^3/year. Comparing the simulation models of GBM and PVHM has its limitations. GBM does not include certain inflows [landward underflow and streamflow infiltration, subtotal 17,930 thousands acre-ft (TAF)/year (22116.330 million m^3/year) on average] and outflows [storage flow depletion, storage depletion masked by seawater intrusion, outflows to the bay and tile drains, subtotal 18,910 TAF/year (23325.142 million m^3/year) on average], which approximately cancel each other out. While these components contribute to the hydrology of the basin, GBM omits these components for simplification, and it represents a limitation of the model.

The GBM was evaluated from 2016 to 2040 under two scenarios to estimate the average net groundwater storage of the area (Fig. 3). Both scenarios (baseline and optimized) began with an overall depletion of -57 million m^3/year in 2015. This significant depletion of groundwater is related to the most recent multiyear drought in California that began in 2012, which exacerbated the exploitation of groundwater resources because of the lack of groundwater regulations and policies in California before the passage of SGMA.

Both projections display similar behavior; however, the optimized scenario shows overall less groundwater depletion for the Pajaro Valley groundwater basin. The optimized scenario projects 10 years where the aquifer storage is zero or positive from 2020 to 2033. Both projections show the greatest depletion in 2040, with aquifer storage levels of -83 million m^3/year and -48 million m^3/year for the baseline and optimized scenarios, respectively. This trend is caused by the drought years of the hydrologic period used for future projections. The highest storage point is 2 million m^3 in 2033 and 35 million m^3 in 2023 on the baseline and optimization scenarios, respectively.

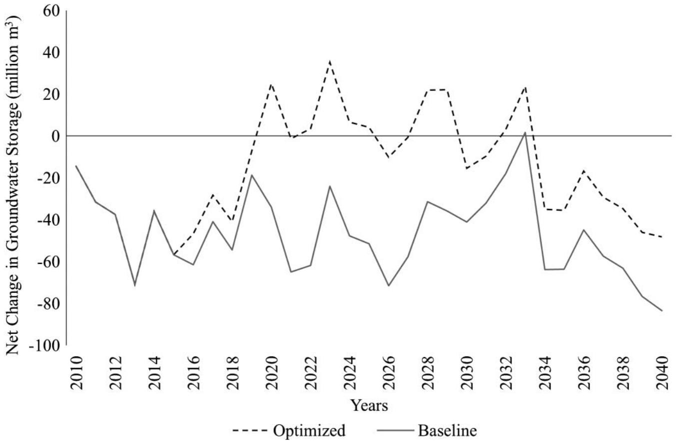

Fig. 3. Comparison of the net change in groundwater storage (million m^3) between the baseline and optimized scenarios of the groundwater box model (GBM).

Overall, the GBM projections from 2016 to 2040 showed an average net groundwater depletion of -48 million m^3/year for the baseline scenario in contrast with -10 million m^3/year for the optimized scenario. This illustrates the possibility of a 79% increase in net groundwater storage from 2016 to 2040. Focusing on a shorter period from 2016 to 2030, the difference between projections is even greater with -47 million m^3/year for the baseline scenario and -5 million m^3/year for the optimization scenario, which is an 89% increase in net groundwater storage from 2016 to 2030. A single factor ANOVA evaluation (p-value of 5.2×10^{-6}) indicated a significant difference in the net groundwater storage between scenarios. These findings support part of the study goal, which was that constraining agricultural water use can result in less groundwater overdraft.

These results illustrate that groundwater simulation models can estimate future trends in groundwater depletion, consistent with previous studies in other agricultural and groundwater-dependent areas of California, while also validating the innovate application of optimization models to explore ecological and sustainable solutions to groundwater and land management challenges (Harou and Lund 2008; Karterakis et al. 2007; Yang et al. 2006). There are opportunities to improve water management in Pajaro Valley to reduce aquifer depletion and prioritize a reliable supply of freshwater for population demands and agriculture activities if farmers are incentivized to making collective decisions to optimize profits while managing groundwater sustainably.

Conclusion

Sustainable water management in human-dominated systems is a complicated process. Pajaro Valley is in an agriculturally developed area with extensive groundwater use, where basin overdraft has threatened freshwater aquifers by triggering water quality degradation and loss of groundwater storage. This study uses inputs of an existing analysis (Hanson et al. 2014) to estimate the sustainable carrying capacity of the groundwater basin on the basis of economic, hydrologic, and agronomic considerations to optimize agricultural profits.

The construction of the GBM estimated a historical depletion of -14.8 million m^3/year from 1966 to 2009. The GBM was optimized to describe a scenario where groundwater sustainability was achieved through the management of agricultural land with the goal of simultaneously maximizing economic benefit and minimizing water use. The ideal scenario resulted in a 15% reduction of the total agriculture area, which translated to 8.5% less food production and a 4% average profit loss. The associated GBM results showed an increase in the groundwater storage of 79% and net groundwater storage of -10 million $\mathrm{m}^3/\mathrm{year}$ for a projection from 2016 to 2040. There is a gap between the optimized and current economic output of Pajaro Valley, which highlights that there is room for coordination to improve the overall economic output in the region, and more importantly, there are other factors that influence decisions about water use in the area.

These results imply that there is significant room to improve water management in Pajaro Valley. Coupled simulation and optimization techniques can be used to allocate land in an optimal and sustainable pattern that decreases aquifer storage depletion while prioritizing freshwater for the population demands and agriculture activities of future generations. Ideally, future models will also incorporate factors such as regulatory requirements, fertilizer and pesticide use, and other historical and social factors that influence decisions about where to farm and what to grow.

The methodology developed this study can be used as a unique approach to address SGMA legislation, which mandates the implementation of sustainable groundwater management plans in critically overdrafted basins, such as Pajaro Valley. Modeling results produced with such methodology can act as a powerful tool to inform agricultural water management strategies that simultaneously address the needs of farmers, municipalities, and economic and ecological concerns, such as the state of groundwater basins. There is significant potential to improve water management policies while meeting economic and environmental objectives for all stakeholders within critically overdrafted basins throughout California.

The value of this study lies in the comparison of the state of groundwater storage under the baseline and optimized scenarios. It provides insights for defining incentives or regulations that can be implemented if a water management goal is to reach the carrying capacity of a groundwater basin. Results can illustrate to water managers the upper bound of what can be achieved in a perfect world where common-pool resources and willingness to cooperate are valued and come together for equitable and ecologically-focused management of water, land, and agricultural resources. This study does not intend to dictate how agricultural water resources and land be distributed because farmers have the freedom to select their crops based on tradition, expertise, profitability, and influence from other farmers. Rather, it provides an overall vision of what can ideally be accomplished through water management strategies that harmonize individual decisions and shared natural resources.

Acknowledgments

Part of this project and the author, Laura E. Garza-Díaz, was financially supported by the European Commission through the program Erasmus Mundus Master Course–International Master in Applied Ecology (EMMC–IMAE) (FPA 532524-1FR-2012-ERA MUNDUS–EMMC). Special recognition to the Operations Supervisor Jesus Martínez and Hydrogeologist Brian Lockwood from Pajaro Valley Water Management Agency for their invaluable help in providing data and access to the field, wells, and the Harkin Slough Project. Moreover, we would like to thank Dr. Manuel Rosas, Emily Paddock, and Allison VandenHout from Driscoll's Company.

Supplemental Data

Figs. S1 and S2, and Tables S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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