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Appendix 3-C
Integrated Groundwater Flow Model (PVIHM); Modifications for Use in the Development of the Groundwater Sustainability Plan for the Petaluma Valley Groundwater Basin

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General Description of Model

The Petaluma Valley Integrated Hydrologic Model (PVIHM) was developed in 2020 by the USGS to simulate groundwater circulation, stream-aquifer interaction, and landscape hydrologic processes within the Petaluma Valley Groundwater Subbasin and surrounding watershed. **Figure 1** shows the spatial extent of the PVIHM, including locations of certain hydrologic boundaries simulated by the model. The model extent primarily coincides with the 2018 Bulletin 118 subbasin boundaries and includes some areas outside of the subbasin boundaries. The PVIHM domain covers the entire subbasin, and additionally covers a portion of the Wilson Grove Formation Highlands to the northwest of the subbasin (PVIHM groundwater active extent). In addition, the watershed area surrounding the groundwater subbasin is included in the model to simulate rainfall and runoff that flows into the groundwater active domain.

The original PVIHM simulated groundwater conditions from October 1959 through September 2015. Additional modifications to the original PVIHM were incorporated by the USGS on behalf of Sonoma Water and the simulation time frame was extended through 2018. These modifications are described in this document.

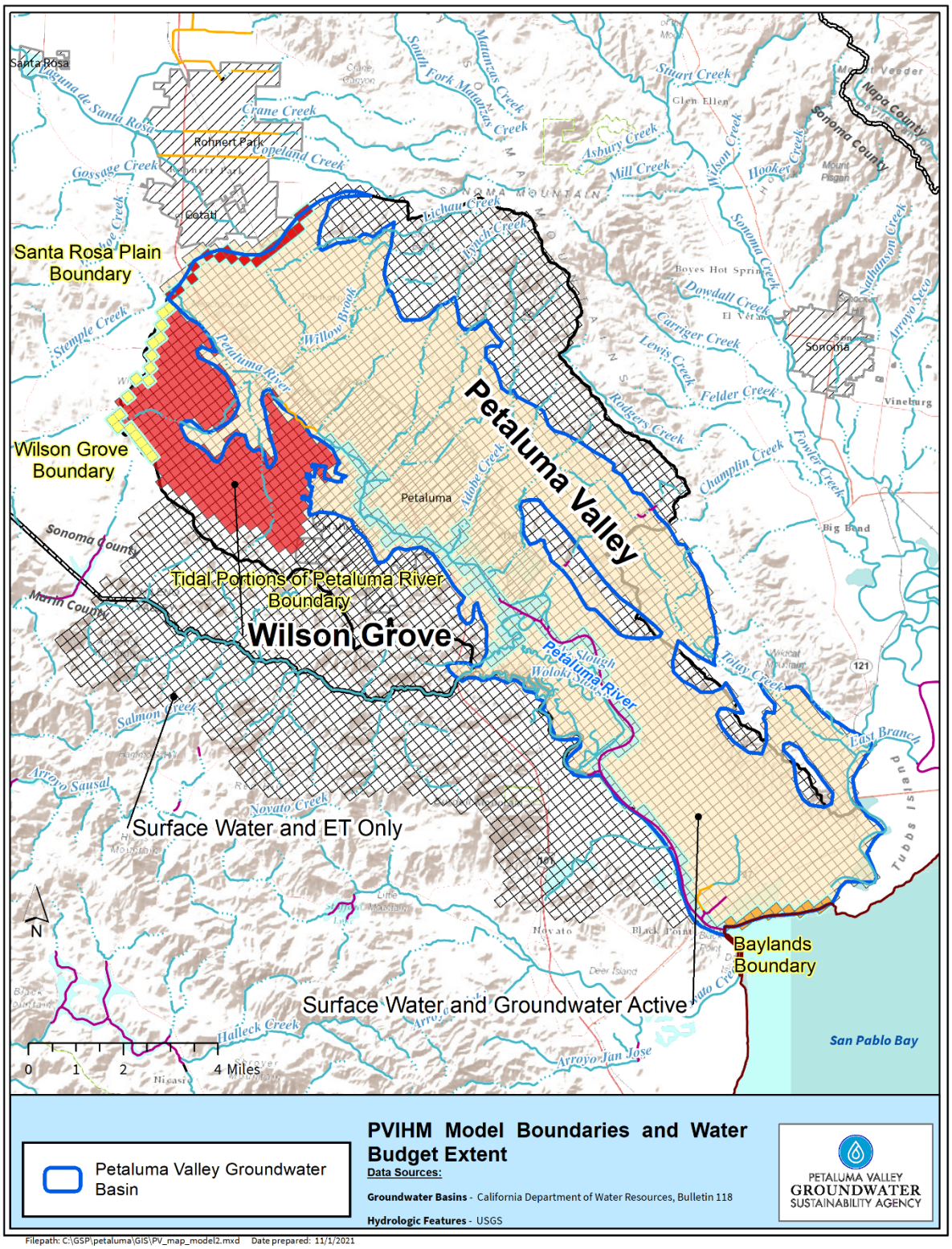


Figure 1: Extent and Boundary Conditions of PVIHM

The PVIHM was developed using the MODFLOW-OWHM2 (Boyce and others, 2020) code. MODFLOW-OWHM2 is based on MODFLOW-2005 (Harbaugh, 2005) with an updated version of the Farm Process (FMP4; Boyce and others, 2020) and incorporates other model enhancements. The PVIHM uses FMP4 to simulate routing of precipitation and irrigation water at the land surface, and to estimate groundwater pumping for irrigation.

Other model input datasets, such as municipal and rural domestic pumping, wastewater flows for recycled water deliveries, are based either on public records or on estimates from land use analysis. Figure 2 illustrates key components and linkages of the PVIHM.

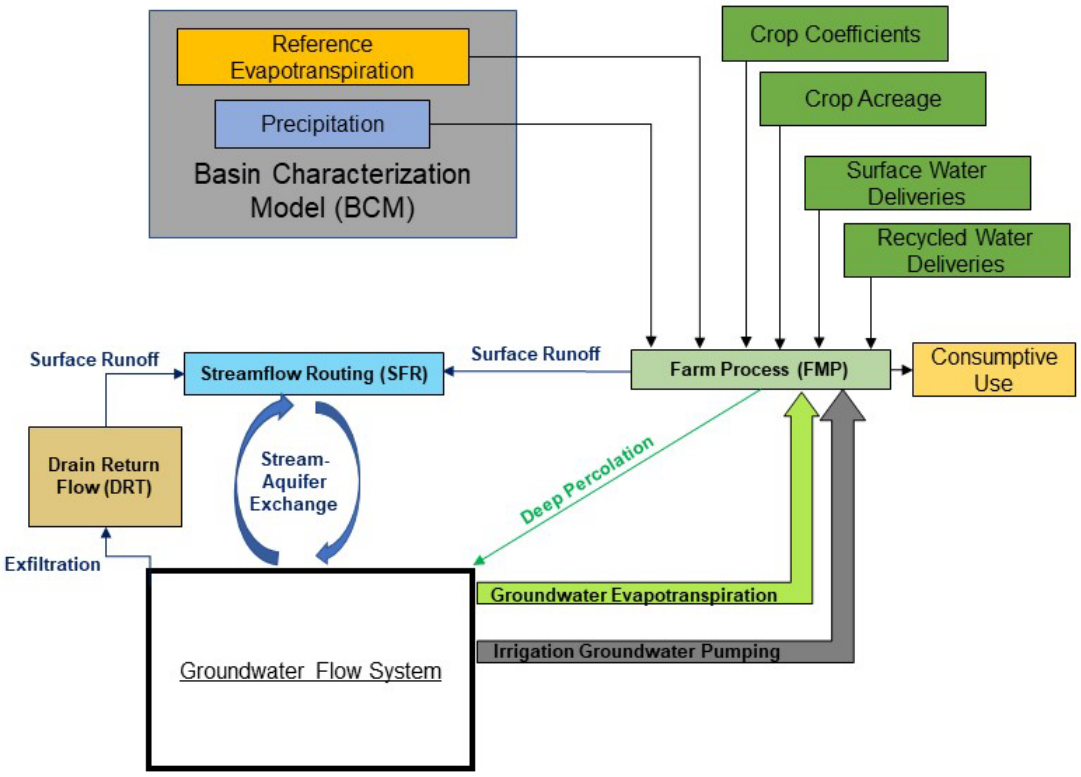


Figure 2: Schematic Illustration of PVIHM Processes

Reference ET and precipitation grids were extracted from Basin Characterization Model (BCM) inputs, and interpolated from the BCM grid to the PVIHM grid.

Model Evaluation and Use for GSP Development

A detailed model review and assessment was performed and concluded that, in general, the model is adequate for use during GSP development, for the following reasons:

- The model uses a public domain, and well documented modeling platform that includes capabilities adequate to develop robust water budgets and assess projects and actions.

- Most model input data were vetted with local information and assumptions follow local understanding of aquifer processes.
- The model was calibrated to historical data and is very well calibrated to the four categories of calibration datasets used (groundwater levels, vertical hydraulic gradients, streamflow, and streamflow gains and losses estimated from seepage runs).

Therefore, the model is an suitable tool to be used for SGMA application during GSP development and implementation.

Recommendations for improving the model were split between those critical for GSP development, and those that could be implemented during GSP implementation. The major recommended model revisions and refinements for GSP development include:

- Extend model simulation period to the end of Water Year (WY) 2018
- Review assumptions used to calculate rural domestic pumping and incorporate septic return flows
- Incorporate simulation of surface water diversions from streams consistent with simulated surface water deliveries to farms

Additional model input reviews, data evaluation, and updates, are recommended during GSP implementation, after additional information is collected. *A detailed plan for further model refinements is provided in the GSP Implementation Section of this GSP.*

Modifications to PVIHM

Rural Domestic Pumping and Septic Return Flows

The Sonoma County parcel database was filtered to locate rural residential parcels inside of the groundwater model domain. The yearly groundwater usage applied to each parcel was determined by the size of the parcel and the parcel type. The groundwater demand was estimated by:

$Q_{parcel} = Q_{indoor} + \%\ Irrigated \times I_d \times P_{av(i)}$

% Irrigated = 2.80%

I_d = 2.9 ft/year; Turf Irrigation Depth

$P_{av(i)}$ = Parcel area (acres)

Q_{indoor} (In-home use) = 0.24 AF/year

Parcel zoning use codes were used to determine if a parcel uses groundwater for indoor and outdoor, indoor only, or outdoor only. Parcels with outdoor and indoor uses are typically common residences, whereas indoor only parcels are those with a mixed residential and

agricultural zoning use code description. The assumption is that the agricultural demands will be satisfied by the Farm Package in MODFLOW-OWHM.

The start of pumping for a given parcel was determined from the year that the parcel database indicated the parcel was developed. Parcels are aggregated spatially by model cell for every stress period. The layers from which the parcels pump groundwater is determined from the reported domestic well depths. The reported well depths are provided by DWR's Well Completion Report Map which describes the number, maximum, minimum, and average depths for wells by township, range, and section. The layer assigned to a given parcel was selected based on the minimum, maximum and mean defined in the DWR dataset for that well's township, range, and section

Surface Water Diversions

Surface water irrigators in the Petaluma Subbasin divert water from streams during the winter into on-farm storage ponds for water use during the primary growing season (*Citation forthcoming*). Consequently, there is a lag between the timing of surface water diversions from streams, and the use of surface water for irrigation. Use of surface water for irrigation is referred to as surface water delivery, meaning that the water is delivered to the point of use.

The PVIHM simulates surface water deliveries to farms as N on-Routed Deliveries (NRD), consisting of a monthly specified delivery volume. NRD volumes as specified as part of model inputs are based on data from the enhanced Water Right Information Management System (eWRIMS) (*Citation forthcoming*).

The PVIHM simulates surface water diversions from streams as Semi-Routed Deliveries (SRD). For SRD, the timing and magnitude of surface water diversions is dependent on both simulated crop consumptive use requirements by the Farm Process and on simulated monthly streamflow upstream of the surface water point of diversion. The PVIHM is configured to simulate monthly diversions as SRD approximately equal to the corresponding monthly NRD volume. The PVIHM includes a cap on monthly surface water diversions calculated based on the annual delivery volumes, to ensure that simulated surface water diversions do not exceed the specified delivery volume, which is based on eWRIMS data (Jon Traum, January 2021, written communication).

Extending Simulation Period through Water Year 2018

Extending the simulation period to the end of WY2018 consisted of updating several PVIHM input datasets with the most recently available data. **Table 1** lists the input datasets that were updated, including the data source and the PVIHM package or process which requires the dataset.

Table 1. PVIHM Input Datasets Used to Extend Simulation Period

Input Dataset	Data Source	PVIHM Package
Recycled water deliveries to farms	City of Petaluma Records	FMP4
Surface water diversions and deliveries to farms	Estimated based on eWRIMS records	NRD
Municipal pumping	City of Petaluma records	MNW
Rural domestic	WY 2015 values repeated through WY 2018	WEL
Land use and irrigation status	LandIQ / CA DWR	FMP
Spatially distributed climate data	BCM v65 inputs obtained from USGS	FMP4
Interbasin flow	Heads in adjacent basins estimated based on historical records	GHB

Recycled Water Deliveries

Total annual recycled water (RW) deliveries to farms were provided by City of Petaluma for calendar years 2015 through 2018 to include in the model. Since only an annual total for all RW customers was provided, deliveries were distributed by month and by water balance subregions. Monthly deliveries for years with similar water year classifications were used to calculate percentages of the annual total to distribute totals by month and by water balance subregion for the update period. Calendar year 2014 proportions were used to allocate deliveries for calendar year 2016 and 2018. Calendar year 2012 proportions were used to allocate deliveries for calendar year 2017. Proportions from October through December 2013 were used to allocate the remainder of deliveries for 2015. **Figure 3** shows total RW deliveries in the historical and update periods.

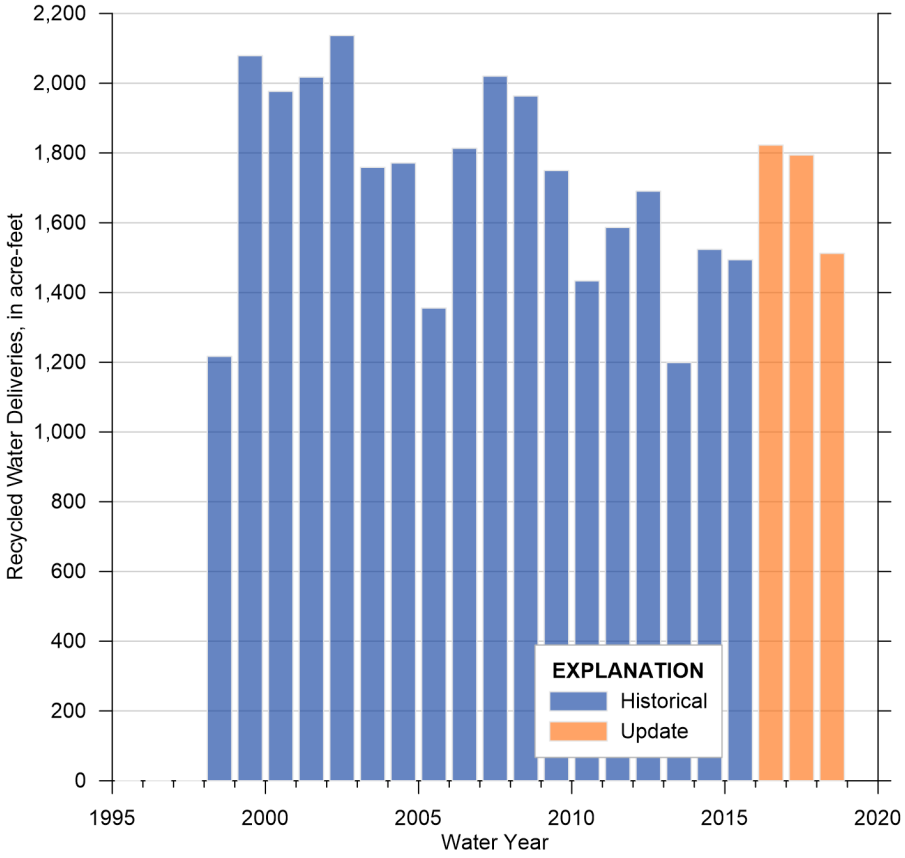


Figure 3. Recycled Water Deliveries for the Historical and Update Periods.

Surface Water Diversions and Deliveries

Surface water deliveries were calculated by repeating values from water years with similar water year classifications. Monthly surface water deliveries for WY 2016 and 2018 used repeated values from WY 2014. WY 2017 used repeated values from WY 2012. Figure 4 shows total surface water deliveries to farms for the historical and update periods.

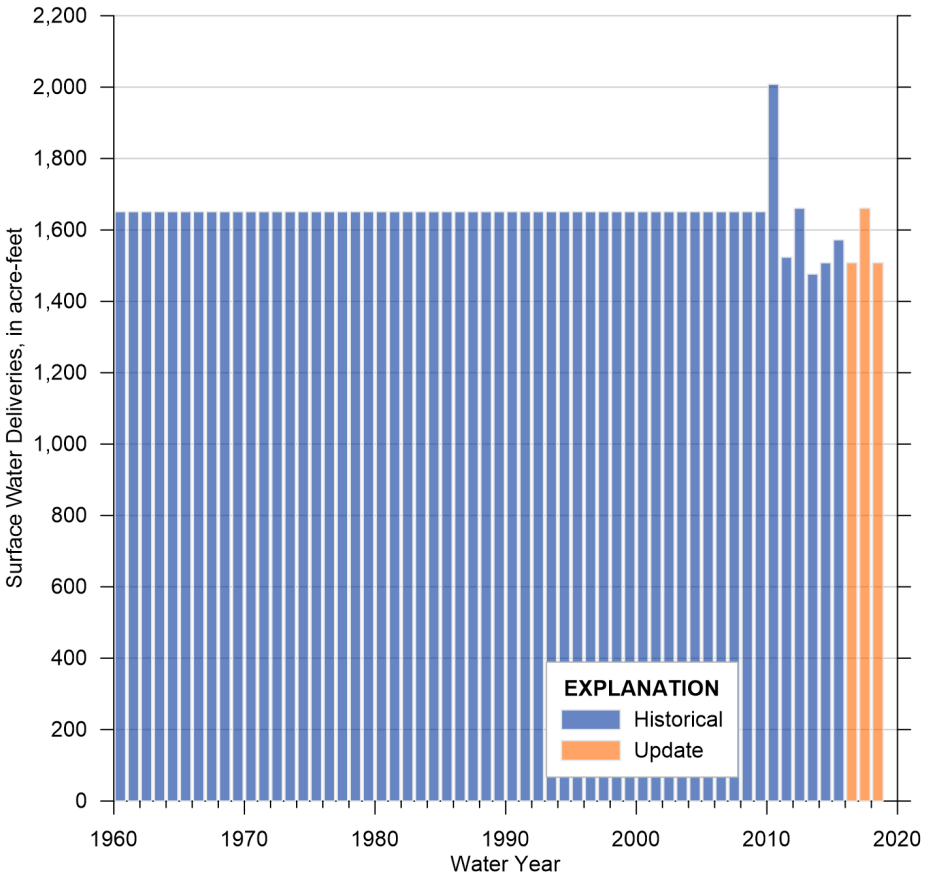


Figure 4. Surface Water Deliveries for Historical and Update Periods.

Simulation of surface water diversions as SRD during WY2015-2018 is consistent with the original PVIHM, with monthly diversion volumes calculated based on both the simulated streamflow, and simulated crop demands. The cap, or upper limit, on surface water diversions was extended over WY2015-2018 using a similar approach to farm deliveries by substituting the equivalent monthly limit from similar water years, as described above.

Groundwater Pumping

Groundwater use in the Subbasin includes pumping by public water systems and by rural water users for both domestic and agricultural irrigation uses.

Municipal Pumping

Total monthly pumping data were provided by City of Petaluma. Two wells, the Stony Point and Frietas wells, supply the total groundwater demand, pumping approximately the same volume. Municipal groundwater pumping rates were simulated using the MODFLOW Multi-Node Well (MNW2) package on a monthly stress period and are displayed in **Figure 4**.

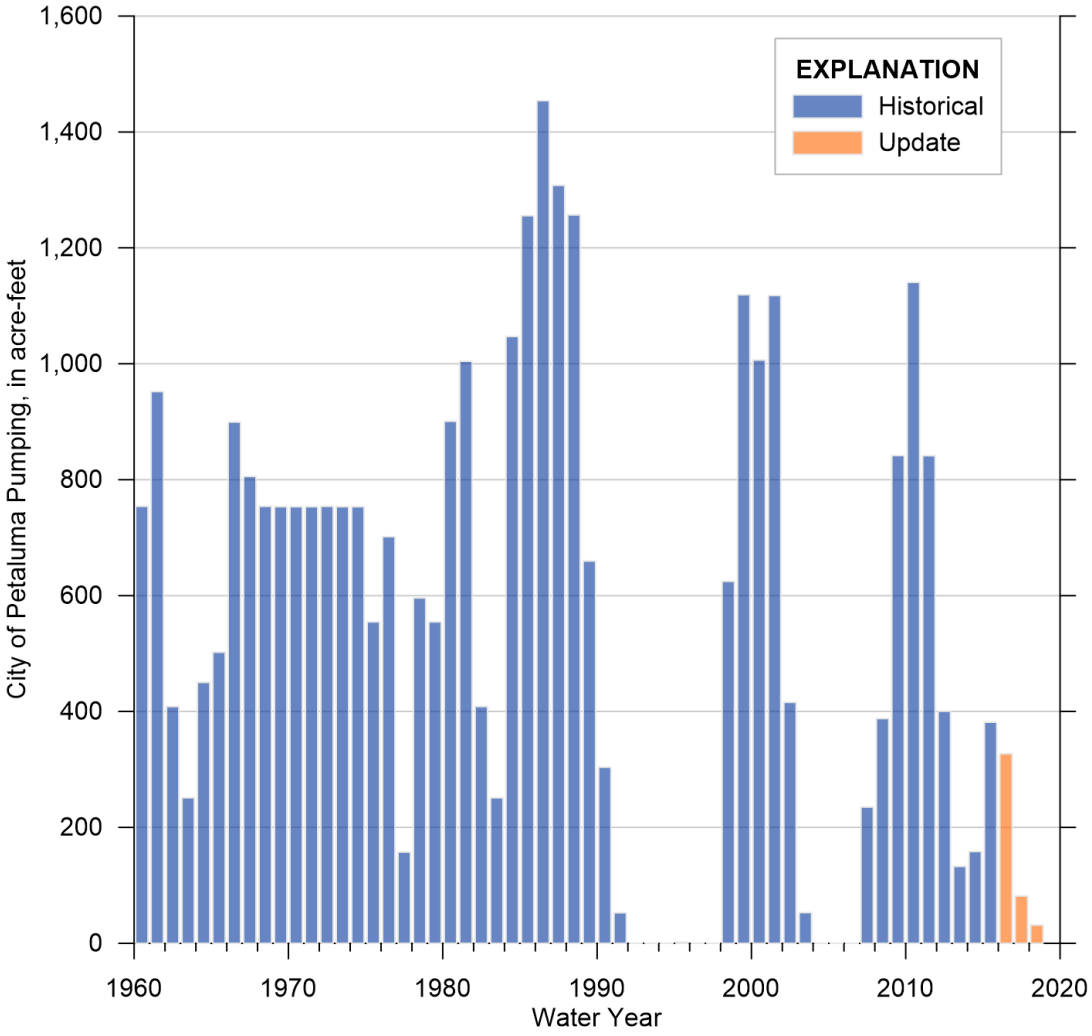


Figure 5. City of Petaluma Groundwater Pumping for the Historical and Update Periods

Farm Process Input Datasets

Datasets required to update the Farm Process in the PVIHM include land use, and monthly, spatially distributed climate variables (precipitation and reference evapotranspiration).

Land Use

Land use simulated by the original PVIHM (Citation Forthcoming) relied on DWR land use datasets for Sonoma County and Marin County. DWR specification of irrigation status (irrigated or non-irrigated) of agricultural lands was also incorporated into the original PVIHM.

Land use data developed by LandIQ (LandIQ, 2017) were used to update FMP inputs from September 2015 through 2018. Land use data for a given year were repeated until new data became available. Two snapshots were available from LandIQ, one for 2014 land use and one for 2016 land use. **Table 2** lists time periods in the PVIHM associated with each land use dataset, for the original model and the update portion.

Table 2. Land Use Data Sets in PVIHM

Land Use Data Set Year	Data Source	Water Years Represented by Land Use Dataset
1959	DWR	1959 - 1978
1979	DWR	1979 – 1985
1986	DWR	1986 – 1998
1999	DWR	1999 – 2011
2012	DWR	2012 – 2013
2014	LandIQ	2014 – 2015
2016	LandIQ	2016 – 2018

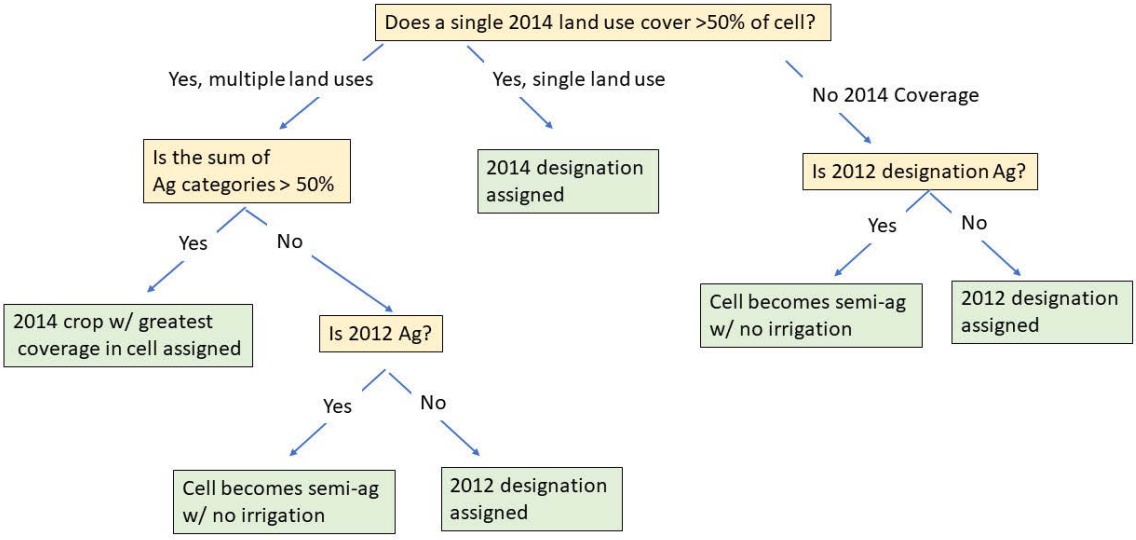
Specification of PVIHM land use during WY2014-2015 differs between the original PVIHM and the temporal update. Land use during WY2014-2015 was based on 2012 DWR data for the original PVIHM, and was updated to use the 2014 LandIQ data in the PVIHM temporal update.

Land use for each model cell was determined based on the spatial land use data described above. Figure 6 shows a flow chart describing how land use was updated based on the 2014 LandIQ dataset. The same methodology was followed for the 2016 LandIQ dataset, except the comparison was made between 2014 and 2016, rather than 2012 and 2014 datasets.

Table 3 illustrates the correspondence between land use categories from the 2014 and 2016 LandIQ datasets, and land use categories simulated by the PVIHM.

Table 3. Correspondence between LandIQ Land Use and PVIHM Land Use Categories

2014 & 2016 LandIQ Land Use Categories	PVIHM Land use Category
Flowers, Nursery and Christmas Tree Farms	Truck
Grapes	Vineyards
Greenhouse	Truck
Idle	Idle
Managed Wetland	Riparian
Miscellaneous Deciduous	Orchard
Miscellaneous Grain and Hay	Grain
Miscellaneous Grasses	Pasture
Miscellaneous Truck Crops	Truck
Mixed Pasture	Pasture
Olives	Orchard
Strawberries	Truck
Urban	Urban
Walnuts	Orchard
Young Perennials	Truck
Apples	Orchard



Irrigation Status of Agricultural Land

The PVIHM requires that the irrigation status of agricultural lands be specified as part of the calculations of groundwater pumping for irrigation to satisfy farm demand. LandIQ land use snapshots for 2014 and 2016 do not define the irrigation status of agricultural lands. Initially, irrigation status arrays for WY 2015 through 2018 were defined based on a combination of land use and the 2012 irrigation status. Specifically, initial assumptions with respect to grain and pasture were as follows:

- Any parcels with mapped land use of grain were simulated as irrigated grain if they were also simulated as irrigated grain in 2012
- All pasture acreage was simulated as irrigated

During subsequent discussions with the Petaluma Valley GSA Advisory Committee, additional feedback received, and based on supplemental data on the 2016 irrigation status of grain, pasture, and miscellaneous grasses in the Petaluma Valley Basin (Tad Bedegrew, CA DWR, written communication, February 2021), it was determined that this approach likely overestimated the acreage of irrigated pasture.

The irrigation status of grain and pasture land use as specified in PVIHM inputs for 2015-2018 was modified for consistency with supplemental data provided by DWR, as shown in Table 4. Revisions to irrigation status were based on review of recent NDVI and aerial imagery to select parcels mapped as either grain, miscellaneous grasses, or pasture, but which could be visually identified as non-irrigated.

The final total areas of irrigated and non-irrigated grain and pasture land uses simulated by the PVIHM are shown in Table 4. The irrigated acreages are reasonably close to the estimates or irrigated and non-irrigated acreage provided by DWR for the purposes of GSP development.

Table 4. 2016 Acreage in Petaluma Valley Basin of Select Grass Crops by Irrigation Status Compared with Representation in PVIHM

	DWR Supplemental Data		PVIHM grid cell area	
Crop	Irrigated, acres	Not Irrigated, acres	Irrigated, acres	Not Irrigated, acres
Grain	125	4533	534	4025
Pasture[1]	457	1704	267	1846
Total	582	6237	801	5871

[1] **Total acreage of pasture and miscellaneous grasses land use**

Precipitation and Evapotranspiration

To update the model through 2018, monthly gridded precipitation and evapotranspiration datasets were used as inputs to FMP4. The update used input datasets to the BCM for both precipitation and evapotranspiration, consistent with the approach used for the original PVIHM (Citation Forthcoming). Historical gridded precipitation and evapotranspiration data for the update period were provided by the USGS.

Interbasin Groundwater Flow

The PVIHM simulates exchange between the Santa Rosa Plain Subbasin and the portion of the Wilson Grove Basin outside the PVIHM active extent using General Head Boundaries (GHB). GHB reference heads for the original PVIHM were calculated based on water levels measured in nearby wells (Citation Forthcoming). GHB reference heads were extended through WY2018 based on Water Year type, using the same correlations described in the section 'Surface Water Deliveries and Diversions'.

DEVELOPMENT OF MODEL INPUTS FOR FUTURE PROJECTED BASELINE SCENARIO

The PVIHM was modified as part of GSP development to simulate a future projected baseline scenario for the purpose of establishing projected water budgets under baseline conditions considering climate change, and projected land use and water demand changes, and to provide a benchmark scenario for evaluating Projects and Management Actions.

Projected Climate Inputs

Based on the results of a separate evaluation of General Circulation Models (GCMs) to use for GSP development, the HadGEM2-ES GCM was selected to develop projected climate inputs for the future projected baseline scenario (see GSP Section 3 and Appendix 3-E). Two Representative Concentration Pathways (RCPs) were reviewed by the Petaluma Valley GSA Advisory Committee, and the RCP 8.5 emissions scenario was selected.

GCM outputs from the HadGEM2-ES model forced by the RCP 8.5 emissions scenario were sampled to the Basin Characterization Model (BCM) grid over the Russian River watershed on a monthly time scale. The PVIHM grid does not align exactly with the BCM grid; therefore, monthly gridded precipitation and reference ET were interpolated from the BCM to the PVIHM grid to prepare model inputs for the future projected baseline scenario.

Surface Water Diversions and Deliveries to Farms

Surface water deliveries to farms simulated as NRDs were defined using a similar approach as used for extending the historical simulation through 2018 and described in the section 'Extending Simulation Period through Water Year 2018'. Each year of the future period was assigned a water year type, and monthly surface water deliveries for each year were set equal to monthly surface water deliveries from a historical year with the same water year type, and for which data on surface water deliveries are available. Table 5 lists the reference water years used to assign monthly surface water diversions in the projected baseline scenario.

Table 5. Reference Water Years Used to Assign Surface Water Diversions and Deliveries in Future Projected Baseline Scenario

Future Water Year Type	Reference Historical Year
Very Dry	1977
Dry	2014
Normal	2012
Wet	2011
Very Wet	1998

Surface water diversions from streams simulated as SRDs used the same approach as for the historical period; however, the upper limit on monthly surface water diversions was assigned based on future water year type, with the same correlations to reference historical years shown in Table 5.

Projected Pumping

Irrigation pumping

Irrigation pumping during the future period was simulated using the Farm Process using the same approach as in the historical simulation.

Municipal and Industrial (M&I) Pumping

Groundwater pumping by the City of Petaluma was projected over the future, as described in Appendix 3-D.

Annual groundwater demand was distributed to monthly pumping rates based on average monthly pumping distribution in historical pumping records. City of Petaluma pumping was assumed to be distributed among six pumping wells, shown in Table 6.

Table 6. Distribution of City of Petaluma pumping by supply well in future projected baseline scenario

Well	Percentage of City of Petaluma pumping served by well
Stony Point	50%
Airport Well	10%
Cross Creek Well	10%
Frates Well	10%
La Tercera Well	10%
Park Place Well	10%

As of 2020, City of Petaluma groundwater pumping was equally split between the Stony Point and Frates Wells (Kent Carothers, personal communication, September 2020). Preliminary simulation results based on equally splitting future projected City of Petaluma demand indicated that the Frates well could not reliably supply 50% of projected demand due to simulated drawdowns past the well screen. It was therefore assumed that half of the City's groundwater demand will be supplied by the Stony Point well, and the remaining half would be evenly distributed among the Airport, Cross Creek, Frates, La Tercera, and Park Place Well (Table 6).

Rural domestic pumping

Rural domestic pumping was projected over the future simulation period, as described in Appendix 3-D.

Projected land use

Agricultural land use changes were projected over the future simulation period, as described in Appendix 3-D.

Interbasin groundwater flow

Future projected groundwater flow between the PVIHM active extent and adjacent basins was simulated using the same approach as in the historical simulation, using GHB cells. GHB reference heads were defined through the future period using the correlations between future water year type and reference historical years shown in Table 5.

Exchange between aquifer and San Pablo Bay

Future sea level rise due to climate change may impact groundwater conditions beneath and upgradient from San Pablo Bay. Sea-level rise guidance provided by the California Natural Resources Agency (CNRA, 2018) was used to provide a sea-level rise trajectory to be simulated. The PVIHM was modified to simulate the 1-in-200 change (0.5% probability) sea level rise trajectory under the high emissions

scenario, which results in a projected sea level rise of 3.5 feet at the end of the projected 50-year water budget. The choice of the 1-in-200 change scenario is consistent with: (1) the choice of emissions scenario considered for future climate to be simulated by the model; and (2) sea level rise assumptions used for the Sonoma Creek Baylands Strategy (Sonoma Land Trust and San Francisco Bay Restoration Authority, 2020). Exchanges between the aquifer and San Pablo Bay, and between the aquifer and the tidally-influenced Petaluma River are simulated in both the historical and future period as a head-dependent flow using the General Head Boundary (GHB) package. Future sea-level rise was simulated by converting the sea level rise trajectory to freshwater equivalent head, and adding to the historic freshwater equivalent head used to represent both the Bay and the tidally-influenced Petaluma River in the PVIHM future simulation.