DEDICATION

Para mi papá Sergio, mi mami Yolanda y mi hermano Sergio Ricardo
¡Gracias por el amor infinito que me dan!

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ABSTRACT

Climate variability, population growth, urbanization, economic development, and the industrialization of food production have intensified water management challenges worldwide (M. A. Hanjra, J. Blackwell, G. Carr, F. H. Zhang, & T. M. Jackson, 2012). These challenges are well illustrated in the study case of Pajaro Valley, a highly productive agriculture area, located within the central coast region of California (CA), United States. In Pajaro Valley, groundwater has been the primary water resource for agriculture, as farmers increase their reliance on groundwater supplies, the natural infiltration of rainfall and percolation of irrigation water is becoming inadequate to refill the aquifer. This reoccurring imbalance between pumping and recharge has severe consequences, such as basin overdraft and depletion, which can cause permanent loss of storage, seawater intrusion, and an unreliable water supply (J. Hoogesteger & P. Wester, 2015). The goal of this study was to build a simulation-optimization model to serve as an integrated agriculture-aquifer management tool in order to decrease groundwater depletion by maximizing agriculture net revenue while allocating land and water in a sustainable way. The methodology started by collecting and analyzing hydrological data and water management information such as water allocation, costs and demand from 1966 to 2015. With these data, the groundwater simulation model was built in the Water Evaluation And Planning system software (WEAP). In parallel, acreage and water allocation objective-functions (mathematical equations) and constraints where defined for a linear optimization model and a genetic algorithm optimization model, developed in MATLAB by the Water Resource Management Research Group of the University of California Davis. Then, the simulation and optimization models were linked throughout Excel Visual Basic and WEAP. The coupled models were run from 1966 to 2015 in periods of 25 years. This linkage addressed the complex nature of determining the best or optimal strategies of water and land

allocation that often affect groundwater management policies for future projections. Simulation model results showed how aquifer storage from 1966 to 2009 was depleted annually in average by -12.85 thousand acre-ft (TAF) (-16 million m^3). Future projection trends showed an increase in storage depletion from 2016 to 2040 of -38.83 TAF (47.89 million m^3). On the other hand, by applying optimization modelling, results in a future projection showed an average annual groundwater storage of -8.42 TAF (10 million m^3) and -8.26 TAF (-10 million m^3) from 2016 to 2040, and of -1.71 (-2 million m^3) and -1.75 TAF (-2million m^3) from 2016 to 2030, using linear optimization and genetic optimization respectively. In average an improvement of 96% for the shorter period and 79% for the larger, is observed from the optimized scenarios when compared to the actual or baseline trend, meaning that optimization models can help the reduction of overdraft and propitiate an increase in the recharge of the basin. The use of combined simulation-optimization models in water management, enhances the possibility to observe a future scenario with desired attributes and trade-offs, by improving water conservation and groundwater resource management policies. In this case, agriculture water use in an optimization scenario, dropped from yearly average of 51 TAF (63 million m^3) to only use 40 TAF (49 million m^3) by 2030 until 2040. However, trade-offs affect food production and profitability, net revenue will decrease in average by 45 million dollars while food production will drop 20%. Overall the use of this simulation-optimization model provides a powerful tool to look at a future window on agriculture water management. Depletion of aquifers and other water bodies pose a threat to the numerous ecosystem services they provide. Awareness of potential impacts and implementation of long-term strategies such as hydro-economic models, can offer better understanding on agriculture water resources at future scenarios. These make a suitable tool for developing improved water management policies and for addressing problems and needs of farmers, general population and ecological concerns.

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NOTATIONS

A = Total crop area (acres)
A% = Acreage share of crops between inland and coastal (%)
Acre-ft = Acre feet
AF = Acreage factor (%)
AFY = Acre feet per year
AgWU = Agriculture water use
ASR = Aquifer storage and recovery
AW = Applied irrigation water
BW = Blend wells of water (AFY)
BWcity = Blend wells from the city (AFY)
BWhs = Blend wells from HSP (AFY)
BWpv = Blend wells from PVWMA (AFY)
CA = California
CDS = Coastal distribution system
CIMIS = California Irrigation Management Information System
COP = Cost of production ($)
COW = Cost of water ($ per acre-ft)
CVP = Central Valley Project
d = Index of agreement
D = Well depth (ft)
DWR = Department of Water Resources of California
DWU = Delivered water users
EC = Energetic cost of pumping water ($ per acre-ft per ft)

EPA = US Environmental Protection Agency
ET = Evapotranspiration
Etc = Crop evapotranspiration (ft)
Eth = Estimated reference evapotranspiration (ft)
Eto = Reference crop evapotranspiration (ft)
ft = feet
GA = Genetic Algorithm
gpd = gallons per day
ha = hectares
HSR = Harkins slough recharge
I = Inflow of the aquifer
IE = Irrigation efficiency (%)
IMU = Inside metered users
IR = Irrigation requirement (acre-ft)
IRe = Irrigation Recharge (acre-ft)
IRWM = Integrated Regional Water Management
ISE = Irrigation system efficiency (%)
Kc = Crop coefficient (dimensionless)
LP = Linear programming
Lpd = Liters per day
Lpf = Liters per flush
Lpm = Liters per minute
LRM = Linear regression model
MAR = Managed aquifer recharge
MJ = Mega-joules
MSE = Mean square error
NSE = Coefficient of efficiency
O = Outflow of the aquifer
OMU = Outside metered users
P = Precipitation (ft)
PBIAS = Error index percent bias
PR = Precipitation recharge (acre-ft)
PVHM = Pajaro Valley Hydrologic Model
PVWMA = Pajaro Valley Water Management Agency
PWU = Population water use (AFY)
R = Total recharge (acre-ft)
R^2 = Coefficient of determination
Ra = Estimated extraterrestrial solar radiation (MJ/m2/day)
RPG = Rural population growth (inhabitants)
RW = Recycled water (AFY)
RWU = Rural water use (AFY)
RWUPC = Rural water use per capita
SBCWD = San Benito County Water District
SCVWD = Santa Clara Valley Water District
SGMA = Sustainable Groundwater Management Act of California Legislation
SU = System's usage (%)

SW = Supplementary water (AFY)
TAF = Thousand acre-ft
T max = Maximum daily temperature (°C)
T min = Minimum daily temperature (°C)
UC = University of California
United States = US
UPG = Urban population growth (inhabitants)
USGS = United States Geological Service
UWU = Urban water use (AFY)
UWUPC = Urban water use per capita
WAWRP = Watsonville Area Water Recycling Project
WEAP = Water Evaluation And Planning system software
WP = Water Price ($ per acre)
WTP = Water treatment plant
WUPC = Water use per capita

1 INTRODUCTION

The culmination of global change drivers including climate variability, population growth, urbanization, economic development and the industrialization of agriculture and food production have intensified water management challenges (M. Hanjra, J. Blackwell, G. Carr, F. Zhang, & T. M. Jackson, 2012). An effective response to these drivers require adaptive integration; because water supply, water quality, water demand and other major water concerns are all hydrological interconnected (Hanak & Lund, 2012).The increase of water demand depends on these global changes, one of the most important effects reside on the agricultural water use. Current traditional agriculture production cannot be sustained without directly affecting society and natural resources, including freshwater. Water scarcity is a worldwide growing problem, especially during long periods of drought. Understanding the issues of water availability and to assess and respond to these environmental challenges in the near future is vital and imperative.

The state of California (CA) is facing one of the most critical scenarios in the United States (US). One of CA's primary economic sectors is agriculture; this region is particularly known for its high-value crops and for being one of the most prolific states for vegetables and fruit production in the country. CA is currently experiencing one of the most severe droughts on record. The water year of 2013-2014 was exceptionally low in rainfall and snowpack, which led to reduced surface water availability (Horney, Larsen, & Macon, 2014). In times of water shortages, this loss will be partially replaced by increasing groundwater pumping (Howwit, Medellin-Azuara, MacEwan, Lund, & Sumner, 2014). Groundwater has been the primary water resource for conventional agricultural in CA, with less reliance on surface waters, but this approach is limiting (Molden et al., 2011). A majority of farmers in CA irrigate their crops with groundwater from wells located on their properties; However, groundwater management has not been properly regulated through decades of pumping and several periods of drought. This has allowed for the exploitation of groundwater resources, causing overdraft throughout the groundwater basins that can result in storage depletion and seawater intrusion. This jeopardizes the ecological services that the groundwater basins provide to the region, including the reliability and productivity of agricultural systems, especially those located on the coast.

Future water management relies on the prevention of groundwater depletion and degradation of water quality; this requires a feasible and consistent maintenance of water supply for encountering the growing agricultural and municipal demand (R. Hanson, 2003). The hydrological budgets that support human demands can be historically quantified and analyzed trough simulation modelling (R. T. Hanson, Loockwood, & Wolfgang, 2014) furthermore, water savings and complex conservation policies can be addressed by optimization modelling and later integrating and assembling both models for an optimal design of resources. These efforts can highlight the potential of sustainable water allocation and its benefits for agriculture, society and the environment.

The hypothesis of this study states that groundwater overdraft can be estimated using simulation modelling and by adapting this model to an optimization approach, reduction of aquifer depletion can be achieved by the optimal allocation of groundwater inputs.

1.1 Research Objectives

The general objective of this study is to build a simulation-optimization model to serve as an integrated agriculture-aquifer management tool in Pajaro Valley CA, in order to decrease groundwater depletion by maximizing the agriculture net revenue while allocating land and water resources in a sustainable way.

The specific objectives are: (1) characterize the land use, water demand, groundwater table and water allocation system by building a simulation model from 1966 to 2015 using the Water Evaluation And Planning (WEAP) system, (2) define the economic aspect of the system which lies in agriculture cost of production and income as well as the general cost of water. (3) design two hydro-economic optimization models, linear modelling and genetic algorithms, for maximizing agricultural profit from a variety of crops, based on water availability by adjusting crop acres. (3) couple the simulation-optimization model on WEAP with Excel, run the model for a future hydro-economic projection from 2016 to 2040 and compare results.

2 BACKGROUND

2.1 Overview of California's Water Management

Once first's European settlers arrived in the 1800s, dramatic modifications and adaptations have been performed in CA. From draining wetlands to re-engineering rivers or converting entire ecosystems to agricultural landscape, all of these activities posed a significant and rapid change throughout CA state (Watt, 2016). Today, CA's water management concerns a wide range of challenges, from meeting the increasing water demand and supply planning, to the creation of legislations or the management of hundreds of agricultural water districts and wastewater plants. Water law has the remarkable potential to adapt to society's needs, the structure of it remains on recognizing and resolve water allocation disputes on a steady but not static way. For instance, the statutory regulation of CA has been changing from the late 1800s on. First, water rights were applied as property ownership; an owner of a land touching a river had a "riparian right". Likewise, farmers had “overlying right” and were able to drill a well and pump water if their land overlay a basin. In 1887, CA’s legislature approved the Wright Act which enables farmers to form irrigation districts. Later, in 1914, CA’s statuary system applied for allocation and water regulation for rivers, but not for groundwater draft. Then, in 1956 the Department of Water Resources (DWR) was created, its strategic goals were to plan, design, construct and manage CA’s water supply. At last, one of the newest legislations was created in 2014, the Sustainable Groundwater Management Act (SGMA), one hundred years later than the streams management and regulation. The state is abundant in water supply, CA’s precipitation produces about 200 million acre-feet (24696.27 million m^3) of water per year, it also receives water from the Colorado and Klamath River. On average CA has 78 million acre-ft (96211.58 million m^3) available from these inputs. To sum that, 12 million acre-ft (14801.78 million m^3) of groundwater is pumped each year. The general water use is 9 million acre-ft (11101 million m^3) for urban use which may increase to 12 million acre-ft (13801.78) by 2020, 39 million acre-ft (48105.79 million m^3) dedicated to environmental uses and 34 million acre-ft (41938.38 million m^3) for agriculture (Littleworth & Garner, 2007). Moreover, CA is the nation’s leading agricultural producer, contributing to more than half of the nation’s fruit, vegetable and nut production. Along with population increase and the agriculture growing sector, CA has an increasing demand on water supply, for this reason, the major role of CA’s water law is to continue developing frameworks and policies to encounter water needs.

2.2 Conjunctive Management and Sustainable Groundwater Management Act (SGMA)

Conjunctive management is the efficient and coordinated management of surface water, recycled water, and groundwater resources, with the purpose of maximizing and sustaining a reliable supply of water. It involves the joint use of these resources through a coordinated strategy. The objective of using this approach is to sustainably use water while dealing with the demand and supply challenges. SGMA mandates the implementation of sustainable groundwater management plans in critically overdrafted basins by 2020. In summary, SGMA legislation provides for sustainable management of groundwater basins, it empowers local agencies for the management of groundwater and establishes minimum standards or a uniform framework for continuous management. Furthermore, by protecting water rights, it provides state technical assistance and improve coordination between land use and groundwater planning.

The necessity of this methodology is due to the hydrological connection between groundwater and surface water systems. The groundwater flow system pattern is not only controlled by the water table configuration, but also by the physical interaction with lakes, rivers, and wetlands on the hydrological cycle. This interrelation also counteracts with the topographic, geologic and climatic settings of the system (Sophocleous, 2002). At some point, groundwater will be recharged through infiltration from precipitation, irrigation or by a stream, and certain times, the groundwater may contribute to the stream's baseflow by discharging water into it.

Several benefits arise from this management strategy, besides the reliability of water supply in a region; it also provides ecological and quality improvements, like the prevention of salt water intrusion or groundwater overdraft.

2.3 Groundwater

Groundwater is the usable water beneath the land surface and it fills the pore places of the alluvium soil or rock formation (Plan, Update 2009). The recharge occurs through natural methods as well as artificial, or managed methods. Currently, natural methods such as infiltration of rainfall, seepage of stream flow, and percolation of irrigation water are the primary sources of recharge in the Pajaro Groundwater Basin.

Groundwater is used worldwide because of its high quality and simple accessibility. Its role in agriculture has become predominant as producers adopted its use on a massive scale (Jaime Hoogesteger & Philippus Wester, 2015). For some farmers, it might be the only source of irrigation. It is called a "horizontal" resource, because farmers are able to sink wells independently and extract water, making groundwater highly reliable (Schllager, 1983). However, the quality and sustainability of groundwater varies throughout the watershed and is dependent on management activities and local practices.

Excessive extraction for irrigation, where groundwater is slowly renewed, is the main cause of depletion; it occurs when the water output exceeds the input. The disproportion between groundwater pumping and aquifer recharge has severe consequences, such as basin overdraft and depletion, which can cause loss of basin storage and saltwater intrusion, affecting water quality. These results pose a threat to the sustainability of the basin. Moreover, population growth and climate change have the potential to exacerbate this problem in some regions (Aeschbach-Hertig & Gleeson, 2012). According to the California Department of Finance, over the next several decades, CA's population will increase about 60% reaching nearly 60 million by 2050 (Hanak & Lund, 2012). This will represent a major driving force for meeting food and water demand. This scenario poses a water security issue in the US and around the globe. On the other hand, climate change also has the potential to directly affect groundwater. Sea level rise, changes in precipitation, drought persistence, shrinking of rivers among others, are some climatic concerns that add uncertainty to the groundwater system's sustainability. Along with the ecological risks, climate change adds pressure and challenges to groundwater's management, policy and effective planning.

2.4 Managed Aquifer Recharge (MAR)

One method to increase water supply for groundwater is by artificial or purposeful recharge, which can be achieved by the use of managed aquifer recharge (MAR). This refers to the "movement of water via man-made systems from the surface to the earth to underground water-bearing strata where it may be stored for future use (Mortimer, 2014). According to the US Environmental Protection Agency or EPA (2015), through infiltration pools or basins, MAR can be used to store rainwater, reclaimed water or even water from sloughs, and then recharge groundwater basins. MAR utilizes three different types of recharge methods: 1) surface spreading which is the intentional spreading of water over permeable soil strata in order to allow water percolation down into the aquifer. 2) Infiltration pits and basins, works as the surface spreading but in less area, commonly uses managed storm-water and 3) injection wells, which are used to pump water into the de aquifer by a drilling well, this method is used when surface infiltration is impractical. Moreover, there are different types of injection wells, the aquifer storage and recovery (ASR) wells. These have a dual purpose, recharge water into the aquifer and recovery water from the same well. In the last 30 years, ASR wells have increased in usage, however, this method is expensive and difficult to maintain because these are prone to clogging by suspended solids.

2.5 Recycled Water

In the near future, the generated wastewater from the municipal sources will increase in response to the continuous population growth, urbanization, food supply, economic development and the depletion of freshwater. The demand for recycled water will also continue to increase. Defined by the Water Code section (13550 n) “"Recycled water" means water which, as a result of treatment of waste, is suitable for a direct beneficial use or a controlled use that would not otherwise occur and is therefore considered a valuable resource.” Normally the source of recycled water is the municipal wastewater which includes domestic and industrial wastewater use, rainwater and groundwater seepage that enters the municipal sewage network (Hussain, Raschid, Hanjra, Marikar, & Hoek, 2001).

The initial stage of processing wastewater is the primary treatment, where coarse solids and dissolved organic and inorganic particles are removed by sedimentation. This is performed by gravitational settling, chemical coagulation or filtration. Then the water flows into a secondary treatment, this process removes 90% of the organic matter, where microorganisms are used to remove contaminants. At last, tertiary treatment wastewater is subject to a third cleaning stage of filtration and UV light disinfection. Appropriate uses of recycled water depend on its quality and type of treatment (Menegaki, Hanley, & Tsagarakis, 2007); for example, primary treated water is suitable for forested land in a controlled way, secondary treated water is appropriate for surface tree irrigation, mainly industrial trees where water is not in contact with crops and tertiary treatment is suitable for crops irrigation.

2.6 California’s Hydrologic Regions

Groundwater basins in CA account for a total number of 431, these underline 40 percent of the total basins of the state; the DWR subdivided the state into specific geographic and delimited areas. These areas are 10 hydrological regions (Figure1) which are main drainage areas of a major river. To identify the basins, each of them has a specific identification number with the format X-Y.Z, in this case, the first number (X) stands for the hydrological regions of CA. Then the second number

(Y) is the groundwater basin number and the third number (Z) stands for any groundwater basin that has been divided into a subbasin.

Figure 1. California´s 10 hydrological regions

2.6.1 Central Coast Hydrological Region

The Central Coast hydro-region has 11300 square miles (29266.866 km^2) with 50 delineated groundwater basins which cover 3740 square miles (9686.55 km^2) (Figure 2). Out of all the hydrological regions, the most reliant on groundwater is the Central Coast region which has a total demand of 1263 TAF (1559 million m^3). and meets more than 80 percent by groundwater. A total of 83 percent of the groundwater in the region accounts for agriculture.

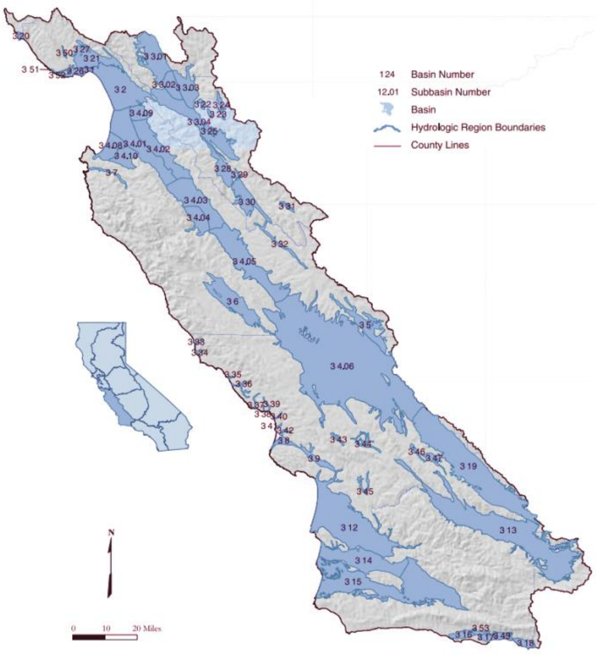


Figure 2. Central coast hydrologic regions (Bulletin-118_3, 2003)

2.6.2 *Pajaro Valley's Regional Basin Setting*

The Pajaro River Watershed (Basin ID 3.2) is part of the Central Coast hydrological region. It comprises 1300 square miles (3367 km2) and it covers portions of four counties: Santa Clara, Santa Cruz, San Benito and Monterey (IRWMP 2014). See Figure 3. Its large size contributes to mutual needs and shared resources in between counties; some of these are the exceptional provisioning ecosystem services it gives. Urban and rural development, agriculture, food and water supply, flood protection, amongst others are some highlights.

These four counties must share resources that provide ecosystem services for urban and rural development, agriculture, water supply, and flood protection. In 2007 an Integrated Regional Water Management (IRWM) plan was created for the region to address these issues. The IRWM plan proposes the use of this approach in order to achieve the region goals of water supply, water quality, flood management, and environmental protection and enhancement (IRWMP, 2014b)

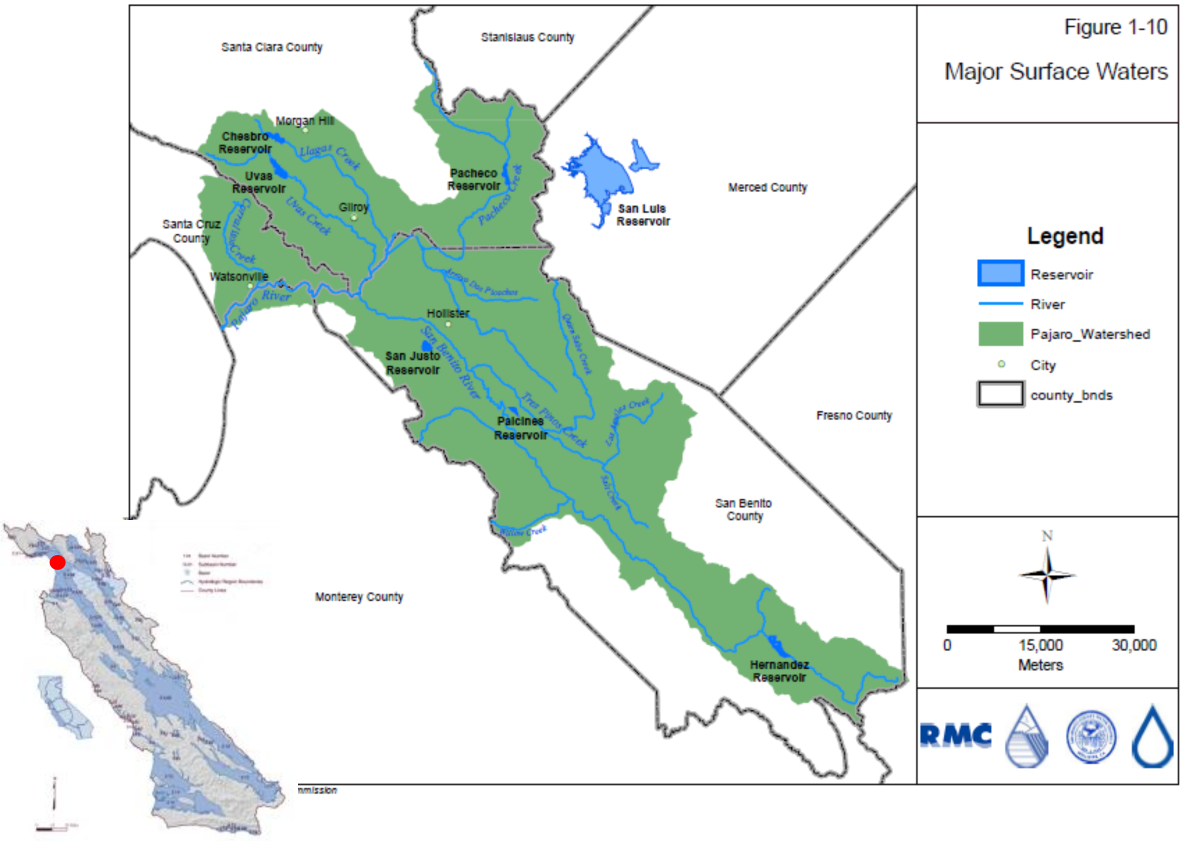
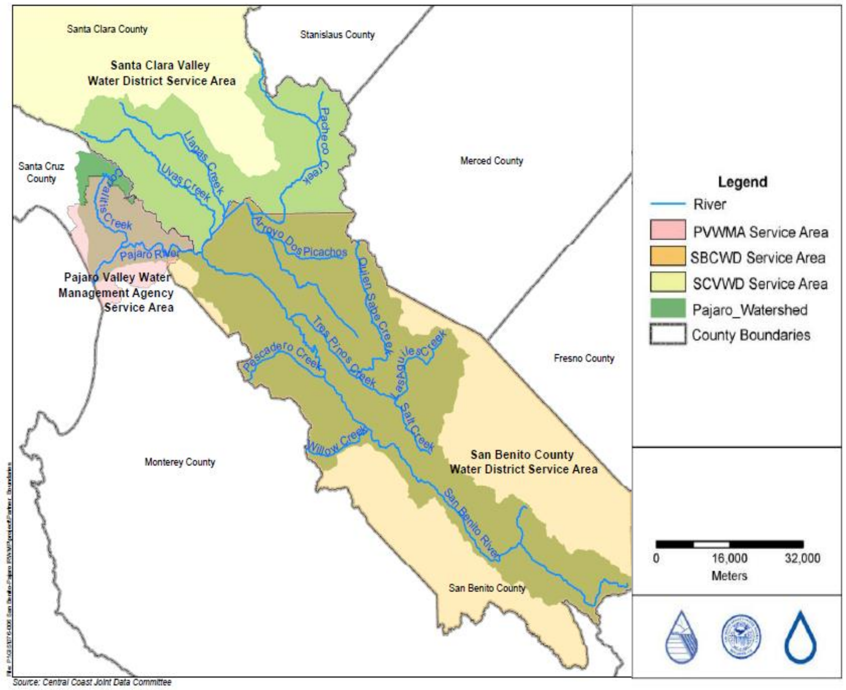


Figure 3. Pajaro River Watershed (Basin ID 3.2) (IRWMP, 2014a)

It was also developed and implemented by three agencies collectively known as Pajaro River Watershed Collaborative, these are: Pajaro Valley Water Management Agency (PVWMA), San Benito County Water District (SBCWD) and Santa Clara Valley Water District (SCVWD) See Figure 4. The three stakeholders share common linkages, interests, and goals including water supply, reliability, groundwater management, recycled water, water quality protection, flood protection, and environmental resource management.

The regional setting must be configured in this way since the Pajaro watershed forms a very complex water system. In a very condensed explanation, runoff from this watershed collects and drains to the Pajaro River, and ultimately drains into Monterey Bay. The SCVWD and SBCWD share an interconnected groundwater basin. This groundwater basin connection is a linkage between the two agencies in regards to groundwater management activities. The PVWMA groundwater basin is bound by the San Andreas Fault to the east, which separates the Pajaro Basin from the SCVWD and SBCWD groundwater basin. However, the Pajaro groundwater basin is influenced by the Pajaro River, which drains South SCVWD and SBCWD service areas. Therefore, drainage activities within the SCVWD and SBCWD service areas influence groundwater in the PVWMA service area (IRWMP, 2014b)



Source: Central Coast Joint Data Committee

Figure 4. Pajaro River Watershed Setting (IRWMP, 2014a)

3 CASE OF STUDY: PAJARO VALLEY

Pajaro Valley is located on the central coast of CA, adjacent to Monterey Bay. Its major city is Watsonville where residential, industrial and commercial land uses predominate. However, the region is mainly used for agricultural purposes, predominately high-value crops such as strawberries and berries which bring in millions of dollars of revenue per year. The area has several water management concerns and issues. Over the last 60 years, the Pajaro Valley basin has records of seawater intrusion and groundwater depletion, since groundwater has been the main source of water for farmers and the municipality.

For that reason, Pajaro Valley is an important study area; many of the water demand, supply, and management challenges are suitable for maximizing opportunities for water conservation and allocation using simulation and optimization models.

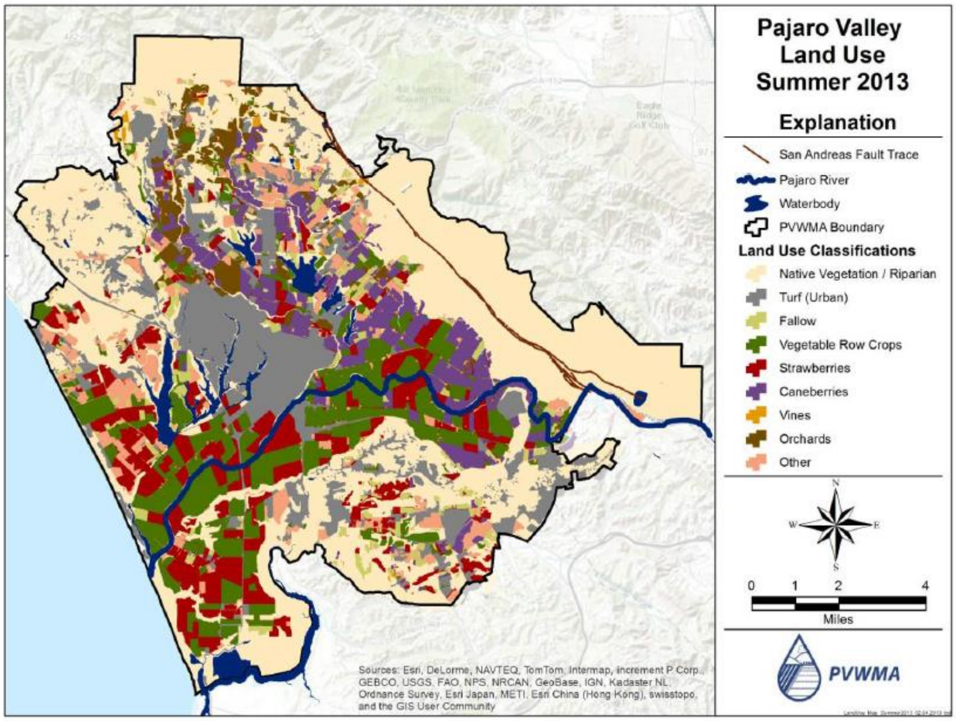
3.1 Geography

Pajaro Valley extends approximately about 79600 acres (~32000 ha). It includes the Pajaro River, which is the largest coastal stream in the valley and its boundaries include the San Andreas Fault in the eastern edge, the Elkhorn Slough in the south and the Monterey Bay on the west.

3.2 Land Uses

The three major land uses are native vegetation, urban/rural and agricultural (Figure 5). Native vegetation is the predominant land use of the area followed by the agricultural land, which has consisted of 27000 acres (10927 ha) since 1989. The main crops grown in the valley are vegetable crops, fruit and nuts, deciduous trees, nursery crops and other crops. Out of this classification, the main crops are vegetables crops such as head lettuce and leaf lettuce, fruit and nuts such as bushberries, vinegrapes and strawberries, deciduous trees such as apples, nursery crops as ornamental flowers and vegetable transplants and at last other crops such as broccoli, onions, mushrooms, leeks, kale among other. (PVWMA, 2013)

Urban areas are primarily located within or adjacent to the City of Watsonville, the biggest city in the valley. The land uses are commercial, industrial, and residential. This type of land use has increased consistently from only 4800 acres (1943 ha) in 1966 to nearly 12900 acres (4856 ha) in 1997 and 13373 acres (5412 ha) in 2006 (PVWMA, 2013). This increase reflects general population growth trends over the last several decades.



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 5. Land use in PVWMA service area. (IRWMP, 2014a)

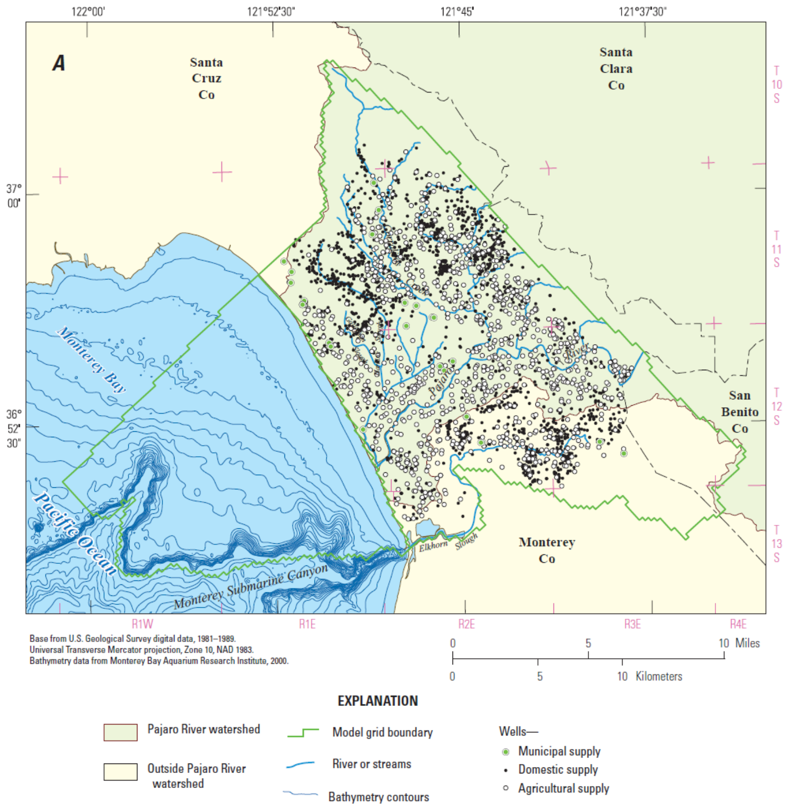
3.3 Economic Activities

Pajaro Valley's economic profile is based principally on multimillion-dollar agricultural production. The crop yields were valued at over $800 million in 2011 (PVWMA, 2013). Big agro companies are set in the valley, such as Driscoll’s and California Giant for strawberries, raspberries, blueberries and blackberries. As in for apples and cider, Martinelli’s & Company. These large agro-corporations in the area have helped the city and the state to become one on the top ranked farming cities in the US. Pajaro Valley ranks fifth for the total agricultural production in CA, it produces the highest value crops in the US (Johns, 2008).

3.4 Water Supply

3.4.1 Groundwater supply

Groundwater development in Pajaro Valley had led to the massive construction of more than 2,700 wells (Figure 6). A 2009 survey counted ~1,695 domestic wells, 32 municipal wells, and ~1,026 irrigation wells. There are records of the increase total pumpage for water supply. In 1964 a total



Base from U.S. Geological Survey digital data, 1981–1989.
Universal Transverse Mercator projection, Zone 10, NAD 1983.
Bathymetry data from Monterey Bay Aquarium Research Institute, 2000.

Figure 6. Distribution of agricultural, urban and domestic wells in Pajaro Valley (R. T. Hanson, Schmid, Faunt, Lear, & Lockwood, 2014b)

amount of 6000 acre-ft (7 million m^3) were pumped and it doubled by 1987-88. Then in 2006-09, pumping leveled off to about 11000 acre-ft (13.56 million m^3). (R. T. Hanson, Schmid, et al., 2014b)

3.4.2 Supplemental Water Supply

The PVWMA implemented the Coastal Distribution System (CDS) used to supply and deliver supplemental water to farms in coastal areas. Water delivered by the CDS replaces groundwater to help to reduce seawater intrusion.

3.4.2.1 The Recycled Water Treatment Facility

Recycled water in Pajaro Valley is currently being produced for landscape irrigation, crop irrigation, and industrial use. The PVWMA implemented the Watsonville Area Water Recycling Project (WAWRP), which led to the building of a facility that combines treated disinfected, tertiary treated wastewater blended with groundwater supplied by the City of Watsonville wells and PVWMA blend wells (R. T. Hanson, Loockwood, et al., 2014).The project was developed in 2009 as part of the long-term plan to halt seawater intrusion. The facility produces 4,000 acre-ft/year (4.934 million m^3/year) of recycled water, which is blended into 2000 acre-ft/year (2.467 million m^3/year) of freshwater. This produces a total of 6000 acre-ft/year (7.401 million m^3/year) for coastal crops irrigation (IRWMP, 2014b). Several studies show that most crops have higher potential yields when using recycled irrigation; furthermore, there is no need to use chemical fertilizers, resulting in reduced operational costs for farmers (Hussain, Raschid, Hanjra, Marikar, & Hoek, 2001).

3.4.2.2 The Harkins Slough Managed Aquifer Recharge and Recovery Facilities

The Harkins Slough Recharge (HSR) is an unconfined aquifer that allows water infiltration trough permeable soils. HSR was developed to fulfill the requirements of water demand for coastal farmers and to give an alternative solution to the overuse of groundwater. It includes the first ASR system in the coastal region, and it is part of an MAR program (R. T. Hanson, Loockwood, et al., 2014) Local runoff is diverted from the Harkins Slough when available, which is estimated to supplied the ASR system with a total of 5120 acre-ft (6.315 million m^3) of water from 2002 to 2009. (R. T. Hanson, Schmid, et al., 2014b)

3.5 Water Management Concerns

The region's water supply consists of groundwater, local surface water, imported surface water from the Central Valley Project (CVP) and recycled water from the WAWRP project. The primary water use in the watershed is agriculture irrigation, accounting for nearly 90% of total water demand, and the rest is for municipal and industrial use (IRWMP, 2014b). Growth in population and urbanization will cause an important increase in water demand in the future.

The major water supply of the Pajaro Valley is primarily met by groundwater. For decades, the population of Pajaro Valley has overexploited the groundwater resources, and it is estimated that the region pumped almost twice as designated "sustainable yield" of water per year (Rudestam, Langridge, & Brown, 2015).

Overdraft of the basin causes depleted storage capacity. Moreover, the close proximity to Monterey Bay caused seawater intrusion in the freshwater aquifers, triggering water quality degradation and permanent loss of storage. This specific problem is dated back to the late 40's in a letter from the general manager of PVWMA that states, “It are generally agreed that there is seawater intrusion in the coastal portions of Pajaro Valley. It probably started as early as 1947 […] (Mann, 1988 in Hanson, 2003)”. Seawater intrusion can reach inland groundwater, especially during drought conditions, when natural recharge of the basin is reduced due to lack of precipitation and stream runoff. Seawater intrusion in the Pajaro Valley basin has been observed up to 3.2 miles (5.2 km) inland. See Figure 7. Long term seawater intrusion per year reaches 200 feet (62 m) rate because inland groundwater levels are only 10 to 20 feet (3.05 to 6.1 meters) above the sea level (Lookwood, Bannister, & Stagnaro, 2013).

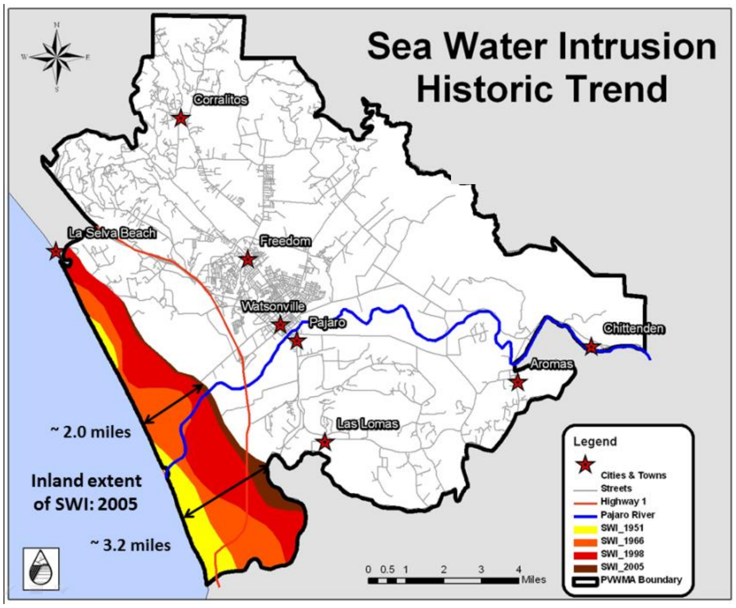


Figure 7. Historic trend of Seawater intrusion (PVWMA, 2013).

Based on an overall basin priority rank, Pajaro Valley basin is the 8th most overdraft basin in CA it has a high designation priority according to the SGMA regulations (CASGEM, 2014). As defined in SGMA, “A basin is subject to critical overdraft when continuation of present water management practices would probably result in significant adverse overdraft-related environmental, social, or economic impacts” (Bulletin-118, 2003).

The PVWMA has worked to mitigate groundwater dependence in the valley by developing new methods to meet water demands and reduce seawater intrusion and overdraft, especially in the coastal areas where the problem is substantial. The Harkins Slough Facility Recovery and the Recycled Municipal Water are implemented to address these problems.

4 METHODOLOGY

With the objective of developing a simulation – optimization model to be used as an integrated agriculture-aquifer management tool in Pajaro Valley CA, this section describes the methods related. A framework of the methodology is observed in Figure 8. First the planning area of Pajaro Valley was constructed in WEAP, followed by the groundwater simulation model where an aquifer storage mass balance was calculated; in here the agricultural, the urban and rural water demand inputs were collected, followed by the supplementary water and aquifer recharge input. Calculations and comparisons of this section were performed in Excel, then validated data was uploaded into WEAP. Next, the economic inputs such as cost of production, income and water costs were calculated in Excel. Afterwards, the optimization model was developed in MATLAB and the optimized output (land use) was uploaded to WEAP. To finalize, the simulation-optimization model coupling of Excel and WEAP was performed in Visual Basic.

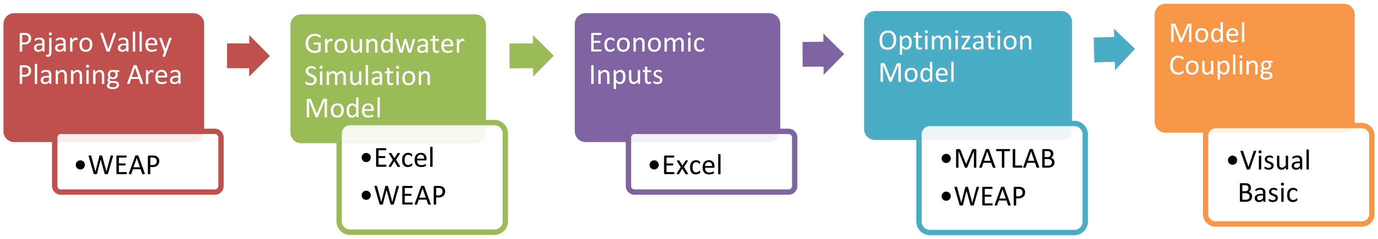


Figure 8. Methodology framework

4.1 Pajaro Valley Water Planning Area

The Pajaro Valley water planning model was set using a platform characterized for conducting integrated water resource management and planning, the WEAP software. Additionally, it has promoting decision-support tools for the evaluation of reservoir operations, in stream flows, hydrology, water demand, consumption, and water quality. It allows data manipulation among different scenarios, defined spatial boundaries and monthly time steps frame. Furthermore, it is possible to link it with other models and software such as Visual Basic, Excel, MATLAB, GIS-interface etc. In this section, WEAP was used to define the area or model setting, the supply and demand site as well as the timeline.

4.1.1 Model Setting

The model setting of Pajaro Valley started by delimiting the area, in this step the Monterey Bay Area was located and the working area was set just beside it. The area used in this model is not escalated nor adequately fitted, however, this does not interfere with the objectives of the study nor was on the scope of it. The setting is formed by 3 different components; 1) supply sites: the Pajaro Valley Aquifer as the groundwater supply and the Pajaro River, then 2) demand sites: the inland and coastal agricultural areas as well as the urban and rural towns, and 3) the wastewater treatment plant with its flow requirement. These three components are joint by transmission links showed in green arrows and return flows by the red arrows. A historic and future timeline were set as well as two different scenarios; the current and optimized. A schematic map of the model is observed in Figure 9.

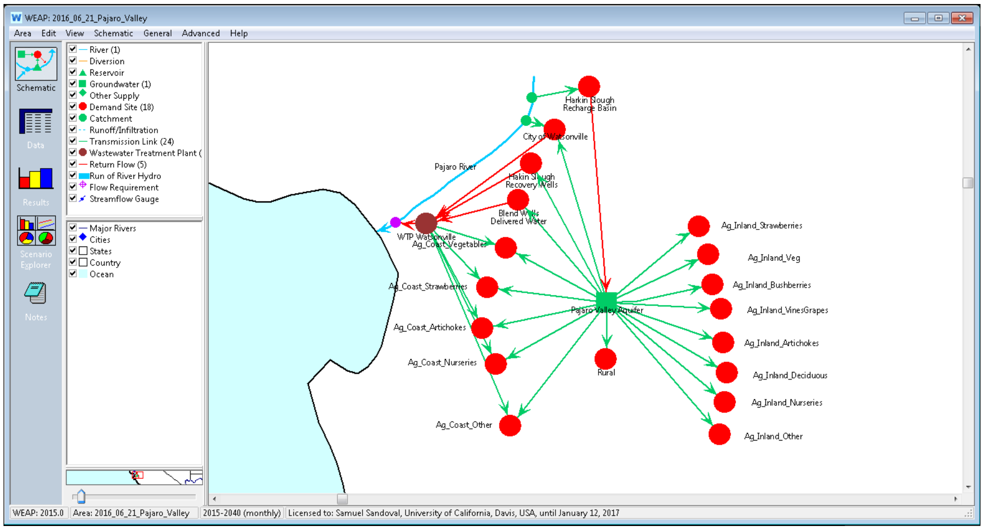


Figure 9. Scheme of Pajaro Valley model setting

4.1.2 Supply sites

Supply sites are interconnected to the demand sites by transmission links or by return flows, in here the Pajaro Valley Aquifer, is the main supply component in the model, as it allocates water for all demand sites. At the same time HSP supply water to the aquifer and it demands water from the Pajaro River. The river provisions water to the Harkin Slough which then is diverted into the HSP, in former years, the river also supply water to the city yet this practice is no longer performed. Followed as a supplementary water input, the Wastewater Treatment Plant (WTP) demands water from the HSP wells, blend wells and the city, then treated water is then supplied to coastal agriculture sites.

4.1.3 Demand sites

The demand sites for the model are separated into three different areas; 1) the urban area which includes water pumpage from wells used for the city of Watsonville, 2) wells used for the municipal and rural residential purposes, and 3) the agricultural area, which includes withdrawals from all the farm wells to supply water for irrigation. Part of the agricultural demand sites are located closer to

Monterey Bay and rely on an aquifer that is susceptible to seawater intrusion, therefore, agricultural land use was categorized in two sub demand sites, inland and coastal.

Additionally, a priority status for water supply was designated to each of the demand sites, where 1 is the highest priority. In this study case, the city and rural towns are set with a priority of 1 meaning they will get first the available water until demand is completed, meanwhile the agricultural areas have a priority of 2.

4.1.4 Timeline

The timeline of the model was divided into three periods; (1) the base year (2015) this specific year provides a snapshot of the actual water demand, resources and supplies for the system. (2) The deterministic hydrology time lapse from 1966-2014, this period of time allows to evaluate the impact of groundwater overdraft and it provides a milestone to identify the problems and challenges that the area has been carrying from almost 50 years ago. (3) The future hydrology period from 2016-2040 is a future simulation, and it can help hydrologist, ecologists, politicians and policy makers to predict groundwater status and its economic impact. They can use this information to apply changes and modifications to the water management plan in Pajaro Valley for the upcoming years.

4.2 Groundwater Simulation Model and its Inputs

The groundwater simulation model evaluates the performance criteria between a proposed or estimated net groundwater budget and a theoretical groundwater budget obtained from the United States Geological Service (USGS) Report; the Integrated Hydrologic Model of Pajaro Valley, Fig. 40 of R.T. Hanson, Schmid, et al. (2014b)

The groundwater model was tested using Microsoft Excel 2016 for a preliminary analysis. General inputs for the simulation model are agriculture water demand, urban and rural water use, supplementary water, and the aquifer recharge. These inputs were then utilized for the aquifer storage mass balance which is describe also in this section. After validation of the groundwater model, input data was uploaded and simulated in WEAP

4.2.1 Agricultural Input

This section describes some of the key concepts used as the input data for calculating the agricultural water demand at a monthly step. For ech sub-agricultural site, specific data was required in order to obtain the water needed for each crop or, in other words, the applied irrigation water (AW). The input variables to calculate the AW for this section are; the total crop area (acreage, acreage factor and percentage of coastal/inland), precipitation, evapotranspiration (crop coefficients, reference evapotranspiration, estimated reference evapotranspiration and crop evapotranspiration), irrigation requirement and irrigation efficiency.

4.2.1.1 Description of the area

As previously mention, the agricultural demand area has two subdivisions, inland and coastal. Inland sites are found at the east of Pajaro Valley aquifer, meanwhile, coastal sites are located near to Monterey Bay and at the west side of the Pajaro Valley aquifer. The area of costal sites was classified as all the crops grown inside highway 1 where most of the seawater intrusion is located, see Figure 7 (Section 3.5). The inland area grows strawberries, vegetables (head and leaf lettuce), bushberries (raspberries and blackberries), vinegrapes, artichokes, deciduous trees (apple orchards), nurseries and others (broccoli, cauliflower, onions, beans, kale etc.) are established.

Regarding the coastal area, strawberries, vegetables, artichokes, nurseries and other fields are grown.

4.2.1.2 Total Crop Area

The crop area data has three main variables; acreage, the percentage of coastal/inland and acreage factor. The variable acreage, which is the extent of land measured in acres (1acre = 0.404686 h) accounts from 1966 to 2015 for the total acres per type of crop in Pajaro Valley. It is important to mention that this variable does not take into account the agricultural sub-divisions of coastal/inland. Now, the acreage factor (AF) is defined as the ratio estimation or percentage of the total crop production area to the total area of the property. AF was set as 0.13 for nurseries and for the rest as 0.80, this for coastal and inland from 1999 to 2015. Coastal and inland AF from 1966 to 1998 was set as 0.13 for nurseries and 0.75 for the rest. This transition of AF is established according to the change of a more intensified period of agriculture due to the multi-year drought of 1984 to 1992, this started at the beginning of 1993 but it was fully intensified in 1999. Finally, the percentage of the area or the share of crops ($A_{\%}$) designates the type of crop within its type of land (inland/coastal). Data was provided by the Water Resource Management Research Group of the University of California, Davis. Total crop area is shown in Equation (1)

$$\mathrm{A_{ik}} = \mathrm{Acreage_{ik}} \times \mathrm{AF_{ik}} \times \mathrm{A\%_{ik}} \qquad (1)$$

Where A_{ik} is the total crop area (acres), the $Acreage_{ik}$ is the land use (acres), AF_{ik} is the acreage factor (%) and $A\%_{ik}$ is the share of crops inland/coastal (%); all variables are in year i and crop k.

4.2.1.3 Precipitation

Precipitation monthly data was obtained from the California Irrigation Management Information System (CIMIS) which was developed in 1982 by the DWR and the University of California, Davis. It manages over 145 weather stations in CA and it was designated to manage irrigators practices resources more efficiently. Three weather stations were selected (Figure 10). For the inland area; the Green Road Valley #111 station (36°56'38.3"N 121°45'50.2"W) and the Pajaro #129 station (36°54'10.0"N 121°44'30.9"W), available data for these stations were from May 1992 to December 2015 and from September 1995 to December 2015, respectively. The coastal data was retrieved from the Watsonville West II #209 station (36°54'47.1"N 121°49'25.1"W) from January 2007 to December 2015.

Regarding inland data, from May 1992 to August 1995, data was selected from the station #111, the rest, from September 1995 to December 2015, was selected from the station #129 due to inconsistencies and missing data of the station #111 from August 2009 to February 2012. According to R. T. Hanson, Schmid, et al. (2014b) the year of 1992 was a dry year, for instance, multiple dry years (1993, 1997, 2002, 2003 and 2004) were plotted for evaluation and contrast against the available data of 1992. This was performed to obtain the unavailable data of January to April of 1992. The selected year was 2003 which had the maximum correlation coefficient of 0.92 for the year 1992, then the unavailable data for 1992 was fulfilled with data of 2003. As for the coastal site, missing precipitation data (January 1992-December 2006) was replaced with the available inland data.

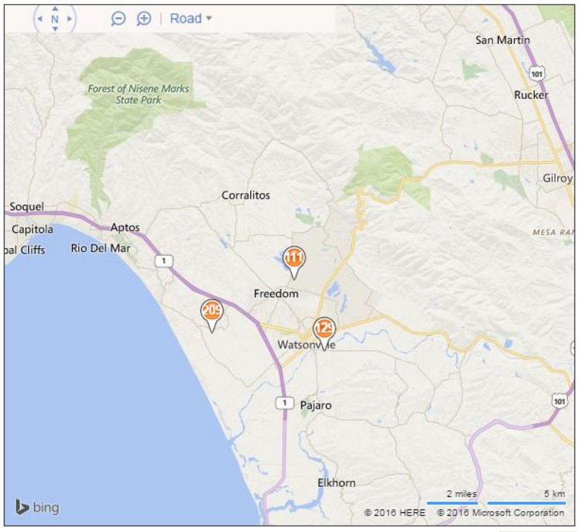


Figure 10. CIMIS weather stations.

Historic precipitation data from January 1962 to December 1991 was retrieved by The PRISM Climate Group, based on the Northwest Alliance for Computational Science & Engineering at Oregon State University. The same coordinates used in CIMIS were set on this database in order to obtain data for the specific place where the three stations previously selected are located.

4.2.1.4 Evapotranspiration

The combination of two separate processes, where water is lost from the soil surface by evaporation and from transpiration by the crop is referred to as evapotranspiration (ET) (R.G. Allen, 1998). There are weather parameters, crop factors and management and environmental conditions that affect evapotranspiration. The reference crop evapotranspiration (ETo) is a hypothetical value independently of the crop type, it means the evapotranspiration rate of an active 8 to 15 cm tall, cool-season, standardized grass surface that is used as a reference value. It should have a uniform height, actively growing, completely shading the ground and not water stressed (Pereira, Allen, Smith, & Raes, 2015). ETo was proposed to enhance the transferability of crop coefficients (Kc) from one location to another. Kc is based on experimental data which refers to the stage of plant growth and the changes of surface soil moisture (Marvin E. Jensen, 1970). It integrates differences between the crop in question and the grass reference surface and for each crop, a Kc is defined. It is mainly a scaling factor, which is used if the crop in question has water consumption larger than the reference evapotranspiration (Kc > 1) or smaller than the reference crop (Kc < 1).

ETo was retrieved from the CIMIS datasets, the stations, and locations where the same as in the precipitation section. Inland ETo data was selected as the same way as in the precipitation section including the calculations for the four missing data from January to April of 1992. As for the coastal records, unavailable ETo information from 1992 to 2006 was calculated using the datasets of coastal and inland areas from 2007 to 2015. These sets were first plotted to analyze their correlation. Figure 11, shows an inland-coastal ETo correlation scatterplot with a coefficient of r=0.97 which shows a high positive correlation and a mean square error (MSE) of 0.031885. These results validated the data and it was used to determine a linear regression model (LRM) equation for each month of the year, and to calculate a monthly coastal ETo data from 1992 to May 2007.

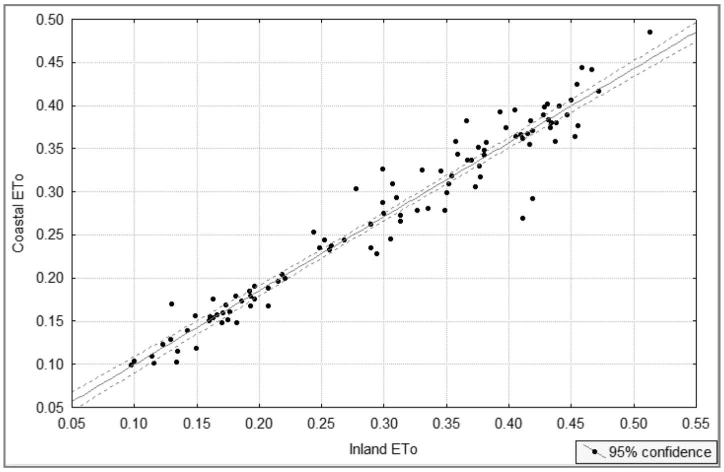


Figure 11. Scatterplot correlation: Inland vs Coastal ETo

Additionally, for unavailable ETo data, an estimate of reference evapotranspiration (ETh) can be calculated. Historical ETh, from 1960 to 2010 was calculated using the Hargreaves-Samani (H-S) equation which explains 80 percent of the ETo (Hargreaves & Allen, 2003). The H-S Equation (2) uses daily maximum and minimum temperatures and net radiation.

$$ETh_{ij} = \frac{0.0023 \times Ra_{jk}\left(\frac{(T\ max + T_{min})_{ij}}{2} \times 17.8\right)(T_{max} - T_{min})_{ij}}{2} \tag{2}$$

Where ETh_{ij} is the estimate of reference evapotranspiration (ft), *T max* is the maximum daily temperature (°C), *T min* is the minimum daily temperature (°C) and *Ra* is the estimated extraterrestrial solar radiation (MJ/m^2/day), all variables for year *i* and month *j*. Data for 1960 to 2010 was obtained from the National Solar Radiation Database, a collection of the National Renewable Energy Laboratory of the US. The selected location was Santa Maria, CA (34° 57′ 5″ N, 120° 26′ 0″ W) since was the nearest collection data point from Pajaro Valley.

Eto and ETh were plotted from 1992 to 2010 to analyze their correlation. Figure (12) shows a positive correlation coefficient of 0.889 and an MSE of 0.814. With this simple test, results show that the historic ETh (1960-1992) values are suitable for Pajaro Valley.

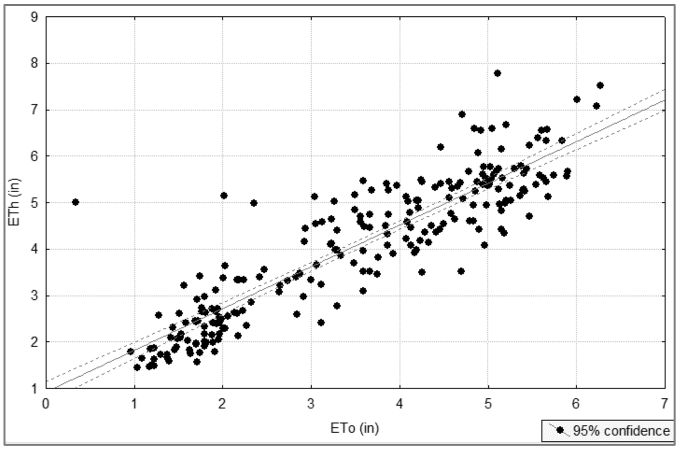


Figure 12. Correlation scatterplot: ETo vs ETh (1992-2010)

For the Kc values, monthly data was obtained from R.T. Hanson, Schmid, et al. (2014). Kc values were divided into two sets from 1963 – 1992 and from 1993 – 2009, although growth dates for each crop vary depending on the planting date and climatic zone, these are assumed to be spatially uniform throughout the valley. These values are specific to each period, traditional agriculture and intensified agriculture respectively.

The Kc, the ETo and the ETh are used to determine the crop evapotranspiration (ETc), which is defined by R.G. Allen (1998), as “the rate of evapotranspiration of a disease-free crop growing in a large field under optimal soil conditions, including sufficient water and fertilizer and achieving full production potential of that crop under the given growing environment; includes water loss through transpiration by the vegetation, and evaporation from the soil surface”. See Equation (3)

$$ETc_{ijk} = Kc_{ijk} \times ETo_{ij} \tag{3}$$

Where ETc_{ijk} is the crop evapotranspiration measured in feet (1ft = 30.48 cm), Kc_{ijk} is the crop coefficient (dimensionless) and ETo the reference evapotranspiration in ft for year *i*, month *j* and type of crop *k*.

4.2.1.5 Irrigation Requirement

The irrigation requirement (IR) of the crop is the depth of water needed for the plant, this term is calculated by the ETc minus the effective precipitation which is the rainfall used to meet crop water requirements; excluding deep percolation and surface runoff (R.G. Allen, 1998). Monthly step IR for inland and coastal crop areas from 1992 to 2015 were calculated using Equation (4)

$$IR_{ijk} = ETc_{ijk} - P_{ij} \tag{4}$$

Where IR_{ijk} in (ft) is the irrigation requirement in year i, month *j* and type of crop k; ETc_{ijk} is the crop evapotranspiration (ft) in year i, month j and type of crop k; And P_{ij} is the effective precipitation (ft) in year *i* and month *j*.

4.2.1.6 Irrigation Efficiency

Irrigation efficiency (IE) or application efficiency is a performance criterion of the irrigation system. It expresses the ratio of the average water depth applied by the target water depth in an irrigation event (Sandoval-Solis, 2013). For example, when the applied irrigation water is equal to the IR, the efficiency will be 1. For each crop, IE values were derived from the product of two factors; the irrigation method/system usage times the efficiency of the irrigation method/system; See Equation (5)

$$IE_{ik} = SU_{ikm} \cdot ISE_m \tag{5}$$

Being IE_{ik} the irrigation efficiency (%) in year *i* and type of crop *k*; *SU* the system's usage (%) for the year i, type of crop k and type of irrigation method *m* and *ISE* the irrigation system's efficiency (%) by type of irrigation method *m*.

Starting with the SU percentage, three years of data for four kinds of irrigation methods; gravity, sprinkler, drip and others were obtained from DWR (2011). Only three years were available, the percentage of irrigation system use by crop in CA for the year 1991 and by Santa Cruz County for the years 2001 and 2010. Data was plotted and an LRM was developed. The regression model produced values of the irrigation system for each crop from 1991-2015. Then, ISE data was retrieved from Sandoval-Solis (2013). Data was shown as the low, mean and high irrigation systems efficiency for gravity, sprinkler, and drip for the overall state of CA. An average efficiency for each irrigation method was calculated and used as the ISE_m, for the type of method *other,* an average efficiency of 0.9 was assumed.

IE from 1966 to 1990 was assumed to be the same as the year 1991 for each crop except for the deciduous crop where from 1966 to 1974 IE was assumed to be 0.5 and from 1975 to 1990 as 0.56. The estimate of this particular crop was verified and compared to the reported values of Rumayor-Rodriguez, A., & Bravo-Lozano, A. (1991) cited by (Peter H. Gleick, 2005) which reported two IE from 1987-1999 of 0.525 and 0.599 for gravity and sprinkler respectively. For the rest of the crops, efficiencies were similar to the calculated ones, for this reason, these were not modified.

4.2.1.7 Applied Irrigation Water

Applied Irrigation Water (AW) is the volume of irrigation water utilized per total crop area. The point where water passes at a diversion section is the point where the water source can be accounted, such as a groundwater well outlet or a canal intake (Sandoval-Solis, 2013). AW takes into account all the variables and inputs mention before. See Equation (6).

$$AW_{ijk} = \frac{IR_{ijk} \times \mathrm{A_{ik}}}{IE_{ik}} \tag{6}$$

Where AW_{ijk} is the applied water (acre-ft); IR_{ijk} is the irrigation requirement (ft); IE_{ik} the irrigation efficiency (%) and $\mathrm{A_{ik}}$ the total crop area (acres). In year *i,* month *j* and type of crop *k*, when applied.

4.2.1.8 Water Demand

Agriculture water demand is calculated using two sets of equations. See Equation (7) and (8).

$$AWD_{ij} = \sum_{k=1}^{K} AW_{ijk} \tag{7}$$

$$AWD_i = \sum_{j=1}^{J} AgWU_{ij} \tag{8}$$

Where AWD_{ij} is the agriculture water use (acre-ft) in year *i*, month *j*; AW_{ijk} is the applied water (acre-ft) in year *i*, month *j* and crop *k*; and AWD_i is the annual water use (acre-ft) in year *i*.

4.2.1.9 Agriculture model testing

Proper model evaluation and calibration are important for the prediction of hydrologic modeling studies, this process is often a comparison between theoretical or observed data and the predictions or outputs calculated for a set of assumptions estimated in the same conditions (B. S. Engel, D. White, M. Arnold, J. Arabi, M., 2007). Recommended evaluation techniques include the screening of a model with at least one dimensionless statistical test and one absolute error index. Then the calibration process which reduces uncertainty in model simulations involves a sensitivity analysis and then an automatic or manual calibration.

- *Model Evaluation*

The agriculture water demand calculation was evaluated by the comparison of an observed-predicted model taken from the USGS Report , the Integrated Hydrologic Model of Pajaro Valley, Fig. 40 of R.T. Hanson, Schmid, et al. (2014b)

AWD results were plotted and compared to the theoretical or observed agricultural water demand data, then four methods for model evaluation were assessed; three tests for the goodness of fit, which included the coefficient of determination (R^2), the index of agreement (d) and the coefficient of efficiency (NSE) and one error index test which was evaluated with percent bias (PBIAS). These validation models were chosen since there are commonly used in hydrologic and hydroclimatic models (da Silva, 2015; Legates & McCabe, 1999) as well as in watershed simulations (Moriasi et al., 2007). Results are shown in Section 5.1.1.

- *Model Calibration*

The calibration procedure started by a sensitivity analysis, the approach used in this study was testing the variability of the output by a step size perturbation of one input parameters at the time. The simplicity of the approach relies on the fact that the evaluated model is linear and has correlated parameters.

Visual evaluation showed that, the IE parameter was the most sensitive variable of all, likely because data for the total crop area (acreage, acreage factor, and percentage of crop) and the inputs used for the IR (ETo, ETh, precipitation and Kc) were obtain from the same sources as the theoretical model and these are fixed throughout the years.

Contrariwise, IEs are not fixed values, conferring to the CDWR (1994) irrigation efficiencies are poorly known and it changes from crop to crop and from farmer to farmer throughout time.

In this study, efficiencies were defined by the irrigation efficiency and by the percentage of use. Available data for Central Valley was accounted just for 2001 and 2010 meanwhile for the year 1999 data was unavailable for Central Valley, so it was assumed to be the average of the state of CA. According to R. T. Hanson, Schmid, et al (2014b), theoretical model efficiencies were adjusted to wet and dry periods during their model calibration. For instance, IE parameters were selected for manual calibration.

First, calculated IE data for each crop was split into two periods, (A) from 1995-2005 and (B) from 2005-2015, then the mean was calculated for both sets and each crop. These values were compared to the theoretical or observed IE means for each crop in Santa Cruz county in 2001 and 2010. Observed data for this step was personally received from the PVWMA. Calibration was performed yearly and manually by increasing or decreasing a number from a range of ± 0.06 to 0.14. This step was performed first visually, allowing the estimated AWD to fit the observed dataset plot. Then the average for period A and B were calculated for the calibrated values. Table 1, shows the calculated, observed and calibrated values for period A and B.

Table 1. Calculated, Observed and Calibrated irrigation efficiencies.

Crop	**Period**	**Calculated**	**Observed**	**Calibrated**
Truck Crops*	A	0.771	0.798	0.808
	B	0.794	0.755	0.770
Deciduous	A	0.623	0.676	0.623
	B	0.812	0.772	0.788
Vineyard	A	0.830	-	0.817
	B	0.857	0.850	0.857

***DWR** and PVWMA **classify truck crops as strawberries, vegetables, bush berries, artichokes, nurseries and other.**
Period A (1999-2015) B(2005-2015)
Observed values: PVWMA for Santa Cruz County

– *Model Validation*

An invalidation test of the simulated model was performed as a validation analysis; it is used as a quality control measure for hydrological and other predictive models. The test, presented by Bardsley and Purdie (2007), is based on random permutations of the model-generated predicted values which provide a simple method for testing the null hypothesis of a model’s invalidation data set.

4.2.2 Urban and Rural Input

Population growth and Water Use Per Capita (WUPC) are key factors to estimate the current and future water demand and urban water use.

4.2.2.1 Population growth

Decennial population data from 1860 to 2010 for the city of Watsonville was obtained from the US Census (2014). Historic records show how the population has grown from 398 in 1860 to around 51,200 inhabitants in 2010. To calculate a future trend, data was plotted and an exponential equation (9) ($R^2 = 0.965$) was calculated using the original census data.

$$UPG_i = (2.6401 \times 10^{-175}) \cdot (x^{54.292}) \tag{9}$$

Where UPG_i is the urban population growth (inhabitants) and *x is* the evaluated year.

From this exponential equation, decadal population growth was calculated again from 1950 to 2050 and an LRM ($R^2 = 0.9915$) was obtained from these results. Using Equation 10. it was possible to calculate an estimation of the population growth for every year from 1950 to 2050.

$$UPG_i = 939.82x - 1837306.8 \tag{10}$$

Where UPG_i is the urban population growth (inhabitants) in years and *x* the evaluated year.

Rural and municipalities population data obtained from the US Census (2014), the towns and settlements used for this study were: Aromas, Las Lomas, Corralitos, Freedom, and Pajaro. Retrieved data is from 2000 and 2010. As for the urban section, data was plotted and an LRM was obtained, (Equation 11) this equation was used to obtain the population for the years in between 2000 and 2010 only.

$$RPG_i = 85.4x - 157514 \tag{11}$$

RPG_i is the rural population growth (inhabitants) in years *i* and *x* is the evaluated year.

4.2.2.2 Water Use per Capita

The urban water use was first divided into two types: indoor and outdoor water use. Indoor use explains water used by household appliances including washing machines and dishwashers, as well as water used by sinks, showers, and toilets. Outdoor water demand applies for landscape irrigation.

Data for indoor and outdoor water demand was retrieved from R. Cahill *et al.* (2013) and by personal communication from PVWMA (2016).

For indoor water, daily use estimations were made for washing machines and dishwashers based on a regular use of 3 loads per week. The average water use efficiencies were used for these appliances, See Table 2.

Table 2. Average indoor water use per appliance.

APPLIANCE	MIN	AVG	MAX	UNITS
Traditional vertical axis laundry washers	45	37.5	30	gallons per load
Average dishwasher	9	11	12	gallons per load
Hand washing		20		gallons per day

The total indoor water use per person can be observed in Table 3. In general, a person in Pajaro Valley is estimated to use 67.8 gallons per day (gpd) (256.7 liters per day (Lpd)).

Table 3 Total indoor water use per appliance

Variable	QUANTITY	
Laundry	60.9	Lpd*
Dishwasher	17.8	Lpd*
Faucets	50.0	Lpm**
Shower	94.6	Lpm
Toilet	33.3	Lpf***
Total indoor water use	256.7	Lpd/person

*** Lpd: liters per day; ** lpm: liters per minute and *** lpf: liters per flush**
1 liter = 0.2642gallons gpd = gallons per day.

WUCOLS (2000) approach was used to estimate outdoor water use. This method uses Equation 6 from section 4.2.1.7 to estimate landscape irrigation. The Costumer division of the City of Watsonville considers the average yard area of 3000 sqaure-ft (278 m^2) planted with a cool season turfgrass with a Kc value of 0.8 normally irrigated by sprinklers systems with an estimated efficiency of 0.75. Furthermore, according to CIMIS the annual average of ETo is 38.67 ft (11.78 m). With this data outdoor water of landscapes is 7736 gallons (29284 liters) per house, per year.

Water Use per Capita (WUPC) was calculated yearly for the urban and rural population from 1999 to 2015. Then, for practical reasons, the WUPC of 1999 which was 163 gpd/person was used also from 1966 to 1998. At last from 2016 on, WUPC in the city of Watsonville was set to be 95 gpd/person assuming a conservation scenario. For rural areas, water use was set to be 29% of what the city of Watsonville uses. The premise of this assumption is the urban-rural population ratio for the year of 2000 and 2010. The proportions of the urban to the rural population, are 31% and 27% for those years, respectively, then the average of this ratio is 29%, the fraction used for the water use on rural areas.

4.2.2.3 Water Demand

Urban and rural water demand or water use were calculated annually using the population growth and the WUPC. See the set of Equations 12 and 13.

$$UWU_i = UPG_i \times UWUPC_i \tag{12}$$

$$RWU_i = RPG_i \times RWUPC_i \tag{13}$$

Where UWU_i is the urban water use in acre-ft per year (AFY) and RWU_i is the rural water use (AFY) in years *i*. UPG_i and RPG_i is the annually urban and rural population growth in years in years *i*; and the $UWUPC_i$ and $RWUPC_i$ is the urban and rural Water Use Per Capita in years *i*.

As a whole, urban and rural water use can be designated as Equation (X).

$$PWU_i = UWU_i + RWU_i \tag{14}$$

Where PWU_i is the population water use and UWU_i is the urban water use and RWU_i is the rural water use in years *i*.

4.2.3 Supplementary Water Input

Supplementary water inputs of the model are 1) the Harkin Slough Project (HSP), which has recharge and recovery wells, 2) the recycled water that enters to the waste water treatment plant (WTP) and 3) potable blend wells.

Recharge wells from the HSP are destined to infiltrate, during high flows, diverted water from Harkins Slough to a recharge basin, then this recharge water is partially recovered through the CDS when agriculture users need it. The recycled water from the city enters to the WTP where is treated and mixed with water from the city and PVWMA blend wells or from the recharge wells of the HSP. This is made to achieve the water quality needed for irrigation or disposal to the sea.

Data from 2002 - 2015 was retrieved from two sources; the first is by the Basin Management Plan Update by PPVMA (2013) solely for 2009, 2010 and 2011 for the three supplementary inputs, and from 2002 to 2012 just for the HSP. The second source was from personal communication with PVWMA (2016), from 2002 to 2008 and from 2012 to 2015 for the three inputs.

Total supplementary water is calculated using the set of Equations 15 and 16.

$$BW_i = BWcity_i + BWpv_i + BWhs_i \tag{15}$$

$$SW_i = RW_i + BW_i \tag{16}$$

Where SW_i is the supplementary water (acres-ft), RW_i is the recycled water (acre-ft) and BW_i is the blend wells (acres-ft), $BWcity_i$ is the water of the blend wells from the city (acre-ft), $BWpv_i$ is water of the blend wells from PVWMA (acre-ft) and $BWhs_i$ is the recovered water from the HSP (acre-ft). All variables are in years i.

4.2.4 Aquifer Recharge Input

Aquifer recharge takes place by two events, precipitation, and irrigation. However, it is important to stipulate that in this study, for both events, soil properties were not taken into account, thus surface runoff was negligible, therefore excess of rainfall and irrigation that percolates into the groundwater was considered after ET was satisfied.

Equation (17) shows how precipitation recharge is calculated.

$$PR_{ij} = \sum_{j=1}^{J} \left(P_{ij} - ETC_{ijk}\right) \times (A_{jk}) \tag{17}$$

Where PR_{ij} is the precipitation recharge (acre-ft) in years *i* and months j, P_{ij} is the precipitation (ft) in years *i* and months j, ETc_{ijk} is the crop evapotranspiration (ft) for year *i*, month *j* and type of crop *k* and A_{jk} is the total crop area (acres) in years *i* and type of crop *k.*

Then irrigation recharge is calculated by Equation 18.

$$IRe_{ij} = \sum_{j=1}^{J} AW_{ijk} - \left(ETC_{ijk} \times A_{jk}\right) \tag{18}$$

Where IRe_{ij} is the irrigation recharge (acre-ft) in years *i* and months *j*; AW_{ijk} is the applied irrigation water (acre-ft) in years *i*, months *j* and type of crop *k;* ETc_{ijk} is the crop evapotranspiration (ft) for year *i*, month *j* and type of crop *k* and A_{jk} is the total crop area (acres) in years *i* and type of crop *k.*

Then the total recharge is calculated using the Equations 19 and 20.

$$R_{ij} = \; PRij + \; IRe_{ij} \tag{19}$$

$$R_i = \sum_{j=1}^{J} Rij \tag{20}$$

Where R_{ij} is the total recharge (acre-ft); PR_{ij} is the precipitation recharge (acre-ft) and IRe_{ij} is the irrigation recharge (acre-ft) in years *i* and months *j*; and R_i is the total aquifer recharge (acre-ft) in *i* years.

Observed data for aquifer recharge was obtained from the USGS report (R. T. Hanson, Schmid, et al., 2014b) from 1996 to 2009. This was used to compare the calculated net groundwater inflow.

4.2.5 *Aquifer Storage Mass Balance*

Overall, the net groundwater budget consists of the inflows and outflows of the system which represent the aquifer storage of Pajaro Valley. Inflows to the aquifer are the recharge from precipitation, recharge from irrigation and the HSP recharge wells. Outflows involve the agricultural pumpage, the municipal (urban and rural) potable wells and the blend wells from the city and from PVWMA.

Equation 21 express the inflows of the system

$$I_i = (PRi + IR_i + HSR_i) \times 1000 \tag{21}$$

Where I_i is the inflow of the aquifer, measured in thousand acre-ft (TAF), PR_i is the precipitation recharge (acre-ft) and IR_i is the irrigation recharge (acre-ft) and HSR_i is the Harkin Slough recharge wells (acre-ft) in years *i*.

Meanwhile, the outflows of the system can be calculated by Equation X.

$$O_i = PWU_i + BW_i + (AWD_i - RW_i) \times 1000 \tag{22}$$

Where O_i is the outflow (TAF), PWU_i is the population water use (acre-ft), BW_i is the total blend wells (acre-ft), AWD_i is the agricultural water use (acre-ft) and RW_i is the recycled water from the city (acre-ft). All variables are in years i.

4.3 Economic Input

This section of the study comprises three main aspects that cover the economic balance of Pajaro Valley: 1) agriculture cost of production (COP), 2) crop income and 3) water costs.

The agriculture sector includes the cost of water (groundwater and delivered or supplementary water), energetic pumping costs and costs of production (i.e. land preparation, fertilization etc.). Whereas municipal (urban/rural) sector costs include; the cost of water and the energetic pumping cost.

It is important to state that costs and revenues were considered using the consumer price index or inflation rate from the year 2015.

4.3.1 Cost of Production

Pajaro Valley agriculture costs of production (COP) of crops can be observed in Table 4. Data was obtained from the *Current cost and Return Studies* from the Cooperative Extension of the Agricultural and Resource Economics of UC Davis (2016). For strawberries, vegetables, bushberries, artichokes, apple trees and others, COP report was obtained from the Central Valley region, meanwhile vinegrape report was retrieved from San Joaquin Valley South region and nurseries costs were obtain from the *Agricultural Alternatives* report from the Pen State University Extension (2014).

Practices and materials used to calculate COP are; land preparation, plant establishment, fertilization, pest management, harvest, labor, equipment costs, property taxes, insurance, office expenses, food safety program, irrigation system, land rent, sanitation services and management salaries.

Table 4. Cost of Production per crop

CROP	YEAR	COP PER ACRE	REFERENCE
Strawberries	2010	$43,107	(UC Cooperative Extension, 2010)
Vegetables	2015	$10,257	(UC Cooperative Extension, 2015)
Bushberries	2012	$35,671	(UC Cooperative Extension, 2012b)
Vinegrapes	2012	$4,632	(UC Cooperative Extension, 2012a)
Artichokes	2004	$10,257	(UC Cooperative Extension, 2004)
Deciduous	2014	$4,997	(UC Cooperative Extension, 2014)
Nurseries	2014	$117,315	(PS Cooperative Extension, 2014)
Other	2015	$15,204.56	Average of vegetables, bush berries and artichokes

4.3.2 Income

Crop values were obtained from 1966 to 2014 from *the Crop Reports and Economic Contributions of Monterey County* and from the *Annual Crop and Livestock Reports of Santa Cruz County*. Crop incomes represent gross values and it does not represent net profit or loss. Table 5. represents the average of income per acre for the years 2010-2014.

Table 5. Average crop income per acre

CROP	INCOME PER ACRE
Strawberries	$69,351
Vegetables	$31,404
Bushberries	$59,823
Vinegrapes	$4,535
Artichokes	$9,235
Deciduous	$5,796
Nurseries	$186,790
Other	$26,509

4.3.3 Cost of Water

The cost of water in Pajaro Valley is defined by the water price and the energetic cost it takes to pump water from the wells, see Equation 23.

$$COW = WP + (EC \times D) \tag{23}$$

Where *COW* is the cost of water ($ per acre-ft), *WP* is the water price ($ per acre-ft), *EC* is the energetic cost of pumping water ($ per acre-ft per ft) and *D* is the well depth (ft). Details can be found in the next sections.

4.3.3.1 Water Price

Water rates are established by the city of Watsonville and PVWMA. Users are charged according to its location, in Figure 13 two different main zones can be observed, the delivered water zone in purple and the outside delivered water zone in white. Overall in Pajaro Valley there are three types of agriculture users, 1) outside metered users (OMU) shown in the white area of the map, 2) inside metered users (IMU) and 3) delivered water users (DWU), were the last two are found in the purple area of the map. In addition, there are water cost rates for urban and rural residential areas. Data from 2000 to 2020 were obtained from the City of Watsonville Public Works & Utilities Department. However, since 2012, augmentation charges were applied, Table 6. shows the cost of service rate and the average increase from 2015 to 2020.

Table 6. Cost of water service rate from 2015 to 2020.

COST OF SERVICE RATE

YEAR	Urban residential	Rural residential	Delivered water (DWU)	Coastal Irrigation (IMU)	Inland Irrigation (OMU)
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	6.60%	6.00%	3.00%	9.50%	9.50%

Then to estimate the values from 2020 to 2040 an LRM from 2010 to 2020 was used to determine the future prices, which may be different from reality but we tought this is a close approximation given the average increase of the next years.

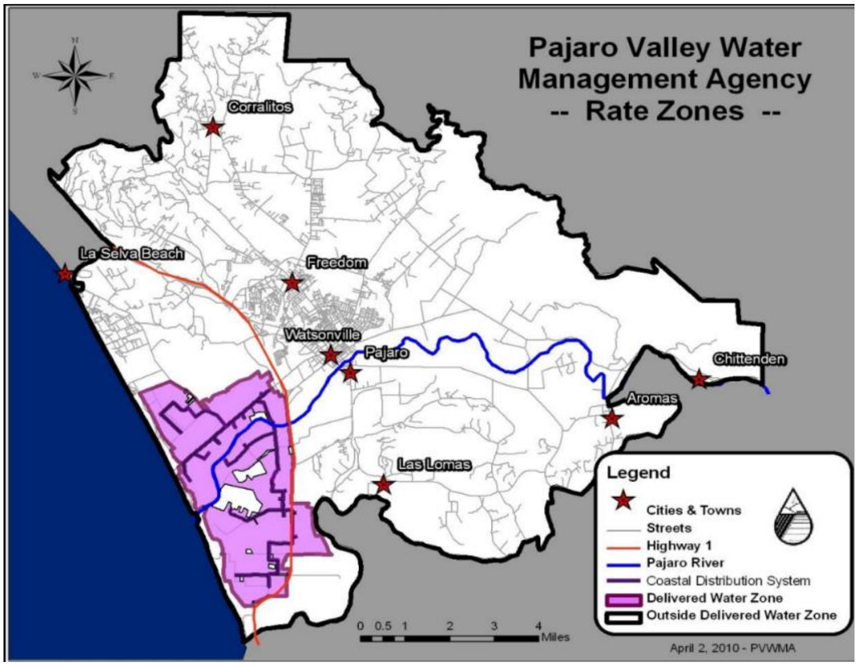


Figure 13. Pajaro Valley water rate zones. (PVWMA, 2010)

4.3.3.2 Energetic costs

Energetic costs for pumping water were obtained from the report “Comparing the Costs of Electric Motors and Engines for Irrigation Pumping” by Sandoval-Solis, Silva-Jordan, & Zaccaria, (2015). In this study, pumping is assumed to be using electrical energy, where the cost ranges from $0.18 to $0.20 from 2006 to 2013.

Wells depth

Wells depth in Pajaro Valley was obtained from the technical memorandum “Distribution of Groundwater Nitrate Concentrations in Pajaro Valley, CA” by Peter Leffler. In this study, a total of 1,706 domestic wells were screened where the maximum depth was 1,260 ft (385.05m) and the minimum 30 ft (9.14 m), the average depth is 297 ft (90.52m). Then for the municipal/public use 52 wells were screened, the maximum well depth has 1,500 ft (457.2m) and the minimum, 152 ft (46.33m), the average well depth was set as 431 ft (131.37m).

4.4 Optimization Model

This section introduces the developed optimization model for maximizing the annual net return with an optimal allocation of crop acreage and the available water resources. The algorithms used are two techniques, linear optimization and genetic algorithm technique.

4.4.1 Linear Programming

Linear optimization normally called Linear Programming (LP) is a mathematical technique used to maximize or minimize functions subject to linear equality or inequality constraints. The algorithm is based on the convex optimization theory, where the linear function equation works on a feasible region normally set as a polyhedron. The algorithm searches for intersections defined by the objective function, where minimizing or maximizing are looked.

LP is used widely for a numerous arrange of fields, it goes from water management resources for groundwater (Karterakis, Karatzas, Nikolos, & Papadopoulou, 2007) to chemical engineering for multi processes (Blömer & Günther, 1998) then it can be applied in ecology for adaptive management (Walters & Hilborn, 1978) and also for economic problems (Zhou & Ang, 2008).

4.4.2 Genetic Algorithm

Genetic Algorithms (GA) is a probabilistic approach based on the premise of evolutionary processes, GA procedure is based on the Darwinian principle of the survival of the fittest (Mardle & Pascoe, 1999). This optimization approach is used as an alternative to traditional linear optimization models when the analyzed problem contains a large number of non-linear interactions. Furthermore, this approach has been applied in several cases such as water recovery (Liu, Agarwal, & Li) industrial manufacture (Tasan & Tunali, 2008), biogas production (Abu Qdais, Bani Hani, & Shatnawi, 2010), ecological forecasts (Record et al., 2010) among others.

The concept of evolution happening on GA starts by stochastically developing generations of individuals (solutions) using a given fitness function, this is the objective function in a mathematical problem. Each individual has a defined genetic code which in this case resembles the variables used to differentiate one from another, then the individuals are evaluated using the fitness function, which drives to the optimal solution. After the first evaluation, a portion of the weaker individuals, with less desirable fitness values, are discarded by natural selection from the generation and the stronger individuals that survive will be used for the crossover or reproduction for the next generation whose fitness will be successively evaluated. An appropriate mutation factor used to randomly modify the genes of an individual is used to develop new generations. The process is repeated until the optimal population of selected individuals with the best individual fitness is located. This is when the algorithm has reached convergence meaning all individuals have similar fitness values.

A brief outline of the implementation of the GA is described below:

Initialization	• Random starting generation of k individuals is set.
Fitness function and evaluation	• A fitness function is developed and each individual is evaluated with it.
Selection	• A proportion of the fittest individuals are selected to breed new generations.
Genetic operators	• Natural selection, crossover and mutation define the next generations to be evaluated and selected.
Termination	• The generational process is repeated until convergence is reached.

4.4.3 *Objective Function*

The objective function of both optimization procedures is maximizing the annual net revenue or profit by optimal allocation of crop patterns and available water resources to 8 types of crops in the inland area and 5 types of crops in the coastal area. Equation (24) shows the mathematical objective function

$$\max \quad F = \sum_{i=1}^{8} [B_i^n A_i^n - (A_i^n \times CD_i) CW_{in}] + \sum_{c=1}^{5} [B_c^n A_c^n - (A_c^n \times CD_c) CW_c] \tag{24}$$

Where $B_{i/c}^n$ represent the monetary benefit (crop costs minus crop revenue) and $A_{i/c}^n$ represents the allocated acreage of crop, where for both variables i stands for inland and c for coastal in year n;

$CD_{i/c}$ is the crop duty or how much water per acre the crop needs, where i stands for inland and c for coastal, and CW_{in} and CW_c are cost of water for inland and coastal agriculture.

As it can be observed the first term of equation represents for inland agriculture, where the summation stands for 8 types of crop while the later represent the coastal agriculture with just 5 crops.

4.4.4 Model Inputs

The model inputs used for the optimization algorithms, in order are: for the benefit variable *B*, the cost of agriculture production (section 4.3.1) and the agriculture revenue (section 4.3.2); for *A*, the acreage of each crop (section 4.2.1.2); for *CD* the agricultural water demand or crop duty (section 4.2.1.8) and for *CW* the cost of water (section 4.3.3).

4.4.5 Model Constraints

Historic data from the year 2000 to 2015 was analyzed for setting the constraints for water allocation. Main constraints are identified as, land availability which means a range of area in which the crops should be grown, the crop duty or water requirement which is the specific amount each crop needs to fulfill and CD values where set as the average from 2002 to 2015 and at last the cost of water was another constraint, in which these values change every year.

Limitations and constraints are listed as follow:

1) Land availability: The total acreage for inland and coastal areas should not exceed 10,961 and 9,591 acres respectively because of the available cultivable land.
2) Water availability: The optimization problem in hand is an annual model which consider total available water for a year. It means water demand by crops must be equal or smaller than available water.

3) Maximum and minimum crop acreage: As land availability for inland and coastal total areas, each crop has certain maximum and minimum available acres, the following dictates the highest and lowest amount of acres.
    a. For inland crops: strawberry acreage has to be less or equal than 2918 and more or equal than 577 acres. Vegetable acreage has to be less or equal than 2507 and more or equal than 506. Bush berries has to be less or equal than 4160 and more or equal than 2125 acres. Vinegrapes has to be less or equal than 164 but less more or equal 10 acres. Artichokes should be less or equal than 256 and more or equal than 34 acres. Deciduous has to be less or equal than 2219 and more or equal than 1224 acres. Nurseries has to be less or equal than 145 and more or equal to 107 acres. Other has to be less or equal than 657 and more or equal than 72 acres.
    b. For coastal crops: strawberry acreage has to be less or equal than 4378 and more or equal than 866 acres. Vegetable acreage has to be less or equal than 5849 and more or equal than 1180. Artichokes should be less or equal than 110 and more or equal than 15 acres. Nurseries has to be less or equal than 97 and more or equal to 72 acres. Other has to be less or equal than 657 and more or equal than 148 acres.
4) Crop Duty
    a. For inland: strawberry, vegetables, bush berries and nurseries: 2.8 acre-ft/acre, vinegrapes: 2.3 acre-ft/acre, artichokes: 1.5 acre-ft/acre, deciduous 1.2 acre-ft/acre, and other 1.6 acre-ft/acre.
    b. For coastal: strawberries and nurseries: 2.6 acre-ft/acre, vegetables: 2.7 acre-ft/acre, artichokes: 1.5 acre-ft/acre, and other 1.5 acre-ft/acre.
5) Demand constraint: Based on historical data, the acreage of vegetable should be 40

percent greater than strawberry,

4.4.6 Model Software

Both models where coded in MATLAB by the Water Resource Management Research Group of the University of California Davis. The LP optimization model was solved using the interior point method provided in the optimization toolbox of MATLAB. On the other hand, the GA optimization model had 13 decision variables, these are the 8 inland crops and 5 coastal crops. The population size of each generation was set to be 20 and the total number of generation were 10,000. In order to select the parents, a binary tournament selection operator was used, this method of selection involves running several "tournaments" among few individuals chosen at random from a population, the winner with the best fitness or best score of the fitness objective is selected for crossover. Then, to ensure diversity a bit string mutation was operated during evolution, this mutation used the probability of "1/number of decision variables" in this case 13. The previous means that 1 of every 13 bits or variables will be selected for mutation.

After obtaining results from the optimization modelling for LP and GA, the new projections for acreages were exported from MATHLAB to WEAP.

4.5 Simulation - Optimization Model Coupling

Microsoft Visual Basic was utilized to couple WEAP with Excel, where WEAP results were exported to Excel. The initial aquifer storage of Pajaro Valley was set to be 1800 thousand acre-ft (1850.22 million m^3), WEAP was programmed to do 50 runs (1966 to 2015) for a time frame of 25 years, the first run started from 1966 to 1991 then the next will start from 1967 to 1992 and so on until the last run from 2015 to 2040 was reached. The processing time for each run is 2.5 minutes giving a total of 30 minutes for the complete run.

Three scenarios were run with the model coupling; Baseline scenario, LP scenario and GA scenario. The Baseline scenario follows the actual trend; it shows how a future projection is observed without any modification on water or land use. Then the optimized scenarios are the LP and GA, both play with the optimal allocation of land use, given by the specific optimization process used, also for both optimized scenarios, available water was stipulated to decrease every 5 years an amount of 4 TAF (4.9 million m^3), starting in 2016 with an available water of 51 TAF (62.9 million m^3) until reaching a maximum of 40 TAF (49.3 million m^3) by 2030 and maintaining it onto 2040.

5 RESULTS

5.1 Simulation Model

5.1.1 Initial Agricultural Water Demand

The initial evaluation is presented in Figure (14). Statistical screening shows an R^2 of 0.787, which means that around 79 percent of the total variance of the observed model can be explained by the predicted model. As an improvement for the coefficient of determination, the index of agreement, which is overly sensitive to extreme values (Legates & McCabe, 1999) showed a value of d=0.706. Meanwhile, NSE gave an unacceptable performance value of -1.199. According to Moriasi et al. (2007), NSE values between 0.0 and 1.0 are acceptable values of performance whereas values ≤0.0 indicates that the mean observed value is a better predictor than the simulated value. The PBIAS, which measures the tendency of the simulated data to be larger or smaller than the observed counterparts, had a value of 0.307. This indicates that the simulated model underestimates the observed model.

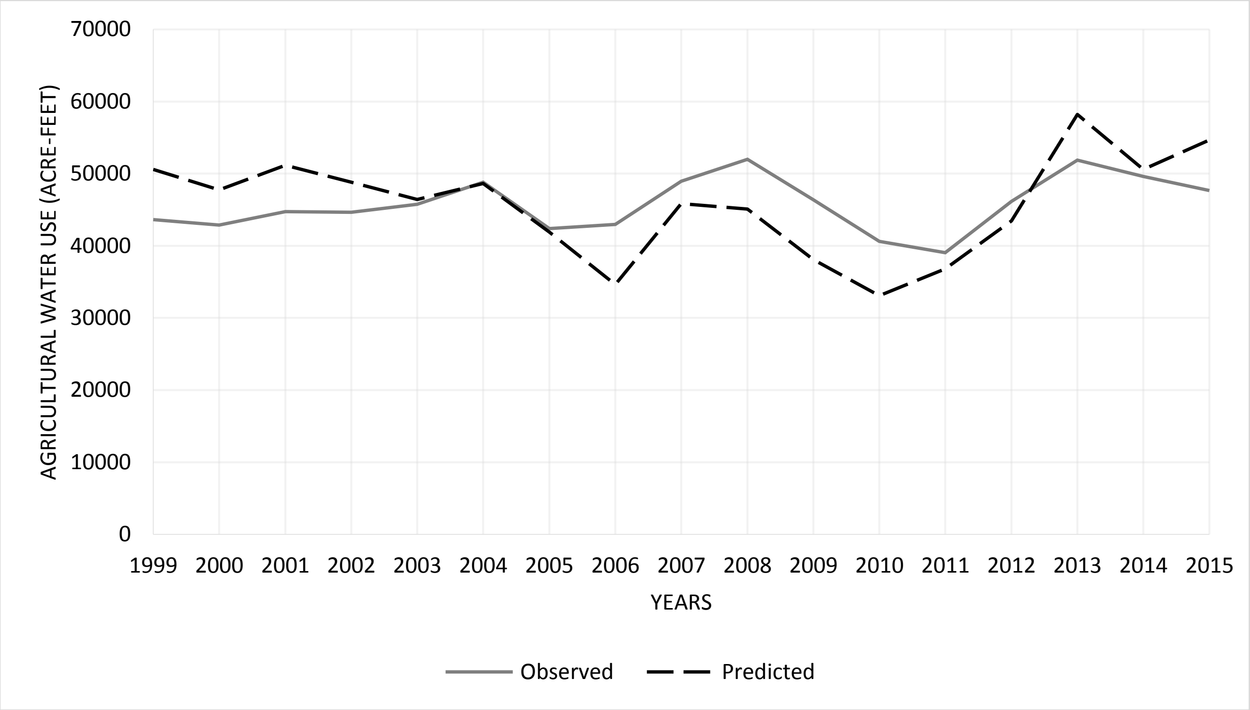


Figure 14. Initial model evaluation for agriculture water demand.

5.1.2 *Calibrated Agricultural Water Demand*

The new model results, after calibration, were then plotted (Figure 15). Visual results showed that the calibration enabled better fitting of the tested parameter. Statistical analysis showed better correlation for the goodness of fit tests. R^2 increased to 0.907 as well as the index of agreement with a value of d= 0.892. For the coefficient of efficiency or NSE, which previously showed an unacceptable negative value of -1.199, the value increased to a positive result of 0.559. The PBIAS analysis changed from a positive underestimated value to -2.32.

The recommended criterion for evaluating the performance of the model was compared to Table 3, of M.G. da Silva et al. (2015). The statistical criterion for NSE and PBIAS showed an acceptable and a very good classification of performance, respectively.

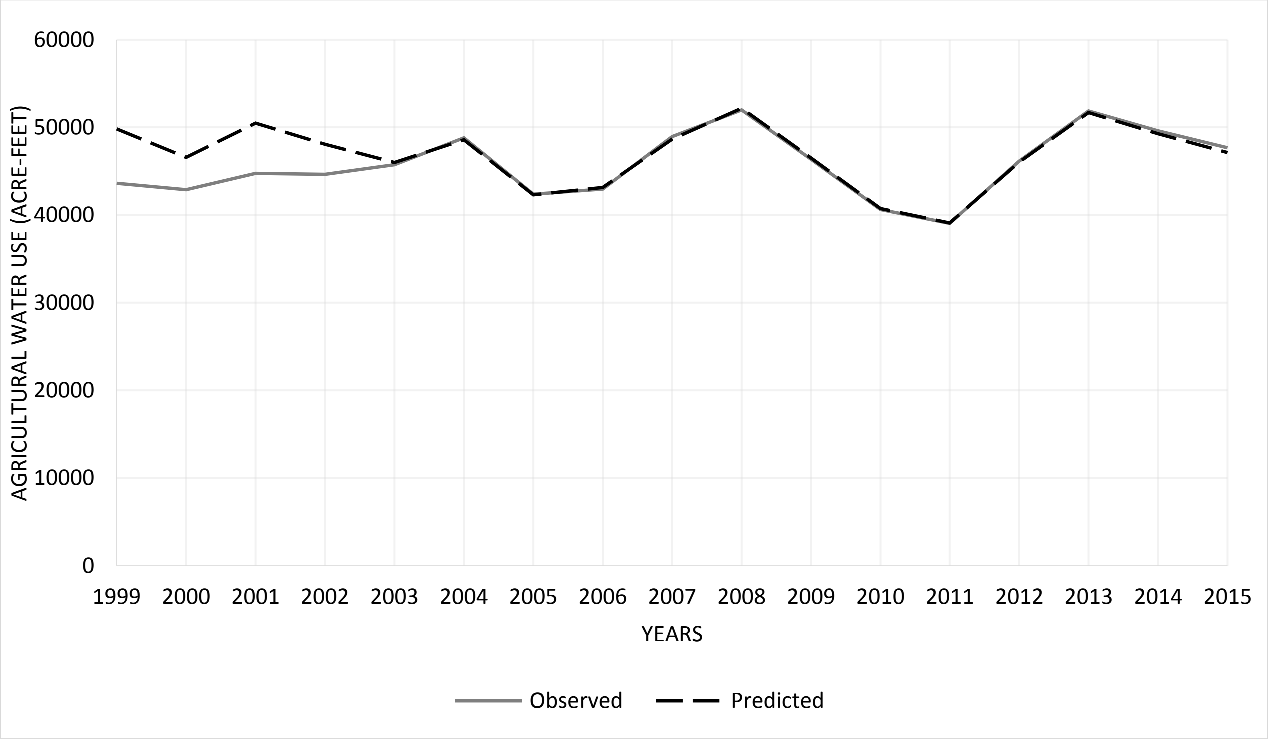


Figure 15. Calibrated model evaluation for agriculture water demand.

The invalidation test was tested for the uncalibrated and calibrated model. 10,000 random permutations and the three goodness of fit test previously used (R^2, d and NSE) were the parameters used. The test for both models gave a *p-value* < 0.05 which rejected the null hypothesis of an invalid predictive model, therefore the calibrated model can be used as an input parameter for the overall modelling of Pajaro Valley

5.1.3 Urban and Rural Water Demand

The annual water demand for both urban and rural areas is shown in Figure (16). In general, water use has been virtually consistent during the last 15 years despite a population increase of 30%. This scenario has to do with their conservation program and projects implemented by PVWMA. As mention before from 2016 on, urban WUPC was set to be 95 gpd (360 lpd), remaining the same for the next 24 years. On the other side for the rural areas the water use was set to be 29% of the urban water use.

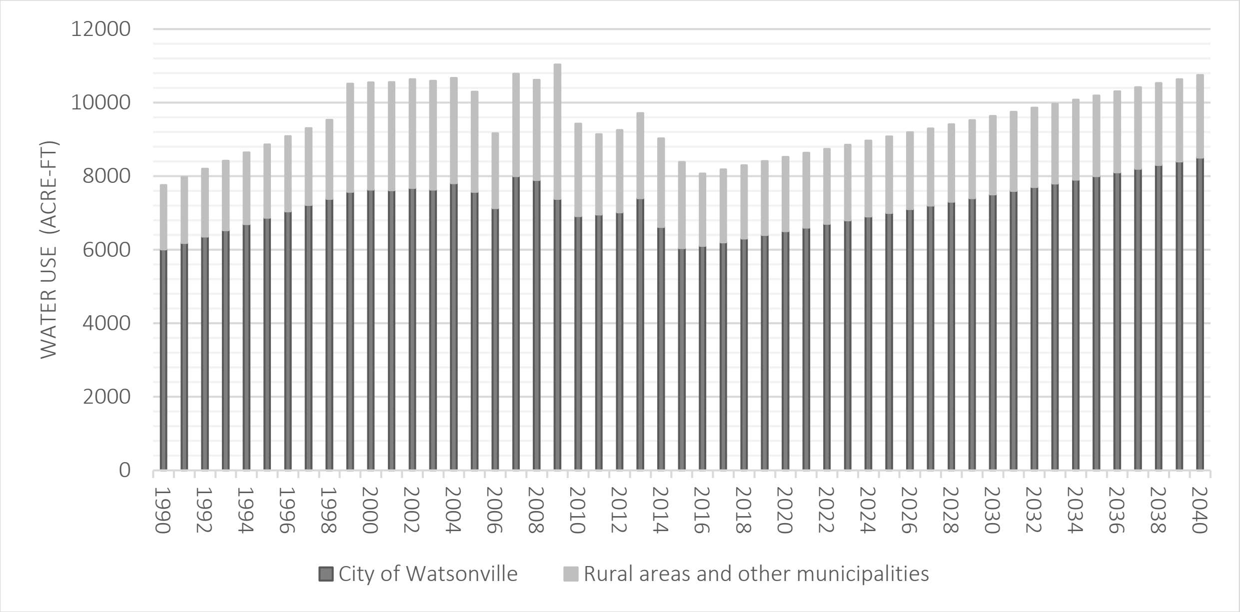


Figure 16. Urban and rural water use.

Regarding the highest point of the 50 years showed, for the urban population was 8005 acre-ft (9.87 million m^3) in 2007 and the lowest point was 6042 acre-ft (7.45 million m^3) in 2015. Rural areas and other municipalities have their highest point on 2009 with a value of 3653 acre-ft (4.50 million m^3) and its minimum point on 2016 with a value of 1970 acre-ft (2.42 million m^3). In general, it can be observed a light increase for the next years, however water use does not overpass the highest amount of water use from previous years, as mention before the conservation efforts from the city of Watsonville and PVMA have helped significantly to maintain water levels in equilibrium despite population growth.

5.1.4 Recharge

Aquifer recharge by irrigation and precipitation was calculated monthly from 1966 to 2015. For visualization purposes Figure (17) shows the monthly average recharge in acre-ft for irrigation and precipitation.

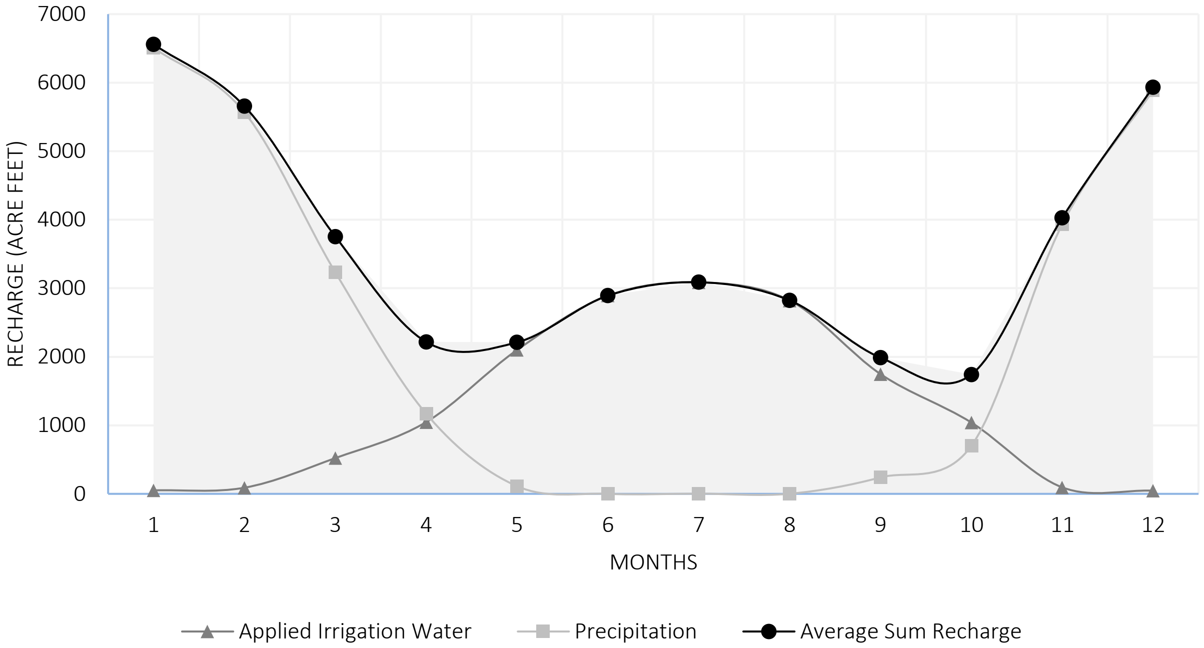


Figure 17. Effective irrigation water and precipitation recharge of Pajaro Valley aquifer.

The gray area indicates the total water recharge from both events. It is noticeable how the aquifer gets most of its recharge during wet months; November, December, January and February where precipitation is most likely to occur. At the same time, at this period, irrigation water remains quite low, with values ranging from 45 to 95 acre-ft (55 thousand and 1.17 million m^3). Then during the dry months of June, July and August, irrigation water that percolates can reach from 2000 to 3100 acre-ft (2.46 and 3.82 million m^3) meanwhile precipitation has null activity during June and July to 112 acre-ft (138 thousand m^3) for May and August.

5.1.5 Net Groundwater Storage

Major inflows and outflows utilized in the hydrologic cycle of the Pajaro Valley groundwater system are shown in Figure (18). The period evaluated is dated from 1996 to 2009, and data is measured in thousand acre-ft (TAF) (1 TAF = 1,233,482 m^3). Results from the calculated aquifer storage mass balance are revised and contrasted with the Pajaro Valley Hydrologic Model (PVHM) from the PVWMA (R. T. Hanson, Schmid, et al., 2014b).

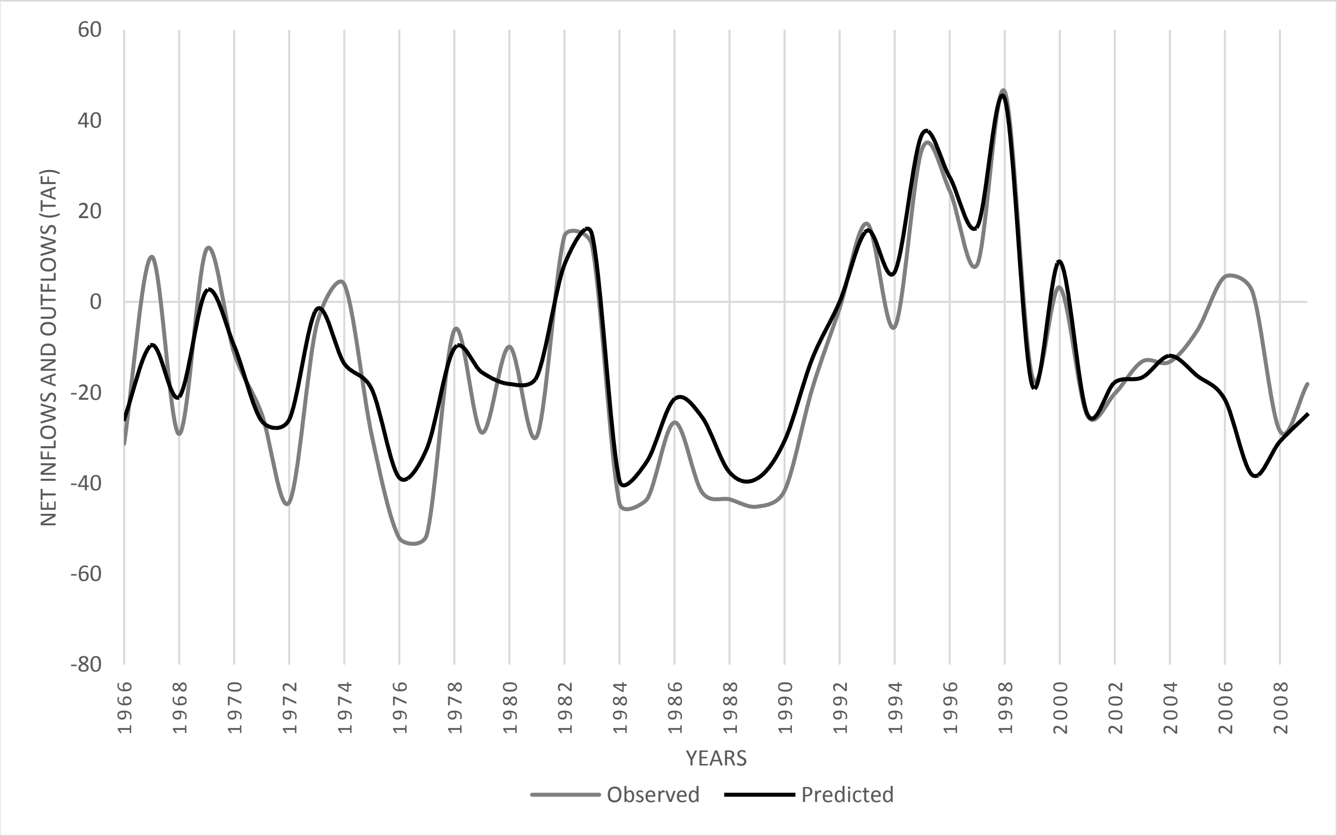


Figure 18. Net groundwater evaluation for simulation modelling from 1966 to 2009

Estimated or predicted inflows range from 20 to 80 TAF (24.6 to 98.6 million m^3) and theoretical inflows range from 13 to 84 TAF (16 to 103 million m^3). On the other hand, estimated outflows range from 33 to 80 TAF (40.7 to 98.6 million m^3) and the observed outflows range from 25 to 73 TAF (30.8 to 90 million m^3). The temporal distribution of inflows and outflows depend merely on climatic influence, meaning that storage replenishment is more likely to occur during wet years, this allows to counter balance depletion from dry years.

Groundwater pumpage is dominated by agricultural practices, being an average of 13.5 times more than the urban and rural water demand. Blend wells and the HS recovery well are a small portion of the total outflow, ranging from 0.45 to barely 1.6 TAF (.55 and 1.97 million m^3), while agricultural wells pump a range of 33 to 80 TAF (40.7 and 98.6 million m^3). Distinctively, recharge to the aquifer from precipitation plays a major role in deep percolation. Rainfall can reach up to 36 TAF (44.4 million m^3) in one month while effective irrigation can reach up to 6.3 TAF (7.7 million m^3) in one month.

The overall groundwater net storage result in an annual overdraft of -12.82 TAF (-14.8 million m^3) as for the PVHM resulted in -12.95 TAF (-15.9 million m^3). Statistical analysis on the aquifer storage gave an R^2 of 0.945, meaning that nearly 95% of the variation can be explained by the estimated groundwater model. The index of agreement gave a value *d* of 0.932, the value denotes that 93% of model prediction error can be accounted for the estimated model. The coefficient of efficiency NSE showed a value of 0.699 representing an acceptable level of performance from the predictive model. At last, for the error index, the PBIAS analysis showed a value of 5.4 meaning an underestimation bias and a good performance.

As in the previous results section, the statistical criterion for NSE and PBIAS showed good and very good classification of performance, respectively for the recommended criterion of model performance evaluation by M.G. da Silva et al. (2015). For instance, the proposed groundwater simulation can be used for further analysis as in this case is the optimization model and no calibration procedure is needed.

5.2 Optimization Model

5.2.1 Optimized Acreages

The optimization of acres was obtained from the LP and GA algorithms. Figure 19. shows the acreages from 2000 to 2040 for the Baseline, GA and LP scenarios in form of stacked histograms and the available water in TAF per year. To start, all scenarios begin in the year of 2000 with approximately 20 thousand acreages (8093 ha) and 50.7 TAF (62.5 million m^3). For the next 15 years the trend looks to diminish until the year 2009 by 15 thousand acres (6070 ha) and water use of 40.5 TAF (49.9 million m^3) and then increase again to 21 thousand acres (8498 ha) and 51 TAF (62.9 million m^3) by 2015. From 2016 on, acres where optimized in relation to the available water for future projections. In the baseline scenario it was proposed that every year from 2016 on, available water sought to be 51 TAF (62.9 million m^3), even though it is more likely that every year fluctuates, 51 TAF (62.9 million m^3) was propose just to observe a constant value for future years. However, for GA and LP optimization, the available water was set to be only 40 TAF (49.3 million m^3) for the last 10 years of the prediction. The crop's acreage that suffered the greatest modification are the bushberries, regarding its economic revenue and water use, this crop tends to be allocated within its maximum acres available, the same applies to nurseries, strawberry and vegetables. On the other side, the acreages that tend to be minimized are deciduous, vinegrapes, artichokes and other in consequence of its low revenue. Also, a comparison between the two algorithms, shows that acres modified by GA show randomness between the acres for every crop, it means that acres are changing every year. On the other side, LP acres are maintained or changed constantly and gradually. This is mainly because of the nature of the algorithm, GA plays with randomness and searches from thousands of possibilities meanwhile LP looks every time for the maximum revenue possible.

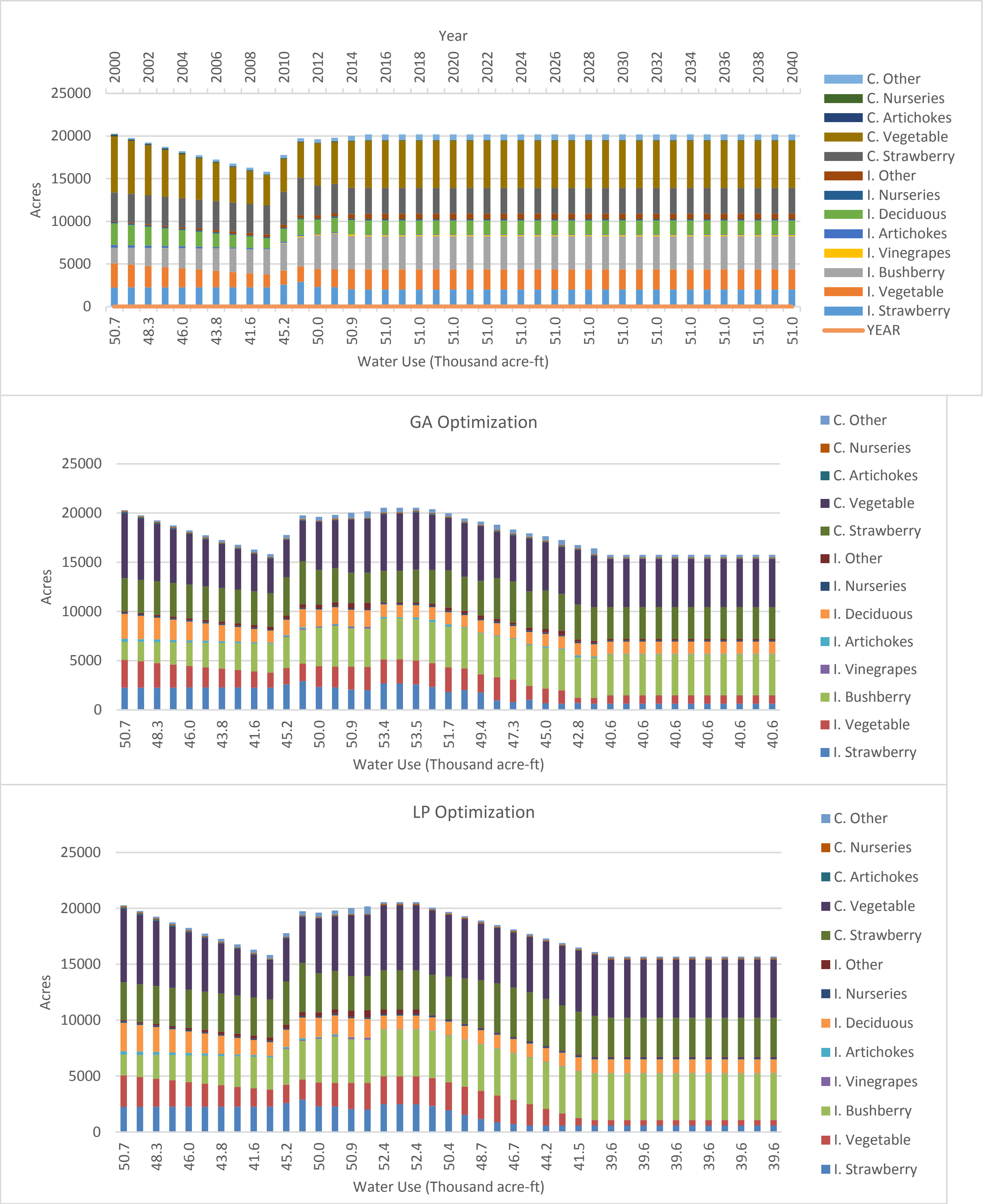


Figure 19. Land use (acres) vs Water use (TAF), projection from 2010 to 2040
Top plot: Baseline scenario, Middle plot: optimized GA scenario, bottom plot: optimized LP scenario.

5.2.2 Hydroeconomic model, a comparison between LP and GA algorithms

Results from the LP and GA algorithms were obtain in order to find the maximum profitability in relation to the available water for agriculture. The maximum economical return was also related to those crops with higher cost-benefit, as mention before, both algorithms tend to increase the number of acres for bushberries, strawberries, nurseries and vegetables since these have higher profitability.

The revenue and water use for both algorithms were compared in Figure 20. In general, the revenue of LP shows higher monetary benefit than GA, the average difference is around 2 million dollars. In a hypothetical scenario of available water ranging from 80 to 61 TAF (98.6 to 75.2 million m^3), the total revenue ranges from 290 to 279 million dollars for both LP and GA. However, if the minimum target of available water for optimized scenarios is going to be set at 40 TAF (49 million m^3) the revenue is reduced in a yearly average by 2.4%. This means a decrease of around 5 million dollars per decrease of 1000 acre-ft from the available water

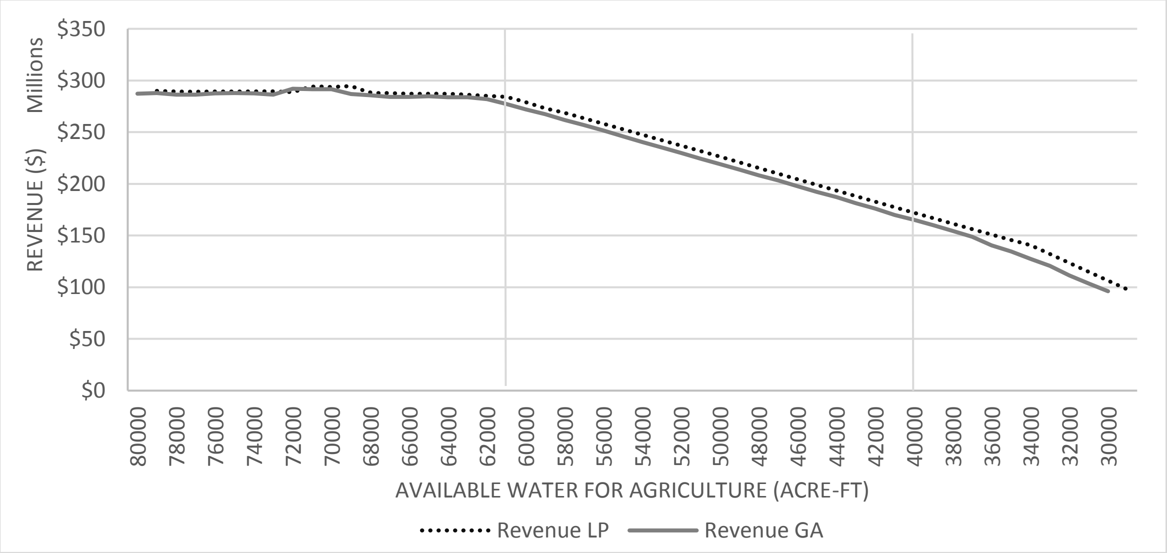


Figure 20. Net Revenue vs Available water for agriculture, a comparison between optimized LP and GA models.

After comparing both algorithms, and seeing how revenue is reduced as available water decreases, a future time lapse of 25 years for water use vs revenue was analyzed for three scenarios; a baseline or current year, and the two optimization models LP and GA (See Figure 21).

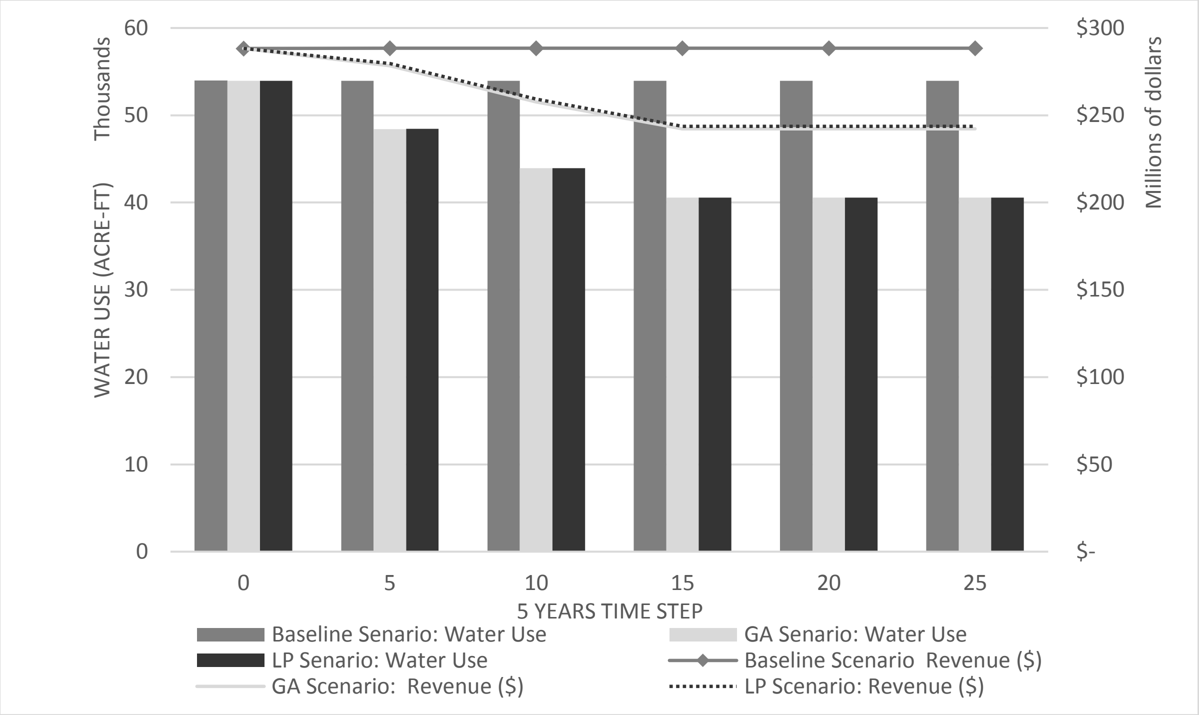


Figure 21. Comparison of water use and net revenue between Baseline, GA and LP scenario for a 25-year scenario.

The baseline scenario takes the 2015-year data for the acreages grown. The initial water use for all scenarios was set to be 53 TAF (65 million m^3) which is the average of the water use of the past 30 years (1985-2015). The baseline scenario used this amount of water throughout the 25 year lapse meanwhile the optimized scenarios were set to decrease its water use by 4 TAF (4.9 million m^3) for the next 10 years, then by 5 TAF (6.1 million m^3) when reaching 15 years, ending with a total of 40 TAF (49.3 million m^3) of available water. Then, for the next 15 years, this amount will be maintained constantly as 40 TAF (49.3 million m^3). By applying this decrease in water use, a total amount of 13 TAF (16 million m^3) will be reduce, which match with the overall net groundwater overdraft of -12.82 TAF (-15.8 million m^3). Figure 21, shows how the reduction of water use for agriculture affects the total revenue, while the baseline scenario remains constant with a total revenue of 288 million dollars and using a 54 TAF (54 million m^3) the LP scenario decreases 45 million dollars and the GA scenario decreases 46 million dollars reaching an amount of 243 and 242 million dollars respectively by decreasing its water use by 13 TAF (16 million m^3).

5.2.3 Food Production

Food production is defined by the total yield of crops measured in tons. In order to obtain this value, the acres of each crop were multiplied by the tons per acre per type of crop. The following can be observed in Figure 22. From the year of 2000 food production started closely to 3400 thousand tons and dropped until 1900 thousand tons in 2009, then it increased again to 2900 thousand tons in 2015.

From 2016 to 2020 LP and GA delivered more food production than the baseline, given the optimized acreages, but from 2022 to 2040, the baseline scenario shows a steady higher amount of food production than the optimized scenarios, due to the fixed acres and available water for that scenario. Overall the average of decrease on food production from GA and LP in comparison with the baseline scenario is by 455 and 428 thousand tons of production, respectively. Then, for the optimized scenarios exist an average difference of 16 thousand tons between GA and LP, being LP higher in food production than GA.

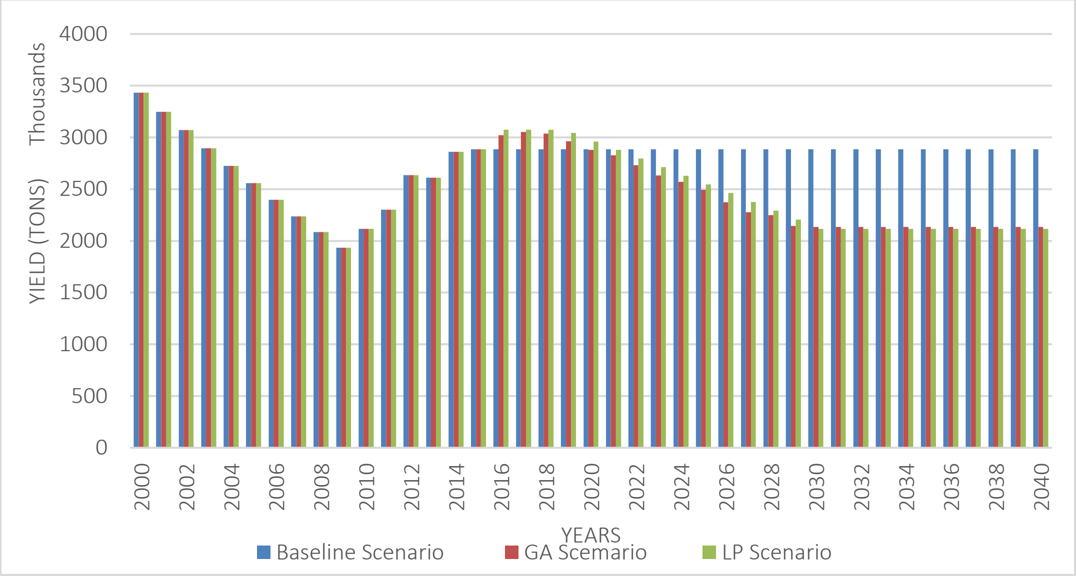


Figure 22. Comparison of food production or yield (tons) between Baseline, optimized GA and optimized LP scenarios.

5.2.4 Groundwater Storage

As mention in previous sections, groundwater storage is calculated by the inflows minus outflows, results from the net Pajaro Valley aquifer storage on the simulation modelling section resulted in an overdraft of -12.8 TAF (15.7 million m^3), this has been observed in the period of 1966-2009. Future projections of the groundwater storage was calculated correspondingly for Baseline, LP and GA scenarios, as mention in Section 4.5, a total of 50 projections were performed by a time frame of 25 years starting from 1966 until 2015.

All scenario results were plotted as 50 future projections from 2015 to 2040. See Figure 23. where the baseline scenario appears in the top followed by the LP scenario in the middle and GA scenario in the bottom.

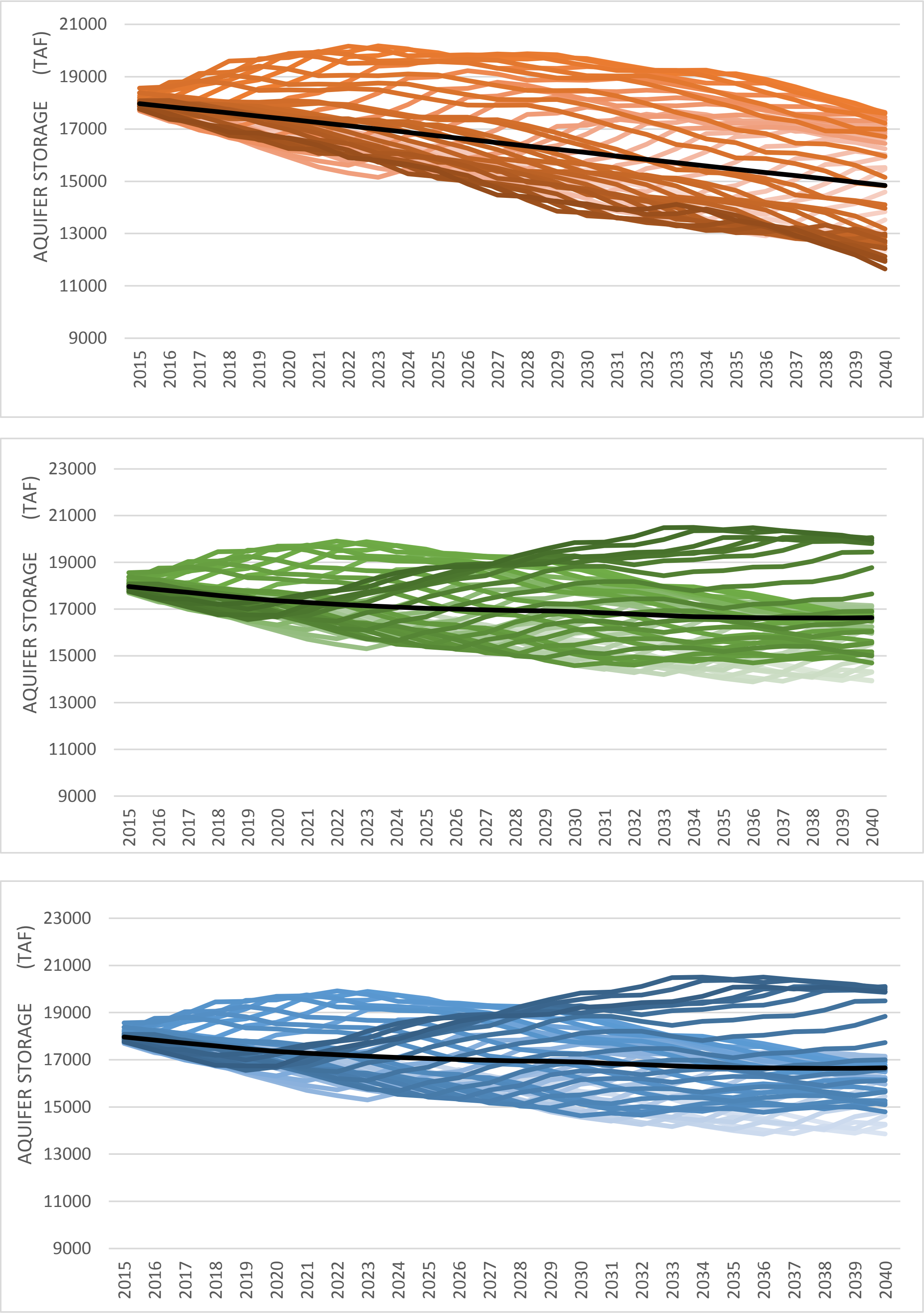


Figure 23. Groundwater storage projection. Top: Baseline scenario, middle: LP scenario, bottom: GA scenario.

Baseline scenario results shows the highest reduction of aquifer storage in comparison with the other scenarios. The lowest point of the baseline is 11,647 million acre-ft followed by LP with 13,886 million acre-ft and GA by 13,847 million acre-ft. On the other side the highest point on the aquifer storage is the GA scenario with a value of 20,504 million acre-ft followed by 20,498 million acre-ft by LP scenario and at last by the Baseline scenario with a value of 20,175 million acre-ft.

In order to observe this results in a conjunctive way, the average groundwater storage of all 50 projections for each scenario is plotted in the Figure 24.

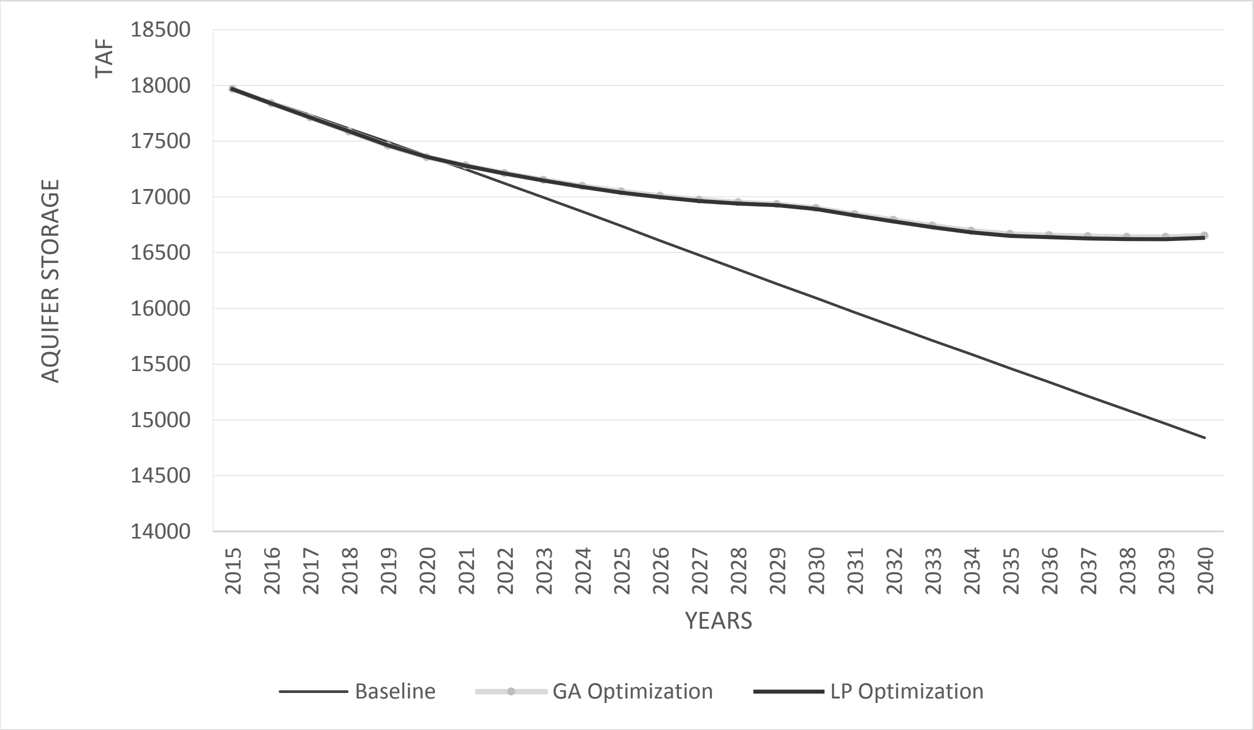


Figure 24. Average groundwater storage in TAF for baseline, GA and LP scenario.

The plot describes the average aquifers storage in TAF during 25 years starting from 2015 until 2040 for the three projections. The baseline, GA and LP scenario all started equally in 2015 with an aquifer storage value of 17,966 TAF (22160 million m^3) and the projection ended in 2040 with an aquifer storage value of 14,839 TAF (18303 million m^3) for baseline scenario and 16,653 and

16,632 TAF (20,541 and 20,525 million m^3) for GA and LP scenario respectively. In all scenarios the storage trend tends to fall, however for baseline scenario the trend decrease dramatically by 17% with a storage loss of -3,127 TAF (-3,857 million m^3). On the other side both LP and GA trends dropped by 7% with a storage loss of -1,334 and -1.313 TAF (1645 and 1619 million m^3) respectively. However, for all three scenarios, the drop off from 2015 to 2021 is by 4%. Then from 2020 to 2040, for the optimized scenarios the decline was reduced to 3% meanwhile for the baseline scenario the decline trend augment to 13%. It is important to notice that from 2031 to 2040, optimized scenarios tend to remain fairly steady.

After observing a reduction of decline percentage for the optimized scenarios, it was decided to observe closely the trend and plot the last 10 years of the projection, from 2030 to 2040.

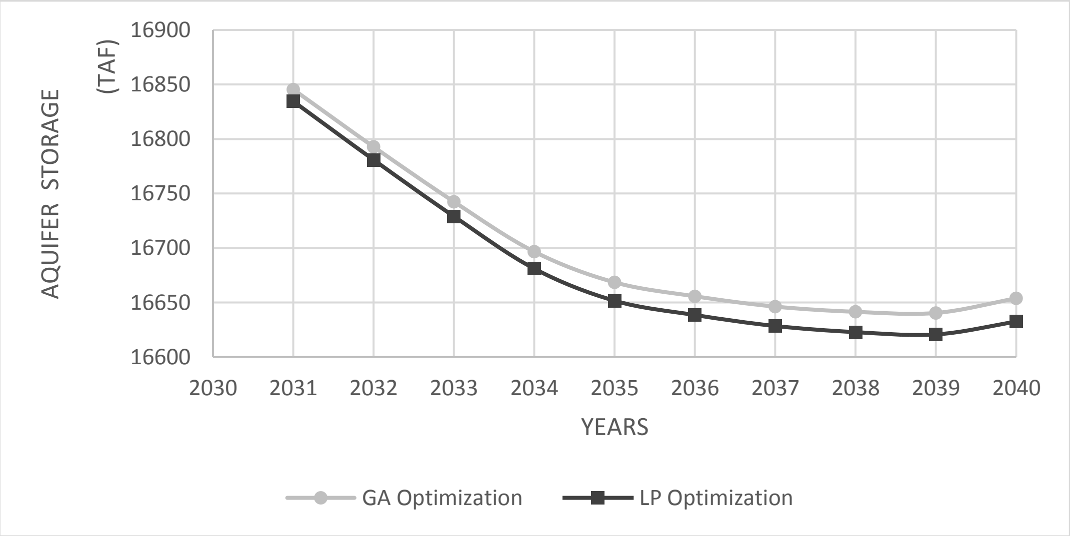


Figure 25. Aquifer storage trend from 2030 to 2040 for GA and LP optimization scenarios.

Figure 25. shows how the last year of both optimization scenarios the aquifer storage slightly incremented, 0.05% for GA scenario and 0.02% for LP scenario for the years 2037 to 2040. Overall, GA shows less aquifer storage depletion than LP scenario but at the same time LP and GA shows considerably more aquifer storage than their counterpart the baseline scenario.

5.2.5 Net Groundwater storage

As in the simulation model results, inflows and outflows in Pajaro Valley were evaluated for 50 years, now it will be evaluated as a future projection from 2010 until 2040. Major inflows are recharge from precipitation and irrigation, future projections of recharge were set in WEAP as cyclical this means that from 1966 to 2015 the hydrological cycle was repeated for the next years. Major outflows were calculated throughout WEAP as water demand. See Figure 26.

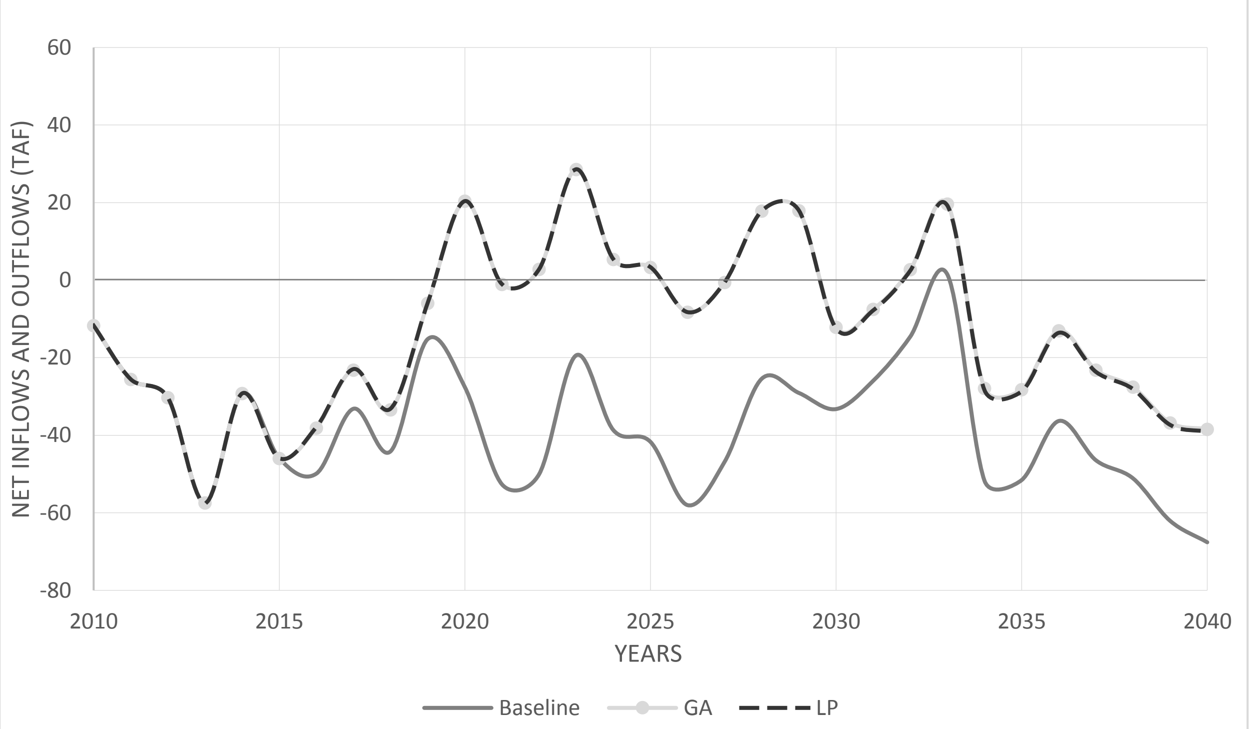


Figure 26. Net groundwater simulation-optimization model, a comparison between the baseline trend and the optimized GA and LP scenarios.

To begin, the baseline and the optimized scenarios start in 2010 with a depletion of -11.71 TAF (14 million m^3), very similar to the average depletion from 1966 to 2009 which was -12.82 TAF (16 million m^3). From 2010 until 2015 net groundwater for all scenarios were set to be the same, until reaching in 2015 an overal depletion of - 45.93 TAF (56 million m^3). The great depletion of groundwater can be highely related to the multi-year drought that hitted CA from 2012 to 2015.

The minimum point reached in the model is in 2040 by the baseline scenario with a value of -67.60 TAF (-83 million m^3) followed by the year of 2039 and 2026 with -62.07 TAF (-76 million m^3) and -58.02 TAF (-71 million m^3) respectively, also accounted for the baseline scenario. Minimum values from LP model for the period of 2016 to 2040 are -39.06 TAF (-48 million m^3) in 2040, -37.88 TAF (46 million m^3) in 2016 and -37.32 TAF (-46 million m^3) in 2039, meanwhile minimum values for GA for the same period are: -38.42 TAF (-47 million m^3) in 2040, -38.25 TAF (-47 million m^3) in 2016 and -36.73 TAF (-45 million m^3) in 2039.

In comparison to the simulation model, minimum values for the observed scenario were: -51 TAF (62 million m^3) in 1977 meanwhile for the estimated were -38 TAF (46 million m^3), and the maximum were 46 TAF (56 million m^3) and 45 TAF (55 million m^3) respectively.

It can also be observed how the baseline scenario never goes above depletion, meanwhile both optimization models have 10 points which are equal or above depletion, specifically from the year 2020 until 2033. The highest point on the optimization models are 28.601 TAF (35 million m^3) for LP and 28.58 (35 million m^3) TAF for GA, both in the year of 2020.

The overall annual groundwater net storage of the baseline scenario for the period of time 2016 to 2040 is -38.83 TAF (-47 million m^3) meanwhile the LP and GA optimization model showed and improvement of an average net storage of -8.42 and -8.26 TAF (-10 and -10 million m^3) respectively. For a shorter period of time, from 2016 to 2030 LP and GA gave an overdraft value of -1.71 and -1.75 TAF (-2.10 and -2.15 million m^3) respectively meanwhile the baseline scenario maintained its annual storage of -37.67 TAF (-46 million m^3).

A single factor ANOVA was performed to evaluate if there exists significant difference among aquifer storage for GA, LP and Baseline scenarios. Results show a pvalue of 0.9817 when comparing LP and GA scenarios, this indicate that both algorithms do not show significant difference. On the other hand, LP- Baseline showed a p-value of 5.2E-06 and GA-Baseline showed a p-value of 4.6E-06, both demonstrating significant difference on aquifer storage.

6 DISCUSSION

In Pajaro Valley, groundwater has steadily been overdrafted since 1966, the aquifer depletion is well illustrated in the simulation model of this study where 49 years of historical annual time series of inflows (precipitation and irrigation recharge) and outflows (agricultural, urban/rural and supplementary water demands) are represented hydrologically. This resulted in an estimated annual average overdraft of -12.82 TAF (16 million m^3) from 1966 to 2009, a future projection until 2040 showed an increase of more than three times that value, reaching a storage depletion of -38.84 TAF (47 million m^3). Our results are supported by another study which shows the overexploitation of groundwater in a 72-year simulated model, in the agriculture area of Tulare, also located in the Central Valley CA. The study by Harou and Lund (2008) presented a future projection of the average overdraft rate which is accounted for -27 million m^3 by 2020, their results were also based on the estimated extraction rates of agriculture and population demand calculated from 1921 to 1993. The comparison of Pajaro Valley and the Tulare case of study addressed that simulation models can estimate future trends of groundwater depletion but also that overexploitation of groundwater resources is a latent situation in CA, especially in the valley where the most proficient agricultural lands are located. Extensive exploration and new policies should be developed in the area to address groundwater depletion such as simulation-optimization modelling.

Being the agriculture water demand a major input on the simulation model, and because the nature of it was estimated by calculations of different variables, the agricultural water use model was validated separately and then used into the groundwater simulation model of Pajaro Valley. Agriculture input was evaluated with a comparison of the observed-calculated model in the previously mentioned USGS report (R. T. Hanson, Schmid, Faunt, Lear, & Lockwood, 2014a). Validation was achieved with proper hydrologic modeling evaluation and calibration methods (B. Engel, Storm, White, Arnold, & Arabi, 2007). However, validation was only concluded after calibration of irrigation efficiencies were performed. Irrigation efficiencies represent a sensitive input because these are not fixed values, are poorly understood, and change based on crop and farmer. The irrigation efficiency used in this study for drip, sprinkler, gravity and other, were the product of two variables; its frequency of use times its system efficiency. The model used as comparison to this study also selected irrigation efficiencies for calibration, due to the sensibility and poor knowledge of the changes of irrigation system through time, they opted by changing it according to the hydrologic year (wet, average or dry), where efficiencies had lower values in dry years. Yet, efficiencies calculation are not constraint to one method of estimating it, on the study by Rosegrant et al. (2000) efficiency is calculated using the Christiensen Uniformity Coefficient which is an approach used as a surrogate for both irrigation technology and irrigation management activities. Rosegrant's study used a hydro-economic optimization model for agriculture in Chile, and it presented efficiencies of 50% for flood or gravity irrigation, 80% for sprinklers and 90% for drip, these are close related to the average systems efficiencies used in Pajaro Valley except that these were constant and did not change through time.

After the simulation model was validated and transferred to WEAP this was coupled with two different types of optimization approaches; linear modelling and genetic algorithms. The objective function was to maximize the agriculture net revenue while determining the optimal crop pattern and available water. The similar objective function is found in several studies; Mainuddin, Gupta, and Onta (1997) determined the irrigation plan by optimal crop area allocation and groundwater requirement, by maximizing the net economic benefit in Thailand. Then Benli and Kodal (2003) developed a linear and non-linear model that allocates optimally available resources and refurnishes crop patters in Turkey by maximizing the economic crop revenue. Their results showed a combination of crop area and net irrigation conditions by lowering the available water, where those vegetables with higher profit values were always set at their upper limits. This outcome reconciles with our findings, where bushberries, nurseries, strawberries and vegetables are always striving for the highest number of acres, given their high economic profit; meanwhile apples, artichokes and vinegrapes always tend to be minimized. Regarding the maximization on net profitability, our findings confirm that the revenue given by LP model shows higher monetary benefit than GA, the average difference is around 2 million dollars; meanwhile, Benli and Kondal study showed the opposite. The reason could be in the nature of both problems, in this study the objective functions are linear, for instance LP shows higher outcome; but for the contrasted study, their problem was non-linear making the LP less suited. This shows that the optimum approach is close related to the complexity of the problematic, however any optimization model will strive for a better future projection outcome.

Optimization modelling to reduce groundwater depletion was part of the study goal, our results support these findings by showing that the aquifer storage increased 79% in contrast with the baseline scenario for a projection from 2016 to 2040, then by 96% from the baseline scenario in a shorter future projection of 14 years (2016-2030). A similar result on a study by Yang et al. (2006) where optimization modelling was set for 12 years of planned irrigation in an agricultural region of China, showed a decrease on the groundwater drawdown by 50%. Groundwater drawdown is the change of the water table or water levels, observed where a well is located in an aquifer due to pumping. The use of optimization models in both cases enhance the reduction of the aquifer depletion by a considerably high percentage even though. On another study developed by Karterakis et al. (2007), LP and GA were used as an optimization methodology for a groundwater management problem in a coastal site in Crere, Grece; results showed that both algorithms converged to a similar freshwater extraction policy suggesting a 35% reduction of seawater intrusion. Again, optimization models, applied on different case of studies strive for the enhance of ecological solutions such as groundwater depletion.

These results corroborates that simulation modelling provides a future portrait of the groundwater table and by applying optimization modelling, variables can be allocated in such a way that helps with the conservation and water resource management. This implies and agrees that there is significant room to improve water management in Pajaro Valley using hydroeconomic modellings, allowing to decrease aquifer depletion and prioritize an insurance of freshwater for the population demands and agriculture activities for a longer period.

7 CONCLUSIONS

Water demands and supplies are not balanced in Pajaro Valley CA, where overdraft of the basin has depleted storage capacity and led to saltwater intrusion of water from Monterey Bay into freshwater aquifers, triggering water quality degradation and permanent loss of storage. The development of an integrated agriculture-aquifer management model, for decreasing groundwater depletion by the efficient and sustainable allocation of water resources in agricultural practices, was accomplished in this study by performing a combined simulation and optimization model.

The simulation model provided a window to the hydrologic past, from 1966 to 2015, in here, inputs to calculate water budgets from the city and agriculture were calculated such as agriculture water demand, urban and rural water use, supplementary water, and the aquifer recharge. Simulation modelling showed a historic and future projection on the aquifer storage of Pajaro Valley, where the trend seems to be unfavorable if overexploiting of the aquifer continues. The simulation model coupled with the optimization modelling of LP and GA, showed an improvement of 79% by 2040 on the aquifer storage, a significant increase and reduction on groundwater depletion in comparison to the actual trend.

Sustainable water management in human-dominates systems are fragile and delicate, correct management utilizing optimization and simulation models have to potential to offer a comprehensive solution in a future projection for water conservation, by ensuring the highest profitability.

The methodology showed in this study can also be used as a framework to address SGMA legislature which mandates the implementation of sustainable groundwater management plans in critical basins, such as Pajaro Valley. Furthermore, results obtained in this study can provide a powerful tool to mitigate overdraft and adapt strategies for agricultural water management in order to address problems and needs of farmers, general population and ecological concerns such as the quality of the freshwater aquifers. This imply that there is sufficient potential to improve water management policies of water use, linked by the economical part which may undergo in a positive impact for human well being as for environmental objectives. Development of hydroeconomic models pose a real and demanding branch of research on hydrology and economics, active research and proposition of resolutions may enhance ecosystems health and strenghts, allowing a sustainable explotiment of water, a vital resource for humans and the environment.

7.1 Limitations

Several limitations of this study are described below.

- Hydrologic data in all future scenarios were obtained assuming a repetition of the historical rainfall, without considering effects of climate change. However, historical hydrologic data included wet and dry years so it was considered sufficient for this study.
- Missing data for reference evapotranspiration and precipitation were assumed to be linear so LRM were often used to calculate absent point data.
- Irrigation efficiencies had to be calibrated, since this portion of the model assumes farmers rotate crops and there is a constant change in farmers since they usually rent the land for growing, irrigation systems change through time at a specific tendency but not necessary linear, as it was approach in this study.
- Farming costs and revenue were deflated or inflated accordingly to populate values from 1966 to 2015.
- Yield production and Crop duty were set in future projections as annual historic averages.
- The aquifer mass balance was conceptualized as one-bucket model in which change of storage is ruled by the inflows and outflows posed. In this study, streamflow or intrusion of seawater were not considered.
- The proposed water budget framework does not consider water quality degradation such as seawater intrusion or chemicals leaching into the aquifer from the agriculture fields or by runoff from adjacent areas.

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