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MODFLOW-Farm Process Modeling for Determining Effects of Agricultural Activities on Groundwater Levels and Groundwater Recharge

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ABSTRACT

Intensive agricultural development in Mexicali valley, Baja-California, Mexico, has induced tremendous strain on the limited water resources. Agricultural water consumption in the valley mainly relies on diversions of the Colorado River, but their water supply is far less than the demand. Hence, the use of groundwater for irrigation purposes has gained considerable attention. To account for these changes, it is important to evaluate surface water and groundwater conditions based on historical water use. This study identified the effects of agricultural activities on groundwater levels and groundwater recharge in the Mexicali valley (in irrigation unit 16) by a comprehensive MODFLOW Farm process (MF-FMP) numerical modeling. The MF-FMP modeling results showed that the water table in the study area is drawn downed, more in eastern areas. The inflow-outflow analysis demonstrated that recharge to the aquifer occurs in response to agricultural supplies. In general, the model provides MF-FMP simulations of natural and anthropogenic components of the hydrologic cycle, the distribution and dynamics of supply and demand in the study area.

Keywords : Mexico, MODFLOW farm process, Agriculture, Groundwater level, Groundwater recharge

1. Introduction

The determination of surface water and groundwater allocations to farms is desirable for legal requirements (e.g. Stream volume adjudications), and for agro-economic decision making ahead of the growing season. The need to specify these flow rates applies to historic and future time intervals (Schmid W. 2004). In Mexico groundwater already represent 38% of total annual water withdrawal and agriculture represents over three-fourths of the total groundwater withdrawal at national levels.

The Baja California-California border region is bounded by a common geography characterized by its booming population, scarce water supply, and arid land. The natural rivers of this region are among the most regulated, used, and contaminated waterways in the world. These rivers are currently used to the extent that they often no longer discharge to their respective termini, i.e. the Colorado River, whose billions of cubic meters of annual flow no longer reach, the Gulf of California. This situation is largely driven by upstream diversions and economic forces that make the border region one of the most productive geographic regions in México. This is also one of the driest regions in Mexico and its explosive growth has put tremendous strain on the limited water resources. Agriculture in the Mexicali Valley withdraws approximately $2.5*10^9\,m^3$ of water annually (Roman-Calleros and Ramírez-Hernández, 2003). Pumping of groundwater for supplementary irrigation in the Valley has reduced groundwater levels significantly in some areas. Increased groundwater use had induced leakage from rivers and canals to groundwater, which has become the predominant form of surface water and groundwater interaction. Surface water and groundwater are highly connected due to the sandy nature of the alluvial aquifer in the Valley.

To help sustainably manage and conjunctively use these resources, there is needed to gain a better understanding of

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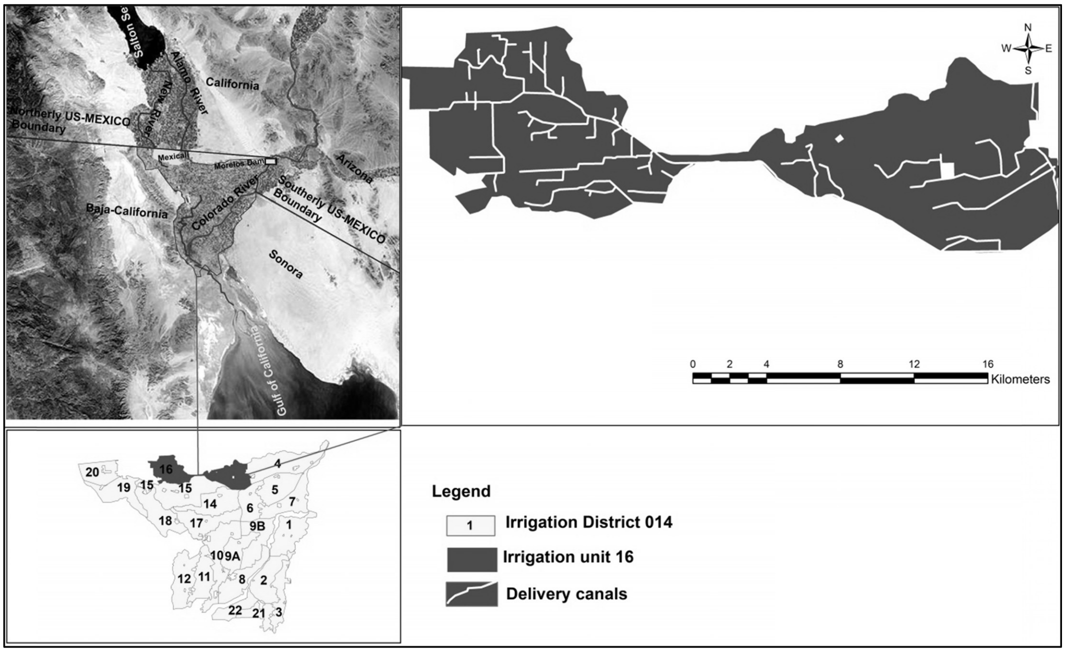

Fig. 1. Location map of the study area (irrigation unit 16).

water movement in the hydrologic system through hydrologic modeling.

MODFLOW Farm Process (MF-FMP) is a unique and versatile alternative that provides fully coupled, cell-by-cell distributed fully iterative simulation of supply-constrained and demand-driven conjunctive use and movement of water from natural and anthropogenic sources.

The alteration of the Colorado River delta of wilderness, to the highly productive agricultural region that exists today in U.S.A-Mexico border region, brings many questions and presents an excellent subject for a groundwater modeling study. How has the aquifer beneath the Colorado River delta responded to the agricultural expansion when the Colorado River water is changed from natural flow to scheduled releases?

The main aim of this study was (1) to investigate the effects of agricultural activities on groundwater level and groundwater recharge and (2) to evaluate the sources of irrigation water in user-defined water balance subregions (WBS) of commonly known by Irrigation Unit 16 (Fig. 1) over 12 years using MODFLOW Farm Process (MF-FMP). The stress packages in MF-FMP, among others, employed are; the Unsaturated Zone Flow (UZF1), Stream Flow Routing (SFR), well package (WEL) and Drain package (DRN).

2. MF-FMP Features

The Farm process (Schmid et al. 2006a, 2006b; Schmid and Hanson 2009a, 2009b) for MODFLOW-2005 (Harbaugh 2005) (MF-FMP) was developed to provide detailed hydrologic budgets for all or part of a hydrologic system and to examine how such budgets change over time. Conservation equations for groundwater, stream, lake, root zone, and land-surface runoff processes are solved simultaneously to simulate a large portion of the hydrologic cycle, and the agronomic and human effects on the cycle. Among the mass conservation equations, the groundwater-flow equation (1) is the governing equation that is solved for groundwater heads.

$$\frac{\partial}{\partial x}\left(K_h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_h\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_v\frac{\partial h}{\partial z}\right)\pm W=0 \quad (1)$$

where h, is groundwater head (L), K_h and K_v are horizontal and vertical hydraulic conductivity (LT^{-1}), respectively, W is volumetric flux per unit volume representing sources and/or sinks, x and y are horizontal co-ordinates (L), z is vertical co-ordinate (L) and t is time (T).

MF-FMP represents the components of evaporation and transpiration derived from precipitation, irrigation, and groundwater on a cell-by-cell basis within user-defined water-balance subregions (WBS). MF-FMP considers two types of water budgeting for the control volume horizontally delineated by land surface areas, called "farms". These water-accounting units can include irrigated and non-irrigated farms, native vegetation, and urban areas. Using the term "farm" in MF-FMP" has become somewhat of an anachronism as MF-FMP has advanced to types of water-accounting units other than just agricultural farms. The water-accounting units in MF-FMP; do not include changes in soil-water storage and, hence, are control interfaces at the land surface.

For a given computational unit; a particular land use area in a given cell, the general mass-balance equation that MF-FMP is based on for the root zone is the following:

$$P^{t+1} + I^{t+1} + ET^{t+1}_{gw-act} - ET^{t+1}_{c-act} - R^{t+1} - DP^{t+1} = \frac{\theta^{t+1} - \theta^{t}}{\Delta t} \quad (2)$$

and

$$R^{t+1} = R^{t+1}_{P} + R^{t+1}_{i} \quad (3)$$

Where P is precipitation (LT^{-1}), I is irrigation water (LT^{-1}), ETgw-act is root uptake from groundwater (LT^{-1}), ETc-act is the total actual crop evapotranspiration (LT^{-1}), R is the runoff from precipitation and irrigation (LT^{-1}), Rp is the surface runoff from precipitation (LT^{-1}), Ri is the irrigation surface return flow (LT^{-1}), DP is the deep percolation that leaves the root zone as the moisture moves downward (LT^{-1}), θ^{t+1} is the soil moisture at the end of a time step (L), θ^{t} is the soil moisture at the beginning of a time step (L), Δt is the time step length (T), and t is the time step index (dimensionless).

MF-FMP computes R as the portion of crop-inefficient losses from precipitation or irrigation that contribute to runoff:

$$R_p = (P - ET_{p-act}) f_r^{p-loss} \quad (4)$$

$$R_i = (I - ET_{I-act}) f_r^{I-loss} \quad (5)$$

Where, ETp-act and ETi-act are the portions of the ETc-act fed by precipitation or irrigation (LT^{-1}), respectively, and f_r^{p-loss} and f_r^{I-loss} are fractions of the respective crop-inefficient losses from precipitation or irrigation that go to a runoff, given as time series data.

MF-FMP computes deep percolation (DP) as the sum of deep percolation below the root zone from precipitation and irrigation, which can be instantaneous or delayed with linkage to the unsaturated zone infiltration package, UZF (Niswonger et al, 2006). It is the user-specified portion of losses of precipitation and irrigation that are not consumptively used by plants and not lost to surface water runoff:

$$DP = (P - ET_{p-act})(1 - f_r^{p-loss}) + (I - ET_{i-act})(1 - f_r^{I-loss}) \quad (6)$$

The current version of MF-FMP does not consider changes in soil-water storage in the root zone (i.e., RHS in equation (2) = 0):

$$P^{t+1} + I^{t+1} + ET^{t+1}_{gw-act} - ET^{t+1}_{c-act} - R^{t+1} - DP^{t+1} = 0 \quad (7)$$

MF-FMP still takes into account that the root zone might be inactive for conditions of wilting or anoxia. However, for any head between the lower and upper extinction depths, MF-FMP derives transpiration from groundwater; the residual crop water demand is then satisfied by transpiration from precipitation or irrigation. That is, at a steady state of soil moisture, ETc-act of equation (7) can be split into six components from three sources: groundwater, precipitation, and irrigation (Tgw-act, Egw-act, Tp-act, Ep-act, Ti-act, Ei-act,). All 6 components contribute to ETc-act However, Tp-act, Ep-act, Ti-act, and Ei-act are outflows out of the landscape budget. In contrast, some parts of Tgw-act and Egw-act are inflows from GW into the root zone (landscape budget) but also outflows from the root zone into the atmosphere.

3. Materials and methods

3.1. Study area

The State of Baja California is located to the Northwest of Mexico, bounded on the north by the State of California, USA, to the east by the State of Sonora, Mexico, to the west by the Pacific Ocean and south by the State of Baja California Sur (Fig. 1).

Within the limits of the State of Baja California and Sonora, is located the section of the Colorado River corresponding to Mexico, where the territorial boundary between the two States, which begins its journey in the dam diverter Jose Maria Morelos up reach the Gulf of California. The Colorado River Delta is one of the world's largest deltas covering over 8,600 km^2 of terrain and extending across the international border between the United States (U.S.) and the Republic of Mexico (Mexico). The Delta developed as a result of the constructive processes of sediment transport by the Colorado River and the destructive processes associated with, 1) the large tidal regime dominated by strong currents in the upper Gulf of California and, 2) tectonic movement along the San Andreas Fault, which has transported sediment NW across the Delta over millennia (Sykes 1935).

Irrigation District 014 (Fig. 1) is divided into 22 irrigation units or irrigation administrative areas, for which pumping and irrigation data are aggregated and maintained by the National Water Commission of Mexico (CONAGUA). The study area; the irrigation unit 16 (Fig. 1) service areas encompass about 20,100 hectares, of which about 85 percent is used for agriculture and, 15 percent is primarily urban land. Elevation in the study area ranges from about 41 m in the northeast to less than 5 m to south.

The Mexicali Valley is characterized by a desert climate dominated by high temperatures and arid conditions. The valley's climate is defined by clear skies and plenty of sunlight, with little precipitation given the atmospheric dominance of high pressure. Average monthly high temperatures in July are 42ºC and the lowest average monthly high of 21ºC occurs in December. The yearly average precipitation is 72.5 mm, with monthly average precipitation values averaging 0 mm in June and 12.4 mm in January.

3.2. Geology and Hydrogeology

There are around five topographical areas in the Gulf of California: (1) the cutting edge subaerial Salton Trough, (2) North Gulf Region, (3) Central Gulf Region, (4) South Gulf Region, and (5) Gulf Mouth Region. During the Early to Middle Miocene (24 to 11 Ma), an earthbound volcanic bend was shaped along what is currently generally the hub

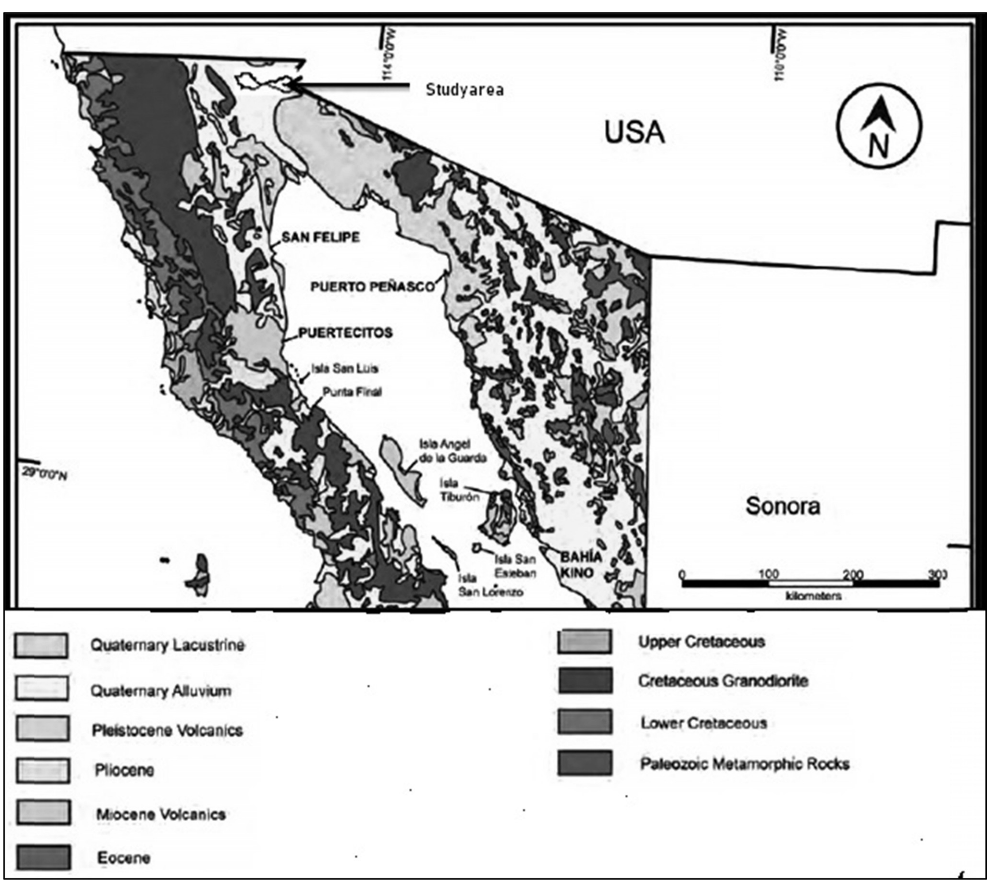

Fig. 2. Geological map of the Baja California North. The study area is showed by an arrow in U.S.A Mexico border region.

of the advanced Gulf of California (Hausback 1984; Sawlan and Smith 1984). Those volcanic rocks comprise the storm cellar for the Gulf Extensional Province (Gastil et al. 1973). They make due as mountains made out of thick andesite streams circumscribing the western side of the inlet in peninsular Baja California (Fig. 2). More youthful volcanism began around 13 Ma in eastern Baja California and inside the creating Gulf of California crack. An examination of a multiple of well logs very near to the study area demonstrate that, there is unconsolidated irregular sequences of clay, sand, gravel and mud persist in area for at least 180 m below the land surface (Feinstein et al., 2008).

Soils in the valley are generally classified under the principle soil order of Aridisols, according to the soil taxonomy developed by the United States Department of Agriculture (USDA). The defining characteristics of such soils are their lack of sufficient moisture for mesophytic plants and limited soil horizon development. Entisols are also present in the valley given its original formation as the floodplain of the Colorado River (Hillel 2008). While localized variations do exist across the valley, the soil texture is generally a sandy clay loam, with limited areas on the western edge of the valley having a greater concentration of clay as a result of erosion associated with the Sierra Cucapa and Sierra Mayor mountains.

The aquifer system is divided into two parts: the upper fine-grained zone and wedge zone and coarse gravel zone (Olmsted et al. (1973). In the valley, the uppermost sediment varies spatially and include coarse alluvial piedmont sand and gravel sediments derived from the Sierra Cucapah, which dominate in the south west (SW) (Puente and De La Pena 1979), and fluvially transported fine, medium, and coarse-grained sediments of clay, sand, and gravel which dominate in the east (Pacheco et al. 2006; Sykes 1935).

Transmissivity values for the upper fine-grained zone were determined to be 150–930 m^2/day Hill (1993). A storage coefficient of 10^{-3} and a specific yield of between 0.18 and 0.35 were estimated (Hill 1993). The Wedge zone (120 m to 680 m below the upper fine zone) is considered single heterogeneous water-bearing hydraulic unit composed of irregularly layered sands, gravels, silts, and clays (Olmsted et al., 1973). The coarse gravel zone overlies the Wedge zone and is a highly permeable water-bearing unit composed primarily of irregularly layered coarse gravel and sand. This unit constitutes the main pathway for horizontal groundwater flow in the system (Mock et al., 1988). Together the wedge zone and coarse gravel zone may represent what is described in research of the modeled Colorado river area area (i.e. Pacheco et al., 2006; Portugal et al. 2005; Chavez et al. 1999; Barragan et al., 2001) as the upper sediments of the Mexican Colorado River delta basin with a composition of fluvial and alluvial not- consolidated sediments of Pleistocene to Recent ages. Transmissivity values for the Wedge zone and Coarse Gravel zone combined were determined to range from 835 to 22,300 m^2/day (Olmsted et al. 1973). Horizontal hydraulic conductivity was calculated to range up to 400 m/day. Vertical hydraulic conductivity, storage coefficient, and specific yield were determined equal values to the upper fine-grained zone; the primary sources of groundwater in the delta are infiltrated Colorado River water and agricultural irrigation (Hill 1993). Surface water is also transmitted in the area via canals, drains, and the main tributary of the Colorado River; the Rio Hardy.

3.3. Conceptual model

MODFLOW farm process (MF-FMP) (Schmid et al. 2006a, 2006b; Schmid and Hanson 2009a, 2009b) with ModelMuse Graphical User Interface (GUI) (Richard B. Winston.2009) was used to determine the effects of agricultural activities on groundwater at irrigation unit 16 and also to determine the surface-water and groundwater allocations to farms, including components of evaporation and transpiration derived from precipitation, irrigation, and groundwater within the selected water-balance subregions (WBS); Results of WBS1 and WBS 3 are presented and found at the end of this article.

The model (Fig. 3) was constructed using uniform grid cells of 250 m by 250 m and the water balance subregions (WBS) are found in Fig. 4 (I). The active grid network has 49 rows and 130 columns with a total of 2962 grid cells. It was aligned with the coordinate system of WGS-1984-UTM-zone-11-N. The regional stratigraphy was conceptualized in two layers. The first layer has a thickness of 120 m from the ground surface (upper fine-grained zone) and the second layer (a combination of wedge zone and course gravel zone) has a thickness of 680 m. To hydraulically

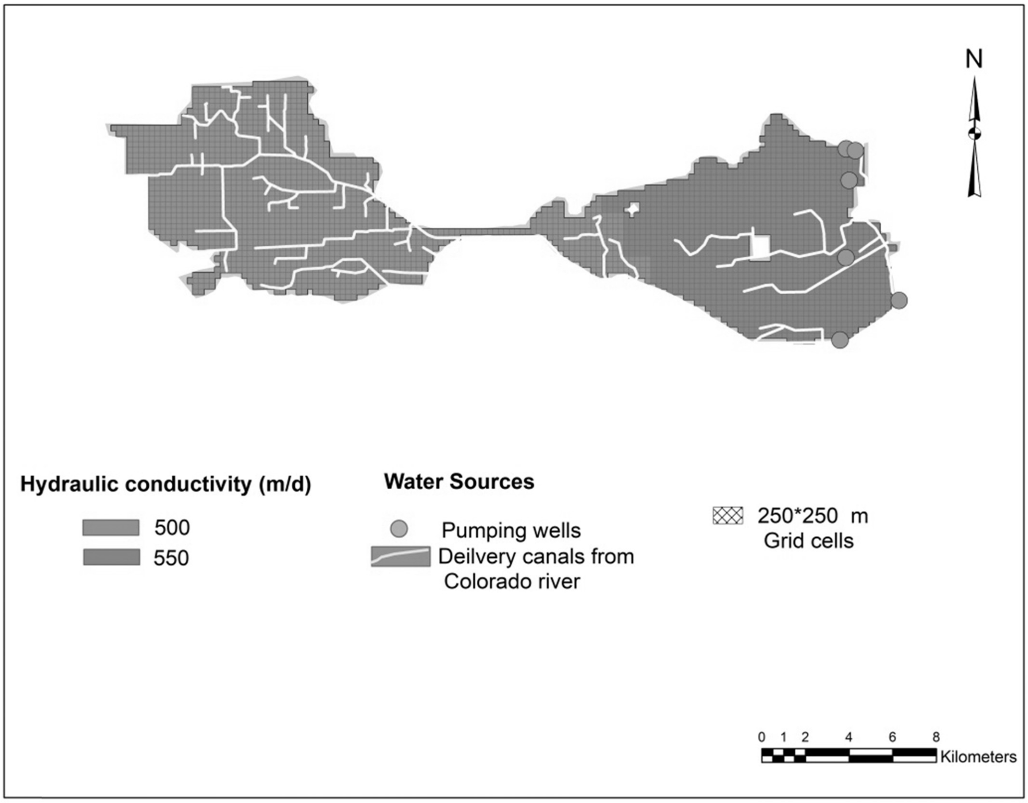

Fig. 3. Distributions of calibrated horizontal hydraulic conductivity (K_h) for the 1st layer, water sources, and grids used for MF-FMP modeling.

characterize the hydrogeological units in the model area, data were reviewed on Transmissivity, specific storage and storage coefficient from a previous parent MODFLOW model study (Bushira. K. M, et al., 2017) and others (Feinstein et al., 2008; Rodriguez-Burgueño, 2012). The degree of permeability in the first layer, in the horizontal directions ($K_{h,}$) is spatially differentiated which contain two zones of hydraulic conductivity (Fig. 3). The specific yield of Layer 1 was a constant value of 0.2. Vertical hydraulic conductivity (Kv) in Layer 1 was 0.03 m/d. Layer 2 has an identical footprint to layer 1 and was designed to reflect a simplified state-of-knowledge of the model area geology. This layer represents the less hydrologically significant thick lower unit of consolidated to semiconsolidated mudstone- siltstone and well-sorted sandstone of marine and continental origin as described by other workers in the area. Layer 2 was designated a uniform (Kh) of 0.001 m/d and specific storage of 0.00003 1/m. Vertical hydraulic conductivity in layer 2 was assigned a value of 0.03 m/d.

Throughout the model, the units of measurements are set to meters for length and days for a time. The time frame of the model simulation is 12 hydrologic years from 1st October 1995 to 30th September 2006.

3.4. Landscape Attributes

The assessment of sustainable yield and analysis of the supply and demand components relative to the hydrologic cycle requires discretization of the irrigation unit 16 into subregions that can be used to estimate the water balance of land use and groundwater. In this study, the WBSs are hydrologic entity delineated farm groups that are used to calculate the overall supply and demand components through time. Irrigation unit 16 was grouped into 6 water balance subregions (Fig. 4). These subregions represent a combination of virtual farms in the unit that can be used to assess the inflow and outflow components of the hydrologic cycle. This article presents the results of simulated supply-constrained and demand-driven components across the landscape for WBS1 on the eastern side and WBS3 on the western side (Fig. 4).

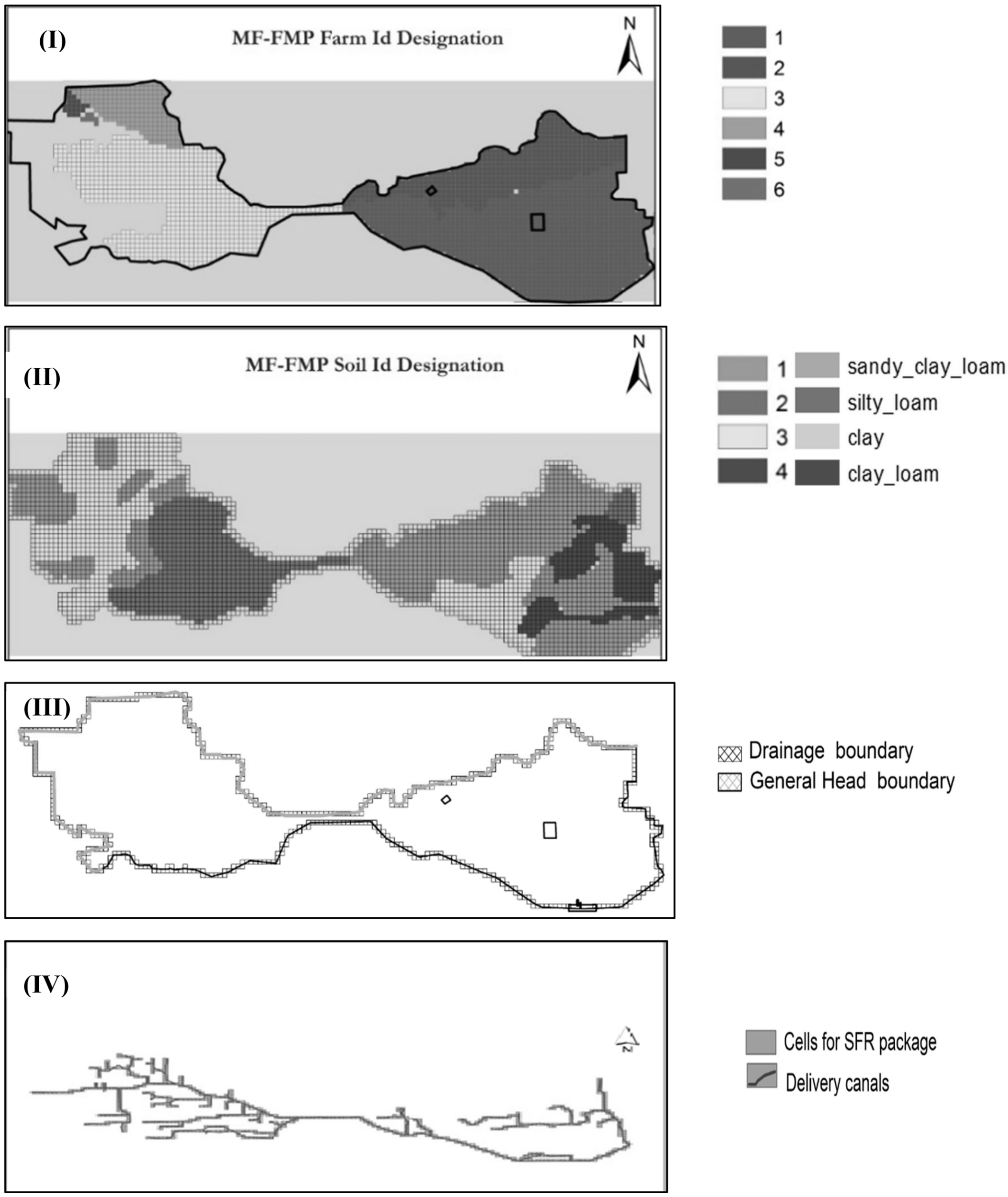

Fig. 4 (I) WBS and WBS id designation, (II) soil distribution and soil id designation, (III) boundary conditions and (IV) distributions of delivery canals for streamflow routing package (SFR).

The main types of crops grown in irrigation district 014 are wheat (65%), alfalfa (19%), and cotton (8%). The main crops in the study area; irrigation unit 16 are wheat and alfalfa (Yamilett K.C. G 2009). The information used in the study area regarding the main types of crop and their properties for MF-FMP modeling were identified (Table 1 and Table 2). These values are derived from the literature and from related studies (Schmid and others, 2006a).

The irrigation efficiency for the study area was reviewed from previous studies (Eliana, et al., 2012 and Feirstein et al. 2008); an efficiency value of 0.65 to 0.85 is adopted in this study.

Four categories of soil are identified in the study area (Fig. 4). The spatial locations and distributions of crop types, soil types and water balance subregions (farms) were pre-prepared as an object shapefile in ArcGIS and exported

Table 1. Summary of irrigation unit 16 virtual crop categories and properties

MF-FMP crop category	Maximum root depth (m)	Crop coefficient (Kc)	Anoxia	Wilting	Fraction of surface-water runoff from precipitation	Fraction of surface-water runoff from Irrigation
Alfalfa	1.2	0.63	-0.49	-405.8	0.6	0.4
Wheat	1.2	0.63	-0.49	-405.8	0.6	0.4

Table 2. Summary of fractions of transpiration and evaporation by year for irrigation unit 16 crop categories (virtual crops)

MF-FMP Crop category	The fraction of transpiration (F_{tr})	The fraction of Evaporation from pre (F_{ep})	The fraction of Evaporation from irrigation (F_{ei})
Alfalfa	0.05	0.95	0.1
Wheat	0.05	0.95	0.1

to ModelMuse, a different soil, and farm id was assigned (Fig. 4). The drains of the irrigated agriculture were simulated with the drain package in MODFLOW. The drain package for the study area was used and the drains set a specified drain elevation that is about 1.8 m below the land surface of drainage model cells (Fig. 4(III)) that are generally coincident with the regions identified as having drains. The remaining border area was analyzed using general head boundary (GHB) (Fig. 4(III)).

3.5. Surface water and Groundwater Agricultural Supply

Surface-water inflows and outflows were simulated with a streamflow routing network composed of 55 stream segments representing the delivery canal which delivery surface water from the Colorado River into the irrigation unit 16. This network (Fig. 4(IV)) was used to simulate the inflows and outflows along the major diversions. These features were simulated using the Streamflow-Routing Package (SFR2; Niswonger and Prudic, 2005); this head-dependent boundary condition allows for streamflow routing and the conveyance of overland runoff and the diversion of water for irrigation.

Groundwater pumpage is a major component of the hydrologic budget in Mexicali Valley and is used for agricultural water supply. Irrigation district 014 which shares the same aquifer with irrigation unit 16 includes more than 639 pumping wells used to supply water for irrigation. All Farm wells are located in the first layer; simulated as a single-aquifer well (Schmid and others, 2006a) that collectively supply water needed for irrigation for each WBS. Farm wells that are single-aquifer wells are simulated using the WEL package (Harbaugh and others, 2000) and the total pumpage for each WBS (that is, virtual farm) is distributed among each of the farm wells within the WBS based on the fraction of total pumping capacity (Schmid and others, 2006a). A total of six groundwater wells are found in irrigation unit 16 which is located on the eastern edge on WBS 1 and WBS2.

The simulated temporal distribution of hydraulic head for the whole irrigation unit 16 was used to identify the effects of agricultural activities on groundwater level and the water budget was used to detect groundwater recharge. In addition, the recharge to the aquifer was determined by analyzing the water budget for each water balance subregions (virtual farms). In this article, the landscape budgets for WBS1 on the eastern side and WBS3 on the western side are presented.

4. Results and Discussion

4.1. Model calibration

The trial and error basic head calibration was conducted using the available observation points. Resulting values of the horizontal hydraulic conductivities for the first layer after calibration are given in Fig. 3. The performance of the calibration is illustrated by comparing simulated versus observed groundwater heads. In view of the available head observation points, the result obtained is fairly acceptable, with an RME (root mean square error) of 0.02 m, a normalized RMS of 2.1% and a correlation coefficient of 0.97.

Reported (measured) pumpage for the period 1995 through 2006 was available for WBS1 and WBS2. The totals of reported agricultural pumpage were compared with agricul-

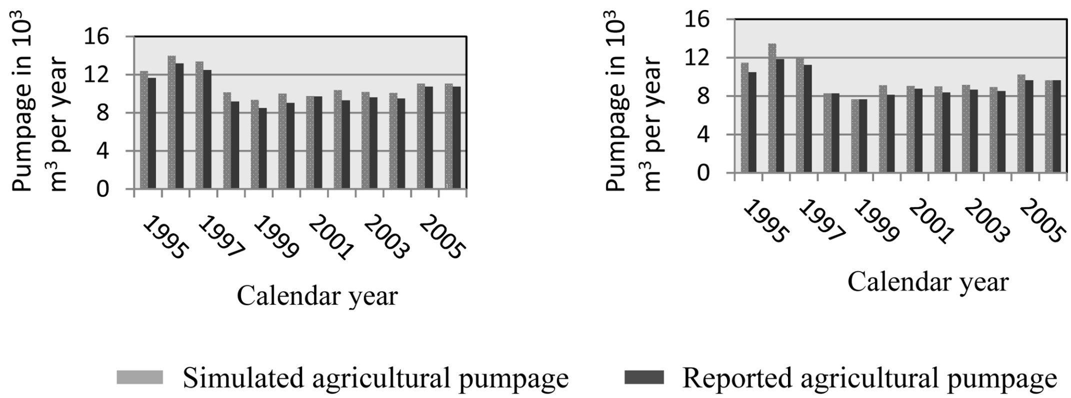

Fig. 5. Total annual reported and simulated agricultural pumpage for WBS1 (right) and WBS2 (left) for the period (1995-2006).

Table 3. Groundwater balance obtained from the MF-FMP model (whole irrigation unit 16)

Inflow	Amount ($10^4 m^3$)	Outflow	Amount ($10^4 m^3$)
Storage	4.15	Storage	123.25
Head dep bounds	1.08	Drains	2.52
Stream leakage	2.10	Head dep bounds	0.14
UZF recharge	178.62	GW ET	123.16
Farm net recharge.	97.84	Surface leakage	36.36
		Farm wells	0.25
Inflow-Outflow		-	$-2.02*10^4$
Percent discrepancy		-	0.71%

Note: *The net recharge is defined as inefficient losses to groundwater recharge after consumption due to excess irrigation and excess precipitation, reduced by losses to surface-water runoff and ET from groundwater (Schmid and others, 2006a).*

tural pumpage estimated through the simulation of water consumption by the Farm Process used in the study area. The reported agricultural pumpage located at WBS1 and WBS2 were used as additional calibration targets.

Simulated and reported total agricultural pumpage are compared for the 2 WBSs (Fig. 5). The model slightly overestimates agricultural pumpage. The percentages of total reported and simulated agricultural pumpage by WBS are also comparable, within a few percent, for the two subregions. The annual total and total agricultural pumpage (Fig. 5) are comparable between reported and simulated values for these 12 years. For the WBS1 and WBS2 model, the average annual differences (reported minus simulated) for total agricultural were -671 m^3/yr. and -570 m^3/yr. for the period 1995–2006, respectively. This represents average differences of about -0.54 and -0.49 percent of the reported agricultural pumpage, respectively. These results show that the simulated pumpage is within the range of uncertainty of the reported pumpage.

The resulting groundwater balance is given in Table 3. The source of water to the groundwater reservoirs in the study area is through agricultural recharge, which amounts in total to $97.84*10^4 m^3$. Leakage from the stream which amounts $2.10*10^4 m^3$ and lateral inflows which amount $1.08*10^4 m^3$ are other components of inflows. About 2.52 $*10^4 m^3$ of groundwater drains out of the system. The study area experiences high groundwater evaporation amount about $123.16*10^4 m^3$. The model balance error is very small, i.e. -0.71%, which shows that the model has converged accurately. The discrepancy is negative; indicating that outgoing groundwater from the study area is higher than incoming groundwater (recharge) which shows aquifer drawdown.

5. Discussion

As indicated by the simulated potentiometric level (Fig. 6), groundwater flows laterally from the highest elevation

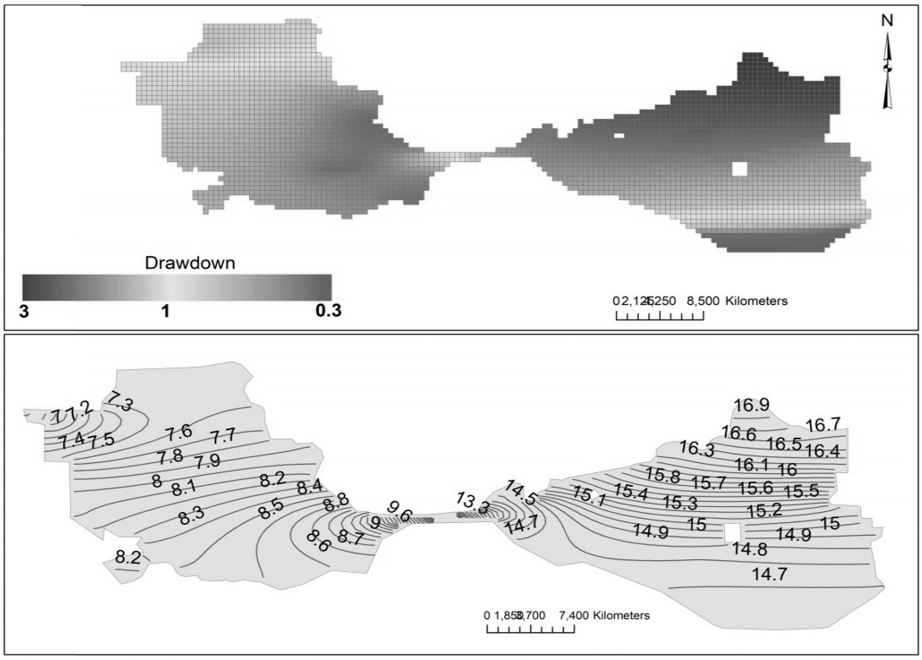

Fig. 6. (I) Simulated drawdown (m) and (II) simulated hydraulic heads (m a.s.l.) for irrigation unit 16.

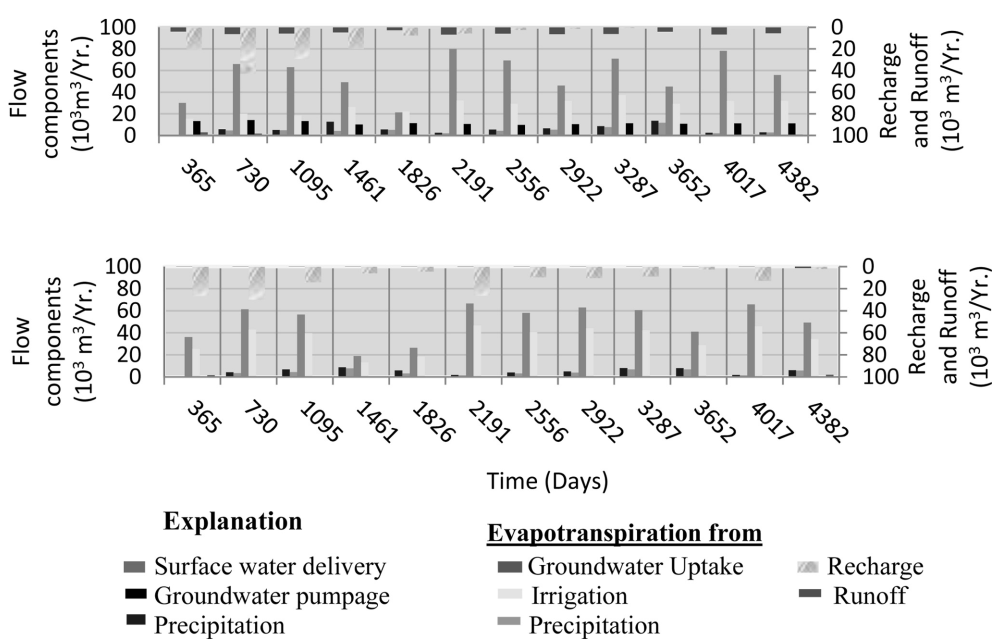

Fig. 7. Farm delivery components and the inflows and outflows for two water-balance subregions (WBS1, top, and WBS3, bottom) from 1995 to 2006. Recharge and runoff, refer the second axis.

points to the lowlands toward the Gulf of California. Simulated water levels range from 19.6 m in the highland areas to less than 10 m in the lowland. The three-dimensional modeling of groundwater in the study area shows aquifer drawdown for the study period. The drawdown map (Fig. 6) shows a drawdown ranges from 3 m to 0.3 m. The drawdown is higher in the northeastern modeling area which is expected because most of the groundwater pumping wells existed nearby.

Figure 7 shows the simulated total farm delivery require-

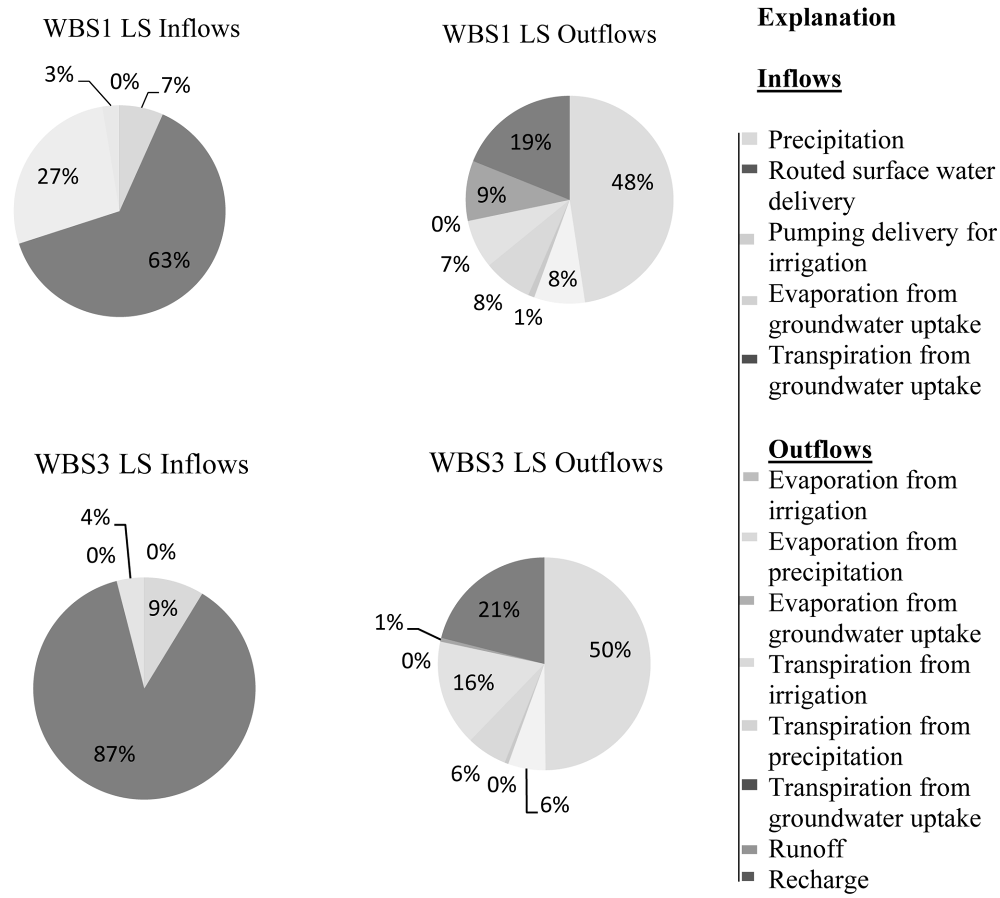

Fig. 8. Graph showing the percentages of total Landscape (LS) inflows and outflows for two water-balance areas from 1995 to 2006 as part of conjunctive use simulated by MF-FMP.
Note: *water budgets are relative to farm units; direct evaporation and transpiration of groundwater uptake on both the inflow and outflows because those fluxes are passing through the land surface (from groundwater to atmosphere/plants through the land surface). Refer section" MF-FMP Features" in this article or referred to Schmid et al. (2006a) for more detail.*

ment for irrigation for a WBS1 and WBS3 for the 12- year period from 1995 to 2006 and Figure 8 summarizes the overall 12-year WBS landscape hydrologic budgets for WBS1 and WBS3.

The results show that WBS1, which constitutes the eastern part of the modeling area, receives comparably more runoff and after the year 1999, lesser recharge than WBS3, which constitutes the western part of the modeling area. The simulated total farm delivery requirement (TFDR) shows that TFDR for WBS1 is fulfilled by 73% from the diversion of the Colorado River through delivery canals and 27% from groundwater pumping. In contrast, the TFDR of WBS3 mainly depends on the diversion of the Colorado River. There is a significant component of evapotranspiration (ET) derived from irrigation in both water balance subregions (Fig. 7, yellow color).

The simulated component for WBS 1 and WBS 3 (Fig. 7) show that groundwater recharge is derived from agricultural supplies nothing that the precipitation is lost due to evapotranspiration. Fig. 7 also demonstrates a reducing trend recharge.

Groundwater-level decline and related storage depletion are occurring in this area as evapotranspiration (ET) from groundwater uptake are about 3% and 4% (Fig. 8, inflow) and recharge to the groundwater is about 19% and 21% on the landscape (Fig. 8, outflow) for WBS1 and WBS 3 respectively. Evapotranspiration from groundwater, water from agriculture wells and routed surface water deliveries supplement the crop consumptive use for WBS1 and the crop consumptive use of WBS 3 is supplemented by surface water deliveries and evapotranspiration from groundwater (Fig. 8).

For each WBS represented by many model cells, the results shown in Figures 6 to 7 are the aggregate of the cells involved. Crop types, crop coefficients, potential or specified evapotranspiration, and other characteristics are defined for each cell, and results such as crop irrigation requirements are simulated for each cell.

Integrated hydrologic models are essential in the analysis of conjunctive use issues; if not, it might be difficult to analyze the flows and interactions between the head and flow-dependent components. MF-FMP is one of the integrated hydrologic models able to simulate coupled processes across the landscape, surface water and groundwater components of the hydrologic cycle.

This study shows how WBS can be used to organize input data and simulated results. Farm process (FMP) input files was easily constructed, updated, and maintained using soil, well, and crop data that did not require substantial external estimation of inflows and outflows (pumpage, recharge, evapotranspiration, runoff, surface water deliveries, etc.) prior to simulation. Because these hydrologic components are simulated separately, the flows and movement were easily analyzed.

6. Conclusions

The sustainability of water resources in part depends on the ability to monitor our aquifers and to simulate and analyze all the components of complex hydrologic systems, including groundwater, surface water, and landscape components. A regional groundwater flow model on irrigation unit 16 was developed and calibrated against available groundwater level observations and measured agricultural pumpage, which converges to a solution with a small water balance error. A conceptual model of the study area with two layers is defined to identify the effects of agricultural activities on groundwater level and groundwater recharges. The main conclusions drawn from the model are:

- The source of water to the groundwater reservoirs in the study area is through net-agricultural recharge, which amounts in total to $97.84*10^4$ m^3. The study area experienced high groundwater evaporation amount about $123.16*10^4$ m^3. The average negative change in storage is indicating that outgoing groundwater from the study area is higher than incoming groundwater (recharge) which shows aquifer depletion.
- Calibration of the model using the available observations of groundwater levels gives a relatively good fit with an RMS of 0.02 m and a normalized RMS of 2.1% with a correlation coefficient of 0.97. The reported agricultural pumpage located at WBS1 and WBS2 was used as an additional calibration target that, the simulated pumpage is within the range of uncertainty of the reported pumpage. The average annual differences (reported minus simulated) for total agricultural were -671 m^3/yr. and -570 m^3/yr. Which represents average differences of about -0.54 and -0.49 percent of the reported agricultural pumpage for WBS1 and WBS2 respectively.
- The simulated potentiometric level shows a hydraulic head range from 19.6 m in some areas to less than 10 m in the lowlands. Groundwater flows toward the Gulf of California.
- The simulated MF-FMP inflow-outflow analysis shows that the WBS1, which constitutes the eastern part of the modeling area, receives comparably more runoff and after the year 1999, lesser recharge than WBS3, which constitutes the western part of the modeling area.
- The simulated component for WBS 1 and WBS 3 confirmed that groundwater recharge is derived from agricultural supplies nothing that the precipitation is lost due to evapotranspiration.
- The landscape budget for WBS1 and WBS 3 shows evapotranspiration (ET) from groundwater uptake are about 3% and 4% and recharge to the groundwater is about 19% and 21% respectively.
- The modeling effort on irrigation unit 16 shows that the aquifer was drawn downed up to 3 m in some areas and drawdown was higher in the northeastern region than western regions.
- The MF-FMP modeling on selected WBS showed that recharge to the aquifer occurring in response to irrigation supplies because there is little precipitation exists; which eventually lost before reaching to the aquifer. Routed surface water delivery, pumping delivery for irrigation and evaporation from groundwater uptakes are

the main landscape inflow components for eastern areas (WBS1) in addition to precipitation. Crop consumptive use in the western side (WBS3) is supplemented by the routed surface water delivery, evaporation from groundwater and precipitation.

The authors believe that these results are very important for future conjunctive water resources management in the region and this work is the first and unique example in the region which might be a guide for development of the integrated hydrologic model using MF-FMP for whole irrigation district 014 which is in need and other agricultural regions which seek integrated modeling with a similar geological environment. Monitoring of diversion rates from the Colorado River to each farm on a better scale as a function of time and detail database on agricultural crops are recommended for future model development.

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