Appendix I

Regional Quantitative Analysis (WEAP, HEC-HMS)

Supporting the Yolo Storm Water Resources Plan (Yolo SWRP)

Final report in fulfillment of Proposition 1 Storm Water Planning Grant Program

Agreement No. D1612620

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Chapter 1. Introduction

Yolo County is largely rural, with almost half of its area under cultivation (Borcalli and Associates, 2000). A large portion of Yolo County is in the alluvial floodplain of the Coastal Range. Historically, it was subject to annual flooding in the winter. Some of the sloughs are reported to have once run perennially (Jones & Stokes Associates, 1996) ; now summer runoff is primarily a result of irrigation return flows in wet years.

Today, noticeable flooding from small to medium storms (from 2 to 5 year recurrence interval) is still common, but disproportionately affects rural residents, farmers, small towns and unincorporated communities as compared to larger cities. In unincorporated communities and Disadvantaged Communities (DAC)'s that lack adequate storm water drainage systems , entire residential neighborhoods can be flooded up to a foot or so, from medium storm events (of about 5 to 10-year return period).

As part of the team developing the Yolo Storm Water Resource Plan (Yolo SWRP), our efforts at the Stockholm Environment Institute (SEI) focus on possible water management efforts <u>at the larger landscape scale</u>, which could result in SWRP benefits and achieve some SWRP objectives, as articulated in the SWRP Guidelines[1] and in Chapter 1 of the Yolo SWRP.

SEI's contributions, reported in this document, were largely related to modeling several aspects of storm water management in Yolo County. For these contributions, we developed, modified and/or used three different models (Table 1.1), which are described in more detail in the subsequent chapters. In the process, several other resources were also gathered/developed, in the form of storm water design related manuals, online resources, GIS datasets, secondary literature, informal interviews with key informants, and a photo catalog. These resources are included with this report. We also conducted several field trips related to Disadvantaged Community (DAC) outreach concerning Madison, which frequently experiences flooding, even from relatively small storms of 2-year recurrence interval.

We note that SEI modeling efforts fit into the larger water management scale and context, that of Yolo County being largely rural. These efforts are therefore pertinent to the conceptual and planning sections of the Yolo SRWP and are not specific to the small-scale (e.g. sub-city scale, implementation-ready) projects that are included in the Plan. The project team arrived at this decision through the course of the project for several reasons. Although SEI has a county-scale WEAP model, it was determined that it was not feasible to include the anticipated benefits of

[1] View the guidelines at:
https://www.waterboards.ca.gov/water_issues/programs/grants_loans/swgp/docs/prop1/swrp_finalguidelines_dec2015.pdf

each project in the Yolo SWRP into the model because each project proponent had developed its own quantitative method (as it was free to do so). The time it would have taken to disaggregate the model into a sub-city scale and in addition use various methods in each case, made it exceed the scope of our effort. Additionally, the volumes of water involved at each project scale, while very important in their own context, are very small compared to the county-wide water balance; the latter is the scale that the WEAP model is most useful for. Further explanation of modifications to the originally proposed work plan are discussed in Appendix C.

A summary of SEI's efforts and resulting findings are captured below, along with the Yolo SWRP Benefits that could be realized upon implementation (Table 1.2).

Table 1.1 Models used in this analysis

Model	Timestep	Duration	Spatial Extent	Spatial Disaggregation	Analysis	Software	Notes
Western Yolo Model	Event-based	Jan 2017 storm and design storm	Western Yolo Sloughs	4 small catchments	Storm runoff in western Yolo sloughs (Chapter 2)	Hec-HMS (http://www.hec.usace.army.mil/software/hec-hms/)	Developed for this analysis
Cache Creek Model	Monthly	Water Year 1976 to Water Year 2010	Cache Creek and Yolo County	9 upper Cache Creek catchments, 3 Yolo County catchments	Storm water conveyance via canal operations for groundwater recharge (Chapter 3)	Water Evaluation and Planning (WEAP) (Yates et al., 2005)	Previously developed (Mehta et al., 2013)
Yolo Storm Water Model	Daily	Water Year 1976 to Water Year 2010	Cache Creek and Yolo County	9 upper Cache Creek catchments, 38 Yolo County catchments	Rainfall capture on farm fields (Chapter 4)	Water Evaluation and Planning (WEAP) (Yates et al., 2005)	Modified from the Cache Creek Model for this analysis

Summary description of activities and outputs

1. Storm runoff in western Yolo sloughs

Madison is one of the Disadvantaged Communities (DAC) in Yolo County that is regularly flooded in the winter. Although a few hydraulic studies have been conducted in the past[2], no permanent solutions have been implemented to date.

The 1999 Madison flood modeling study conducted by Borcalli Associates, Inc. informs us that Madison is "***..subject to flooding from South Fork Willow Slough, Cottonwood Slough, the Madison Drain, and local runoff from agricultural land north, west and south of Madison***"(Borcalli and Associates, 1999, pp. 4–6). We were interested in characterizing upstream runoff contributions – namely in three sloughs, Lamb Valley Slough, South Fork Willow Slough, and Cottonwood Slough – that are west and south of Madison. The Western Yolo Model (Table 1.1) was built in HEC-HMS for these sloughs to estimate peak and volumetric runoff for one actual and one design storm. Details of this analysis are presented in Chapter 2.

2. Storm water conveyance via canal operations for groundwater recharge

The Yolo County Flood Control and Water Conservation District (District)'s service area covers approximately 30% of the county's land area. The District also provides a large share of the County's surface water supply for irrigation – at 234,000 acre-feet in wet years, almost a quarter of the county's total estimated irrigation requirements. Its extensive canal system is largely unlined and known to contribute to substantial groundwater recharge (Borcalli and Associates, 2000; Mehta et al., 2013; YCFCWCD, 2012). In a previous modeling study, SEI had found that winter recharge of diverted Cache Creek streamflows was one of the most promising of several winter runoff management strategies investigated (Mehta et al., (accepted)). Chapter 3 of this report includes quantitative estimates from the Cache Creek WEAP Model (Table 1.1), run for 35 years at a monthly timestep.

3. Rainfall capture on farm fields

In recent years, the idea of capturing winter rainfall on agricultural fields has gained ground, due to its potential to provide both flood management and water supply benefits (through groundwater recharge). We assessed two scenarios of capturing precipitation on selected farm fields using the Yolo Storm Water WEAP model (Table 1.1). Fields were selected based on crop coverage and the Soil Agricultural Groundwater Banking Index (O'Geen et al., 2015). A daily

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[2] For example, (Borcalli and Associates, 1999; Wood Rodgers Inc, 2017)

timestep WEAP model was used. In the more conservative scenario, surface runoff reduction was estimated as 5,000 acre-feet on average over 35 years of simulation; and 9000 acre-feet in the less conservative scenario. The modeled water balance shows that almost all of this reduced runoff augments groundwater recharge.

4. Additional on-farm

In Chapter 5, we discuss two additional on-farm options for winter run-off mitigation and groundwater recharge : flooding of fields and winter irrigation. The chapter summarizes learnings from recent literature and interviews with key informants. No modeling analysis was conducted for this Chapter.

5. Flow monitoring network

This output, described in Chapter 6, compiles recommendations on establishing and enhancing existing flow monitoring sites in western Yolo County, focusing on storm runoff from Lamb Valley, South Fork Willow and Cottonwood Sloughs. Related pictures from the sites and site descriptions are included.

6. Other Outputs

To produce the final outputs above, several intermediary products were collected or produced. These are summarized and provided in Chapter 7.

Summary of Findings

Noticeable flooding from small to medium storms disproportionately affects rural residents, farmers and unincorporated communities as compared to larger, wealthier cities. Flooding in the Madison and Esparto area exists after small to medium storms (even less than 5 year recurrence interval) as a result of a combination of sources: runoff from farm fields, slough overtopping from capacity restrictions (sloughs too confined due to restrictive vegetation, silting or undersized culverts and bridges), capacity exceedance (too much water, even if sloughs are clear), and aggregated effects of all these processes in low-lying parts of the landscape.

Field investigations, combined with the findings of earlier foundational studies, lead us to conclude that storm water management will need to occur at multiple scales simultaneously;

1. management and maintenance of storm drains at the local scale so that sloughs can more effectively convey water
2. on-field management of winter run-off at the distributed, farm-field scale to reduce runoff into the sloughs

3. management of upstream storm flows in sloughs to reduce flows in the slough before reaching areas vulnerable to flooding, and
4. canal operations to convey water out of flood-prone areas, or take advantage of storm flows for groundwater recharge with minimal risks compared to other recharge options

The area could also greatly benefit from the knowledge of canal and slough flows that would be gained from an increased flow monitoring network in areas that contribute to flooding.

The scope of the storm water management measures explored in this report is limited to the small and medium storms. These measures will be too small to handle the rare, big storms (with say 50 to 100 year or more return periods[3]). Nevertheless, these measures are warranted and justified because they are needed, are feasible, and because the greatest proportion of cumulative long-term flood damage in these rural areas is from small and medium storms (US Soil Conservation Service, cited in Jones and Stokes, 1996).

[3]For some management possibilities for large storms, see for example the CalTrans studies on Highway 16 http://www.dot.ca.gov/d3/projects/subprojects/0C470/files/newsPDFs/0C470Road.pdf

Table 1.2 Outputs related to SWRP Benefits

SWRP Objectives		SEI Activities					
		Storm runoff in western Yolo sloughs	Storm water conveyance via canal operations for groundwater recharge	Rainfall capture on farm fields	Additional farm field-groundwater recharge strategies	Flow monitoring network	Other Outputs
Reasonable Use Focus	Increase adoption of agricultural Best Management Practices			x	x		
Risk Management Focus	Manage watershed activities to reduce large erosion events			x	x	x	
	Provide adequate flood protection	x		x			
Understand Watershed Function Focus	Monitor conditions/improve understanding to support sustainable groundwater basins					x	x
	Maintain/enhance watershed and natural resource monitoring network and information sharing					x	x
Water Quality Focus	Address pollutant sources to meet runoff standards and Total Maximum Daily Load (TMDL) targets			x			
	Reduce public health risks by reducing contaminants in drinking water sources			x			
Water Supply Focus	Provide agricultural water supplies to support a robust agricultural industry		x	x	x		
Storm Water Focus	Optimize the rural storm water conveyance system to drain and retain storm water flows as necessary. Provide proper rural drainage and keep conveyance systems clear of debris to minimize county road flooding during storm events.	x	x	x		x	
	Enable proper rural retention and modify rural landscape to maximize groundwater recharge of excess storm water.		x	x	x		

Chapter 2. Storm runoff in western Yolo sloughs

Executive Summary

Storm runoff was estimated from three watersheds in the foothills west-southwest of Esparto, which may contribute to flooding in Madison. These three drainages are Lamb Valley Slough, South Fork Willow Slough, and Cottonwood Slough. A fourth, small drainage boundary was identified that feeds directly into the Madison Drain. One subwatershed was also identified in each of the three slough drainages to a point to intersections with Winters canal. Total runoff from the modeled area resulting from an actual January storm was 577 acre-feet, with 307 acre-feet from the upstream portions of the sloughs. Peak flows ranged from 276 to 1,088 cfs across the three sloughs. For a 100-year 24-hour storm, total runoff was 6,383 acre-feet with peak flows ranging from 2,053 to 6,491 cfs. It is difficult to determine how realistic these estimated flows are however, because there are no flow gauges or sensors in the area. We recommend adding flow monitoring to better understand the hydrologic behavior of these sloughs and the Winters Canal.

Introduction

The Willow Slough Watershed Integrated Resources Management Plan (Jones & Stokes Associates, 1996), although more than 10 years old, contains the most relevant information regarding flooding, and in general, about integrated water resources management possibilities and challenges in southwestern Yolo County. It informs us that flooding is common in the valley floor in this part of the county, in response to small and medium storms of less than 10-year recurrence interval. Our field investigations (Chapter 6), and flood photo catalog (Chapter 7, see "Relating Madison flooding to flood and rainfall frequency") confirm this narrative. Sources of flooding from small to medium events that have been identified include runoff from agricultural fields, and overflowing sloughs. Sloughs overflow due to channel constriction caused by debris obstruction, silting and/or overgrown channels, and undersized bridges and culverts downstream. It is also likely that even if slough channels were clear, they would not have the capacity to convey flows from large storms.

This chapter was motivated by the regular flooding experienced by the town of Madison, which faces flooding problems in events of 5- to 10-year frequencies, or even more frequently occurring storms. Sources of flooding seem to be many, echoing the general regional causes of flooding mentioned above. For example, the 1999 Madison flood hazard modeling study conducted by Borcalli Associates, Inc., informs us that Madison is "***..subject to flooding from South Fork Willow Slough, Cottonwood Slough, the Madison Drain, and local runoff from agricultural land north, west and south of Madison***"(Borcalli and Associates, 1999, pp. 4–6). Although there is reference to several hydrologic models that were built for this region, there are no flow gauges in these sloughs to compare and calibrate any of the modeling efforts so far. We were also unable to access previous HEC models from this region, referred to, for example, in Jones and Stokes (1996) and Borcalli and Associates (1999). Hence, we constructed our own model of the watersheds and outlets of interest. We used the model to estimate flows in sloughs at locations upstream of Madison. The information produced could be used to design appropriate stormwater management measures that could prevent or slow down storm flows reaching Madison. Examples of such measures include detention ponds/check dams, off-stream storage, and diversions into Winters Canal.

Methods

Storm runoff was estimated for selected watersheds using the HEC-HMS modeling platform. HEC-HMS offers several different options (algorithms) for runoff volume and hydrograph estimation. Most of these require information regarding the watershed, such as topography, landuse/landcover and soil properties. We used the SCS Curve Number loss method and SCS Unit Hydrograph transform method. These require the estimation of watershed area, Curve Numbers, percent imperviousness, and lag time. In order to generate these input parameters for HEC-HMS, several datasets were downloaded (Table 2.1) and processed, as described in the following sections. Additionally, HEC-HMS has multiple options for entering storm event data for modeling. We modeled two storms, which required downloading datasets from two sources (Table 2.1).

Table 2.1. Input data and sources

Dataset	Source	URL	Accessed/ downloaded	HEC-HMS input derived from dataset
Elevation	NED 10m elevation	https://nationalmap.gov/3DEP/3dep_prodserv.html 1 deg x 1deg tiles n39w123 and n39w122 covering study area	Apr 27, 2017	Watershed area, Lag time
Landcover Percent Impervious	NLCD 2011 (2014 update)	https://www.mrlc.gov/nlcd11_data.php	Oct 7, 2017	Curve Number, Percent Imperviousness
Soils in Yolo County	SSURGO dataset NRCS Soil Explorer	https://gdg.sc.egov.usda.gov/ https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx	Oct 7, 2017	Curve Number
Hourly Precipitation (Brooks, BSS)	CDEC	http://cdec.water.ca.gov/cdecstation2/?KNO	Aug 1, 2017	Actual storm event
Precipitation-frequency and duration tables	NOAA precipitation frequency server	https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_printpage.html?lat=38.6793&lon=-121.9693&data=depth&units=english&series=pds	July 18, 2017	Design storm event

Watershed area

Watershed boundaries (Figure 2.1) were delineated using a 10m resolution National Elevation Dataset (NED, Table 2.1). Watershed delineation routines are standard in most GIS software: depressions in the elevation data are filled to develop a conditioned Digital Elevation Model (DEM), which is then used to derive flow accumulation and direction maps. We used ArcGIS to develop these maps and to identify specific points (called pour points) of interest as watershed and sub-watershed outlets. We then generated watershed boundaries to those points using the above mentioned maps. Pour points were selected (as shown in Figure 2.1) to generate watershed boundaries for Lamb Valley Slough, South Fork Willow Slough, and Cottonwood Slough with outlets closest to Esparto and Madison. Upstream pour points were selected to estimate flows to the outlet close to the edge of the foothills, at locations where potential flood monitoring and/or mitigation could occur. For Lamb Valley Slough, the subwatershed is delineated to the bridge near the cemetery. For South Fork Willow and Cottonwood Sloughs, they are delineated to intersections with Winters Canal. In addition, one pour point was placed at the western edge of Madison Drain to estimate local contributions to this channel, which regularly overflows.

Figure 2.1. Study Area

Watershed boundaries for Lamb Valley Slough, South Fork Willow Slough, Cottonwood Slough, and Madison Drain are shown in solid colors, along with canals and sloughs. Also shown are the upstream sub-watersheds for each slough. US means upstream point and DS means downstream point.

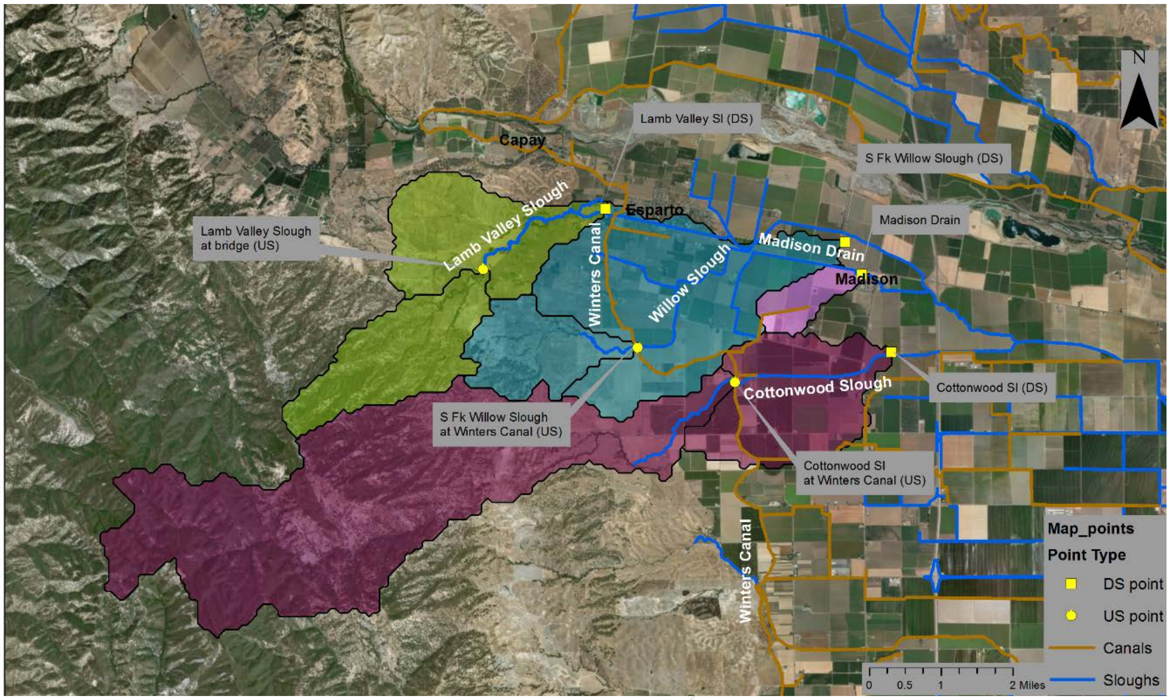


Table 2.2. HEC model input parameters for each watershed

Soil groups are hydrologic soil groups, CN is Soil Conservation Serivce Curve Number, imperv is impervious, L is the length of the longest flow path, S is maximum capacity of the soil to retain water, Y is the average slope of the drainage and Tl is lag time.

Watershed	Area sq mi	Dominant Landcovers Class	% Area	Soil Groups Group	% Area	Weighted CN	Imperv (%)	L ft	S (in)	Y (%)	Tl (min)	Tl (hr)
Lamb Valley Slough to Esparto	6.4	Herbaceuous	64	C	38	77	0.11	37346	2.9	19.7	85	1.4
		Shrub/Scrub	20	D	62							
		Cultivated Crops	10									
Lamb Valley Slough to Bridge	3.0	Herbaceuous	49	C	27	75	0.05	23340	3.3	27.7	52	0.9
		Shrub/Scrub	41	D	73							
		Mixed Forest	6									
Cottonwood Slough	17.5	Shrub/Scrub	36	C	28	82	0.14	82908	2.3	27.7	118	2.0
		Herbaceuous	27	D	48							
		Cultivated Crops	25	Rock	18							
Cottonwood Slough to Winters Canal	13.8	Shrub/Scrub	46	C	13	81	0.04	69702	2.3	35.0	93	1.5
		Herbaceuous	34	D	61							
		Mixed Forest	10	Rock	23							
Willow Slough	8.8	Cultivated Crops	43	B	5	78	1.29	42829	2.9	4.0	207	3.4
		Herbaceuous	34	C	88							
		Hay/Pasture	13	D	7							
Willow Slough to Winters Canal	2.1	Herbaceuous	88	C	72	76	0.04	19113	3.2	12.1	66	1.1
		Shrub/Scrub	6	D	28							
Madison Drain	0.75	Cultivated Crops	75	B	57	78	1.29	9619	2.7	0.5	166	2.8
		Hay/Pasture	20	C	43							

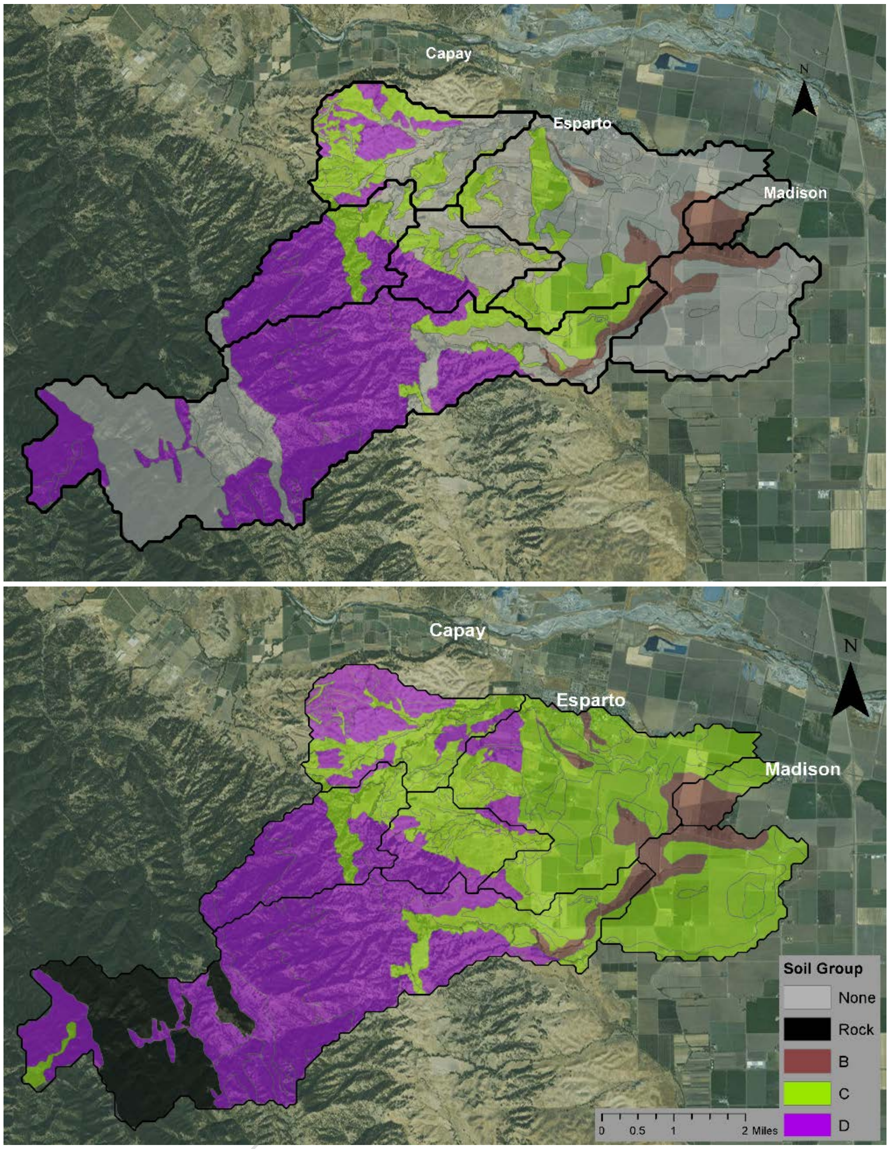
Curve Number

Curve Numbers are based on landcover conditions and soil hydrologic groups. To develop a Curve Number for each drainage area, landcover and soil data were downloaded from the National Landcover Dataset (NLCD) and the SSURGO soils dataset (Table 2.1).

Because the NLCD dataset landcover classes do not directly exist in Curve Number tables, they need to be mapped to categories that do. Table A 1 in Appendix A shows the mapping we used. When the SSURGO soil data (Table 2.1) are downloaded, they are divided into spatial and tabular datasets. Recommend changing to “SSURGO data were processed in ArcGIS, with the help of information from the NRCS Soil Explorer in filling in data gaps. (Table 2.1). The final classification of soils in the study area is shown in Figure 2.2. A substantial portion of Cottonwood slough watershed is classified as being rocky. All land area underlain with “Rock” was assigned a Curve Number of 98, which indicates high runoff potential.

Figure 2.2. Study area soil classifications

Top figure shows the study area with raw classifications from SSURGO spatial and tabular data. Bottom figure shows the study area after areas with no classification ("none") were reclassified based on nearby dominant soil types.



Using ArcGIS, polygons with unique land class-soil group combinations were generated in each drainage area. Table 2.2 shows a summary of the percent area of dominant landcover classes and soil groups for each drainage area. As with any intersection, some slivers existed where the landcover layer boundaries and soil layer boundaries did not perfectly align. These slivers accounted for <0.18% of the study area and were omitted from the remainder of the analysis.

Each of these polygons was assigned a Curve Number using Table A 1. From this, an area-weighted curve number was calculated for each watershed (Table 2.2).[4]

Percent Imperviousness

Percent Imperviousness of each drainage was calculated using the NLCD 2011 Percent Developed Imperviousness dataset. This dataset gives the percent of imperviousness cover per pixel for the coterminous U.S. The calculated percent impervious area for each watershed is shown in Table 2.2.

Lag Time

We calculated the watershed lag time (T_l in hours), defined as the time between the center of mass of the effective rainfall to the resulting hydrograph peak, using the Watershed lag method[5]. This requires the estimation of various parameters representing the topography of the drainage area. Using the previously mentioned flow accumulation and direction maps (see Watershed area section above), L, S, and T_l were calculated, and then used to calculate the lag time, using Equation 2.2.

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[4] The majority of the steps outlined in the "Creating SCS Curve Number Grid using HEC-GeoHMS" tutorial by Venkatesh Merwade (https://web.ics.purdue.edu/~vmerwade/education/cngrid.pdf) were followed in this analysis to calculate the Curve Number for each watershed, and this can be viewed for more detailed information about the data processing. Because at the time of this analysis HEC-GeoHMS was no longer supported by the Army Corps of Engineers and the newest version by ESRI was not yet developed, the weighted Curve Numbers were calculated manually for this analysis rather than using the automated tool mentioned in the tutorial.

[5] See Chapter 15 in the National Engineering Handbook (developed by the USDA and NRCS) for a detailed explanation of the variables and equations described in this section: https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=27002.wba

Equation 2.1

$$S = \frac{1000}{CN} - 10$$

Where
S=Maximum potential retention (in)
CN=Weighted curve number for the basin

Equation 2.2

$$T_l = \frac{L^{0.8} * (S + 1)^{0.7}}{1900 * Y^{0.5}}$$

Where
T_l= Lag time in hours
L= Length of the longest flow path (ft)
S= Maximum potential retention (in)
Y=Average slope (%)

Precipitation Events

We modeled one actual storm that occurred in the area and one design storm. For the actual storm, the closest station with hourly precipitation data was the Brooks precipitation station. We downloaded data from the Brooks station for a storm event that occurred January 3 and January 4, 2017, totaling 1.59 inches over 21 hours (Table 2.1, Table A 2). The January storm event may represent a rather typical storm as its recurrence interval is less than two years. The storm was entered into the HEC-HMS model as a specified hyetograph.

The NOAA precipitation frequency data server (Table 2.1) provides and estimated rainfall total of 5.7 inches for a 100-year, 24-hour design storm for a point over Madison. Fifteen-minute interval precipitation data for the design storm was produced and is shown in Table A 3[6]. These synthetic data were also entered as a specified hyetograph. Both storms were applied uniformly across each watershed.

Results and Discussion

January 2017 Storm Event

Estimated runoff volume from the actual storm of January 3-4 2017, for the entire area modeled, was 577 acre-feet. 307 acre-feet of this runoff volume was estimated as contributions from the upper portions of the watersheds (i.e Cottonwood and South Fork Willow Sloughs above their intersection with the Winters Canal and Lamb Valley Slough above the bridge, Table

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[6] Fifteen-minute interval precipitation values were produced using: Haan, Charles Thomas, Billy J. Barfield, and Julie Candler Hayes. *Design hydrology and sedimentology for small catchments*. Elsevier, 1994. Table 3.4, p. 48.

2.3). Cottonwood Slough contributes the largest volume of water, both in the upstream area and overall (Table 2.3), which is consistent with its area being the largest (Table 2.3).

Relative contributions of runoff volume from upper subwatersheds follow their relative areas. Hence, the majority of runoff volume from the South Fork Willow Slough is from the downstream portion of the watershed; the opposite is true of the Cottonwood Slough watershed; and runoff volume from the upper Lamb Valley Slough watershed is generated about 40% of the entire Lamb Valley Slough watershed (Figure 2.3).

Estimated peak flows from this storm are listed in Table 2.3, and modeled hydrographs are presented in Figure 2.3. The peaks at the downstream points of Lamb Valley Slough and in Cottonwood Slough appear to occur shortly after the peak flows in the respective upstream points (Figure 2.3). The peak in Willow Slough’s upstream point occurs approximately 3 hours before the peak in the downstream point (Figure 2.3). Additionally the peak flow in downstream Lamb Valley Slough and Cottonwood Slough occurs 1 and 1.5 hours after the peak precipitation, respectively, and occurs while it is still raining where the peak flow in downstream Willow Slough occurs 3.5 hours after the peak precipitation and once the rain has stopped (Figure 2.3).

Design Storm

Modeled runoff volume from the 100-year, 24-hour design storm of 5.7 inches was an estimated 6,383 acre-feet from the study area. 3,536 acre-feet of this runoff volume was contributed from the upstream watersheds (Table 2.3). As expected from this larger storm, larger volumes of runoff are generated. Similar patterns of proportional runoff from the upstream areas compared to overall watersheds are seen in this storm as with the previous storm (Figure 2.4).

Table 2.3 Summary of drainage area, modeled peak flow and modeled flow volume, for each watershed and storm. US means upstream point and DS means downstream point. (DS values correspond to total runoff from that watershed)

	Watershed	Drainage Area (mi²)	Peak Flow (cfs)		Flow Volume (AF)	
			Jan 2017 Storm	100-year, 24-hr storm	Jan 2017 Storm	100-year, 24-hr storm
DS	Cottonwood Slough	17.5	1,088	6,491	355	3,527
US	Cottonwood Slough at Winters Canal	13.7	922	5,549	253	2,685
DS	S Fk Willow Slough	8.8	276	2,053	130	1,599
US	S Fk Willow Slough at Winters Canal	2.1	112	880	24	357
DS	Lamb Valley Slough at Esparto	6.4	322	2,421	81	1,120
US	Lamb Valley Slough at bridge	3.0	165	1,370	30	494
	Madison Drain	0.75	28	200	11	136

Figure 2.3. Runoff from drainage areas and their relative upstream watersheds for the January 2017 storm. US means upstream point and DS means downstream point. (DS values correspond to total runoff from that watershed)

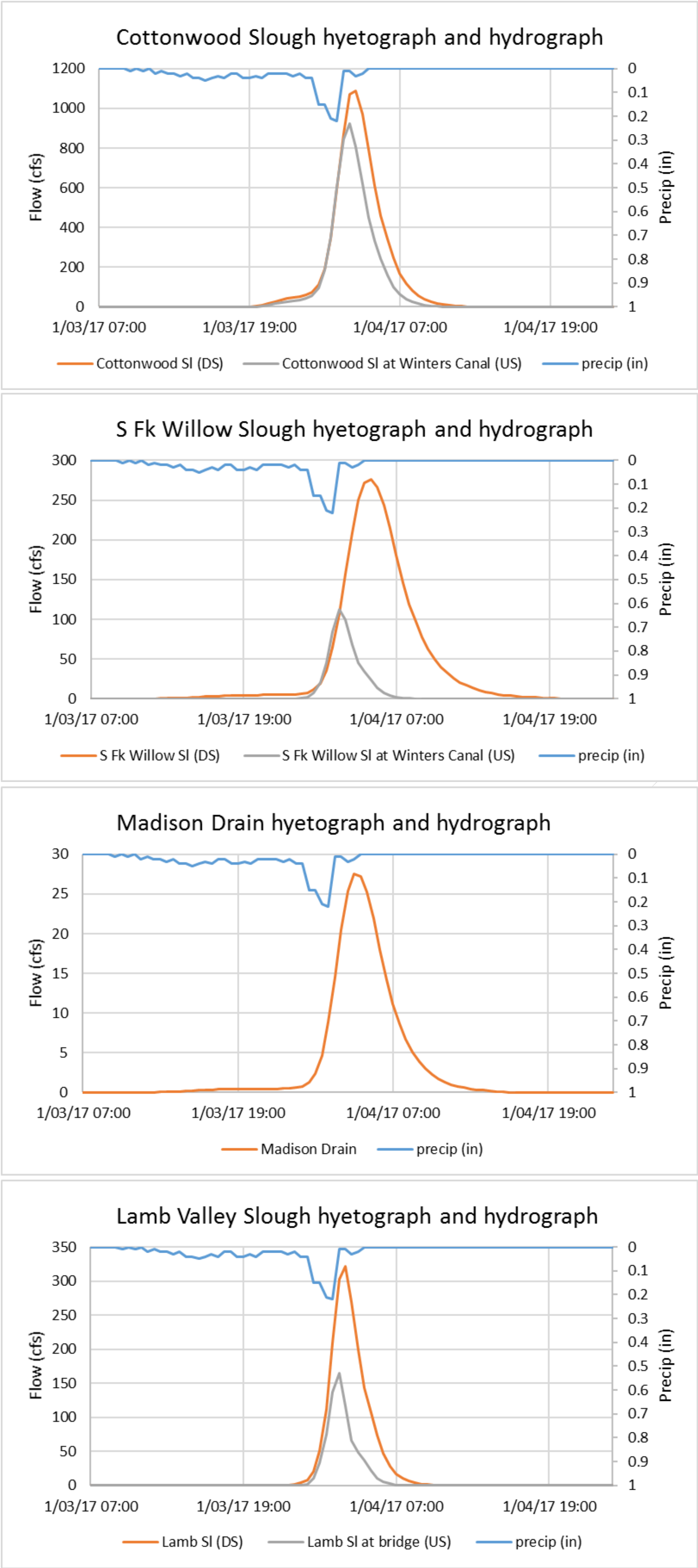
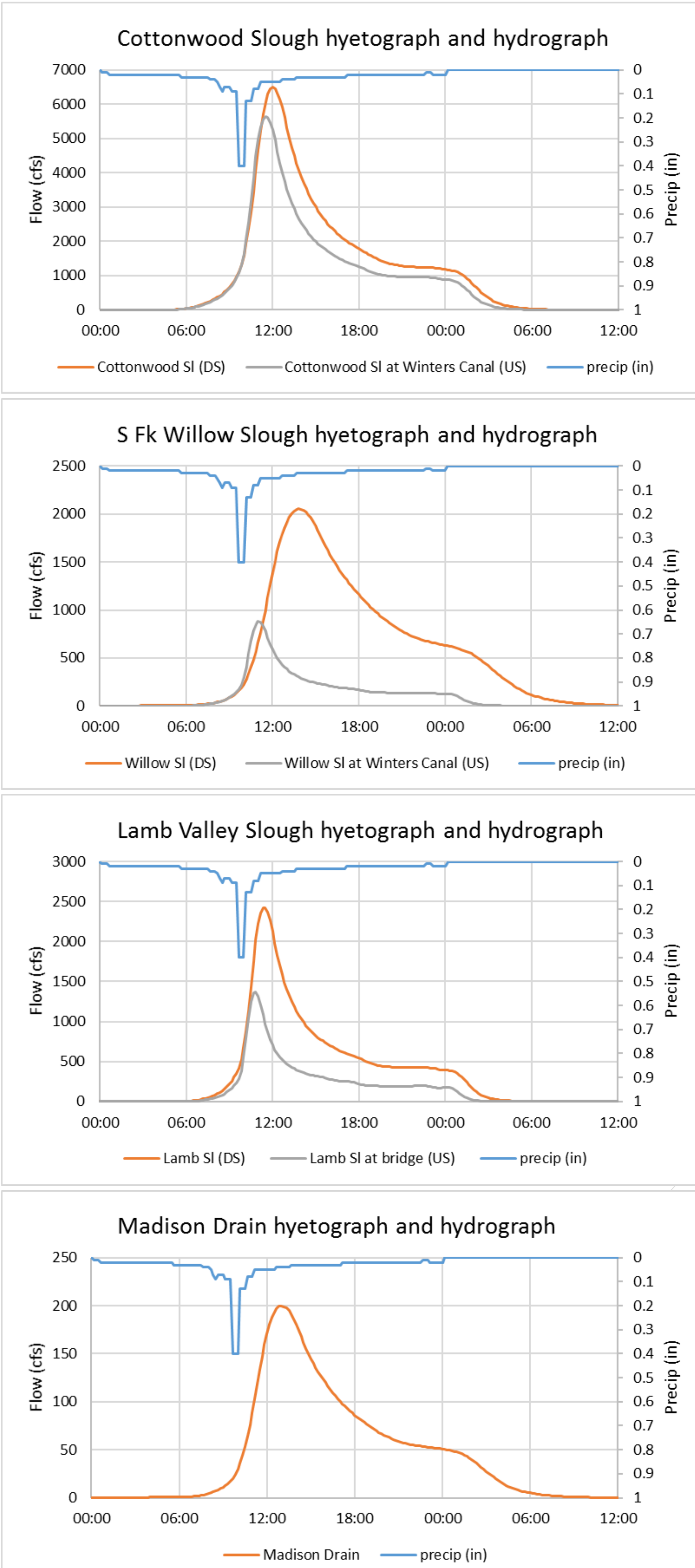


Figure 2.4. Runoff from drainage areas and their relative upstream watersheds for the 100-year, 24-hour design storm. US means upstream point and DS means downstream point. (DS values correspond to total runoff from that watershed)



It is difficult to determine if the modeled flows from either storm are reasonable because there are no flow measurements in any of the sloughs. We can compare our results to other models that have been developed in the area. These are mentioned in The Willow Slough Watershed Integrated Resources Management Plan (Jones & Stokes Associates, 1996):

"The accuracy of simulated peak flows is unknown because of the lack of gauged streamflow data to calibrate the model. A comparison of the results of different flood studies reveals the range in simulated flows that can result from different, but perhaps equally reasonable, assumptions for model input data. For example, Borcalli & Associates (1993) estimated a 10-year peak flow in Dry Slough at Road 95 of 1,400 cfs, whereas Yolo County Resource Conservation District et al. (1981) estimated that the 10-year peak flow for only a part of that drainage area (Chickahominy Slough at Road 89) is 3,190 cfs. Similarly, Nolte & Associates (1993) calculated a 100-year peak flow of 2,600 cfs in Chickahominy Slough near Winters Canal, which contrasts with the estimate of 4,580 cfs developed for this study."

While our estimates for the 100-year, 24-hour storm (approximately 2,000-6,500 cfs, Table 2.3), fall within the range mentioned above, we still do not know whether ours, or any of the other studies are accurate. Additionally, it is difficult to compare our models directly with others', as they were developed using different methods, estimated flow at different locations, and are disaggregated in different ways.

To get a better understanding of the behavior of these sloughs during storms, we visited them on three different occasions (see Chapter 6 for documentation of these trips). One visit (on January 9, 2018) occurred shortly after a storm similar to the January 2017 storm modeled here (total precipitation was about 3 inches over two days, with no rainfall in the weeks leading up to the storm which is similar to the antecedent conditions assumed in our model). We found no flowing water in any of the upstream points of the sloughs and while there was some pooled water, it did not appear as though there was significant water flowing previously. We did however, find flowing water in the downstream points, but found that this was due to water flowing out of the Winters Canal into the sloughs. It was later discovered that there was an operational malfunction at the head of the Winters Canal. The findings during the field visit would suggest that our model is over predicting flow in the sloughs, as there should not be any flowing water in a storm similar to the size of the January 2017 modeled storm.

Recommendations and Conclusions

1. Establishing flow monitoring stations

Despite several studies of flooding on one or more of the sloughs spanning now more than 30 years (Jones & Stokes Associates, 1996), these sloughs remain ungauged. Recommended sites for establishing new flow/flood monitoring stations are listed in Chapter 6, based on field visits.

2. Establishing a Citizen Science data collection program until a flow monitoring network can be installed.

Because substantial time may pass before a monitoring network can be installed, we recommend developing a Citizen Science data collection method in the meantime. The goal would be for individuals to note when and where flowing water is seen in the sloughs, just as was done during field visits for this study. This would provide a better understanding of which storms cause flooding and where (more information in Chapter 6).

3. Upstream mitigation methods

In addition to assessing sites for monitoring feasibility, we recommend that the upstream sites also be considered for management measures such as diversions (into the Winters canal), on or off-channel detention ponds, or check dams. Removing flows from the slough upstream would mean they are less full by the time they reach the valley floor and Madison. Because the majority of runoff within the Cottonwood Slough watershed results from the upstream area, diverting flows from this slough into Winters Canal or off-channel storage may provide the most benefits and the most flood relief downstream, of the three watersheds assessed here. Diverting flows from Lamb Valley Slough into Winters Canal or off-stream storage would also likely provide some benefits in flood relief to Esparto as well as Madison. Likely, a combination of mitigation efforts among the three sloughs is needed. Currently, diversions into the Winters Canal are not immediately feasible as the Canal flows over the sloughs at the crossings and a pump would be necessary. However, we suggest further consideration for infrastructure modifications or additions, and evaluation.

4. Investigate canal contributions to slough flows

While no water was found flowing in the upstream points of the sloughs on the January 9th 2018 field trip (see Chapter 6 for documentation of sites visited), flowing water was seen in downstream points of the sloughs. We also found water flowing in Winters canal, and some of this water was spilling into sloughs. It was discovered later that (i) some malfunction at the head of Winters canal allowed Cache Creek water at Capay dam to flow into Winters Canal, and (ii) that there appears to be a historical practice of keeping canal sluice gates at slough intersections open during the winter. As a result, during our field trip water from Winters Canal was contributing to flows in the sloughs. If canals have diverted water (from Cache Creek) in them during wetter periods, it could pose an added flooding risk to communities like Madison. District operations during and immediately after storms should be evaluated to determine whether any flexibility exists in canal-slough gate operations (see Chapter 6 for more information).

5. On-farm mitigation methods

Other mitigation methods such as capturing floodwater on farm fields for recharge should be considered. Forcing precipitation to infiltrate on the fields rather than runoff may result in smaller peak flows in the sloughs. This could be effective in reducing flooding caused by water from South Fork Willow Slough because the majority of its contributing area is agricultural and downstream of potential diversion locations. This could also reduce local flooding from surrounding fields. See Chapter 4 for a more detailed explanation of this recommendation.

Chapter 3. Storm water conveyance via canal operations for groundwater recharge

Executive Summary

As part of the quantitative analysis for the Yolo Storm Water Resources Plan (Yolo SWRP), we assessed the long term (35 year) groundwater recharge potential from diversions of Cache Creek winter flows into the Yolo County Flood Control and Water Conservation District's (District) unlined canal system. The assessment utilized The Cache Creek Model (Table 1.1). Using the 1976-2010 historical period as a baseline, the average net change in groundwater recharge from this strategy is estimated as 24,893 acre-feet (AF), varying widely across the years from a minimum of 266 AF to a maximum of 38.9 thousand AF (TAF). The benefits are constrained by canal capacities for diversions as well as the infiltration rates (about 150 cfs is assumed to infiltrate as water flows from the top of the canal to the bottom). Estimates appear to match the magnitudes of diversions actually implemented in the past two years. We recommend continued canal recharge diversions when applicable. We also recommend monitoring canal flows in the winter, which historically has not been done.

Introduction

In this chapter, we investigate the potential for augmenting winter groundwater recharge by diverting excess storm water flows from Cache Creek into the District's unlined canal system. Based on data from water releases and sales, canal leakage losses ranging from 18,000 acre feet (in 2009) to 64,000 acre feet (1989) have been estimated (Borcalli and Associates, 2000; YCFCWCD, 2012), most of which is considered to infiltrate into the aquifer. Wee leveraged past modeling work by SEI, which studied this management strategy along with other strategies.

Methods

This analysis was conducted with the previously developed Cache Creek Model (Table 1.1). In Mehta et al. (2013), the Cache Creek Model was applied to investigate the performance of the District under several scenarios and uncertainties. The uncertainties explored included climate and land use changes, and the shape of any policies that might emerge from the (then imminent) Sustainable Groundwater Management Act. Performance under 84 different future scenarios was assessed against three measures: financial viability of the District, water supply reliability to growers in Yolo County, and the groundwater level sustainability. While details of this analysis are in Mehta et al. (2013), Table 3.1 summarizes the strategies explored in that work, as some of them are relevant to the analysis conducted here. Figure 3.2 shows the spatial extent and scope of the Cache Creek Model.

Table 3.1 Summary of management strategies modeled in earlier work

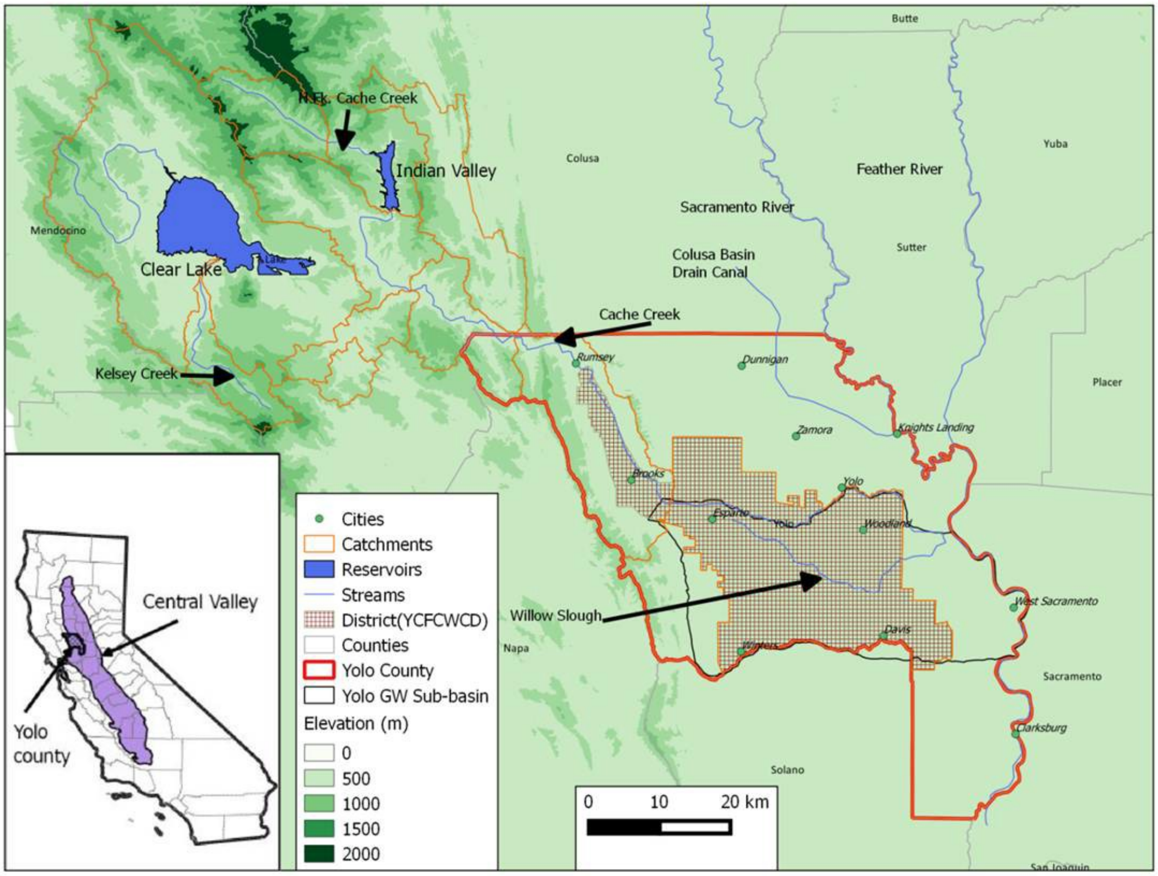
Index	Strategy	Description
1	Baseline	Current management into the future
2, 3, and 4	Groundwater infrastructure operated by the District	Add 2, 10 and 20 pumps that would respectively extract approximately 2,000, 10,000 and 20,000 AF/yr, supplied for summer irrigation. Capital costs of USD225,000 / pump. Loan payment at 1.7% interest over 15 years.
5	Canal recharge	Direct winter flows from Cache Creek (during Nov-Feb) into the canal network, recharging up to 150 cfs when Cache Creek flows are greater than 100 cfs. Use existing infrastructure.
6	Periphery pond storage	Build periphery storage of up to 20,000 AF in four ponds that will be filled in the winter and utilized in the summer. Some of the directed flows will percolate (up to 50 cfs), the rest (up to 80 cfs) will be available to fill the ponds in Nov-Feb. An investment of $20 million is estimated, financed at 1.7% interest over 15 years. Water supplied by this source priced at $100/AF
7	Combined strategy	Combine strategies 3, 5 and 6.

For the current Yolo SWRP study, two scenarios were run in the Cache Creek Model: the "baseline", representing historical conditions from Water Years (WY) 1976-2009 and "canal recharge", strategy 5 (Table 3.1). In the "canal recharge" strategy, during November through February, when Cache Creek flows are greater than 100 cfs, water is diverted into the canals up to 150 cfs.

Important assumptions

In this scenario it is assumed that all water that is diverted into the canals recharges groundwater. Estimates of losses (infiltration) to groundwater from various methods range from 0.3 cfs/mile to 13.4 cfs/mile (YCFCWCD, 2012). When multiplied by 166 miles of canal, canal-wide estimates of infiltration to groundwater range from a minimum of 49.8 cfs to a maximum of 2,224 cfs. We assumed an infiltration rate of 150 cfs over the entire canal system, which falls between these estimates. This means that if 150 cfs is released into the top of the canal, we assume all water will have infiltrated by the time it reaches the bottom of the canal system. These scenario assumptions were elicited in consultations with District management.

Figure 3.1 Modeled area of the Cache Creek model



Results and discussion

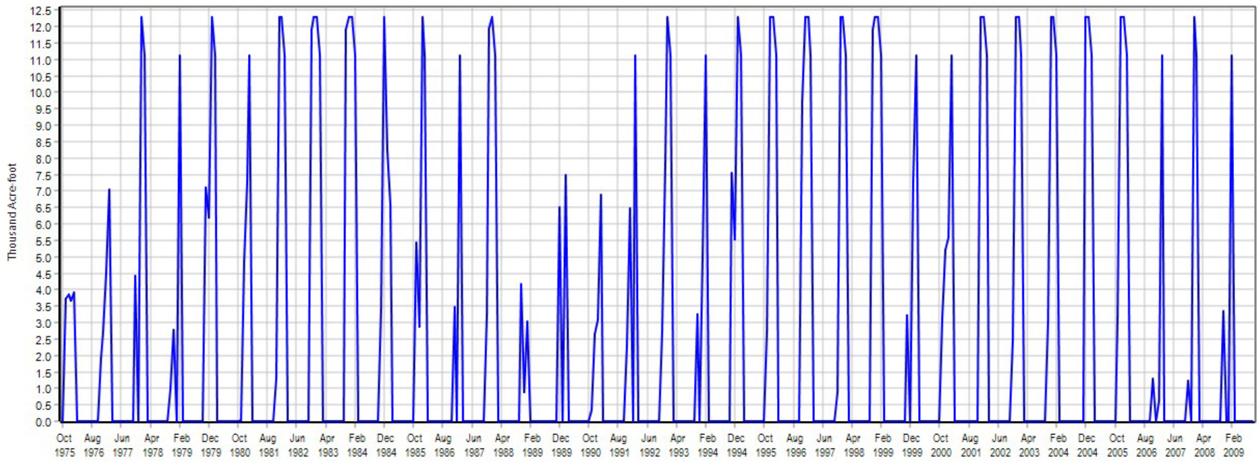
Diversions into the canals

Modeled diversions of Cache Creek storm water runoff into canals are compared against a baseline without winter diversions. Over the 35-year simulation period, the average annual volume of diversions equals 28.8 TAF, with a minimum of 8.1 TAF and a maximum of 47.6 TAF. Table 3.2 below lists the corresponding monthly average diversions over a 35-year simulation period. Figure 3.2 shows the 35-year monthly time series of diversions estimated by the model.

Table 3.2 Average monthly canal diversions in winter months, in TAF

Month	TAF
November	3.6
December	6.9
January	8.3
February	10.1

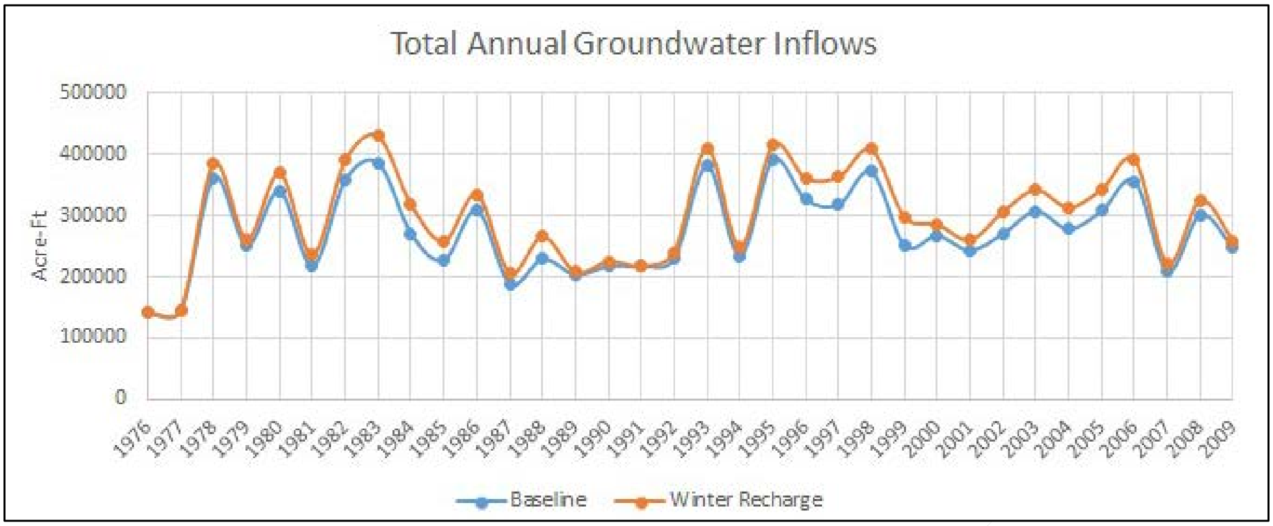
Figure 3.2 Modeled monthly diversions into YCFC canal system Water Year 1976:WY 2010, in TAF, under the "winter recharge" scenario



We can compare our modeled diversions in the "canal recharge" scenario against some recent experience. In 2016 and 2017, the District applied for temporary permits from the State Water Resources Control Board (State Water Board) for diverting excess storm water into the canals for groundwater infiltration and underground storage. In 2016, diversions occurred between February 4 and April 15 and resulted in a total of 50 inconsecutive diversion days and total diversions of 11,128 acre-feet. In 2017, diversions occurred between March 16 and April 30 and resulted in a total of 41 inconsecutive diversion days and total diversions of 6,210 acre-feet (Kristin Sicke, personal communication, 1/12/2018).

Comparing actual diversions per day (223 AF/day in 2016 and 151 AF/day in 2017) to the average, maximum, and minimum modeled results (240 AF/day, 396 AF/day, and 68 AF/day, respectively) volumes actually diverted appear to correspond fairly well with the range of modeled results. The timing of the diversions in the model will need to be updated to reflect a later start and a later end, which is tied to and dependent on the State Water Board's permitting process and the Dist. Although all the diverted water is assumed to recharge groundwater, these diversions could possibly reduce surface-to-groundwater flow in downstream, losing reaches of Cache Creek. The model captures this trade- off, which on average over the 35-year simulation period is about 4,000 AF. Therefore, the net change in groundwater recharge of the "canal recharge" scenario averages 24.4 TAF, with a minimum of 0.27 TAF and a maximum of 47.2 TAF. Figure 3.3 below shows the 30-year annual time series of groundwater inflows estimated by the model under both "baseline" and "canal recharge" scenarios.

Figure 3.3 Monthly potential recharge WY 1976:WY 2009, in TAF



Flood mitigation benefits

Only if flows above 100 cfs occur in Cache Creek, is the water up to 150 cfs diverted from Cache Creek at Capay Dam into the canals. Therefore, the potential flood mitigation benefits of reducing Cache Creek flows by 150 cfs occur downstream of Capay Dam, and are relevant only if Cache Creek over tops its banks downstream of Capay dam, and that spillage causes problematic flooding.

Historical flow records and flood frequency analysis inform us that Cache Creek's channel capacity downstream at and around Yolo is lower than upstream at, for example, Rumsey. According to a hydraulic analysis of Cache Creek between Road 94B and I-5 (near Yolo) from 2002, the "natural banks between Road 94B and Yolo begin to overtop between 36,000 to 38,000 cfs" (MBK Engineers, 2002). This flow is just around the 20-year return period for Cache Creek at Yolo, according to a flood frequency analysis presented in the 2017 Cache Creek Area Plan update (Tompkins et al., 2017). The flooding in that region in March 1995 and February 1998 was the result of Cache Creek overtopping its banks (MBK Engineers, 2002)**.** In the December 31, 2005 flood event, Cache Creek exceeded its flood stage of 81 feet at Yolo. In general, a threshold flow of concern has been identified for Cache Creek at about 20,000 cfs (Yolo County, 2006).

A possible exploration of the benefit of diverting 150 cfs of flow out of Cache Creek, would be to compare the corresponding water surface elevations i.e. for example, comparing the water surface elevations (and thereby extent of flooding) when flow at Yolo was 34,600 cfs (the peak recorded on Feb 3 1998), against 150 cfs less. This is left to a future effort, since water surface modeling was out of the scope of our effort, and the monthly WEAP model used in this chapter would not be useful for assessing peak *event* flows. Additionally, due to the key questions listed below, it is unlikely that during the largest storms that cause flooding from Cache Creek, canal diversions would be feasible. This is explained in further detail below.

Key Questions

1. Canal capacity

One of the questions conditioning the practicality of diverting winter Cache Creek flow at Capay Dam into the District's canals is whether the canals have enough capacity to carry the flows. There is a high probability that the canals may already be carrying water when Cache creek has really high flows (say, greater than 10,000 cfs in Cache Creek at Rumsey), from a variety of sources, including:

- Direct runoff from precipitation on canal reaches;
- agricultural field runoff
- planned, required, or inadvertent releases from Capay Dam into canals at headgates, for example as seen on January 9, 2018 during a field visit)

If the canals are carrying water during these higher flow periods in Cache Creek, would the canals be able to handle the additional inflows?

2. Permitting

That State Water Resources Control Board's (State Water Board) Division of Water Rights issues water rights permits and licenses as an authorization to develop a water diversion and use project. The District has existing appropriative water rights for diverting water from Cache Creek during the irrigation season; however, that right is specific to a certain time in the year and primarily for applying the water to an irrigation beneficial use. For the District to apply surface water to underground storage, or groundwater recharge, the District must apply for a separate water rights permit specific to diverting excess storm flows to groundwater recharge. The excess flows to groundwater recharge temporary permitting process is currently streamlined through the State Water Board's process and does not require California Environmental Quality Act (CEQA) procedures. However, the District must consult with the California Department of Water Resources and Department of Fish and Wildlife, the United States Bureau of Reclamation, and the Central Valley Regional Water Quality Control Board prior to receiving an approved permit from the State Water Board. Since the District has submitted applications over the past three years, the internal process has become streamlined, but typically takes six weeks to allow for District staff time and communication with state and federal agencies.

Under the existing temporary permit conditions, diversions are allowed from February 1 through April 31, 2018. Diversions at the Capay Diversion Dam can only occur if there is 50 cfs in Cache Creek at the Yolo gauge from February 1 through March 31, or 100 cfs in Cache Creek at the Yolo gauge during April. Future temporary permitting start dates will depend on the time the application is submitted, but the end date will always be April 30 because of the District's need to switch to the irrigation season.

Recommendations

1. Flow monitoring

Given the key question on canal and slough flows during storm events mentioned above, we recommend flow monitoring at the intersections of western Yolo sloughs with canals; canals with road intersections; and sloughs with road intersections. Recommended locations are listed in Chapter 6. Additionally, monitoring of the canal flows while winter flows are being diverted (at the inflow from Cache Creek to the outflows) could provide additional verification for our assumption – if the canals are not spilling over, or releasing water into the intersecting sloughs, we can affirm that all water that enters the canal infiltrates. Monitoring, along with more detailed hydraulic modeling that includes the infiltration capacity limitations in canal reaches, could provide even more insight.

2. Consider timing of winter diversions

The District has already successfully implemented canal recharge the past two winters. However, given the key questions above, it may be unlikely that diversions into the canal system could reasonably take place in peak flood events, for example, those approaching 20,000 cfs in Cache Creek at Rumsey. During large storms (10 year return period and larger) it is possible the canals are already full of water and adding more could cause an increased risk to flood prone areas downstream. Additionally, these large flows may happen before the permitting process begins. It is more likely that these diversions should take place for relatively smaller storm frequencies. This way, the groundwater recharge benefit could be obtained without increasing minor flooding risks in small western Yolo towns or country roadways. As the District continues to implement canal recharge when possible, the potential for canal spills into sloughs should be explicitly monitored.

Chapter 4. Rainfall capture on farm fields

Executive Summary

The potential recharge benefits resulting from capturing precipitation on selected farm fields during the winter in Yolo County for groundwater recharge were estimated using a WEAP model. Modeled estimates suggest implementing rainfall capture on all fields considered suitable by this analysis, could result in an average of 5,000 to 9,000 acre-feet of reduced storm water runoff from the county that would instead be recharging groundwater. Implementing this strategy would require growers to build temporary berms on their fields to prevent storm water runoff. Landowner participation would be a key determinant for implementation, as would site-specific detailed studies of soils, crops and groundwater depths. We suggest investigating growers' willingness to participate, and conducting pilot studies in the area southwest of Madison and Esparto, as this could contribute to flood mitigation benefits in these towns.

Methods

WEAP model development

For this analysis, we modified the Cache Creek Model to develop the Yolo Storm Water Model. In short, the modifications included dividing the county area into 38 catchments representing entities with water or land use management responsibilities and converting the catchments to a daily timestep. Explanation of these modifications and model re-calibration are outlined in Appendix B.

Scenario development and field selection

The fields included in this analysis were selected based on soil suitability and crop type. Determination of suitable soils and crops are based on O'Geen et al. (2015) and communication with experts. O'Geen et al. (2015) developed the Soil Agricultural Groundwater Banking Index (SAGBI), which categorizes soil suitability for groundwater banking across the state of California based on six soil criteria: deep percolation, root zone resistance time, chemical limitations, topographic limitations, and surface condition. The index results in a rating of 0 to 100, with 0 being the least suitable soil and 100 being the most. The authors categorized these ranks into five classifications: excellent, good, moderately good, moderately poor, poor, and very poor. The authors used existing soil surveys. They also assumed that all tree and vine cropland areas with a restrictive layer were modified by deep tillage (a common practice) thereby increasing drainage (O'Geen et al., 2015). The soils classification used in this analysis is this “modified” version and is shown in Figure 4.1a for Yolo County. Based on the spatial dataset (Figure 4.1a) and conversations with the authors[7], two groups of soil classifications were considered “suitable” in this study: 1) soils categorized as moderately good to excellent and 2) soils categorized as moderately poor to excellent.

As on-farm rainfall capture could result in pooled water, and extended periods of wet root zone conditions, crop tolerance to flooding is an important concern. Some perennial crops may be better able to tolerate flooding than others (O’Geen et al., 2015 Table 1) and if flooded, annual crop fields need to be dry in time for growers to prepare them for spring planting. Based on prevalent perennial crops in Yolo County, information from Table 1 in O’Geen et al. (2015) and communication with experts[8], the following crops were considered amenable for rainfall capture: alfalfa, almond and pistachio, other deciduous, pasture, tomato, and vine. Crop coverage in the model varies from year to year as described in Appendix B. To determine what area of each crop coverage within each catchment should be included in this analysis, SAGBI soil categories (Figure 4.1a) were intersected with the selected crop categories for the 2014 County Crops spatial data layer (Figure 4.1b, see Appendix B for details on how this layer was developed). We used the 2014 layer because it was the most recent spatial dataset available to us at the time, and reflected the recent conversion of annual crops to perennials seen in Yolo County. It should be noted however, that this was also a drought year and therefore crop coverage may reflect growers decisions to grow more drought tolerant crops.

Two scenarios for rainfall capture were developed:

- **<u>Scenario 1</u>**: Areas classified as moderately good, good, or excellent underlying the selected crops (Figure 4.2, black area)
- **<u>Scenario 2</u>**: Areas classified as moderately poor, moderately good, good or excellent underlying any of the selected crops (Figure 4.2, black and gray area)

From this, a percentage of the area of each crop within each catchment that should be included was calculated, and this percentage was applied to every year in the model. The overall percentage of each crop category area in the county where this was implemented is shown in Table 4.1. Because area of crop coverage changes each year in the model, the actual area

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[7] In personal communication with Dr. Anthony O’Geen (Sept 20, 2017), Dr. O’Geen suggested that even moderately poor soils could be sufficient for groundwater banking for certain crops. In email communication with Dr. Helen Dahlke (Sept 21, 2017), Dr. Dahlke noted that in the field, success with recharge has only occurred on moderately good or better soils.

[8] In email communication with Dr. Helen Dahlke (Sept 21, 2017), Dr. Dahlke mentioned that other than alfalfa, almonds and grapes, there are no known other crops that would tolerate flooding. In personal communication with Anthony O’Geen (Sept 20, 2017), Dr. O’Geen mentioned that alfalfa should be considered for flooding, with restrictions on timing, and annuals should be considered with restrictions reflective of planting dates. Dr. O’Geen also mentioned grapes, prunes, plums, almonds, walnuts and peaches could be tolerant of flooding.

where this is implemented this year varies, but the percent of each cropped area remains the same. The areas that were included in one year are shown in Table 4.2 and Table 4.3 so that the scale of this analysis between the scenarios can be compared.

Figure 4.1 SAGBI categorization of Yolo County (a) and WEAP crop categorization of Yolo County from the 2014 County Crops dataset (b)

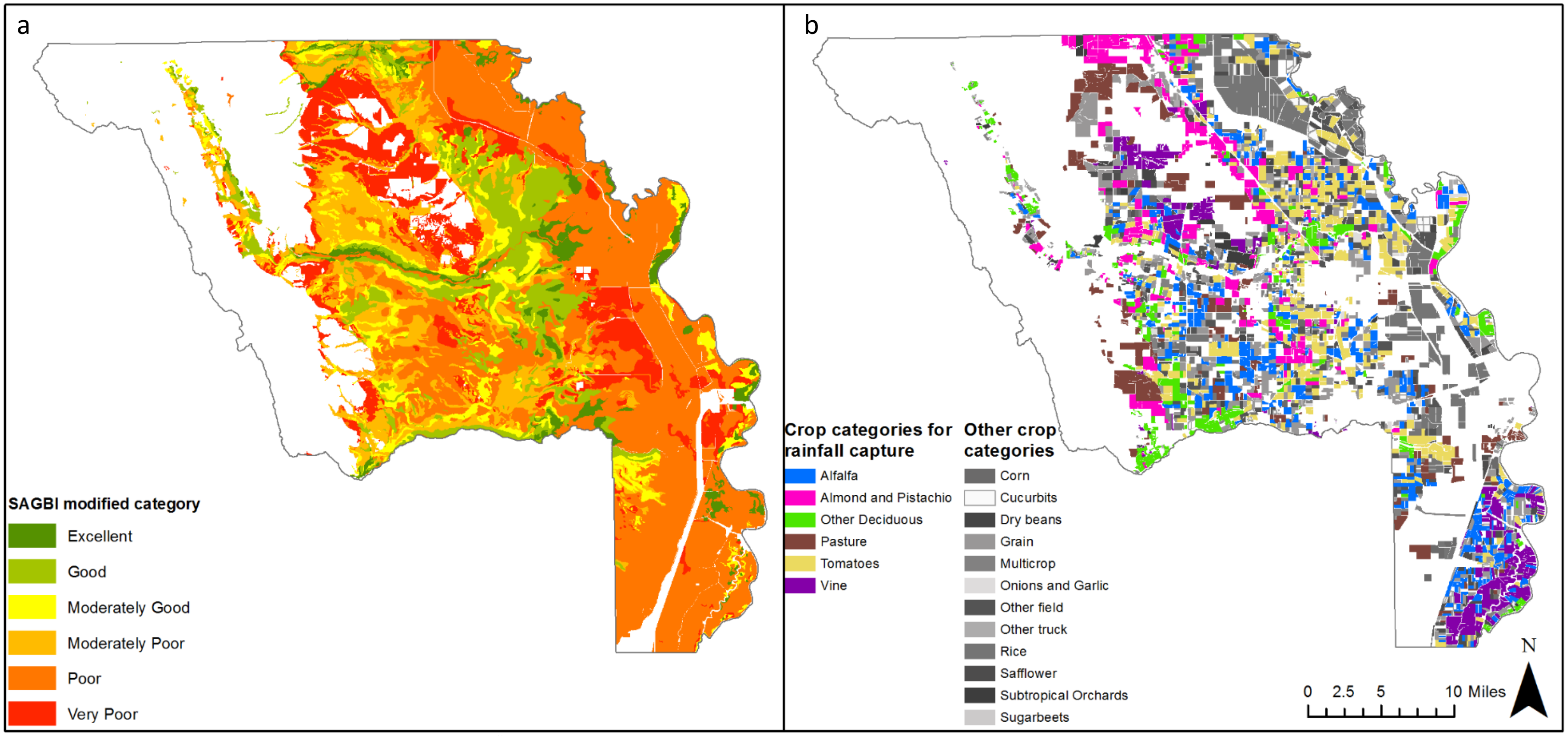


Figure 4.2 Fields where rainfall capture was modeled in this study.
Areas included in Scenario 1 are shown in black. Additional areas added in Scenario 2 are shown in gray. Madison and Esparto are shown in red and blue, respectively and a zoom-in of the surrounding area is shown in the box to the right.

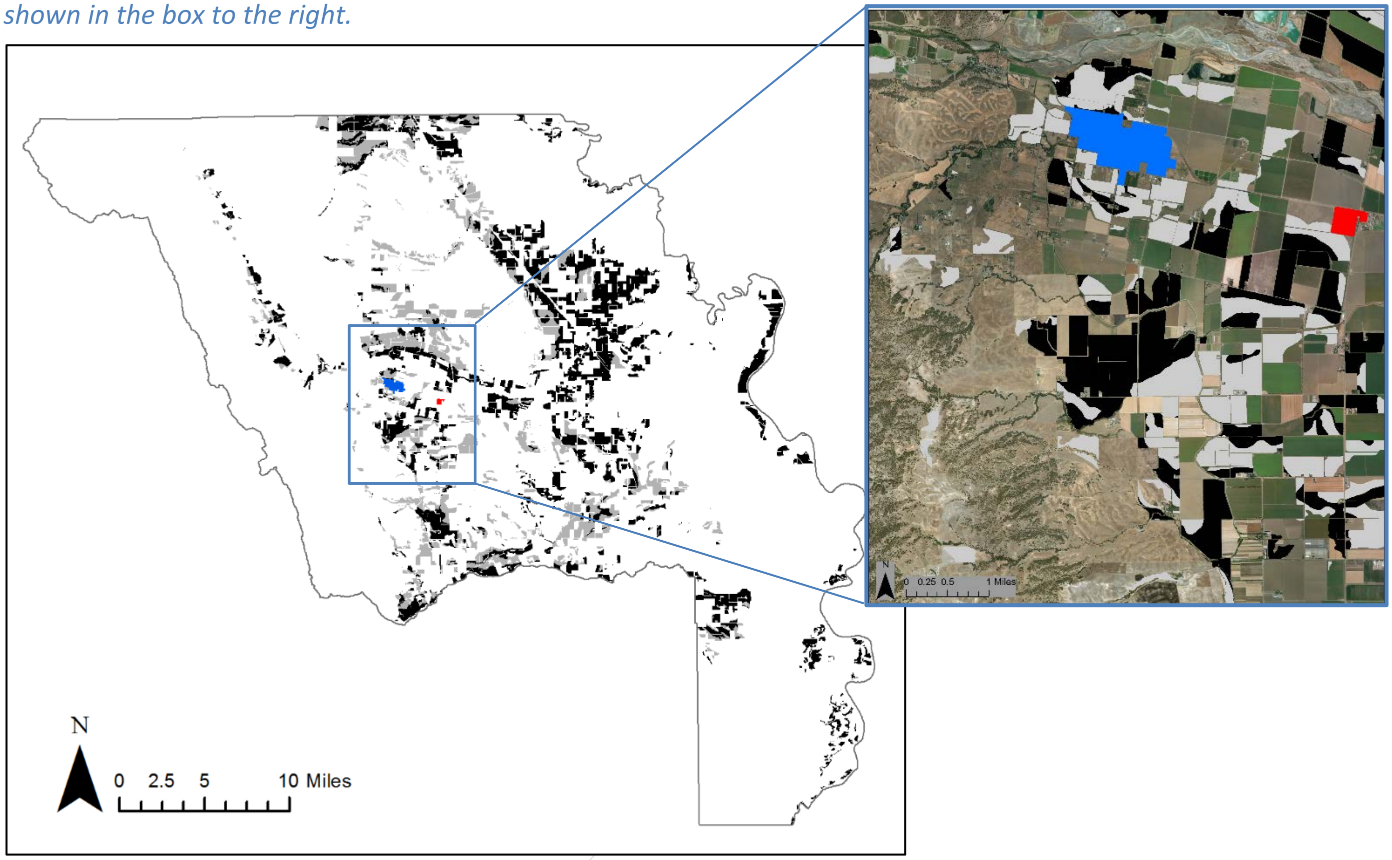


Table 4.1 Percent of county crop areas where rainfall capture was modeled.

Crop	**Percent of County Crop area to implement rainfall capture on**	
	Scenario 1	**Scenario 2**
Alfalfa	25	45
Almond and Pistachio	39	74
Other Deciduous	53	80
Pasture	9	21
Tomatoes	40	57
Vine	12	27

Table 4.2 Example areas of Yolo County where rainfall capture was modeled in Scenario 1, in acres.

WEAP Crop Category	SAGBI Soil category			
	Excellent	Good	Moderately Good	Total
Alfalfa	932	4,276	3,515	8,723
Almond and Pistachio	1,241	5,186	4,053	10,479
Other Deciduous	2,113	3,940	3,607	9,659
Pasture	451	913	928	2,293
Tomatoes	2,345	8,413	4,808	15,566
Vine	1,192	193	947	2,332
Total	8,274	22,920	17,858	49,052
Total county irrigated area				290,716

Table 4.3 Example areas of Yolo County where rainfall capture was modeled in Scenario 2, in acres.

WEAP Crop Category	SAGBI Soil category				
	Excellent	Good	Moderately Good	Moderately Poor	Total
Alfalfa	932	4,276	3,515	7,246	15,970
Almond and Pistachio	1,241	5,186	4,053	9,242	19,721
Other Deciduous	2,113	3,940	3,607	4,912	14,571
Pasture	451	913	928	3,133	5,426
Tomatoes	2,345	8,413	4,808	6,697	22,263
Vine	1,192	193	947	3,013	5,345
Total	8,274	22,920	17,858	34,244	83,296
Total county irrigated area					290,716

Major assumptions

The time when rainfall capture was allowed on fields in the model is based on the crop coverage of the area and shown in Table 4.4. From November to mid-March, alfalfa is not actively growing, and therefore the period when rainfall capture is allowed is restricted to November 15 to March 15.[9] The same assumption was made for pasture. Almond/pistachio orchards are only allowed to hold rainwater until mid-January because almond trees begin to bud and emerge from dormancy in late January to early February.[10] The same assumption was made for the other perennial crop: deciduous trees and vines to be conservative.

The timing of rainfall capture on tomato fields was determined based on expert opinion on tomato planting dates. [11] Recent practices have shifted to planting transplants rather than seeds, which can occur between mid-March and as late as early June. Earliest harvest can occur in early July, with some extending into mid-October. Although not all growers will plant and harvest at the same time, to be conservative, we allowed rainfall capture on tomato fields to begin in mid-November (when rains typically begin) until mid-February (Table 4.4).

[9] Personal communication with Anthony O'Geen, and student Sept 20, 2017
[10] http://thealmonddoctor.com/2009/06/22/the-seasonal-patterns-of-almond-production/
[11] Personal communication with Gene Miyao, Nov 7, 2017.

Table 4.4 Periods when rainfall capture is allowed on fields in the model, per crop

Crop category	Period when rainfall capture is allowed
Alfalfa	Nov 15-Mar 15
Almond and pistachio	Nov 15-Jan 15
Pasture	Nov 15-Mar 15
Other deciduous trees	Nov 15-Jan 15
Tomato	Nov 15-Feb 15
Vine	Nov 15-Jan 15

In both scenarios, for fields selected for rainfall capture, it was assumed that an approximate 8-inch berm was built around the field. This is the same height of the berms built around rice fields, so it was assumed reasonable for growers to implement. For each field, the maximum percolation rate, which determines the rate at which the water leaves the bottom of the root zone and contributes to groundwater was assumed to be 2.5 inches per day, as observed by Bachand et al. (2014) in a field study with similar soil.

Results and Discussion

The water balance of the catchments is presented in Table 4.5. This is the sum of water flowing into all catchments that contain fields shown in Figure 4.2 (precipitation and irrigation); and the outflows to the atmosphere (transpiration and evaporation), the neighboring surface water bodies (surface runoff) and the underlying groundwater basins (flow to groundwater). Implementing rainfall capture in Scenario 1 results in, on average, 5,000 acre-feet less of runoff into surface water bodies, and that 5,000 acre-feet is instead recharged (Table 4.5). Scenario 2 results in 9,000 acre-feet less runoff and more groundwater recharge (Table 4.5).

The benefits do, however, vary from year to year. The years when the runoff and groundwater recharge are impacted the most are wet years, therefore this is most effective in years with high precipitation and may need to be combined with other methods, such as canal recharge of storm water runoff to augment groundwater recharge in dry years (Figure 4.4). These estimated volumes from rainfall capture are similar in magnitude to the canal recharge volumes reported earlier (6,000 – 11,000 acre-feet in recharge, see Chapter 3 for details). This suggests that if this strategy were implemented on the ground in conjunction with canal recharge, the groundwater recharge and supply reliability benefits could be approximately doubled. Or, that this could be a good replacement for canal recharge in years that are too wet to implement that strategy due to the concerns stated in Chapter 3. This is referring to county-wide overall benefits, as the groundwater recharge resulting from this strategy would occur in a different location from canal recharge.

Figure 4.5 suggests that daily runoff can be effectively reduced with this method. This may be especially pertinent to Madison and Esparto. There is a large area of fields that was deemed potentially suitable by our methodology southwest of Madison and Esparto (Figure 4.2), (see Chapter 2 for a detailed explanation of flooding issues in these areas).

Model results do not predict any standing water on the fields. This may be because of the high percolation rate used, 2.5 inches per day, based on a study of on-farm flood capture in the King's River basin (Bachand et al., 2014). Because the rate is so high, the root zone never becomes fully saturated and therefore water never pooled on the surface. It is straightforward to run the model with more appropriate percolation rates, as needed.

Table 4.5 Average of Annual water balance for each scenario, and the difference between them, rounded to the nreaest thousand acre foot. The difference is also shown in Figure 4.3.

	Baseline	Scenario 1	Δ Scenario 1 and Baseline	Scenario 2	Δ Scenario 2 and Baseline
Evaporation	-357	-357	0	-357	0
Flow to GW	-580	-585	5	-589	9
Irrigation	962	960	-2	961	-1
Precipitation	1,171	1,171	0	1,171	0
Surface Runoff	-190	-185	-5	-181	-9
Transpiration	-1,013	-1,012	-1	-1,012	-1

Figure 4.3 Difference between average annual water budget for the two scenairos, in acre feet

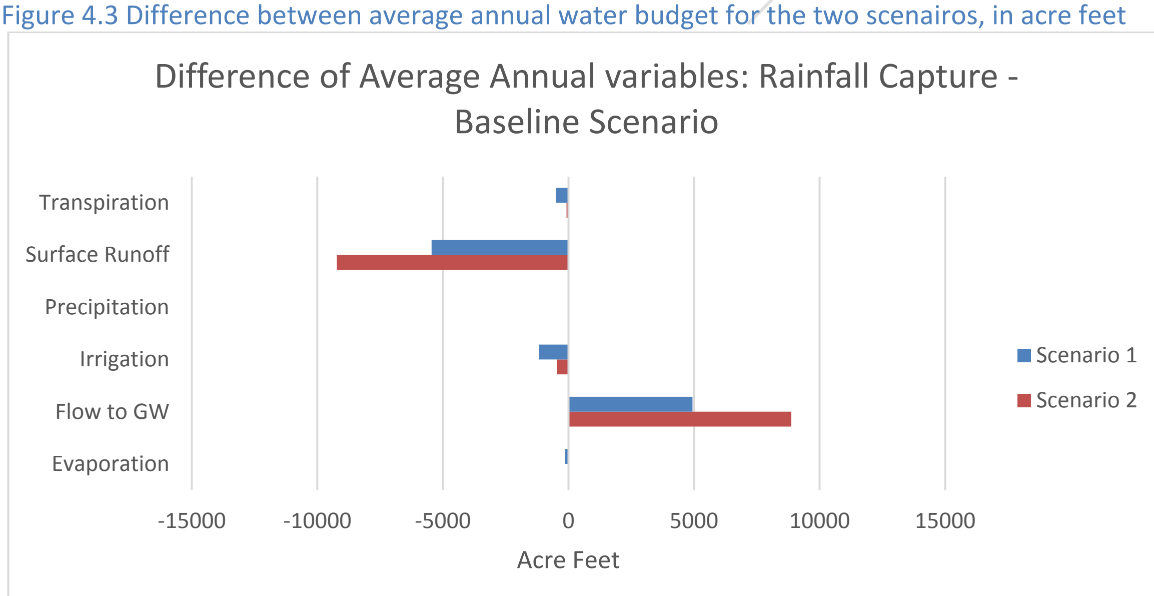


Figure 4.4 Difference of annual surface runoff and flow to groundwater between the rainfall capture and baseline scenarios.

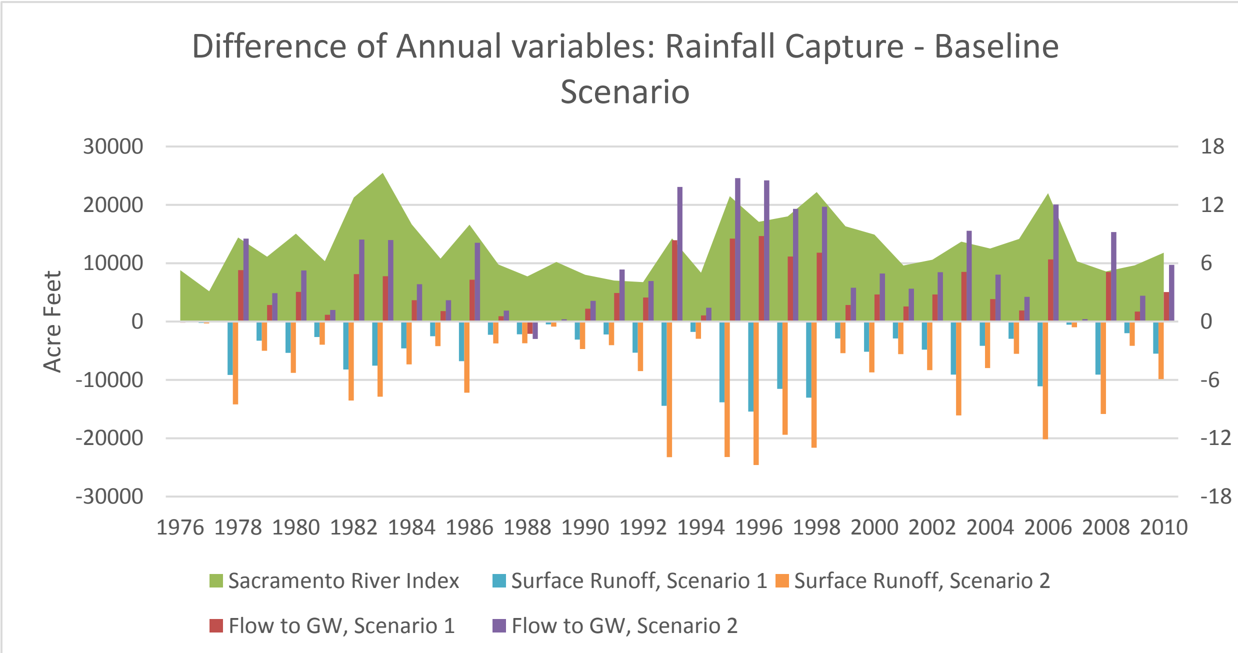
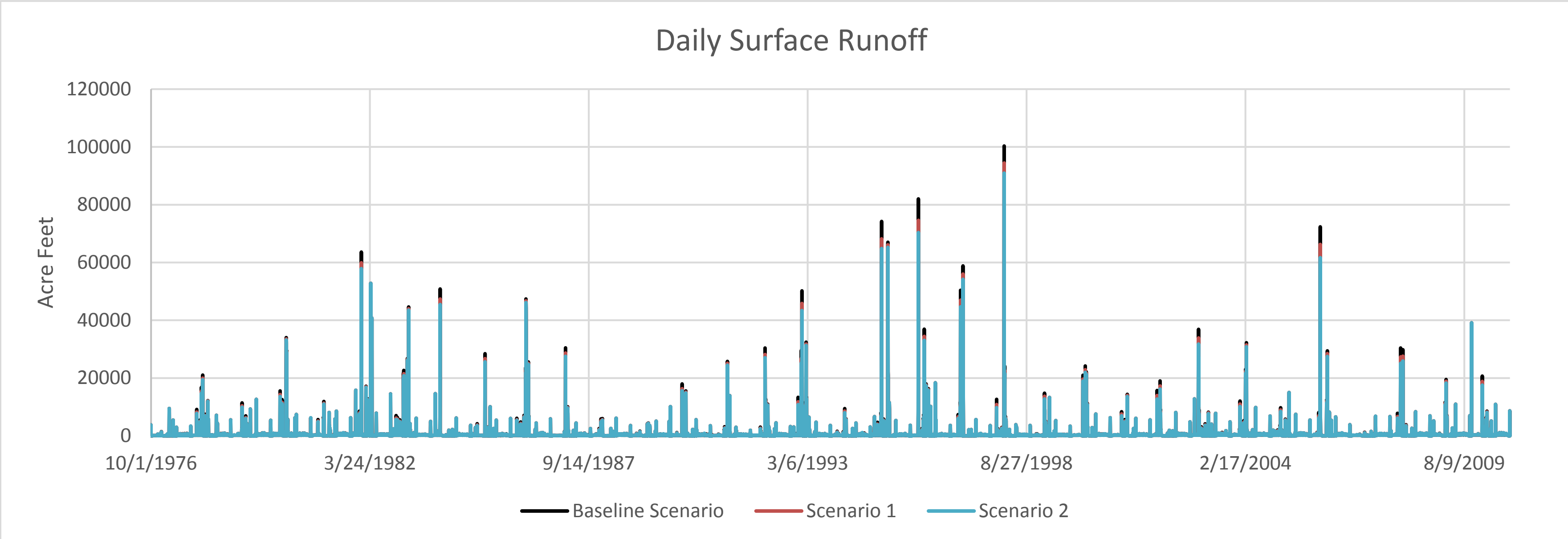


Figure 4.5 Daily runoff from managed catchments, with and without rainfall capture



Limitations and Risks

One of the major determinants to implementing on-farm rainfall capture is growers' willingness to participate. Grower hesitation can arise from many concerns, including perceived or actual risk to their crops, costs and other inconvenience of modifying their property, and allowing time for the field to drain and dry. There is inherent risk in allowing pooled water on fields of any crop, and there is still not sufficient information to definitively say one site is fitting and another is not. Infiltration rates vary across the county, and often diverge from those listed in soil surveys. Field experimentation on effects and results of flooding different soils and different crops are still underway[12] (these are slightly different strategies than what is proposed here, but with potentially similar impacts to crops); the impacts to overall crop health are still relatively uncertain. Building a berm may be inconvenient. Additionally, impacts to drip irrigation lines that could get submerged in pooled water in the fields should be considered. Because of these considerations, the area included in the two scenarios here is likely an overestimation of the area that could be included in implementation.

Suitable fields may be further limited by characteristics not assessed in this analysis. The water quality implications of this strategy may limit the extent of potential implementation. Nitrogen and other potentially harmful contaminants in the vadose zone can be pushed into the aquifer if ponding were to occur. We also did not assess depth to groundwater as a part of this analysis; some areas we considered suitable may have groundwater tables that are too shallow for implementing on-farm rainfall capture.

Recommendations and Conclusions

1. Investigate growers' willingness to participate

Based on conversations with the District[13], growers within their service area may be more likely to participate in a management strategy such as this if asked by the District because of the long standing good relations and trust they have with the District. We suggest this be a place to start these conversations. Additionally, as shown in Figure 4.2, many fields southwest of Madison and Esparto were considered suitable for rainfall capture based on our criteria. This may be a potentially viable solution for localized flooding in these areas (see Chapter 2 for a detailed explanation of flooding issues in these areas). Even more specifically, these landowners should be prioritized initially to gauge willingness to participate.

[12] Email communication with Dr. Helen Dahlke (Sept 21, 2017)
[13] Personal communication with Kristin Sicke, District Assistant General Manager, December 20, 2017.

2. Better understand groundwater considerations not assessed here

We imagine that on-farm rainfall capture could pose fewer risks to groundwater quality than other groundwater recharge options such as actively flooding fields (e.g. in the Kings river study) because ponding at the surface (and subsequent downward flushing of nutrients and pesticides) will be less frequent (see Chapter 5 for more information about other on-farm management options). This strategy would rather result in surface water quality benefits by reducing runoff from fields which may carry contaminants to surface water bodies. It seems likely that the benefits to reducing contamination in surface water might be greater than the risks to groundwater. However, the risks to groundwater contamination by nutrients and pesticides should be better understood.

As mentioned earlier, the fields selected here should likely be further narrowed down by an assessment of groundwater depth, where fields with high groundwater tables should be removed from consideration.

3. Better estimate infiltration rates

One major assumption in our modelling efforts was the percolation rate. The high rate we used prevented water from pooling on the surface in the model, suggesting that the risks presented by pooling would not be an issue. This is unlikely to be valid everywhere on the landscape and should be further investigated on-site.

4. Implement a pilot project

On-farm flood flow capture and groundwater recharge management studies are already underway in California and in Yolo County (Bachand et al., 2014; Dahlke et al., 2018a). We suggest implementing a pilot project, which incorporates the above three recommendations. We recommend choosing suitable fields in the area southwest of Madison (Figure 4.2). Alfalfa fields seem promising candidates from recent studies, both from crop impact and groundwater quality risk perspectives (Dahlke et al., 2018b). In parallel, an outreach effort can be made to find willing landowners. A collaboration between the District, willing landowners and UC Davis researchers could help facilitate the implementation.

Chapter 5. Additional on-farm storm water management

In this chapter, we discuss other on-farm strategies for combining flood mitigation with groundwater recharge benefits in the winter. This discussion is based on literature review and expert interviews; we did not develop model-based quantitative benefits.

The first option is building berms around fields (like what is discussed for on-farm rainfall-capture in Chapter 4) and flooding the fields to a ponded depth with surface water. The same concerns mentioned in Chapter 4, namely, selecting areas of suitable soil and crop type and determining suitable timing for allowing flooding, exist for this option as well as some additional concerns and limitations.

Two challenges facing the implementation of this type of farm flooding are infrastructure and growers' willingness to participate. Substantial infrastructure may need to be developed to deliver water to all fields deemed suitable for applying flood flows, unless the existing canal infrastructure is deployed. Additionally, annual temporary permits, as was needed by the District to conduct canal recharge (Chapter 3) would be needed and therefore could narrow the window of time when this could occur. In 2016 and 2017 when the District did release storm water into their canals for recharge, they did not apply any excess storm flows to farm fields. However, as recently as February 2018, conversations between District managers and growers about applying storm water for irrigation did take place (Kristin Sicke, personal communication 2/20/2018.)

Because this strategy involves ponded water, the risks to growers and their crops may be more than that from simply retaining rainfall as described in the previous chapter. It has been suggested that growers' willingness to participate and the timing of their seasonal operations may be the biggest limiting factor to implementing something like this.[14] Additional risks include the potential impacts to soils e.g. bulk density or erosion, the spread of soil borne diseases and weeds from one area to another.[15] However, it is important to note that some growers are already doing this, specifically in fields in the Yolo Bypass. In this area, some tomato fields are part of an annual crop rotation with rice and other crops that are flooded for wildlife habitat in the winter.[16] This may suggest that in this area, the impacts of flooding do not impede tomato growth, but more should be learned from this particular community of growers.

[14] Personal communication with Anthony O'Geen, Sept 20, 2017: Determining where to flood is highly dependent on who is willing to have their fields flooded.
Personal communication with Gene Miyao, Nov 7, 2017: Many tomato farmers think that flooding is generally a good idea for groundwater recharge but are not necessarily interested in allowing it to happen on their fields
[15] Personal communication with Gene Miyao, Nov 7, 2017.
[16] Ibid.

As for timing, not all storms may be well suited for this practice, particularly those later in the season when the ground is already saturated and fields may already have ponded water.

At the same time, if growers with relatively dry fields remove water from canals and sloughs, this may alleviate overflowing of canals and sloughs in known problem areas (See Chapter 6).

The window where permits to divert surface water are available to the District, is later in the season: February to April, which poses additional challenges to ensuring fields are dry for planting. Planting dates can vary from year to year, with warmer drier winters forcing growers to plant earlier than cooler wetter winters.[17] While the risks and uncertainties of this practice are greater than rainfall capture, the potential benefits to groundwater recharge and water supply reliability are likely much greater.

The concerns for impact to groundwater quality, where nutrients and contaminants accumulated in the soil would be forced into the aquifer by the flooded field is likely greater with this option than with rainfall capture or winter irrigation (winter irrigation is explained in the next graph). The Central Valley Regional Water Quality Control Board has had concerns over water quality issues with applying storm flows to farm fields: conditions have been included in the temporary permit to ensure that farmers are participating in the Yolo County Farm Bureau's Irrigated Lands Regulatory Program.[18]

The second option, which may be more appealing to growers than on-farm flooding, is winter irrigation. This involves using the existing infrastructure to irrigate fields in the winter with surface water, with the main goal of recharging groundwater as opposed to irrigating crops. In the winter, because evapotranspiration is low, most of the irrigated water would contribute to groundwater recharge. This could also be implemented on fallowed fields. For this option, temporary permits to use surface water in the winter months would likely be needed but the risks to crops and equipment of ponded water do not exist, as growers could control the amount or frequency of irrigation. This would likely be a good strategy in winters when there are intermittent rainstorms throughout the season, and fields are not already entirely saturated.

Field studies are already underway, improving our understanding of the risks and opportunities (Bachand et al., 2014; Dahlke et al., 2018a). There is good potential that other on-farm studies could be conducted in Yolo County, similar to the one conducted by (Dahlke et al., 2018a) in Yolo County.

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[17] Personal communication with Kristin Sicke, Yolo County Flood Control and Water Conservation District, 21 February, 2018.
[18] Contribution from Kristin Sicke, Yolo County Flood Control and Water Conservation District, 8 February, 2018.

Chapter 6. Flow monitoring network and slough maintenance

Executive Summary

This chapter compiles recommended locations for establishing new flow/flood monitoring stations, and focusing slough maintenance efforts, based on previous chapters' findings and the observations from three field trips. The observations also led to some recommendations beyond monitoring.

Documentation of potential monitoring sites

Three field trips were conducted through the course of the project, motivated by the regular flooding in Madison, and our investigation into western Yolo sloughs, described in Chapter 2. Locations visited on these trips (4/13/2017, 11/16/2017, 1/9/2018) are mapped here: https://goo.gl/maps/3XviRKyeeJH2, and shown in Figure 6.1. Table 6.1 below summarizes the locations and observations from these trips. Field visits and observations led to our recommendations for added and improved monitoring throughout the area. Note that the GPS locations correspond to where the pictures were taken. Photographs from these sites are provided in the pages that follow this table.

Figure 6.1 Map of locations visited throughout three field trips, shown by blue markers

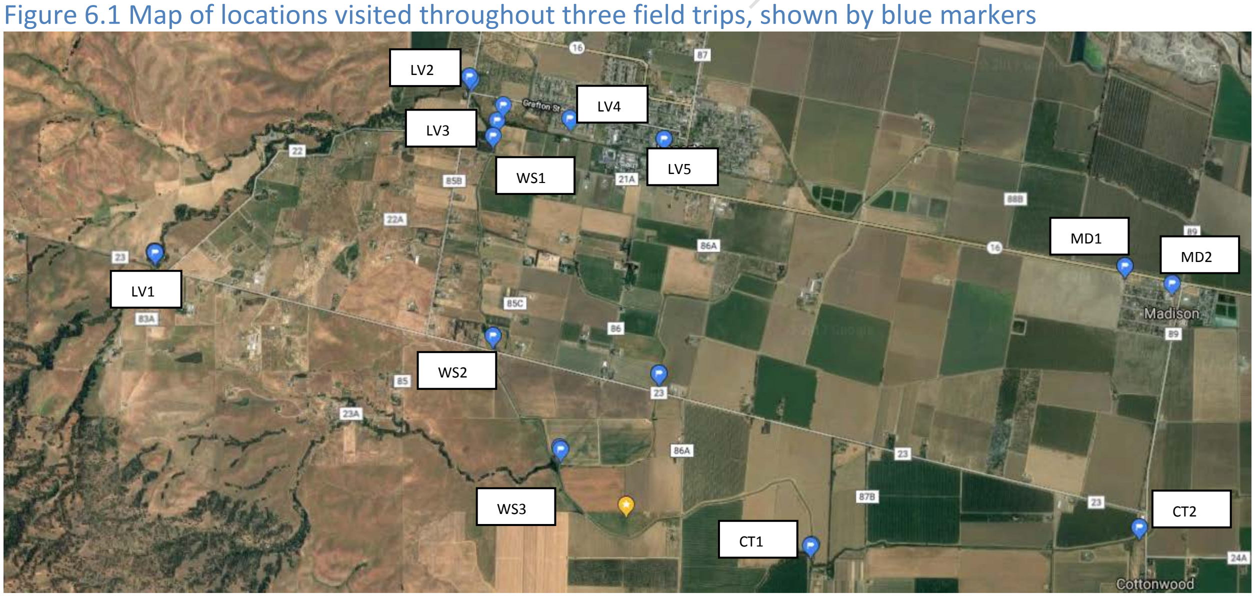


Table 6.1 Summary of locations visited

Location	Accessed	Latitude	Longitude	Dates Visited	Other Observations	Pictures	Recommend
LV1. Lamb Valley Sl at Rd 23 Bridge	By road	38.682785	-122.069251	4/13/2017 11/16/2017 1/9/2018	Trash barrier fence is present under the bridge No flowing water on all 3 visits Standing pools on last 2 visits	*LV1a_20171116_141530.jpg LV1b_20171116_141530.jpg LV1c_20170413_.jpg*	Flow monitoring. Channel is open and conducive for gauge at/near bridge
LV2. Lamb Valley Sl at 85B near Esparto	By road	38.696418	-122.038182	11/16/2017 1/9/2018	No flowing water	*LV2a_20171116_143714.jpg LV2b_20180109_143445.jpg*	Flow monitoring. Probably in downstream section, or at bridge.
LV3. Lamb Valley Sl at Winters Canal	0.21 miles off road	38.694135	-122.034960	11/16/2017	No flowing water A broken weir downstream Canal Camera may be able to capture slough	*LV3a_WintersCanal_IMG_20171116_145406.jpg LVSb_WintersCanal_IMG_20171116_145309.jpg*	Keep existing canal flow gage switched on; Monitor flow in slough. Canal releases impact points LV4 and LV5 below. Recommended not spilling into the slough during storms.
LV4. Lamb Valley Slough in Esparto near storm water detention pond	By road. Access from ponds by gate. Overgrown channel.	38.693089	-122.028259	1/9/2018	Observed flowing water. The flow here is result of 3 potential sources: upstream in Lamb Valley Slough (LV1-2), Winters Canal (LV3) and adjacent detention ponds. This contributes to flooding at LV5.	LV4_20180109_145114.jpg	Flow monitoring may be possible if channel and access were cleared.
LV5. Lamb Valley Sl in Esparto at Plainfield St Bridge/culvert	By road	38.691540	-122.018967	1/9/2018	Flowing water, probably spilling from Winters canal, & small drip from Esparto detention pond	LV5a_20180109_143425.jpg LV5b_20180109_143445.jpg	Channel may need deepening. Flow overtops at this point fairly regularly. Upstream flows could be regulated better through coordinated canal spills/no-spills.
WS1. Winters canal Rd 21 A near Rd 85B	By road	38.691662	-122.036026	11/16/2017 1/9/2018	Ponded (Not flowing water) on 11/16/2017 Flowing water on 1/9/2018	*WS1_WintersCanalRd21A_20180109_131420.jpg*	Keep existing canal flow station switched on.
WS2. Winters Canal Rd 23 near Rd 85C	By road	38.676262	-122.035858	1/9/2018	Flowing water	*WS2_WintersCanal_Rd23_85C_20180109_125417.jpg*	
WS3. S Fk Willow Sl at Winters Canal	0.75 miles off road	38.667606	-122.029369	11/16/2017	Distance between canal and slough top of water: ~5ft, bottom of slough: ~7ft Canal Camera may be able to capture slough	*WS3a_WIntersCanal_Int_SFk_WIllowSl_20171116_152414.jpg WS3b_20171116_152638.jpg*	Keep existing canal flow station switched on; Monitor flow in slough. Channel appears conducive to monitoring.

Location	Accessed	Latitude	Longitude	Dates Visited	Other Observations	Pictures	Recommend
WS4. S Fk Willow Sl at Rd 23	By road	38.673233	-122.019608	1/9/2018	Flowing water, probably spilling from Winters canal	*WS4a_SFlWillowSl_Rd23.jpg* *WS4b_SFlWillowSl_Rd23_20180109_124448.jpg*	
CT1. Cottonwood Sl at Winters Canal	0.75 miles off road	38.659988	-122.004253	11/16/2017	No flowing water. Heavily vegetated. Canal camera cannot spot slough.	*CT1a_SL_NR_WINTERSCANAL_20171116_155147.jpg* *CT1b_WINTERSCANAL_NR_CTN_SL_20171116_155729.jpg*	Keep existing canal flow station switched on; Monitor flow in slough.
CT2. Cottonwood Sl at Rd 89	By road	38.661362	-121.971626	1/9/2018	Flowing water, probably spilling from Winters canal	CT2a_SL_AT_RD89_20180109_124436.jpg CT2b_SL_ATRD89_20180109_123813.jpg	
MD1. Madison Drain at rock wall	By road	38.681817	-121.972956	4/13/2017 11/16/2017 1/9/2018	Channel clear, banks overgrown, water flowing (4/13/2017) Heavily overgrown (11/16/2017) Channel and banks Cleared and flowing water (1/9/2018)	MD1_20170413.jpg MD2_20171116_135100.jpg MD3_20180109_121116.jpg	Keep channel clear
MD2. Madison Drain at Rd 89	By road			1/9/2018	Flowing water, Channel clear but silted up	MD4_20180109_122437.jpg	Water overtops road here quite regularly. Keep channel clear; remove silt
WA1. West Adams Canal near Capay bridge	By road	38.711582	-122.047264	1/9/2018	Flowing water	WestAdamsCanal_20180109_133224.png	-

Plate 6-1 Madison Drain. From left to right: April 13, 2017; November 16, 2017; January 9, 2018. This is Location MD1 in Table 6.1.

Plate 6-2 Madison Drain at Rd 89 on January 9,2018. This location is MD2 in Table 6.1.

Plate 6-3 Lamb Valley Slough on Rd 23 Bridge. From left to right: Downstream reach from bridge (Nov 16, 2017); Upstream reach from bridge (Nov 16, 2017);From the bridge (April 13, 2017). This is location LV1 in Table 6.1.

Plate 6-4 Lamb Valley Slough at Rd 85B on November 16,2017. This is location LV2 in Table 6.1

Plate 6-5 Lamb Valley Slough at intersection with Winters Canal. Location LV 3 in Table 6.1. Top: on top of canal crossing the slough. Bottom: downstream view of slough from canal. Notice an old weir. Both photos are from November 16, 2017.

Plate 6-6 Lamb Valley Slough in Esparto. From left to right: Lamb Valley Slough near Esparto storm water ponds (location LV4 in Table 6.1); center and right:Lamb Valley slough at Plainfield St in Esparto (location LV5). All [photos are from January 9, 2018.

Plate 6-8 Winters Canal at Rd21 A and Rd23 op: Winters canal at Rd 21A (location WS1 in Table 6.1); bottom: at Rd 23 and 85C (location WS2 in Table 6.1). Both photos are from November 16,2017.

Plate 6-9 Intersction of Winters Canal and South Fork Willow Slough. This corresponds to location WS3 in Table 6.1. Both photos are from November 16, 2017.

Plate 6-10 South Fork WIllow Slough at Rd 23. This is location WS4 in Table 6.1. Both photos were taken November 16, 2017.

Plate 6-11 Cottonwood Slough near Winters Canal. Left: Cottonwood slough where Winters canal crosses it; Right Winters canal gate and telemetry close by (location CT1 in Table 6.1). Both photos were taken November 16, 2017.

Plate 6-12 Cottonwood Slough at Rd 89. This is location CT2 in Table 6.1. Both photos were taken January 9, 2018.

Plate 6-13 West Adams canal near Capay bridge on January 9, 2018. This is location WA1 in Table 6.1

Recommendations

Based on the previous chapters and field trips throughout Yolo County, we suggest improving the flow monitoring and slough network in five ways.

1. Switch on and monitor the *existing District* canal flow monitoring network during the winter, when it is usually dormant. A practice of doing this in tandem with forecast monitoring, as well as during actual storm events, is advised (LV3, WS1, WS3, CT1, Figure 6.1, Table 6.1).

2. Add new flow monitoring locations, likely in the form of a stage monitor due to the dynamic dimensions and obstructions and debris in sloughs, focusing on western Yolo sloughs: Lamb Valley, Cottonwood, and South Fork Willow Sloughs. Establishing new flow networks upstream as well as close to canal and road intersections in the valley floor will help close a major knowledge gap that is documented in every hydraulic monitoring study reviewed by us, since at least 1995 (LV1, LV2, LV3, WS3, CT1, Figure 6.1, Table 6.1).

3. Add an additional gauge for flow monitoring at Capay Diversion Dam. Although this site was not visited throughout this project, it is assumed that adding this knowledge will assist in informing where flows in the Winters Canal originate from, and therefore how to either mitigate them when needed, or determine the best time periods for implementing canal recharge.

4. We also recommend establishing a citizen science/citizen monitoring effort involving the landowners and small towns in western Yolo County. This could be a good way of involving the community actively, and generating richer, finer-scale information on flows, problem spots in the short term, for flood management opportunities in the future. At the simplest level, community members could document locations, dates, and times where they do or do not see flows in the sloughs, especially following storms as we did in Table 6.1. At a more advanced level, community members could be trained in measuring slough discharge with a flow meter.

5. We recommend keeping sloughs clear of silt, debris and vegetation to maximize the capacity of the existing infrastructure. This includes deepening channels that have been restricted due to sediment deposits, especially those that are known to cause flooding (LV5, MD2 Figure 6.1, Table 6.1) and potentially replacing culverts that are known to restrict flows. The Willow Slough Management Plan highlights in importance of coherent slough management. For example, clearing the slough in an area that doesn't typically back up may result in increasing flows in the sloughs, so that when those flows reach a constriction such as a bridge or culvert, the flooding issue is actually worse than if vegetation in the slough upstream would have helped slow the streamflow (Jones & Stokes Associates, 1996). We recommend a drainage district be established to manage the sloughs throughout the Esparto Madison area so that one area's diligent management doesn't result in added flooding in another area downstream.

Chapter 7. Other Outputs

In this Chapter we compile the several outputs – intermediary and final that were produced. (Table 7.1)These have been provided to the District.

Table 7.1 Summary of outputs produced for the SWRP

Output Name	Type	Description/ source	Suggested citation for future users
		Outputs relevant to Chapter 2	
WYSlough_catchments.zip	Multiple shapefiles	Boundaries of Western Yolo sloughs	
Catchment_pour_points.zip	shapefile	Pour points of Western Yolo sloughs	
soilmu_a_ca113_WYSloughs.zip	Shapefile	SSURGO soil for Western Yolo sloughs (Figure 2.2 top)	
soilmu_a_ca113_WYSloughs_revised.zip	shapefile	SSURGO soil for Western Yolo sloughs, revised to fill in missing NRCS soil groups (Figure 2.2 bottom)	
WYSlough_catch_SSURGO_NLCD.zip	Multiple shapefiles	Western Yolo slough catchments, divided by soil group and NLCD landuse category, used to calculate weighted Curve Numbers per catchment	
WYSlough_CN.xlsx	Excel file	Calculations for weighteCurve Numbers for each catchment, based on shapefile above	
Western_yolo_model.zip	HEC-HMS Model folder	Western Yolo event-based slough runoff HEC-HMS model	
		Outputs Relevant to Chapter 3	
Cache_creek_model.zip	WEAP model folder	Monthly WEAP model for canal recharge analysis	
		Outputs relevant to Chapter 4	
sagbi_mod.zip sagbi_unmod.zip	shapfiles	Modified and unmodified SAGBI data from (O'Geen et al., 2015), can be viewed on https://casoilresource.lawr.ucdavis.edu/sagbi/. Modified data were used in the anaysis.	
Suitable_area_modgood_exc.zip	shapefile	Farm fields considered suitable in Scenario 1 for groundwater banking strategies.	
Suitable_area_modpoor_exc.zip	shapefile	Farm fields considered suitable in Scenario 2 for groundwater banking strategies.	
Yolo_storm water_model.zip	Weap model folder	Daily WEAP model for rainfall capture analysis	
		Outputs relevant to Chapter 6	
Photo catalog of Madison flooding	Excel file with pictures linked	See Chapter 6 for description.	
Flow monitoring and field observations	Excel file with pictures linked	This is in Table 6.1 of this report	
		General Outputs	

Literature review and Bibliiography	Word document	Selected papers/reports provided	
Final report	Word document	This report	

Photo catalog: Madison flooding

As mentioned earlier (see Chapter 2, and also Table 6.1 above), Madison experiences regular flooding. We assembled a photo catalog, in the form of a spreadsheet linked to the locations of pictures taken, and metadata (as far as possible) on dates and times. Photographs were contributed by Leo Refsland (Madison Service District), Madison residents and the YCFCWCD staff. The catalog has been shared with the YCFCWCD and with Madison Service District, with the expectation that it will be a living document to be added to over time. **As of 2/22/2018, we had cataloged more than 200 photos with the earliest from 1978 and the latest from 2017.**

Figure 7.1 Screenshot of photo catalog of Madison floods

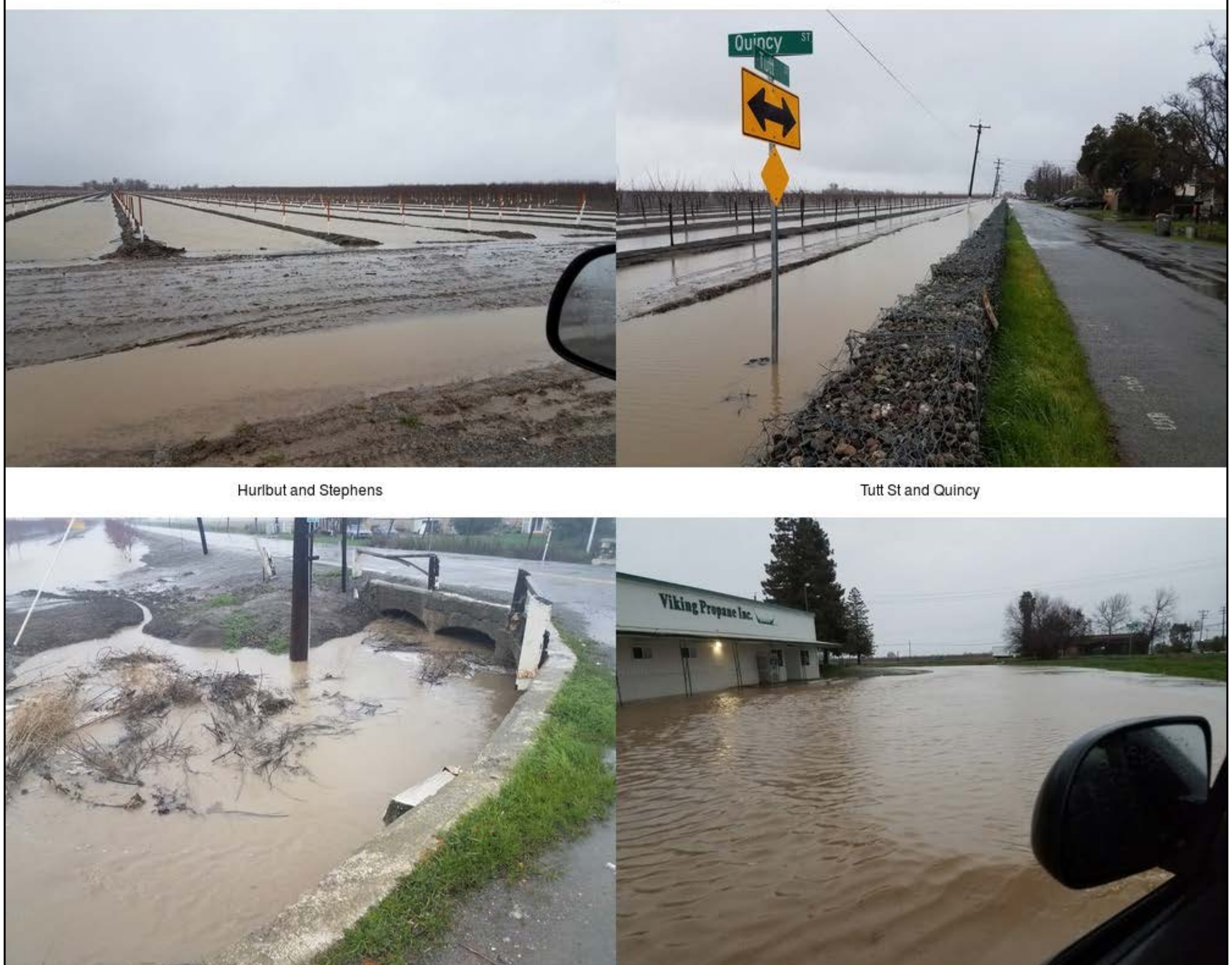
A	B	C	D	E	F	G	H	
Filename	Source of	Date-time	Latitude	Longitude	Altitude(m)	True Direction	Source of metadata	URL to Google Maps
8-26-13 182.JPG	Leo	2012:12:23 17:15:30	38.6803	-121.96833	30	164.400269	Camera info	https://www.google.com/maps/place/38%C2%
8-26-13 178.JPG	Leo	2012:12:23 17:13:44	38.6808	-121.96833	34	101.553932	Camera info	https://www.google.com/maps/place/38%C2%
8-26-13 181.JPG	Leo	2012:12:23 17:15:22	38.6803	-121.96833	30	152.445831	Camera info	https://www.google.com/maps/place/38%C2%
8-26-13 177.JPG	Leo	2012:12:23 17:13:39	38.6808	-121.96833	36	95.114479	Camera info	https://www.google.com/maps/place/38%C2%
8-26-13 185.JPG	Leo	2012:12:23 17:16:51	38.68	-121.96833	36	102.945557	Camera info	https://www.google.com/maps/place/38%C2%
8-26-13 186.JPG	Leo	2012:12:23 17:17:10	38.68	-121.96833	31	131.445831	Camera info	https://www.google.com/maps/place/38%C2%

Relating Madison flooding to flood frequency and rainfall frequencies

We combined some of the storm photos collected, with Cache Creek flow records and rainfall records at the Brooks station. In the following three pages, we can see how flooding looks for 2, 5 and 10 year storms.

Flood event	Cache Creek flow at Rumsey		Rainfall		
	Observed peak flow (cfs)	Flow frequency	Event rainfall (inches)	Rainfall frequency	Cumulative rainfall from Oct 1 (inches)
Jan 7-Jan 8 2017	21,500 *3:30pm, Jan 8, 2017*	Between 2 to 5 years	3.5 *48 hr period ending 4pm Jan 8th, 2017*	2 years *For 48 hr duration*	12.05

January 8 2017



Hurlbut and Stephens

Tutt St and Quincy

Madison drain culvert at Rd 89

Viking propane near Rd 89

Flood event	Cache Creek flow at Rumsey		Rainfall		
	Observed peak flow (cfs)	Flow frequency	Event rainfall (inches)	Rainfall frequency	Cumulative rainfall from Oct 1 (inches)
Dec13-Dec 16 2002	24,805 *6:45am, Dec 16, 2002*	Close to 5 years	5.31 *96 hr period ending 4pm Dec 16th, 2002*	5 years *For 96 hr duration*	7.88

Dec 16 2002

Tutt St betweeen Main and Quincy

Southeast corner of Main and Tutt

Flood event	Cache Creek flow at Rumsey		Rainfall		
	Observed peak flow (cfs)	Flow frequency	Event rainfall (inches)	Rainfall frequency	Cumulative rainfall from Oct 1 (inches)
Dec 30-31 2005	35,263 *9:15am, Dec 31, 2005*	10 years	3.39 *24 hr period ending 4pm Dec 31, 2005*	Between 5 - 10 years *For 24 hr duration*	29.54

Dec 31 2005

Rd 90 looking north to I505 overpass

Rd 90 and Willow Slough

Tutt St near Quincy

17921 Tutt and Main

Hwy 16 near Esparto welcome sign

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Appendix A. Western Yolo Model Supplementary Information

Table A 1. Landcover-soil group look up table

NLCD (2011)		Reclassification to Curve Number classes		Curve numbers for Hydrologic Soil Group				
ID	Label and Description	Reclass ID	Reclass Description	A	B	C	D	Rock
11	**Open Water**- areas of open water, generally with less than 25% cover of vegetation or soil.	1	Water	0	0	0	0	98
12	**Perennial Ice/Snow**- areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.	2	Ice	98	98	98	98	98
21	**Developed, Open Space**- areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.	3	Open Space (Good condition)	39	61	74	80	98
22	**Developed, Low Intensity**- areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.	4	Residential avg lot size 1/3 acre (30%imp)	57	72	81	86	98
23	**Developed, Medium Intensity** -areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.	5	Residential avg lot size 1/3 acre (1⁄8 acre or less (town houses) (65% imp.)	77	85	90	92	98
24	**Developed High Intensity**-highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.	6	Urban districts commercial and business (85% imp.)	89	92	94	95	98
31	**Barren Land (Rock/Sand/Clay)** - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.	7	Fallow, bare soil	77	86	91	94	98

NLCD (2011)		Reclassification to Curve Number classes		Curve numbers for Hydrologic Soil Group				
ID	Label and Description	Reclass ID	Reclass Description	A	B	C	D	Rock
41	**Deciduous Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage	8	Woods, Good	30	55	70	77	98
42	**Evergreen Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.	8	Woods, Good	30	55	70	77	98
43	**Mixed Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.	8	Woods, Good	30	55	70	77	98
52	**Shrub/Scrub**- areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.	9	Brush—brush-weed-grass mixture with brush the major element	30	48	65	73	98
71	**Grassland/Herbaceous**- areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.	10	Pasture, grassland, or range—continuous forage for grazing	39	61	74	80	98
81	**Pasture/Hay**-areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.	11	Pasture, grassland, or range—continuous forage for grazing	39	61	74	80	98
82	**Cultivated Crops** -areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.	12	Straight rows, good	67	78	85	89	98
90	**Woody Wetlands**- areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	13	NA					

NLCD (2011)		Reclassification to Curve Number classes		Curve numbers for Hydrologic Soil Group				
ID	Label and Description	Reclass ID	Reclass Description	A	B	C	D	Rock
95	**Emergent Herbaceous Wetlands**- Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	13	NA					

Table A 2. Actual January storm event

Date, time	Cumulative Precip depth (in)
1/2/2017 12:00	0
1/2/2017 13:00	0.04
1/2/2017 14:00	0.04
1/2/2017 15:00	0.04
1/2/2017 16:00	0.04
1/2/2017 17:00	0.04
1/2/2017 18:00	0.04
1/2/2017 19:00	0.04
1/2/2017 20:00	0.06
1/2/2017 21:00	0.06
1/2/2017 22:00	0.06
1/2/2017 23:00	0.06
1/3/2017 0:00	0.06
1/3/2017 1:00	0.06
1/3/2017 2:00	0.06
1/3/2017 3:00	0.1
1/3/2017 4:00	0.12
1/3/2017 5:00	0.12
1/3/2017 6:00	0.13
1/3/2017 7:00	0.13
1/3/2017 8:00	0.15
1/3/2017 9:00	0.16
1/3/2017 10:00	0.17
1/3/2017 11:00	0.2
1/3/2017 12:00	0.24
1/3/2017 13:00	0.29
1/3/2017 14:00	0.36
1/3/2017 15:00	0.45
1/3/2017 16:00	0.52
1/3/2017 17:00	0.56
1/3/2017 18:00	0.64
1/3/2017 19:00	0.71
1/3/2017 20:00	0.75
1/3/2017 21:00	0.78
1/3/2017 22:00	0.83
1/3/2017 23:00	0.91
1/4/2017 0:00	1.21
1/4/2017 1:00	1.64
1/4/2017 2:00	1.66
1/4/2017 3:00	1.71
1/4/2017 4:00	1.72

Table A 3. 100 year, 24 hours design storm event

Time	Cumulative Precip Depth (in)
0:00	0.00
0:15	0.02
0:30	0.05
0:45	0.07
1:00	0.10
1:15	0.12
1:30	0.15
1:45	0.17
2:00	0.20
2:15	0.23
2:30	0.25
2:45	0.28
3:00	0.31
3:15	0.34
3:30	0.37
3:45	0.40
4:00	0.43
4:15	0.46
4:30	0.49
4:45	0.53
5:00	0.56
5:15	0.59
5:30	0.63
5:45	0.67
6:00	0.71
6:15	0.75
6:30	0.79
6:45	0.84
7:00	0.88
7:15	0.93
7:30	0.98
7:45	1.04
8:00	1.10
8:15	1.17
8:30	1.24
8:45	1.34
9:00	1.44
9:15	1.57
9:30	1.71
9:45	2.31
10:00	2.91

Time	Cumulative Precip Depth (in)
10:15	3.10
10:30	3.29
10:45	3.41
11:00	3.53
11:15	3.61
11:30	3.70
11:45	3.77
12:00	3.85
12:15	3.92
12:30	3.99
12:45	4.05
13:00	4.11
13:15	4.17
13:30	4.23
13:45	4.28
14:00	4.33
14:15	4.38
14:30	4.44
14:45	4.48
15:00	4.53
15:15	4.57
15:30	4.61
15:45	4.65
16:00	4.69
16:15	4.73
16:30	4.76
16:45	4.80
17:00	4.84
17:15	4.87
17:30	4.90
17:45	4.94
18:00	4.97
18:15	5.00
18:30	5.03
18:45	5.07
19:00	5.10
19:15	5.13
19:30	5.16
19:45	5.20
20:00	5.23
20:15	5.26
20:30	5.29

Time	Cumulative Precip Depth (in)
20:45	5.32
21:00	5.34
21:15	5.37
21:30	5.40
21:45	5.42
22:00	5.45
22:15	5.47
22:30	5.50
22:45	5.53
23:00	5.55
23:15	5.57
23:30	5.60
23:45	5.62
0:00	5.65

Appendix B. Yolo Storm Water Model Development

Acronyms

AF - Acre Feet
CFS - Cubic Feet per second
CWA - Clean Water Agency
RD - Reclamation District
UCD - University of California Davis
USBR - U.S. Bureau of Reclamation
UWMP - Urban Water Management Plan
WY - Water year
YCFC - Yolo County Flood Control and Water Conservation District

Model Overview

The Yolo Storm Water Model (YSWM) is a modification of the Cache Creek Model , described in Mehta et al. (2013). The model covers the entirety of Yolo County (valley floor) as well as the Cache Creek upper watershed. The development and calibration of the Cache Creek upper watershed is documented in Mehta et al., 2013, and the only change to this area within this version of the model is the climate input data. This area of the model is only further discussed in the Climate data section further on this appendix. The main modifications made since Mehta et al., 2013 are changes to the break up and operation of the valley floor modeled area, which is further discussed below. The majority of the model operates at a monthly timestep, except the valley floor catchments, which operate at a daily timestep. All calculations and analyses relative to this analysis are conducted and reported at the daily timestep.

Spatial Coverage of the model

WEAP Catchments

The area of Yolo County is broken into 38 subareas, called catchments within WEAP. Most valley floor catchments represent a governing body with water or land use responsibilities (entity), and the remaining cover the areas between entities' boundary areas. Catchment boundaries were developed using the entities' boundaries, YCIGSM area boundaries[19] (so that this model's outputs can be compared to YCIGSM outputs) and USGS HUC 8 area boundaries[20] (for significant hydrologic boundaries). Certain entities' areas are divided into multiple catchments (ie, YCFC) because the entity's boundary expands across another boundary (such as

[19] http://www.ycfcwcd.org/documents/ycigsm_report_060106.pdf
[20] https://water.usgs.gov/GIS/huc.html

a HUC boundary or CASGEM boundary), and some are fully contained in only one catchment. The complete list of Valley Floor and Cache Creek watersheds is given in Table B 1 and the areas they represent are show in Figure B 1. Each catchment contains land use information (as outlined in the Land Use Section, below), climate information (as outlined in the Climate data Section), is connected to at least one groundwater node and, if irrigation occurs within the entity's boundary, the catchment is connected to at least one water source (both outlined in the Catchment Interactions with Surface and Groundwater Section).

Catchment Interactions with Surface and Groundwater

Rainfall-runoff calculations occur within the catchments, so volumes of runoff and infiltration from the catchment area are generated for each time step based on precipitation information, irrigation (based on crop type and soil moisture in the previous time step), land use, and soil parameters. The valley floor catchments use WEAP's MABIA method for calculating rainfall-runoff, irrigation demand, evapotranspiration and other catchment data, consistent with FAO 56.[21] Each catchment is connected to at least one surface water and groundwater object, representing the runoff and infiltration from that land area to the surface water body and groundwater body, respectively. Some catchments run off to more than one water body or infiltrate to more than one groundwater subbasin because the catchment area overlies two watersheds or groundwater subbasins.

The surface water bodies and groundwater basins included in the model are listed in Table B 1. Figure B 2 depicts the catchment delineations in WEAP, and how they overlap with the watersheds of Cache Creek, The Colusa Basin Drain, Willow Slough and the Sacramento River (the main water bodies represented in the model), in Yolo County, and Figure B 3 shows how they are represented within WEAP. Figure B 4 depicts how the catchments overlap with the Bulletin 118 groundwater subbasins[22], and Figure B 5 shows their representation within WEAP.

If an entity has water demands other than irrigation (for example, cities which have municipal and industrial demands), the entity is also represented by a demand object. The demand object is connected to at least one water supply to meet the corresponding demands. Data within the demand object such as water demand per capita, population etc. were derived from public documents such as Urban Water Management Plans. For the purposes of this study, demand

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[21] More information about WEAP's MABIA method can be found here: http://www.weap21.org/WebHelp/Mabia_Algorithms.htm, and the FAO 56 documentation can be found here: http://www.kimberly.uidaho.edu/water/fao56/fao56.pdf.

[22] http://www.water.ca.gov/pubs/groundwater/bulletin_118/california's_ground_water__bulletin_118-75_/b118-1975.pdf

objects and their associated information do not affect the analysis nor the results, and therefore are not further discussed here.[23]

Most catchments which represent entities that have Water Rights are connected to those surface water bodies for which they have rights, with transmission links. Rules on the transmission links limit available water based on the water right.[24] The exceptions are the Woodland-Davis Clean Water Agency and the Yolo County Flood Control and Water Conservation District, which have more complex water rights and distribution systems and therefore are represented by diversion arcs in WEAP. All catchments and demand objects are set up such that they use surface water primarily, if it is available, and only use groundwater when there is not sufficient surface water to meet the demand. Because the scenario implemented here only deals with rainfall capture, available surface or groundwater was not required nor limiting for this analysis and therefore is not further discussed here.

[23] Additional information about each individual demand node and its data can be found within the model, in the data view, under the notes tab for each demand.

[24] Additional information about each water right and when water is available to each catchment can be found within the model, in the data view, under the notes tab for each transmission link.

Table B 1. List of WEAP objects in the model. Demand and Waste water treatment plant nodes are not listed as they are not relevant to this analysis.

Valley Floor Catchments	Cache Creek Upper Watershed Catchments	Surface Water Bodies	Groundwater Basins
Bird Creek	Bear Creek	Bear Creek*	Capay
Buckeye Creek	Clear Lake	Cache Creek	Colusa
Cacheville CSD catch	Copsey Creek	Clear Lake	Lake County*
Capay Other	Kelsey Creek	Colusa Basin Drain	Solano
CBD North	Lower Cache Creek	Copsey Creek*	Yolo
CBD South	Lower Indian Valley	Indian Valley Reservoir	
Davis catch	Middle Indian Valley	Kelsey Creek*	
Dunnigan Other	Seigler Canyon	North Fork Cache Creek	
Dunnigan Water District	Upper Cache Creek	Putah Creek	
Esparto CSD catch	Upper Indian Valley	Sacramento River	
Goodnow Slough		Willow Slough	
Knights Landing catch		YCFC Canal System*	
Madison CSD catch		Yolo Bypass*	
North Delta East			
North Delta West			
Oat Creek			
RD 108			
RD 1600			
RD 2035			
RD 537			
RD 730			
RD 785			
RD 787			
RD 827			
Sac River			
UCD catch			
West Sac catch			
Willow Slough			
Winters catch			
Woodland catch			
YCFC Capay			
YCFC Dunnigan Hills			
YCFC East			
YCFC Hungry Hollow			
YCFC West			
YCFC Zamora			
Yolo Zamora North			
Yolo Zamora South			

*WEAP elements are not relevant to this analysis and therefore are not shown in Figure B 1, Figure B 2 or Figure B 4.

Figure B 1. Map of the catchments within the WEAP model. Cache Creek upper watershed catchments are shown in shades of gray and valley floor catchments in color. The main surface water bodies included in the model are shown, and the county boundary is outlined in black.

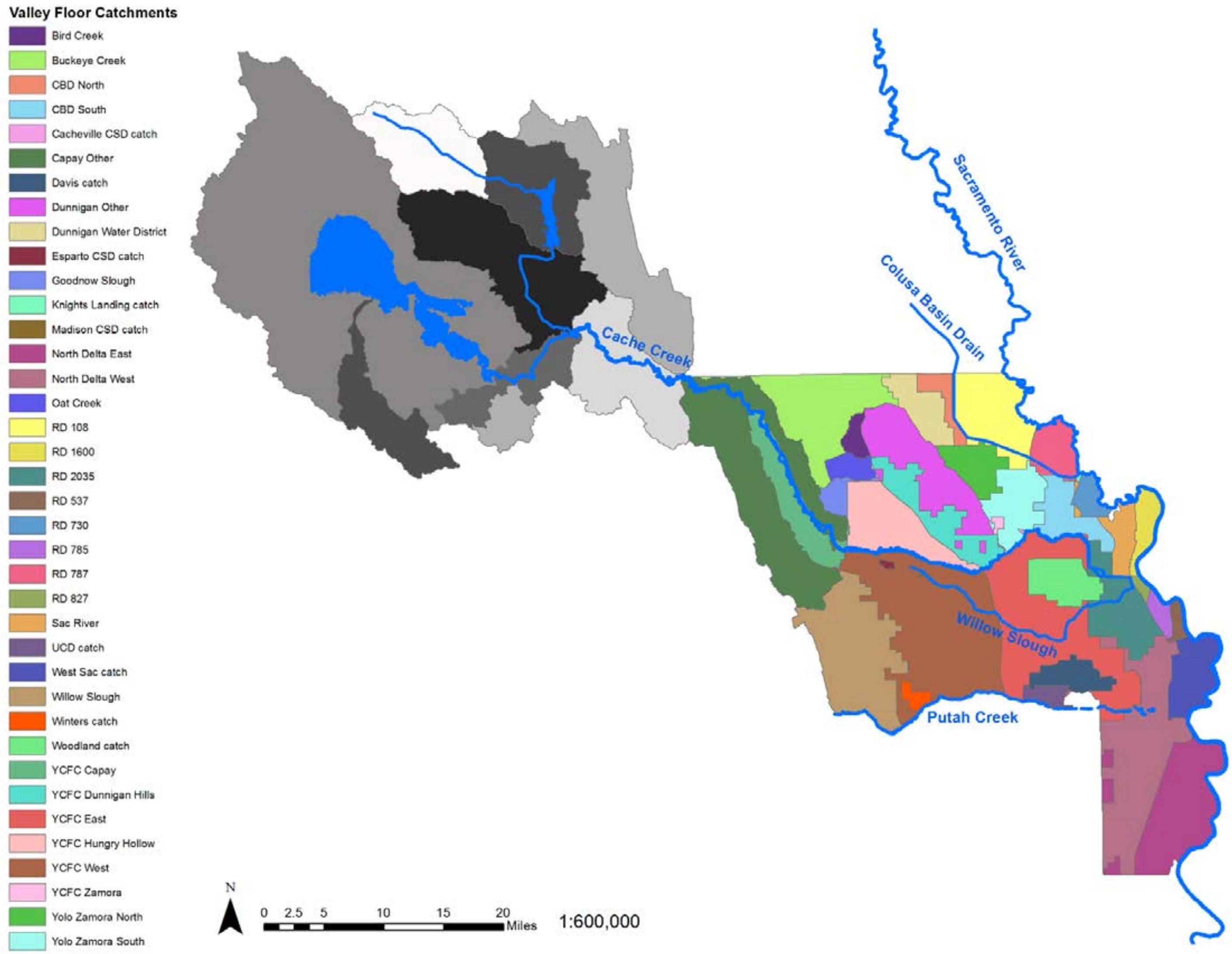


Figure B 2. Map of catchments in WEAP and watersheds for the water bodies represented in WEAP

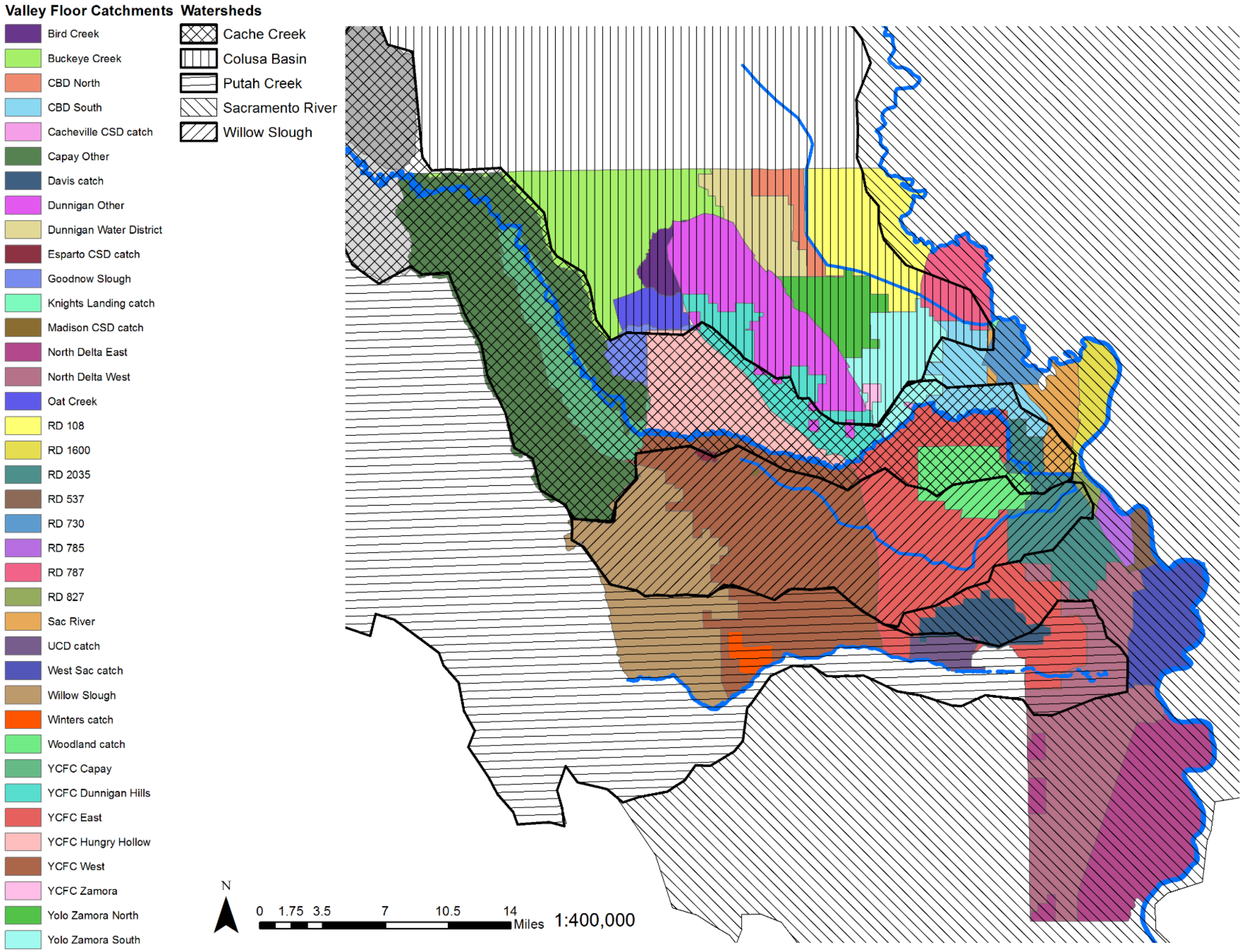


Figure B 3. WEAP Schematic of catchments and surface water bodies

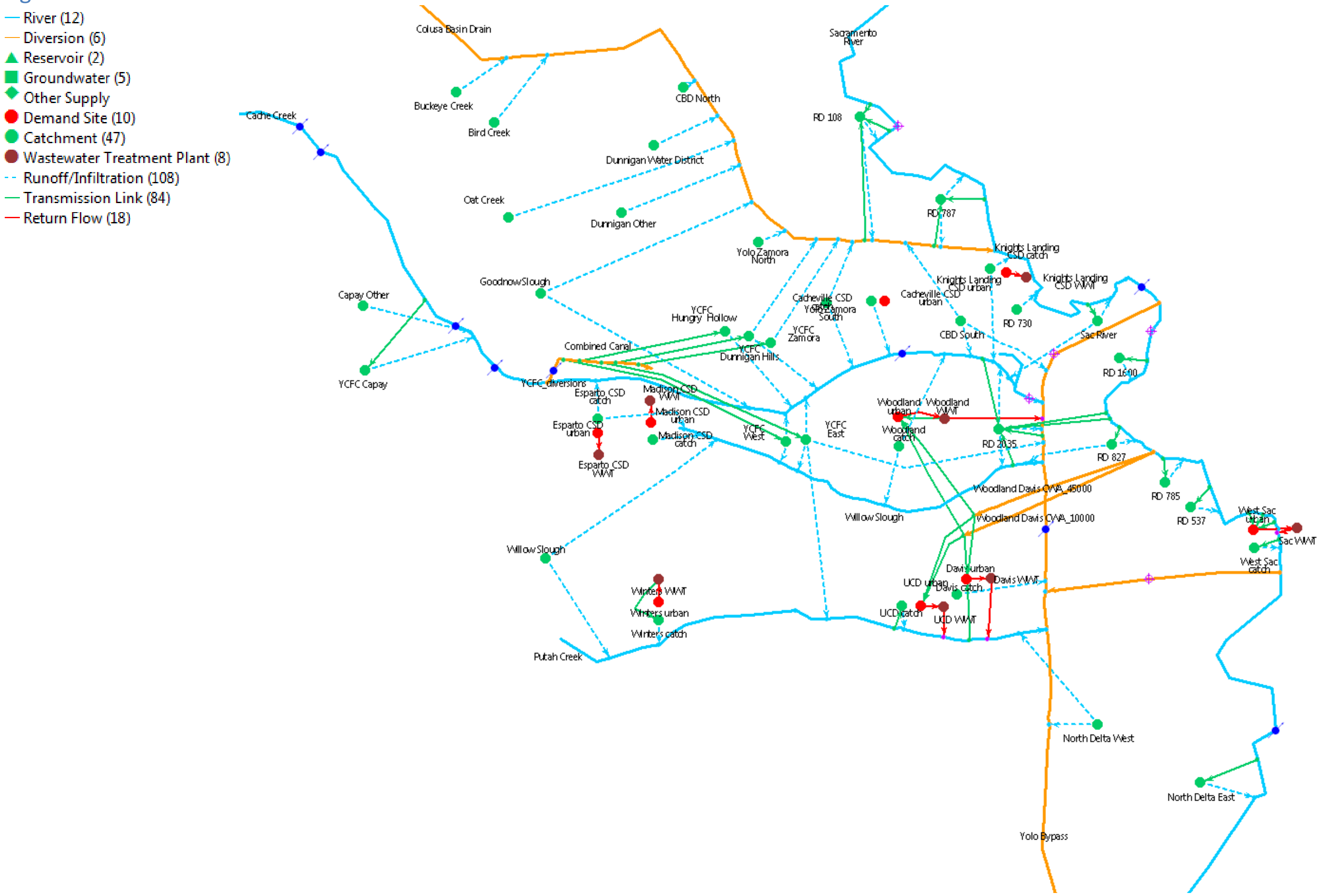


Figure B 4. Map of catchments in WEAP with Bulletin 118 groundwater subbasins underlying Yolo County.

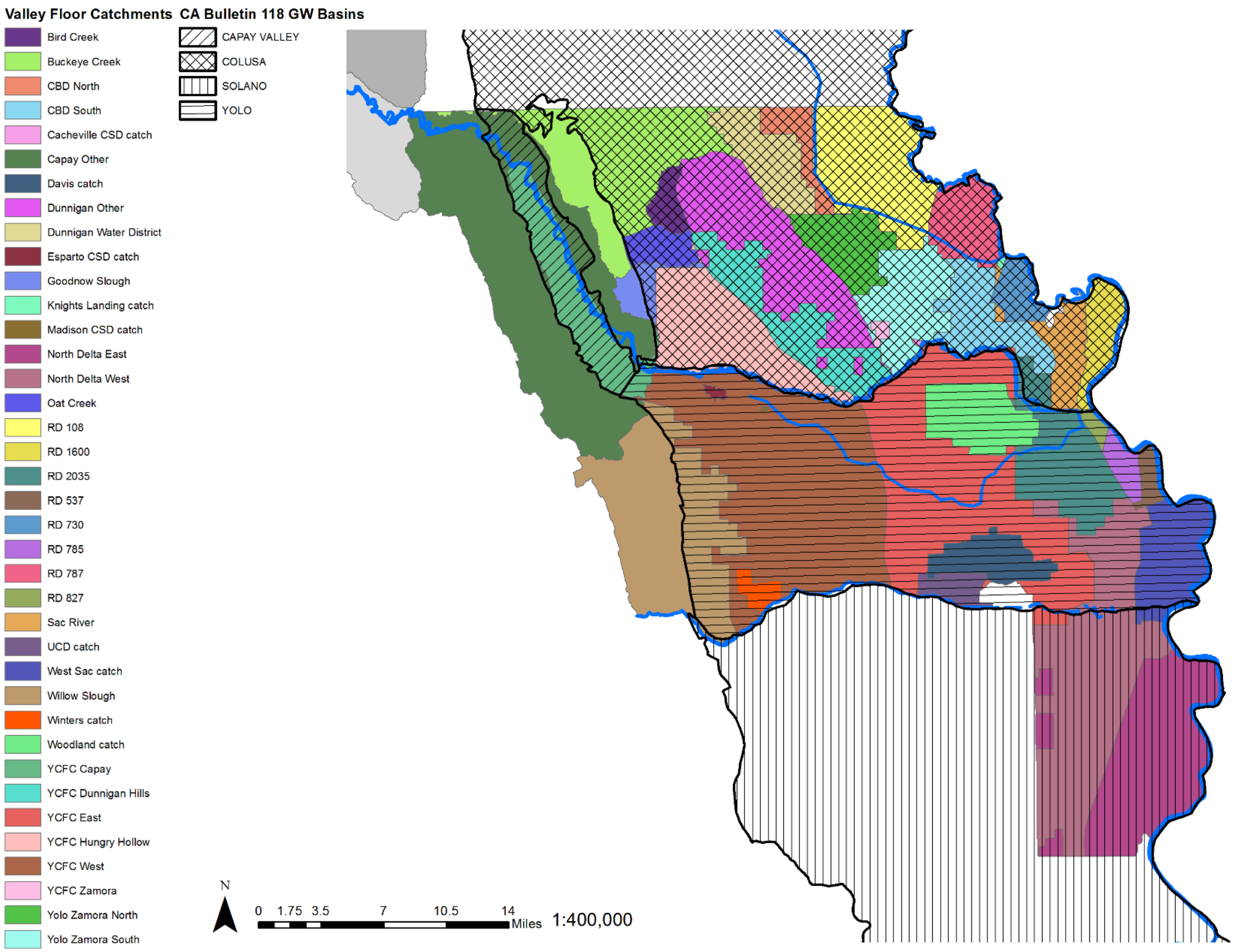
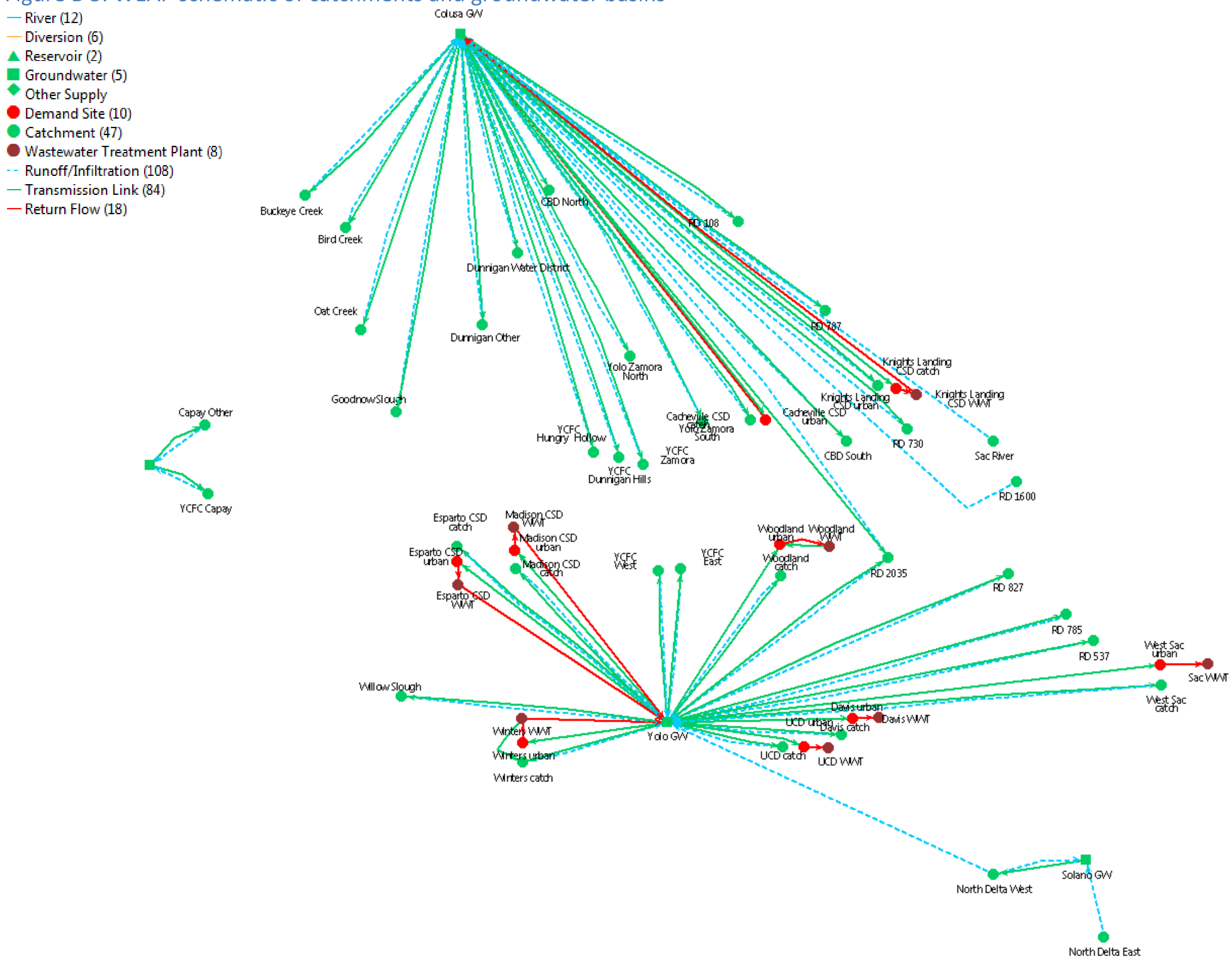


Figure B 5. WEAP schematic of catchments and groundwater basins



Land Use

Crop Coverage

The irrigated agricultural area within the model is divided into 16 crop categories. Categories were derived based on the DWR water use surveys[25] (water use surveys). Table B 2 shows the names and definitions used in the DWR dataset and the corresponding name in the WEAP model.

Land use data from DWR is only available for years 1981, 1989, 1997 and 2008. However, there is significant fluctuation in crop coverage and total irrigated area annually within the County, as made clear by the Yolo County Agricultural Commission's Crop Reports (Crop Reports).[26] To represent this annual fluctuation between these years (and before 1981), these two data sets were combined in the model. From the Crop Reports, the total irrigated area was estimated as the sum of the total acreage of each crop listed in the Crop Reports, minus the "Pasture, Dry" acreage. Livestock is not included in the model. From the Crop reports, the total area of each irrigated crop category within the County in each year was also estimated. This required mapping the Crop Report categories to the WEAP categories, which was straight forward and by comparing crop names. From the four water use surveys, the percent of each crop's area that falls within each catchment was calculated. This percent per crop per catchment was then multiplied by the annual acreage per crop from the Crop Reports, resulting in a dynamic cropping pattern where the area of each crop in each catchment varies each year, as well as the total irrigated area, but each catchment's area and the county's area remain constant.

[25] http://www.water.ca.gov/landwateruse/anlwuest.cfm
[26] http://www.yolocounty.org/general-government/general-government-departments/agriculture-cooperative-extension/agriculture-and-weights-measures/crop-statistics.

Table B 2. DWR crop names, and corresponding model assignations

DWR Landuse Codes from Landuse Surveys	DWR Crop name from wateruse dataset	DWR Crop Definition	WEAP crop category	Notes
G	Grain	Wheat, barley, oats, miscellaneous grain and hay, and mixed grain and hay	Grain	Winter wheat is the representative crop
R	Rice	Rice and wild rice	Rice	
F1	Cotton	Cotton		No cotton acreage in Yolo, so not included
F5	SgrBeet	Sugar beets	Sugar beet	
F6	Corn	Corn (field and sweet)	Corn	
F10	DryBean	Beans (dry)	Dry Beans	
F2	Safflwr	Safflower	Safflower	
F(all other)	Oth Fld	Flax, hops, grain sorghum, sudan, castor beans, miscellaneous fields, sunflowers, hybrid sorghum / sudan, millet and sugar cane	Other field	Dominated by sunflower in Yolo County
P1	Alfalfa	Alfalfa and alfalfa mixtures	Alfalfa	
P(all other)	Pasture	Clover, mixed pasture, native pastures, induced high water table native pasture, miscellaneous grasses, turf farms, bermuda grass, rye grass and klein grass	Pasture	Note this is irrigated pasture.
T15	Pro Tom	Tomatoes for processing	Tomatoes	
T26	Fr Tom	Tomatoes for market		
T9	Cucurb	Melons, squash and cucumbers	Cucurbits	
T10	On Gar	Onions and garlic	Other truck	
T12	Potato	Potatoes		
T(all other)	Oth Trk	Artichokes, asparagus, beans (green), carrots, celery, lettuce, peas, spinach, flowers nursery and tree farms, bush berries, strawberries, peppers, broccoli, cabbage, cauliflower and brussel sprouts		
D12	Al Pist	Almonds and pistachios	Almonds	Dominated by Almonds in Yolo County
D(all other)	Oth Dec	Apples, apricots, cherries, peaches, nectarines, pears, plums, prunes, figs, walnuts and miscellaneous deciduous	Other Deciduous	Dominated by walnuts in Yolo County
C	Subtrop	Grapefruit, lemons, oranges, dates, avocados, olives, kiwis, jojoba, eucalyptus and miscellaneous subtropical fruit	Subtropical	Dominated by olives in Yolo County
V	Vine	Table grapes, wine grapes and raisin grapes	Vine	

Non-crop land use categories

The non- agricultural areas in each catchment (e.g. urban areas, native vegetation etc.) were also categorized based on the DWR dataset into three categories: native vegetation, urban, and water. The area of urban and water was calculated using the three DWR datasets during each year they are available. They remain constant between the years and before 1981. The area of native vegetation makes up the difference of all of the other categories subtracted from the total area of the catchment.

Crop data for rainfall capture field selection

The areas that were selected as locations to simulate rainfall capture were based on crop type and soil type as described in the Methods Section in Chapter 4. To use the most recent crop coverage information available to select areas for implementing rainfall capture, we downloaded (in April 2017) GIS data from the Yolo County website, which are likely based on Pesticide Use Reports (PUR). These were available from 2009 every year to 2014. The 2014 spatial data set was used in this analysis. PUR data has more than 100 crop types; and therefore, another lookup table (Table B 3) was devised to match these crop types to the WEAP model crop names in Table B 2. If an area delimited by the County Crop data was categorized as covered by one crop type, Table B 3 was used to reassign a WEAP crop type to that area.

Table B 3. County Crop-WEAP Look up table

County crop category	WEAP crop category (from Table 1)	County crop category	WEAP crop category (from Table 1)	County crop category	WEAP crop category (from Table 1)
ALFALFA	Alfalfa	ORG WATERMELON	Cucurbits	ORG WHEAT FOR FOD	Grain
ALFALFA GRASS M		PICKLE		RYE	
ALFALFA SEED		PUMPKIN		TRITICALE	
ORG ALFALFA		PUMPKIN SEED		WHEAT	
ALMOND	Almond and Pistachio	SQUASH		WHEAT FOR/FOD	
NUTS		SQUASH SEED		WHEAT SEED	
ORG ALMOND		WATERMELON		BANK	N/A
ORG PISTACHIO		WATERMELON SEED		BEEHIVE	
PISTACHIO		ZUCCHINI		COMM. FUMIGATN	
CORN	Corn	BEAN DRIED	Dry beans	COMMR/INST/IND	
CORN FOR/FOD		BEAN DRIED SEED		DAIRY EQUIPMENT	
CORN SEED		BEAN SUCCULENT		DITCH	
ORG CORN FOR FOD		BEAN UNSPECIFD		FUMIGATN	
ORG CORN HMN CO		BEANS		HUMAN CON	
COTTON	Cotton	FAVA BEAN		INDUSTRIAL SITE	
CANTALOUPE	Cucurbits	GARBANZO BEAN		LANDSCAPE MAIN	
CUCUMBER		LIMA		ORG UNCULTIVATED AG	
CUCUMBER SEED		ORG BEAN UNSP		RECREATION AREA	
HONEYDEW MELON		BARLEY	Grain	REG PEST CONTRL	
MELON		BARLEY FOR/FOD		RESEARCH COMMOD	
MELON SEED		FORAGE HAY/SLGE		RIGHTS OF WAY	
ORG CUCUMBER		GRAIN		SOIL FUM/PREPLT	
ORG MELON		OAT		SOIL FUM/PREPLT	
ORG PUMPKIN		OAT FOR/FOD		UNCUL NON-AG	
ORG PUMPKIN		OAT SEED		UNCULTIVATED AG	
ORG SQUASH		ORG BARLEY		UNDECLARED COMM	
ORG SQUASH		ORG OAT FOR/FOD		VETCH	
ORG SQUASH SUMMER		ORG TRITICALE		GARLIC	Onions and Garlic
ORG SQUASH WINTER		ORG WHEAT		ONION DRY ETC	

County crop category	WEAP crop category (from Table 1)	County crop category	WEAP crop category (from Table 1)	County crop category	WEAP crop category (from Table 1)
ONION GREEN	Onions and Garlic	PERSIMMON	Other deciduous	BERRY	Other truck
ONION SEED		PLUM		BLACKBERRY	
ORG GARLIC		STONE FRUIT		BLUEBERRY	
ORG ONION DRY		TANGERINE		BOK CHOY LSE LF	
ORG ONION SEED		WALNUT		BROCCOLI	
POME FRUIT	Other Deciduous	CANOLA (RAPE)	Other Field	BROCCOLI SEED	
POMEGRANATE		HOPS		BURDOCK (ROOT CROP)	
PRUNE		MUSTARD		CABBAGE	
APPLE		OF-FLOWER SEED		CABBAGE SEED	
APRICOT		OF-FLWRNG PLANT		CARROT	
CHERRY		ORG LEEK		CARROT SEED	
CHESTNUT		ORG MUSTARD		CAULIFLOWER	
FIG		ORG SASFFLOWER		CAULIFLOWR SEED	
GP-DEC. TREE		ORG SORGHUM MILO		CHINESE GREEN	
JUJUBE		ORG SUNFLOWER SEED		CHRISTMAS TREE	
MULBERRY		RAPE		CILANTRO	
NECTARINE		SORGHUM FOR/FOD		COLE CROP	
ORG APPLE		SORGHUM MILO		COLLARD	
ORG APRICOT		SORGHUM SEED		COLLARD SEED	
ORG CITRUS		SOYBEAN		DAIKON	
ORG FIG		SOYBEAN GRAIN		DANDELION GREEN	
ORG NECTARINE		SOYBEAN SEED		EGGPLANT	
ORG PEACH		SUDANGRASS		FRUIT	
ORG PEAR		SUNFLOWER		GF-EVG. TREE	
ORG PLUM		SUNFLOWER SEED		HERB	
ORG STONE FRUIT		ANISE	Other truck	KALE	
ORG WALNUT		ARTICHOKE		KALE SEED	
OT-DEC. TREE		ARTICHOKE SEED		KOHLRABI	
PEACH		ASPARAGUS		KOHLRABI SEED	
PEAR		ASPARAGUS SEED		LEEK	

County crop category	WEAP crop category (from Table 1)	County crop category	WEAP crop category (from Table 1)	County crop category	WEAP crop category (from Table 1)
LETTUCE LEAF	Other truck	ORG SWISS CHARD	Other truck	ORG PASTURELAND	Pasture
N-GRNHS PLANT		ORG TURNIP		OT-TURF	
N-GRNHS TRANSPL		ORG VEGETABLE		PASTURELAND	
N-OUTDR FLOWERS		ORG VEGETABLE LEAF		RANGELAND	
N-OUTDR PLANTS		ORG VEGETBLE FRTNG		RYEGRAS FOR/FOD	
N-OUTDR TRANSPL		ORG-N-GRNHS TRANSPT		TURF/SOD	
OP-PINE TREE		OTHER		ORG RICE	Rice
ORG ARUGULA		OT-ROSE		RICE	
ORG ASPARAGUS		PEAS		WILD RICE	
ORG BOK CHOY LSE LF		PEPPER FRUIT SD		SAFFLOWER	Safflower
ORG BROCCOLI		PEPPER FRUITNG		BANANA	Subtropical Orchards
ORG CABBAGE		PEPPER SPICE		CITRUS	
ORG CARROT		POTAT		GRAPEFRUIT	
ORG CAULIFLOWER		POTATO		KIWI	
ORG COLLARD		RADISH		LEMON	
ORG DAIKON		RADISH SEED		OLIVE	
ORG FENNEL		SPICE		ORANGE	
ORG KALE		SPINACH		ORG POMEGRANATE	
ORG LETTUCE LEAF		STRAWBERRY		BEET	Sugarbeets
ORG LETTUCE LEAF		SWEET BASIL		BEETS	
ORG PEAS		SWISS CHARD		ORG BEET	
ORG PEPPER FRUITING		TURNIP		ORG TOMATO	Tomatoes
ORG PEPPERS		TURNIP SEED		ORG TOMATO PROCESSING	
ORG RADICCHIO		VEGETABLE		TOMATILLO	
ORG RADISH		VEGETABLE FRTG		TOMATO	
ORG RADISH		VEGETABLE ROOT		TOMATO PROCESS	
ORG RADISH		WINTER		TOMATO SEED	
ORG SPICE/HERB		GRASS SEED	Pasture	GRAPE	Vine
ORG SPICE/HERB		OP-TURF		ORG GRAPE	
ORG SPINACH		ORCHARDGRASS		OT-VINE	
				WINE	

Beyond developing the crop lookup table, the county crop dataset required some additional cleaning before use. First, some polygons were assigned multiple county crop types. Second, there were many overlapping polygons.

Steps for addressing multiple county crop categories for one polygon

In some cases, single polygons from the County Crop dataset were assigned multiple crop types. The following steps were followed to reassign these areas one single WEAP crop category.

With each unique multicrop entry, each individual entry was separated out and mapped to a WEAP category using Table B 3.

Example:

County Multicrop	**WEAP Crop 1**	**WEAP Crop 2**	**WEAP Crop 3**	**WEAP Crop 4**
ALMOND, SOIL FUM/PREPLT	Almond and Pistachio	Delete		
CANTALOUPE, SOIL FUM/PREPLT, CUCUMBER SEED	Cucurbits	Delete	Cucurbits	
CABBAGE SEED, BARLEY FOR/FOD, CARROT SEED, UNCULTIVATED AG	Other truck	Grain	Other truck	Delete

1. Non-crop entries, ie “UNCULTIVATED AG”, or “SOIL FUM/PREPLT” which, based on the lookup table mapped to “N/A” were deleted.

   Example:

County Multicrop	**WEAP Crop 1**	**WEAP Crop 2**	**WEAP Crop 3**	**WEAP Crop 4**
ALMOND, SOIL FUM/PREPLT	Almond and Pistachio			
CANTALOUPE, SOIL FUM/PREPLT, CUCUMBER SEED	Cucurbits		Cucurbits	
CABBAGE SEED, BARLEY FOR/FOD, CARROT SEED, UNCULTIVATED AG	Other truck	Grain	Other truck	

2. If the above steps resulted in a single WEAP category, this was the final WEAP category (first example, below). If all remaining WEAP categories were the same, this was the resulting WEAP category (second example, below). If the remaining WEAP categories were different, the final WEAP category was considered “Multicrop” (third example, below). However, if a tree crop and an annual crop were combined in the county’s designation, this was categorized based on the tree crop and was not classified as “multicrop” (fourth example, below). If a county category had multiple trees and/or multiple other crops listed with a tree crop, the WEAP category “multicrop” was designated.

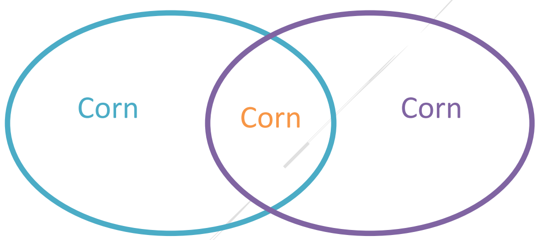
Example:

County Multicrop	Final WEAP Crop
ALMOND, SOIL FUM/PREPLT	Almond and Pistachio
CANTALOUPE, SOIL FUM/PREPLT, CUCUMBER SEED	Cucurbits
CABBAGE SEED, BARLEY FOR/FOD, CARROT SEED, UNCULTIVATED AG	Multicrop
ALMOND, WHEAT FOR FOD	Almond and Pistachio

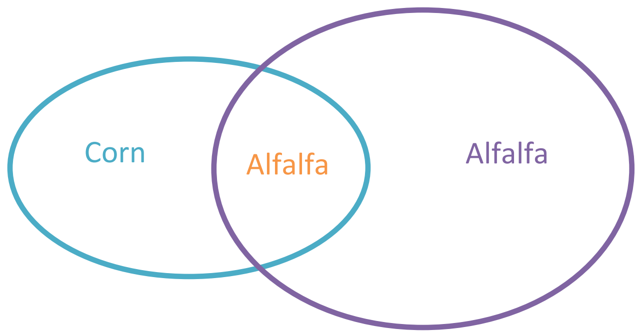
Steps for addressing overlaps in County Crop dataset

In some cases, two or more polygons from the County Crop dataset had overlapping areas. To eliminate these overlaps, the following steps were followed:

1. Every polygon in each County Crop shapefile was mapped to a WEAP Crop category (using the methods outlined above)
2. Polygons with “N/A” and blank WEAP Crop categories (blank occurred when the original County Crop was blank) were deleted from the shapefile
3. A shapefile of the intersecting areas was developed, and those areas were mapped to a single WEAP_Crop:
    a. If two overlapping polygons had the same WEAP Crop, this was the single WEAP Crop assigned to the intersecting area.



    b. If the two overlapping polygons had different WEAP Crop types, the single WEAP Crop for the intersecting area is the same as the original polygon with the largest area.



4. The shapefile of intersections was clipped from the County Crop shapefile and then combined with the clipped County Crop file to generate one shapefile, with intersecting areas as their own individual polygons.
5. If some intersections still occurred after this process, the intersecting areas were clipped out of the polygon and were not replaced.

Even after cleaning, there is still some uncertainty with this dataset that could not be resolved at the time of this analysis, such as whether the PUR data includes lands on which no pesticides were used which may exclude some areas that may have the correct crop type. However, the dataset was deemed sufficient for use in this analysis with the understanding that it may represent an underestimation of the total crop coverage in the county. Once every polygon in the data set was assigned a single WEAP crop, and not overlapping with any other polygon, it was used to select the areas that would receive the rainfall capture management strategy. This methodology is outlined in Chapter 4 in the main body of the document.

Climate data

Apart from the reorganization of the valley floor catchments, the other major change in the model from its version in Mehta et al., (2013) was an update on climate data. Because the valley floor catchments are simulated using the MABIA method, which generates daily outputs, the model requires daily input data for these catchments. Although the Cache Creek upper watershed catchments remained operating at the monthly time step with WEAP's rainfall runoff method, so that all data in the model were from the same source, the climate data for these catchments were also updated. Climate data were downloaded from PRISM[27] and incorporated into the model as shown in Table B 4.

[27] http://www.prism.oregonstate.edu/explorer/

Table B 4. PRISM Climate data for corresponding catchments

	Time Step	Variables downloaded*	Duration available	Derived variables*	Download date
Cache Creek Upstream Catchments	Monthly	P, T_{avg}, T_{dew}	1/1/1949-03/1/2017	RH_{avg}	4/16/2017
Valley Floor catchments	Daily	P, T_{min}, T_{max},VPD_{min}, VPD_{max}	1/1/1981-6/5/2017	RH_{max}, RH_{min}	6/6/2017

P = precipitation (mm); T_{avg}=Average temperature (°C); T_{dew}=dewpoint temperature (°C); Tmin=minimum temperature (°C); T_{max}=Maximum temperature (°C); RH=average relative humidity (%); RH_{max}=Maximum relative humidity (%); RH_{min}=minimum relative humidity (%); VPD_{min}=minimum Vapor pressure deficit (hPa); VPD_{max}=maximum vapor pressure deficit (hPa).

Relative humidity for Cache Creek upstream catchments was calculated as:

$$RH = \frac{e_a}{e_s}$$

Where:

E_a (Pa)= vapor pressure at dew point temperature T(°C):

$$e_a = 0.6108^{\frac{17.27*T_{dew}}{T_{dew}+237.3}}$$

Es=saturation vapor pressure at ambient temperature T(°C):

$$e_s = 0.6108^{\frac{17.27}{T+237.3}}$$

Relative humidity for valley floor catchments was calculated as:

$$RH = 100 - (100 * \frac{VPD}{SVP})$$

Calibration

The model was calibrated for solar radiation, reference evapotranspiration (ET), actual ET, applied water, streamflows in Cache Creek at various points and reservoir volume in Clear Lake and Indian Valley reservoirs. Table B 5 below shows the data sources and period for each calibration. Calibration for solar radiation, and ET are most relevant for this analysis, and therefore are discussed in detail below. Other calibration metrics are shown but not discussed in detail.

Table B 5. Calibration field and datasets

Type	Subtype	Location	Period	Data source
Catchment water balance	Streamflow	Hough Springs	Oct 1976-Sept 2008, monthly	USGS: https://waterdata.usgs.gov/ca/nwis/uv?11451100
Catchment water balance	Streamflow	Kelsey Creek	Oct 1976-Sept 2008, monthly	USGS: https://waterdata.usgs.gov/ca/nwis/uv?11449500
Catchment water balance	Streamflow	Cache Creek at Yolo	Oct 1974- Sept 2009, monthly	USGS: https://waterdata.usgs.gov/nwis/uv?site_no=11452500
Catchment water balance	Reference ET (ETo)	Davis CIMIS station	Available and downloaded: Aug 1982 to July 2017, monthly timestep	CIMIS: http://www.cimis.water.ca.gov/WSNReportCriteria.aspx Downloaded on 8/28/2017
Catchment water balance	Applied Water	DWR water portfolio, at Detailed Analysis Unit (DAU) resolution	Available and downloaded: 1998-2010, annual timestep	DWR Land and Water Use http://www.water.ca.gov/landwateruse/anlwuest.cfm
Operations	Reservoir Levels	Clear Lake and Indian Valley	1974-2009, monthly timestep	YCFC, personal communication, 2015

Solar Radiation and Reference ET

Modeled Solar radiation and reference ET were compared against CIMIS downloaded data from the Davis CIMIS station. Average monthly modeled and CIMIS solar radiation values are shown in the following tables and figures (Solar radiation: Table B 6 and Figure B 6, reference ET: Table B 7, Figure B 7) for water years 1983-2015.

Table B 6. Monthly average solar radiation (WY 1983-WY-2015)

Month	Modeled S (W/m^2)	CIMIS S (W/m^2)	Diff (Model-CIMIS), (W/m^2)
Jan	91	80	11
Feb	128	124	4
Mar	181	183	-2
Apr	245	250	-5
May	295	294	1
Jun	325	328	-3
Jul	333	330	3
Aug	301	298	3
Sep	242	238	3
Oct	169	168	1
Nov	109	103	6
Dec	82	72	10

Figure B 6. Monthly average solar radiation (WY 1983-WY-2015)

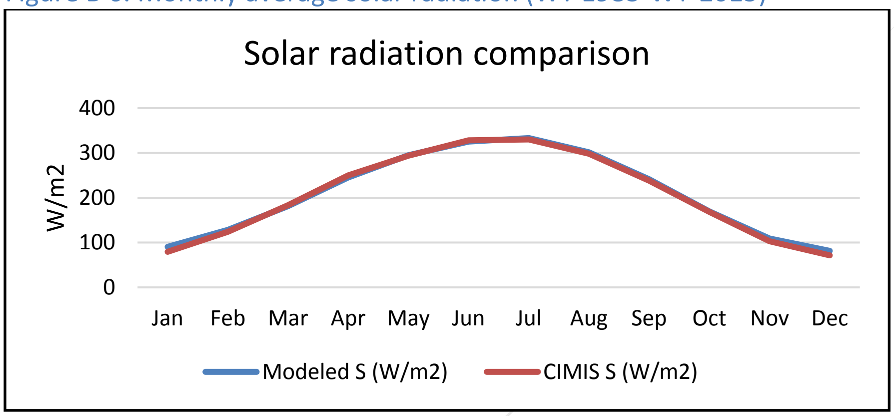
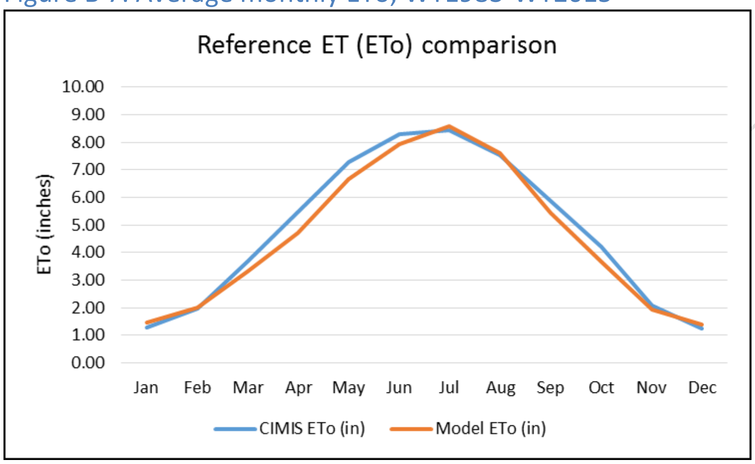


Table B 7. Average monthly Reference ET (ETo) WY 1983-2015

Month	CIMIS ET_o (in)	Model ET_o (in)	Percent Difference
Jan	1.27	1.48	16.54
Feb	1.96	2.01	2.55
Mar	3.69	3.30	-10.57
Apr	5.46	4.71	-13.74
May	7.27	6.68	-8.12
Jun	8.30	7.95	-4.22
Jul	8.45	8.60	1.78
Aug	7.53	7.60	0.93
Sep	5.86	5.46	-6.83
Oct	4.21	3.66	-13.06
Nov	2.08	1.95	-6.25
Dec	1.26	1.38	9.52
Total	**57.34**	**54.77**	**-4.48**

Figure B 7. Average monthly ETo, WY1983-WY2015



Actual ET

To calculate actual ET, WEAP uses a dual crop coefficient (k_c) model, one k_c for bare soil evaporation and one for crop ET. The k_c values for the crop ET, called k_{cb} in WEAP, were developed based on the Sacramento San Joaquin Basin Study (Basin Study)[28], which uses a single crop coefficient model, where bare soil evaporation and crop ET are calculated based on a single k_c value. In the WEAP Crop library, we began with k_c values and growth period lengths for the initial, development and late stage growth periods from the Basin Study (Table B 8), but most had to be adjusted due to the differing model types. Actual ET for each WEAP Crop,

[28] Available at: https://www.usbr.gov/watersmart/bsp/docs/finalreport/sacramento-sj/Sacramento_SanJoaquin_TechnicalReport.pdf

calculated as the monthly total, averaged over the catchments included in the Lower Cache Creek DAU (Figure B 8) from the year 2005, was compared to total monthly ET from the Basin Study for the corresponding crops. In WEAP, the k_{cb} values were adjusted until the total ET from WEAP during the irrigation season was within 3% difference of the same value from the basin study. For tomato, grain and other truck, only adjusting k_{cb} was not sufficient, and therefore the length of the growth periods was also adjusted (Table B 8). For other truck, cucumber was selected as the representative crop, but significant adjustments had to be made from the initial cucumber values to achieve similar ET values (see cucumber/other truck in Table B 8 and Figure B 9). The final k_{cb} and growth stage lengths are shown in Table B 8 and Figure B 9 compared to the Basin Model.

Even with additional adjustments, grain actual ET could only be calibrated within a 5% difference from the Basin Model (Table B 9). This due to the difference in June between the two models (Figure B 9, grain), which is likely occurring due to discrepancy over whether precipitation occurred in that month. Precipitation occurs on some days in the WEAP model which is a result of the gridded climate data, but was not registered at the CIMIS station in Davis despite being overcast on those same days. Because grain does not grow during the main growing season, is not typically irrigated, and covers a small area in Yolo County, it has a small impact on the water budget and therefore we did not adjust further to improve actual ET.

For some crops, k_{cb} and stage length adjustments were not sufficient to calibrate actual ET. For alfalfa and pasture, the "fraction covered" variable in WEAP, the fraction of the ground covered by the crop, was set to 1 for the entire year. The irrigation schedule was adjusted for safflower to stop irrigation on July 15, even though harvest occurs on July 31, based on the literature which states that safflower is minimally irrigated, sometimes only once a season, and irrigation could be stopped as early as May.[29] The final ET from the WEAP model incorporating all adjustments and Basin Study for each crop are shown in Table B 9 and Figure B 10.

[29] https://coststudyfiles.ucdavis.edu/uploads/cs_public/63/a9/63a948b0-8cef-4843-b66c-ac27006f726f/safflowersv2011.pdf

Figure B 8. Map of Lower Cache Creek DAU (outlined in black) and WEAP catchments compared with the DAU data to calibrate applied water (colored).

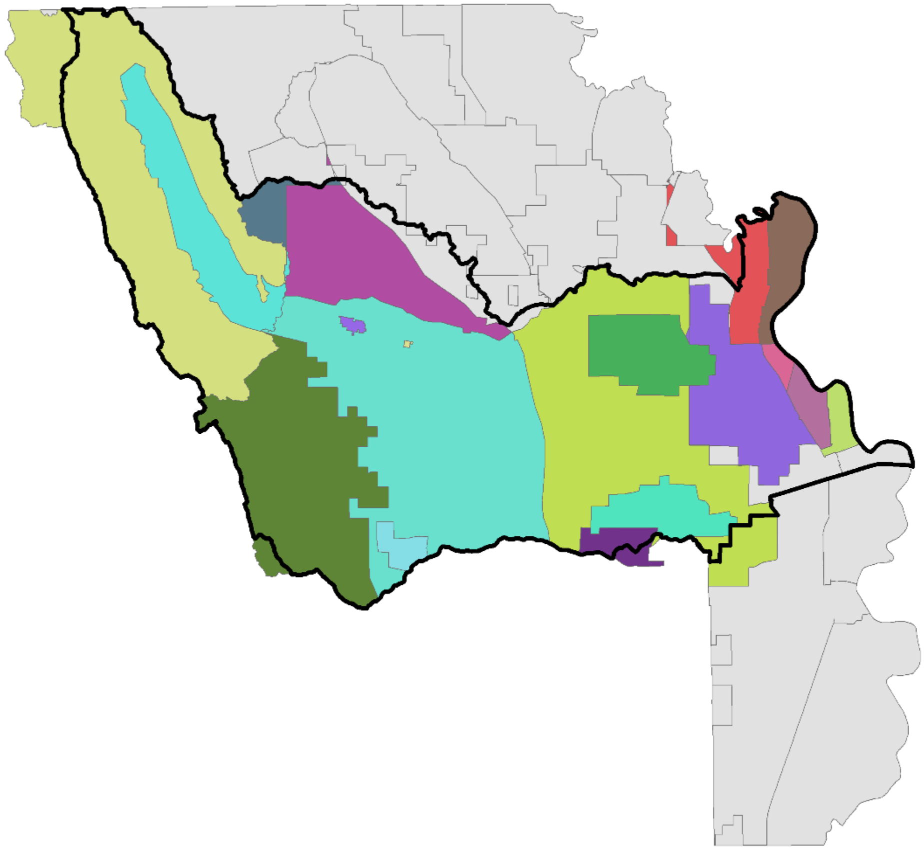


Table B 8. Growth stage length and kc values from the Basin Study and the WEAP model

Basin Study								WEAP model								Both models	
Crop name	Stage length (days)				Crop Coefficients			Crop Name	Stage length (days)				Crop Coefficients			Plant Date	Tot
	Init	Dev	Mid	Late	K_c ini	K_c mid	K_c end		Init	Dev	Mid	Late	K_{cb} ini	K_{cb} mid	K_{cb} end		
Alfalfa	91	91	91	91	1	1	1	**Alfalfa**	91	92	91	91	0.9	0.9	0.9	1-Jan	365
Almonds[1]	0	115	92	23	0.55	1.2	0.65	**Almonds**	0	115	91	23	0.4	0.95	0.65	1-Mar	229
Apple	0	115	57	57	0.55	1.15	0.8	**Other Deciduous**	0	115	57	57	0.6	0.95	0.85	1-Apr	229
Corn (grain)	31	38	46	38	0.2	1.05	0.6	**Corn**	31	38	46	38	0.12	0.85	0.52	1-May	153
Corn (silage)	21	27	59	0	0.2	1.05	1	**Other Field**	21	27	59	0	0.15	0.85	0.85	1-May	107
Cucumber	18	26	35	14	0.8	1	0.75	**Other Truck**	21	30	40	17	0.15	0.4	0.3	15-May	93
Melon[2]	26	36	41	21	0.75	1.05	0.75	**Cucurbits**	26	36	40	21	0.15	0.7	0.15	15-May	123
Pasture	91	91	91	91	0.95	0.95	0.95	**Pasture**	91	92	91	91	0.9	0.9	0.9	1-Jan	365
Rice	33	18	68	19	1.2	1.05	0.8	**Rice**	33	18	69	19	1.16	0.9	0.9	15-May	139
Safflower	21	34	43	24	0.2	1.05	0.25	**Safflower**	21	34	43	24	0.15	0.85	0.25	1-Apr	122
Tomato	38	38	46	31	0.2	1.2	0.6	**Tomato**	48	39	45	21	0.05	0.85	0.35	1-Apr	153
Wheat	53	74	64	21	0.3	1.05	0.15	**Grain**	53	79	39	41	0.05	0.7	0.05	1-Nov	212
Wine grapes	0	54	108	54	0.45	0.8	0.35	**Vine**	0	54	107	54	0.15	0.65	0.3	1-Apr	215

[1] Mid-season crop coefficients for almonds and other tree crops may vary between 0.90 – 1.15 depending on whether a cover crop is present.

[2] The growing season for melons was revised from 229 days given in CUP to 123 days.

Figure B 9. Growth stage length and kc values from the Basin Study and the WEAP model

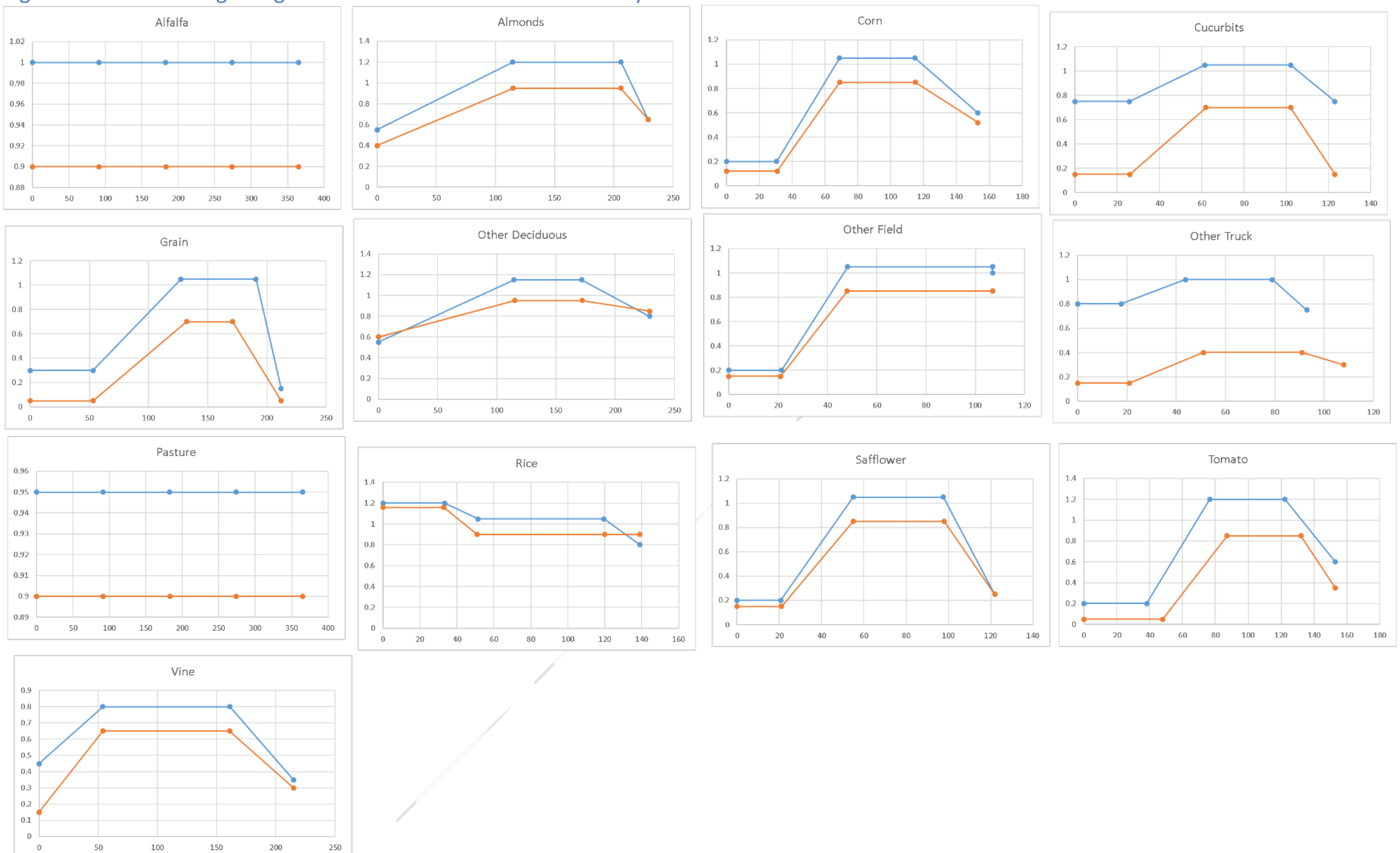


Figure B 10. Actual ET comparisons between the Basin study, the WEAP model and C2VSim

Table B 9. WEAP and Basin Study actual ET

	Irrigation Season	BasinStudy Actual ET (in)	WEAP Actual ET (in)	Percent Difference
Alfalfa	Apr-Sep	36.9	36.3	-1.5
Almond	March-Oct	47.2	47.1	-0.1
Oth Dec	Apr-Nov	43.5	44.4	2.0
Corn	May-Sep	28.2	27.5	-2.6
Oth Fld	May-Aug	22.9	22.8	-0.6
Oth Trk	May-Aug	19.7	19.8	0.7
Cucurb	May-Sep	23.0	22.6	-1.5
Pasture	Apr-Sep	35.3	35.9	1.7
Rice	May-Sep	33.9	33.6	-0.8
Safflwr	Apr-Jul	20.2	20.1	-0.7
Tomato	Apr-Aug	27.9	28.4	1.8
Vine	Apr-Nov	32.2	32.7	1.6
Grain	Nov-May	16.0	16.6	3.8

Applied Water

The applied water in the model was calibrated to DWR's applied water data (Table B 5) for the Detailed Analysis Unit titled "Lower Cache Creek" (Figure B 8). Average annual applied water was calculated over 1998-2010 in af/ac for all crops that existed in those years. For other crops, only the years where those crops existed in both models were averaged.[30] Each crop was compared between the WEAP calculated values and the DWR DAU values. Where applied water did not match between the WEAP model and DWR reported values, the irrigation efficiency for each crop was adjusted until the average was within 0.05 af/ac and 2% difference of the DWR reported values for all crops except rice and safflower. For rice, the variable "release requirement" was adjusted to calibrate applied water to the standards stated above. The final irrigation efficiencies and applied water for the Lower Cache Creek DAU, WEAP model, percent difference between them, and other nearby DAU's is shown in Table B 10, Figure B 11 and Figure B 12.

[30] For most crops, the average is calculated as annual applied water averaged over 1998-2010. Although cotton exists in the DAU dataset, there was no area within the WEAP model with cotton and therefore it is not included. Dry beans are only compared for year 1998 because it is the only year in the model with dry beans. Other truck in the WEAP model is compared to the average of other truck and onions and garlic in the DWR data. Sugar beet applied water was only averaged over 1998-2000 because these are the only years in both data sets with sugar beet plantings. Average applied water on tomatoes in the WEAP model are compared with the average of fr and pr tomato categories in the DWR data.

Table B 10. Comparison of average applied water from DWR DAU's and WEAP for each crop.

Crop	Irrigation Efficiency	WEAP Applied Water	Lower Cache Creek DAU Applied Water	Percent Difference	Sacramento DAU Applied Water	Vacaville DAU Applied Water	Willows Arbuckle DAU Applied Water
Alfalfa	57	5.20	5.29	-1.74	5.93	5.18	4.59
Almond	82	4.01	4.10	-2.11		3.82	3.26
Corn	68	2.91	2.99	-2.74	3.08	2.95	2.57
Cucurb	88	1.88	1.83	2.49	1.96	1.82	1.39
DryBean	83	1.95	1.91	1.84		2.55	2.05
Grain	36	1.15	1.16	-1.21	1.27	1.1	0.92
Oth Dec	76	4.14	4.12	0.62	3.91	3.89	3.26
Oth Fld	62	2.58	2.58	0.12	2.46	2.53	2.16
Oth Trk	50	2.83	2.88	-1.99	3	2.97	2.41
Pasture	52	5.68	5.77	-1.66	5.79	5.65	4.76
Rice	2*	5.51	5.52	-0.18			5.12
Safflwr	100	1.24	0.90	27.70	0.89	0.82	0.89
SgrBeet	72	4.00	4.02	-0.49	4.02	3.97	3.04
Subtrop	85	3.37	3.30	2.16	3.74	3.39	2.54
Tomato	70	2.92	2.98	-2.09		3.01	2.715
Vine	100	2.21	1.59	27.92	1.77	1.49	1.88

*This value is the release requirement in flooding, in millimeters. This is the value that was adjusted in calibration for rice rather than irrigation efficiency

Figure B 11. Comparison of average applied water from Lower Cache Creek DAUE and average irrigation from WEAP for each

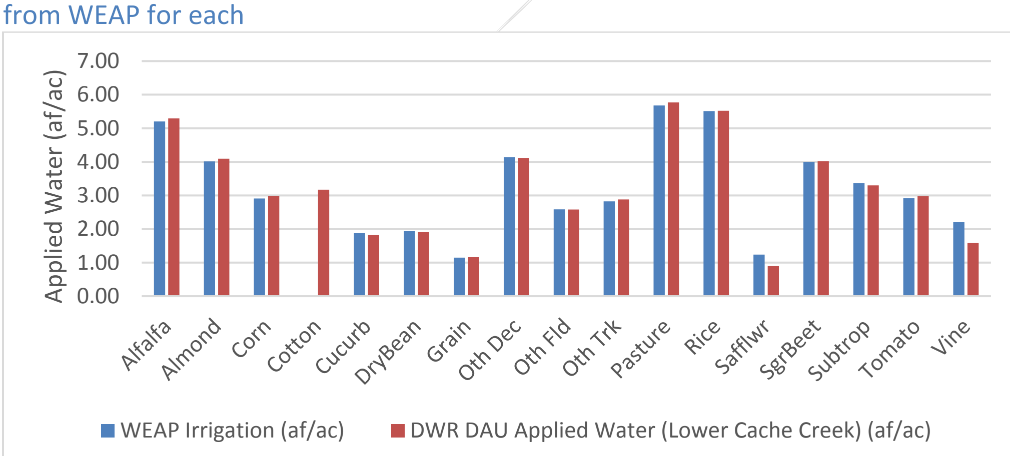
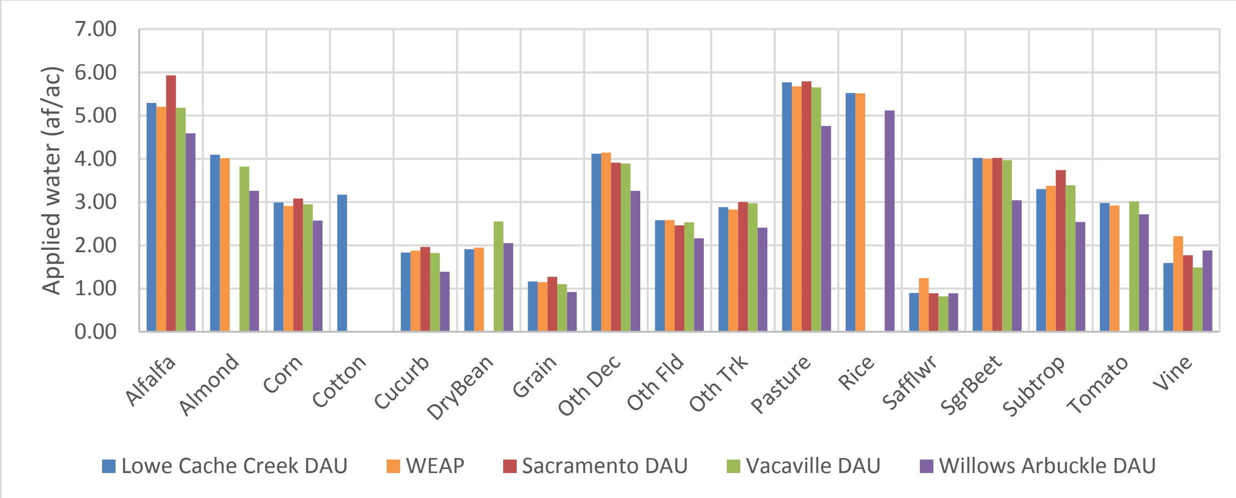


Figure B 12. Comparison of average applied water from nearby DAUs and WEAP for each crop.



Streamflows

Streamflows in North Fork of Cache Creek and Kelsey Springs, the tributaries to Indian Valley Reservoir and Clear Lake, respectively, which have USGS stream gauges, were calibrated in the model by adjusting soil parameters in the catchments which runoff into these creeks. Cache Creek downstream, at Yolo, was also calibrated by adjusting reservoir outflows and soil parameters in the corresponding catchments. Calibration statistics are shown in Table B 11 and the observed and modeled streamflows for each creek are shown inFigure B 13, Figure B 14 and Figure B 15.

Table B 11. Calibration statistics for streamflows, compared to USGS gauges.

	Kelsey Creek	North Fork Cache Creek	Cache Creek
NSE	0.89	0.82	0.81
RMSE (AF)	2,592	5,609	40,247
PBias (%)	-5	-13	-13
Calibration period	Oct 1976-Sept 2008, monthly	Oct 1976-Sept 2008, monthly	Oct 1974- September 2009, monthly

Figure B 13. Observed and modeled streamflow in Cache Creek at Yolo

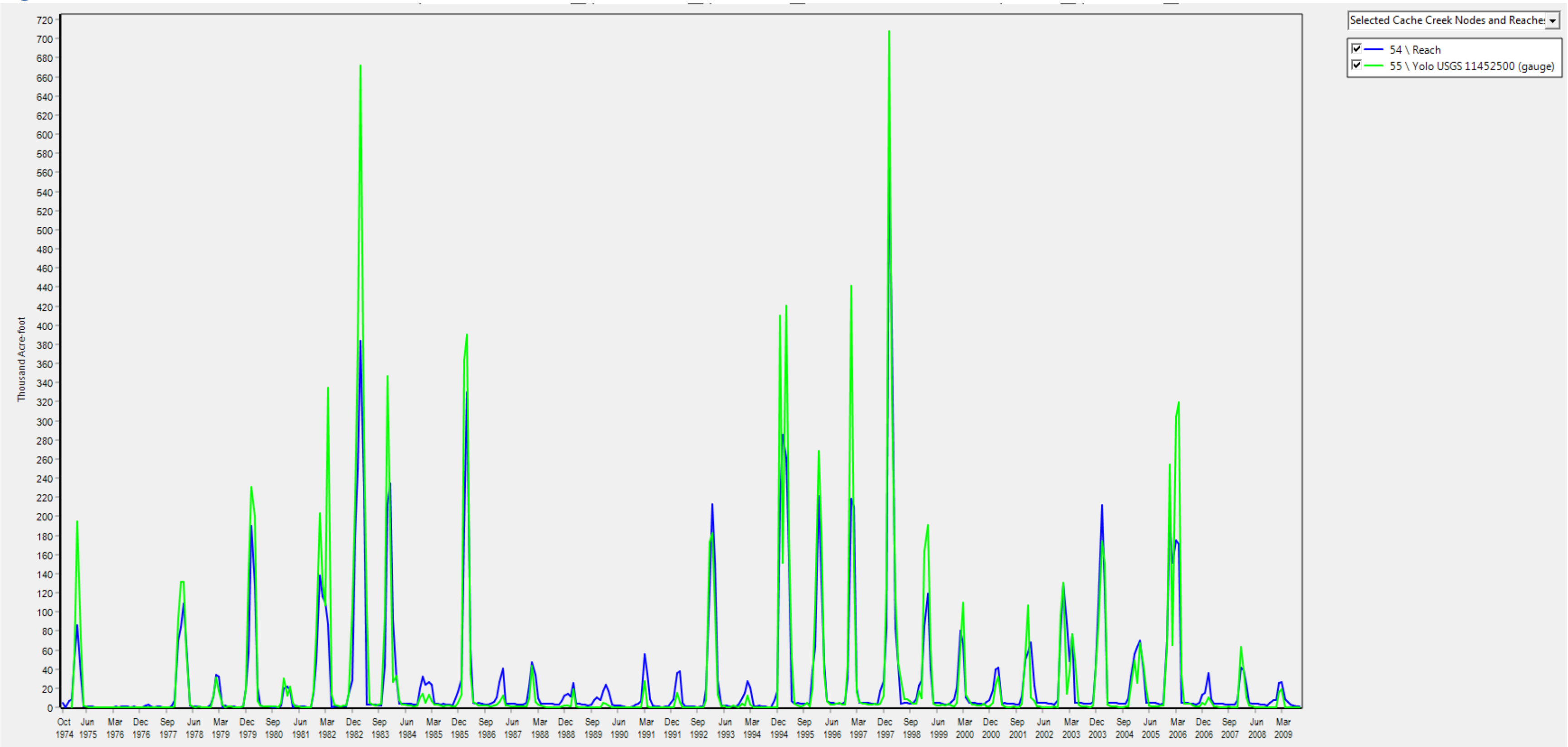


Figure B 14. Observed and modeled streamflow in Kelsey Creek

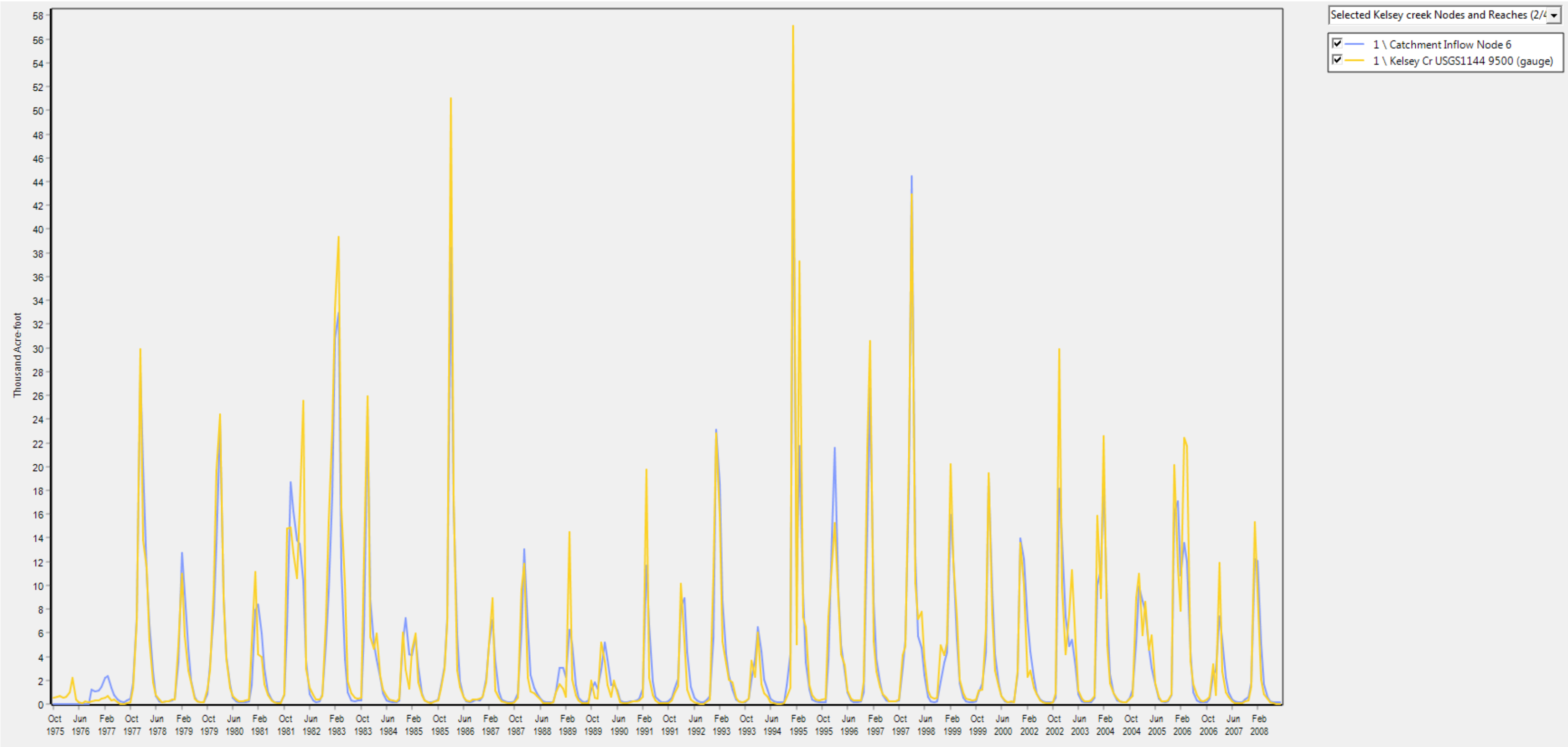
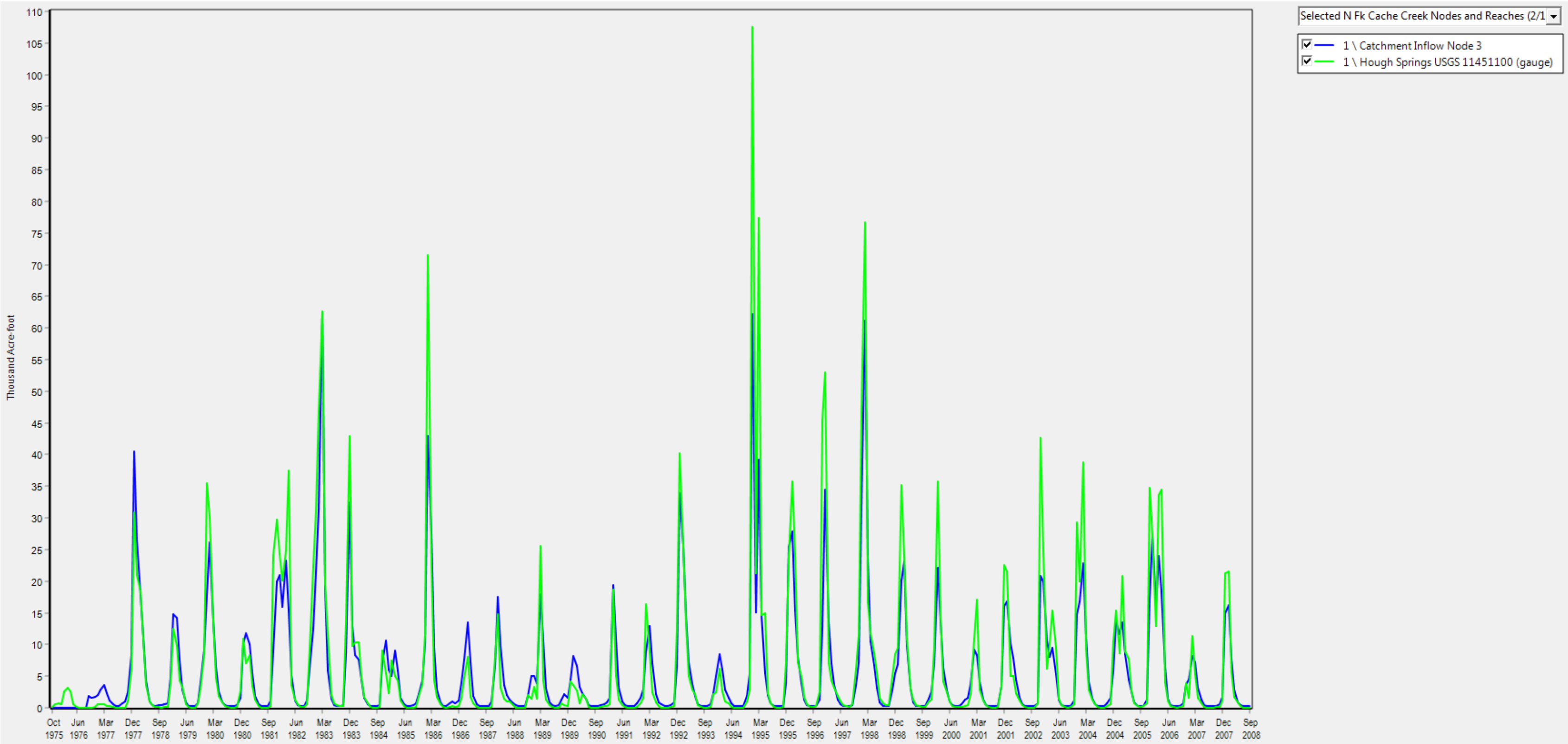


Figure B 15. Observed and modeled streamflow in the North Fork of Cache Creek at Hough Springs



Reservoir Volumes

After streamflows upstream of Clear Lake and Indian Valley were calibrated, the reservoirs were calibrated by adjusting reservoir operating rules which deliver water to the YCFC catchments. Those rules and calibration methods are described in detail in Mehta et al., 2013 and were not further adjusted in this version of the model. The resulting statistics for the two reservoirs are shown in Table B 12 and the modeled and observed volumes are shown in Figure B 16 and Figure B 17.

Table B 12. Calibration statistics for the two reservoirs in the model

	Clear Lake	**Indian Valley**
NSE	0.91	0.89
RMSE (AF)	32,937	31,001
PBias (%)	-1.4	-2.4
Calibration period	Water Year 1974-2010 (monthly)	Oct 1975- May 2010 (monthly)

Figure B 16. Clear Lake observed and modeled volumes.

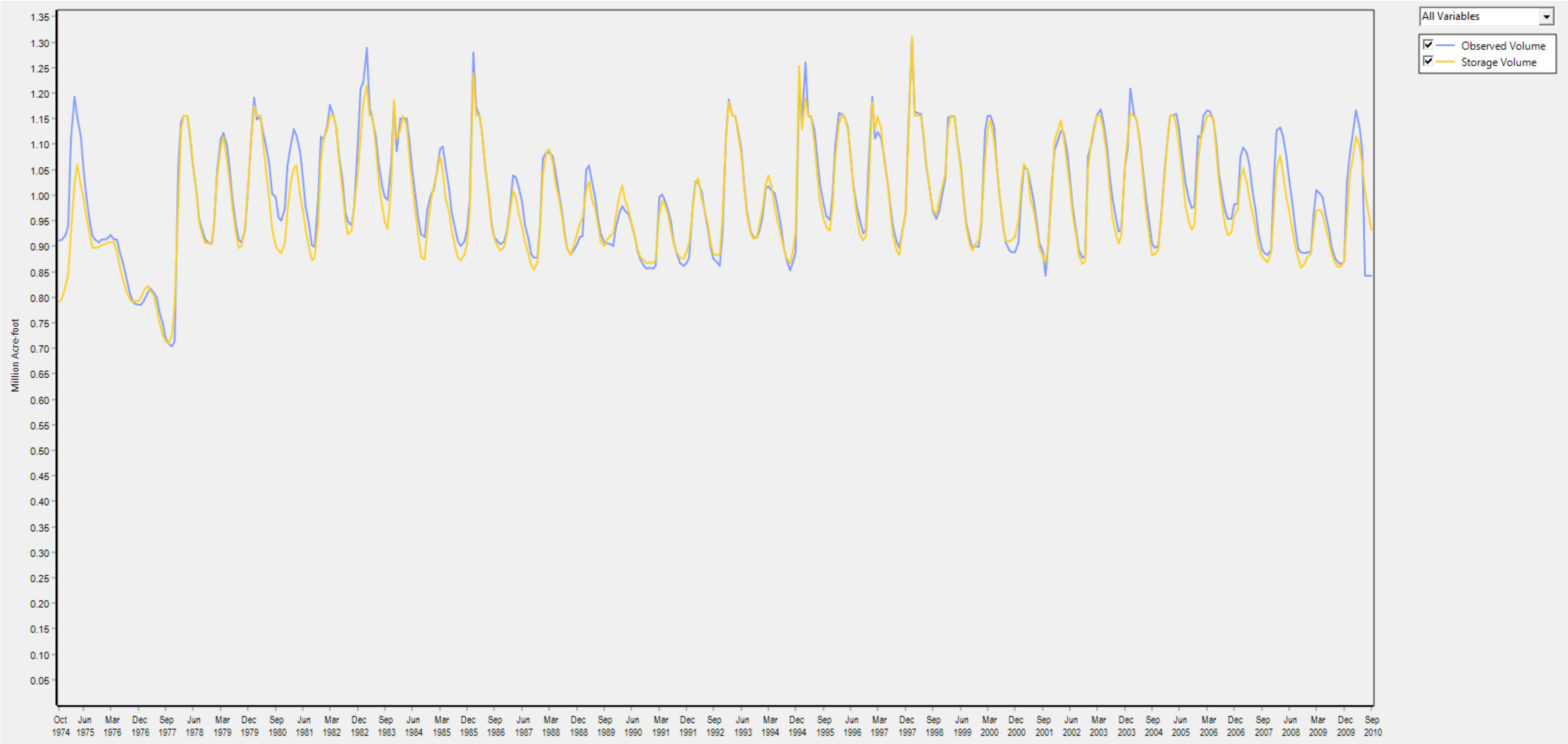


Figure B 17. Indian Valley Reservoir observed and modeled volumes

Appendix C. Justification for modifications from original scope of work

For various reasons, the work presented in this document is a slight modification from what was originally proposed in our scope of work. This appendix lays out the modifications and rationale for them.

Original scope of work:

"The SWRP will include an expansion of the WEAP model by SEI for the entire planning area and investigate the impacts of existing and potential new storm water management strategies, of water purveyors within this expanded area plus [Yolo County Flood Control and Water Conservation District] that will address the following questions:

- *What are the opportunities for co-benefits of augmented groundwater recharge with storm water and the resulting increased summer irrigation water availability?*
- *What do individual recharge plans mean at a collective scale for the planning area/county?*
- *How will this improve the water system resiliency in the face of climate change/variability?*

Once the WEAP model is updated, it is anticipated that the above questions will be answered by the model outputs: groundwater recharge volume, groundwater quality impacts/improvements, water supply availability for agricultural irrigation, and financial impacts."

As the main text of the report describes, SEI modified an existing WEAP model for the entire planning area, dividing it into 38 catchments, plus the upstream Cache Creek watershed (modifications from the Cache Creek Model to the Yolo Storm Water Model, Table 1.1). SEI then used both the Cache Creek Model and the Yolo Storm Water Model for two for the analyses presented in this report in Chapter 3 and Chapter 4. In Chapter 3, we investigated the runoff and groundwater recharge trade-offs of canal operation from diverting Cache Creek winter flows into Yolo County Flood Control and Water Conservation District's unlined canal system. In Chapter 4, the same trade-offs were investigated in implementing a farm-field scale management of winter field runoff by imagining the construction of berms around selected fields.

In each scenario, a long historical period of 35 years was simulated, from water years 1976-2010. This period captures very dry periods (e.g. 1976/77; late 1980's) as well as wet periods, allowing us to understand the potential impacts of climate variability on water management scenarios.

As the introduction describes, over the course of the project, the project team collectively decided that the best use of the WEAP model was at the larger landscape scale, and not at the scale of individual projects, which were largely at the sub-city scale. Additionally, each projects quantitative benefits were estimated by different methods by each entity, which made it difficult to incorporate into one platform. As a result, the focus of WEAP scenarios remained at the larger scales of water management. This also meant that water quality and financial metrics could not be investigated.

Along with this decision, the project team also agreed that event-based modeling of upstream sloughs could be informative. Thus, SEI built a HEC-HMS model of slough watersheds (the Western Yolo Model, Table 1.1, an addition to the original scope of work), and also conducted three field trips in service of understanding the interplay between flows from upstream sloughs, runoff from farm fields, local drainages and canal operations. These investigations, in concert with a deeper literature review, plus the modeling described above, led to our final conclusions and recommendations.