Central Valley Refuge Management under Non-stationary Climatic and Management Conditions

Karandev Singh | Mustafa Dogan
Jay Lund | Josue Medellin-Azuara
Jon Herman | Samuel Sandoval
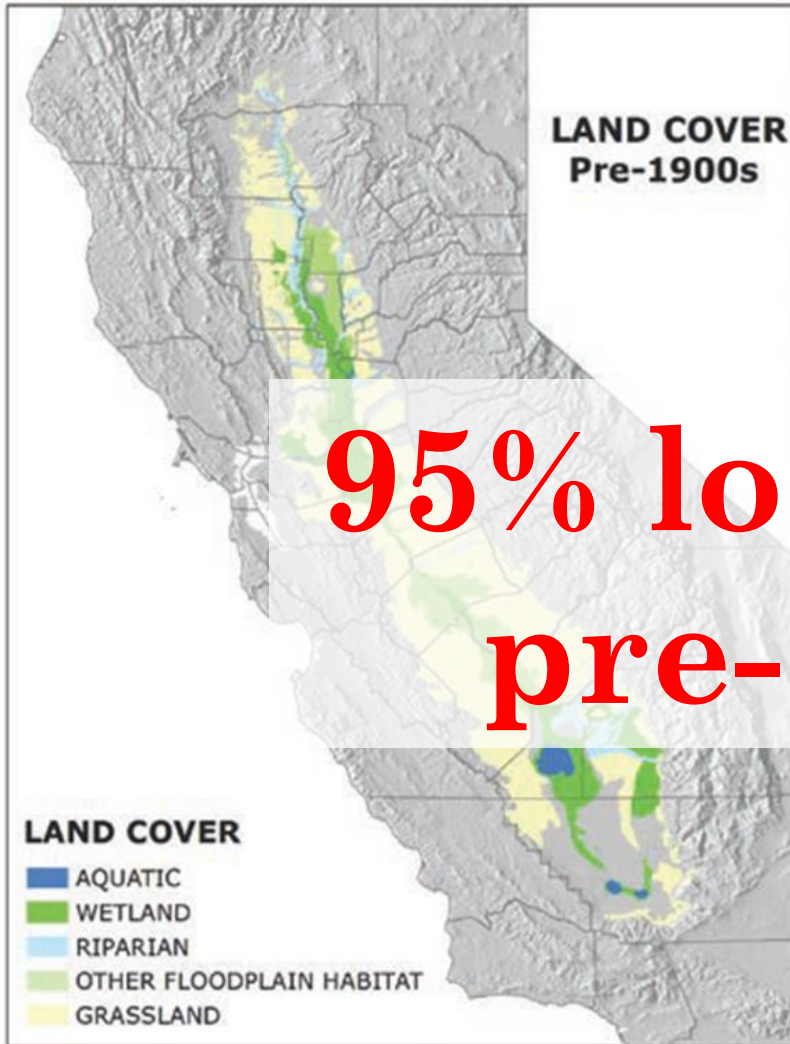Josh Viers | Jenny Ta
Rachel Esralew

California Water and Environmental Modeling Forum
April 12, 2016

60 %

migratory bird population

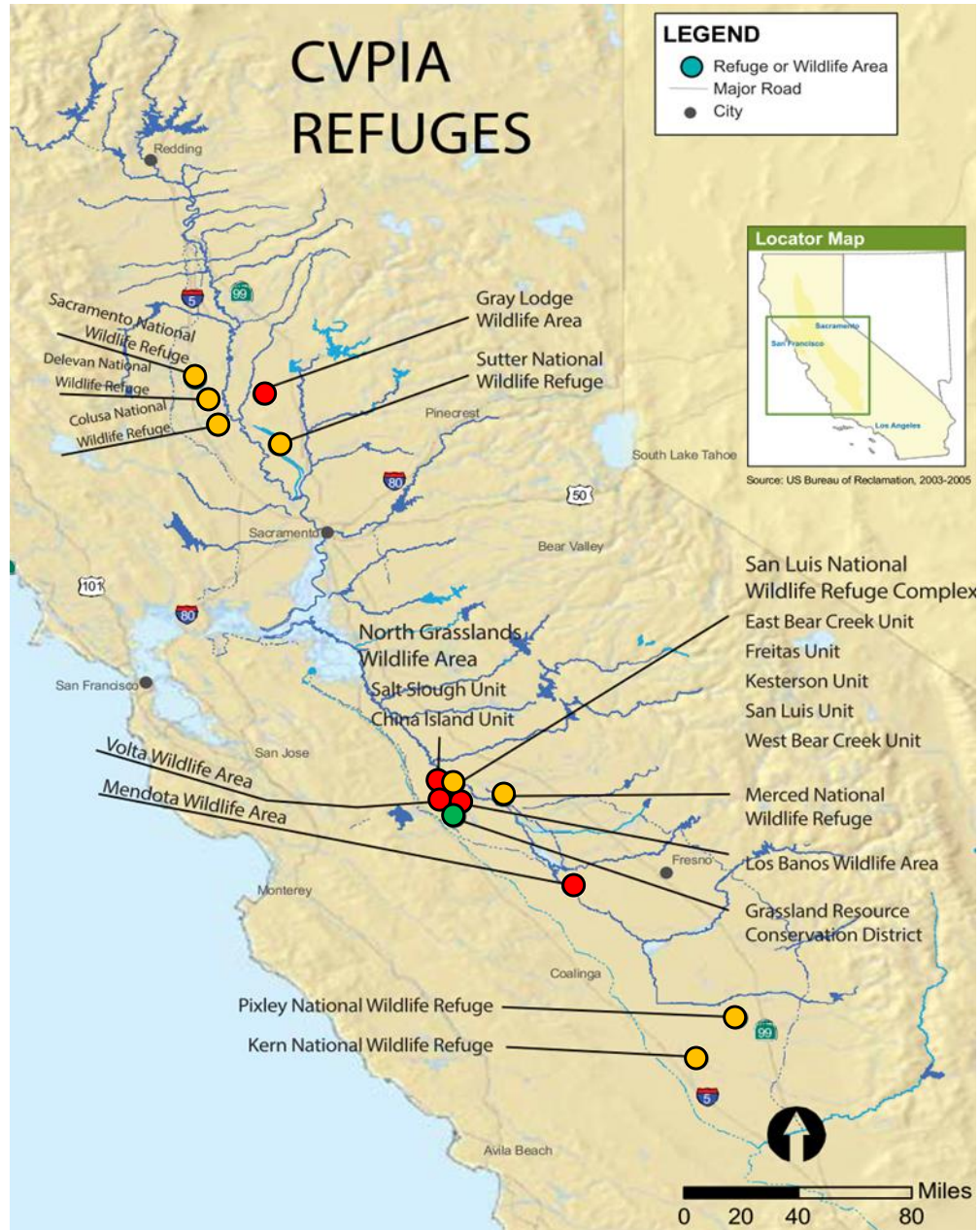**50 %**

threatened & endangered species

95% lost since pre-1900s

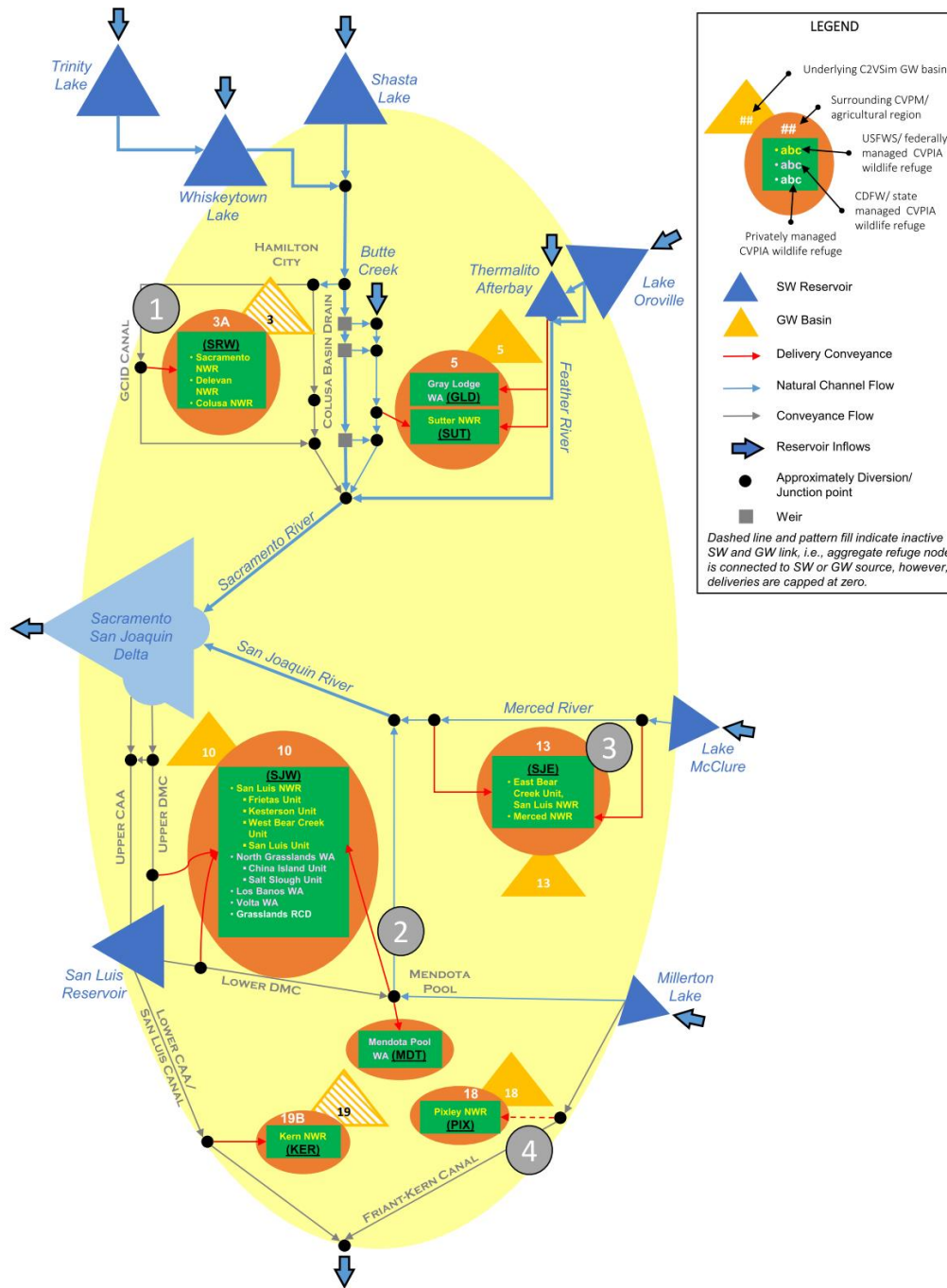**LAND COVER Pre-1900s**

LAND COVER circa 1990

LAND COVER
■ AQUATIC
■ WETLAND
■ RIPARIAN
■ OTHER FLOODPLAIN HABITAT
■ GRASSLAND

LAND COVER
■ AQUATIC
■ WETLAND
■ RIPARIAN
■ OTHER FLOODPLAIN HABITAT
■ GRASSLAND

20 – 40 million/yr

5.5 million/yr

CVPIA Refuges

- USFWS Managed

- CDFW Managed

- Privately Managed

4

LEGEND

- Underlying C2VSim GW basin
- Surrounding CVPM/ agricultural region
- USFWS/ federally managed CVPIA wildlife refuge
- CDFW/ state managed CVPIA wildlife refuge
- Privately managed CVPIA wildlife refuge

- ▲ SW Reservoir
- ▲ GW Basin
- → Delivery Conveyance
- → Natural Channel Flow
- → Conveyance Flow
- ⇒ Reservoir Inflows
- ● Approximately Diversion/ Junction point
- ■ Weir

Dashed line and pattern fill indicate inactive SW and GW link, i.e., aggregate refuge node is connected to SW or GW source, however, deliveries are capped at zero.
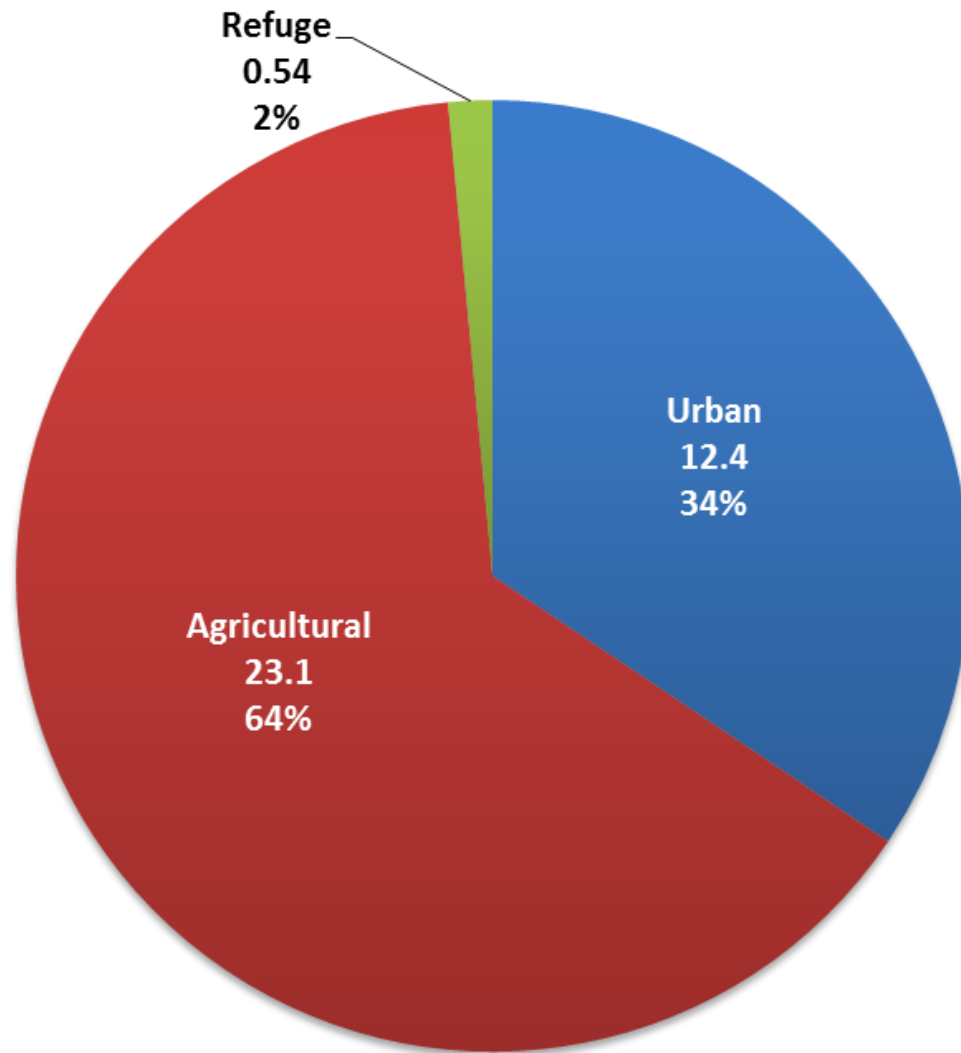
5

Level 2 vs. Incremental Level 4 Deliveries *
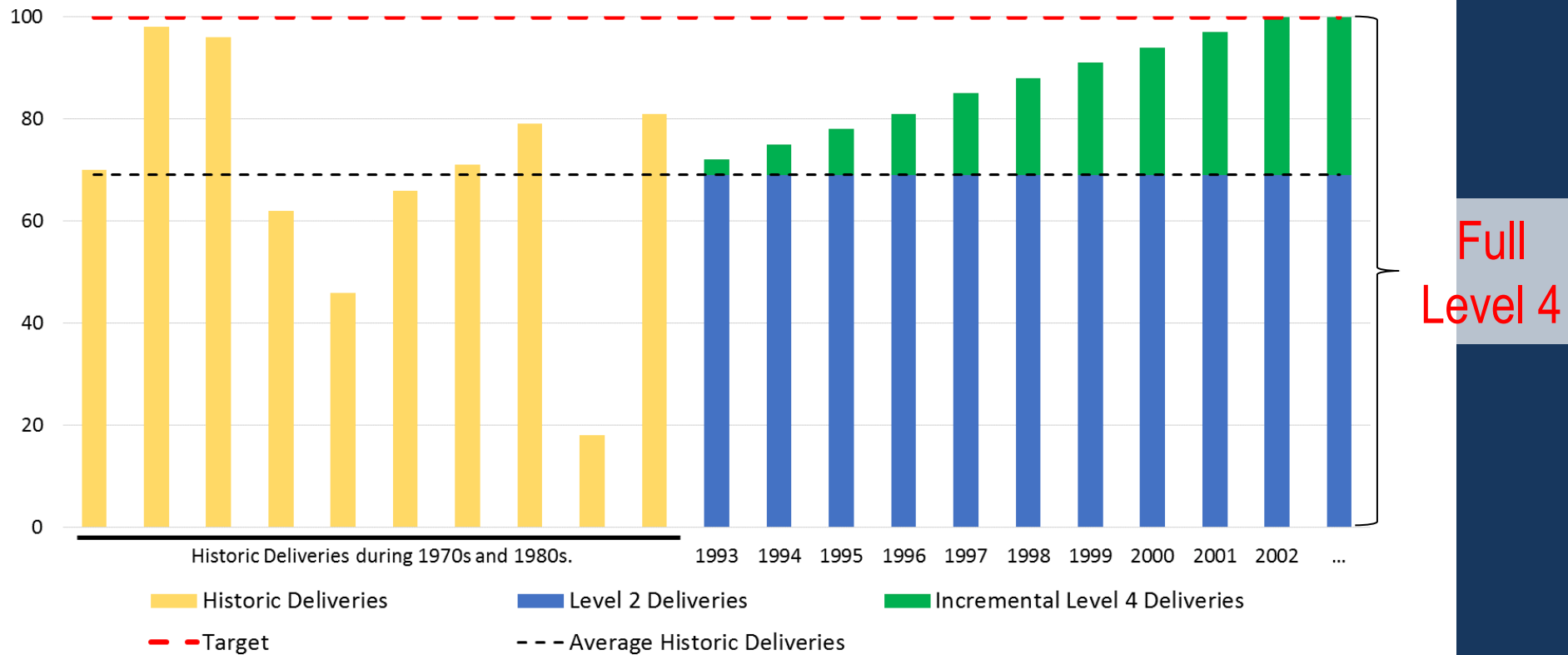
* For illustration only.

Applied Water Use (MAF/yr)

Water Year	Level 2			Incremental Level 4			Full Level 4		
	Historic [a]	Target [b]	Percent Target Delivered	Historic	Target	Percent Target Delivered	Historic	Target	Percent Target Delivered
2001[*]	354,746	423,151	84%	62,615 [c]	119,039 [c]	53%	417,361	542,190	77%
2002[*]	370,342	423,151	88%	79,400	132,265	60%	449,742	555,416	81%
2003[*]	379,146	423,151	90%	77,471	132,265	59%	456,617	555,416	82%
2004[*]	372,232	423,151	88%	66,044	132,265	50%	438,276	555,416	79%
2005[*]	374,417	423,151	88%	82,911	132,265	63%	457,328	555,416	82%
2006	380,073	423,151	90%	89,345	132,265	68%	469,418	555,416	85%
2007	388,525	423,151	92%	45,049	132,265	34%	433,574	555,416	78%
2008	398,010	423,151	94%	37,066	132,265	28%	435,076	555,416	78%
2009	397,239	423,151	94%	41,313	132,265	31%	438,552	555,416	79%
2010	391,587	423,151	93%	71,743	132,265	54%	463,330	555,416	83%
2011	393,508	423,151	93%	99,038	132,265	75%	492,546	555,416	89%
2012	396,129	423,151	94%	51,356	132,265	39%	447,484	555,416	81%
2013	401,205	423,151	95%	42,141	132,265	32%	443,346	555,416	80%
2014[d]	257,847	423,151	61%	18,022	132,265	14%	275,869	555,416	50%
Average [e]	375,358	423,151	89%	61,608	132,265	47%	438,551	555,416	79%

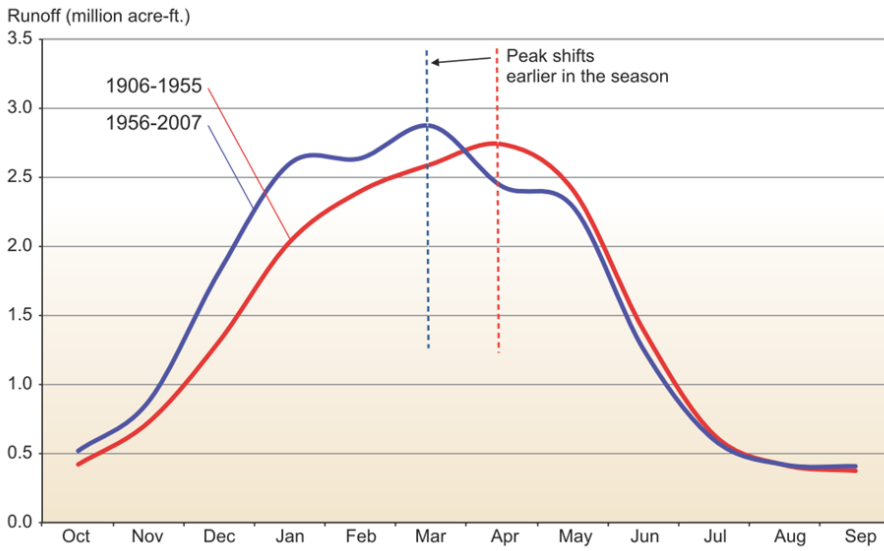[*] No Merced NWR historic delivery data available for these Water Years.
[a] Source: Rachael Esralew, USFWS Hydrologist
[b] Source: (USBR, 2010a-b; USBR, 2011a-l)
[c] Central Valley Project Improvement Act of 1992 stipulated that Incremental Level 4 deliveries will increase by 10 percent every water year beginning 1993 and reach 100 percent by 2002. Therefore, the target incremental Level 4 deliveries for 2001 are set at 90 percent.
[d] First year in recorded when the allocations were set below 100 percent.
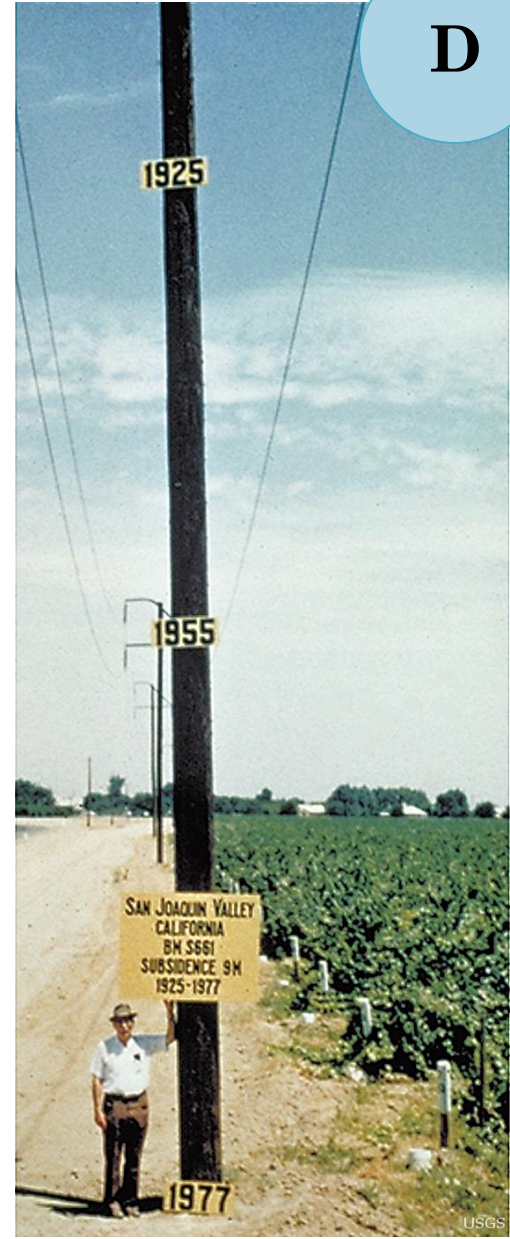[e] Incremental and Full Level 4 deliveries averaged over 2002 and 2014.

Runoff (million acre-ft.)

1906-1955
1956-2007

Peak shifts earlier in the season

A

B

U.S. FISH & WILDLIFE SERVICE — DEPARTMENT OF THE INTERIOR

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION — NOAA — U.S. DEPARTMENT OF COMMERCE

CALIFORNIA DEPARTMENT OF FISH & WILDLIFE

C

CALIFORNIA WATER FIX
RELIABLE. CLEAN. WATER.

NORTH-OF-THE-DELTA OFFSTREAM STORAGE

D

1925
1955
SAN JOAQUIN VALLEY CALIFORNIA BM S661 SUBSIDENCE 9M 1925-1977
1977
USGS

Refuge Management Challenges

- How to do more with less?

  Demand Management

- How to secure reliable water supplies at affordable prices?

  Supply Management

10

Scenario #	Abbreviation	Hydrology	Delta Export/ Outflow Regulations	Isolated Facility/ Peripheral Tunnels	Long-term Groundwater Overdraft	Refuge Deliveries
1	HEREC	Historic	Existing	No	Yes	Historic
2	HERIF	Historic	Existing	Yes	Yes	Historic
3	HHOEC	Historic	High Outflow	No	Yes	Historic
4	HHOIF	Historic	High Outflow	Yes	Yes	Historic
5	HERECG	Historic	Existing	No	No	Historic
6	HERIFG	Historic	Existing	Yes	No	Historic
7	HHOECG	Historic	High Outflow	No	No	Historic
8	HHOIFG	Historic	High Outflow	Yes	No	Historic
9	CEREC	Warm-Dry	Existing	No	Yes	Historic
10	CERIF	Warm-Dry	Existing	Yes	Yes	Historic
11	CHOEC	Warm-Dry	High Outflow	No	Yes	Historic
12	CHOIF	Warm-Dry	High Outflow	Yes	Yes	Historic
13	CERECG	Warm-Dry	Existing	No	No	Historic
14	CERIFG	Warm-Dry	Existing	Yes	No	Historic
15	CHOECG	Warm-Dry	High Outflow	No	No	Historic
16	CHOIFG	Warm-Dry	High Outflow	Yes	No	Historic

Historic Deliveries: Level 2 and incremental Level 4 deliveries to CVPIA refuges between March 2001 and February 2014.
Existing Delta Export and Outflow: D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp (and BDCP Alt 2a-H3 if tunnels are used to export water).
High Outflow Delta Export and Outflow: D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H4.
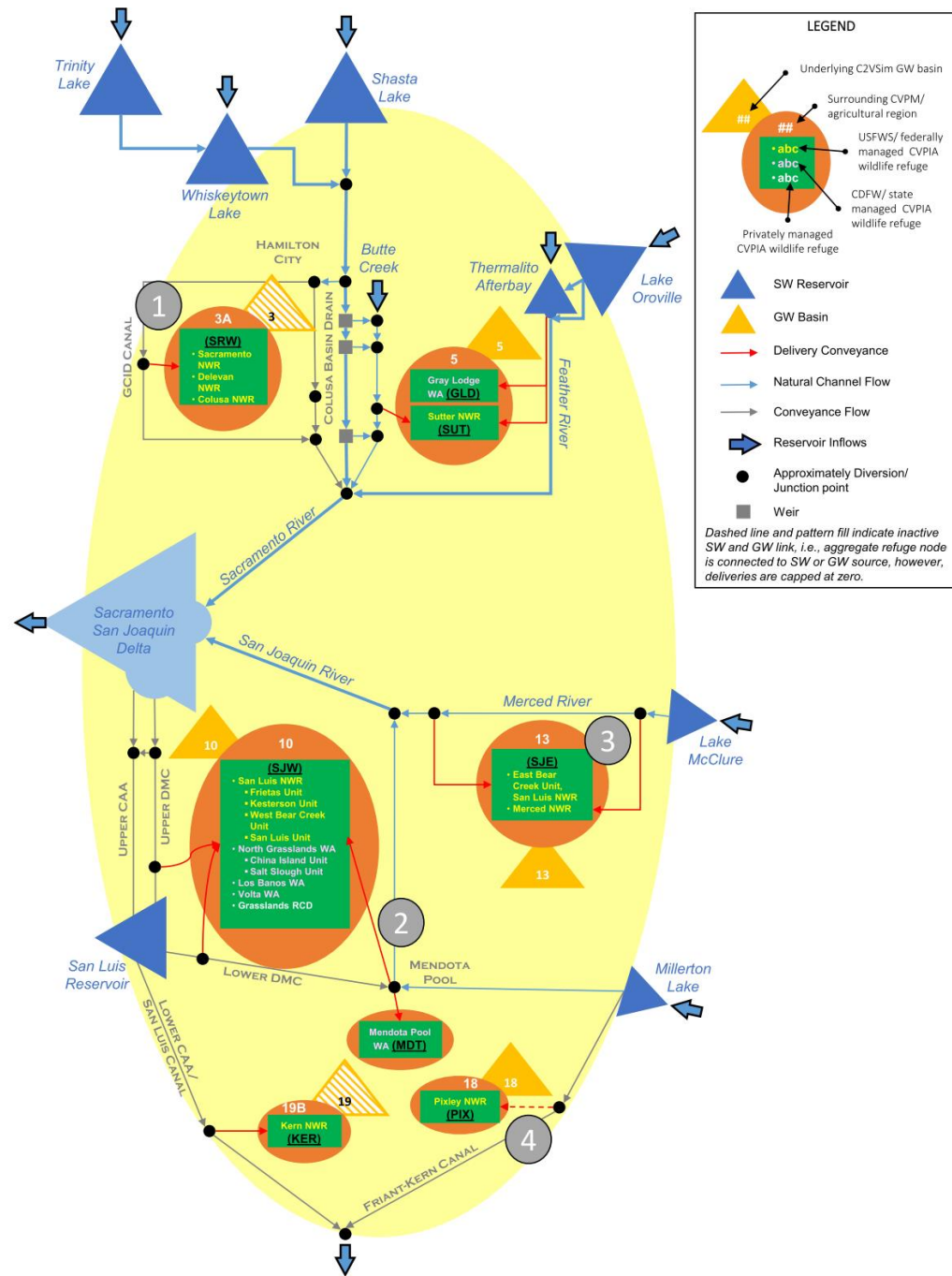
CALVIN

- integrated water resource model

- hydro-economic model of State of California

- explore <u>supply-side</u> management objectives

Limitations

All models are wrong, but some are useful" – G.E.P. Box

- planning model

- economics-driven response

- simplified representation of Delta

- indirect consideration of WQ

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More GW?

Opportunity cost of expanding GW deliveries ($/AF)

	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft
Upper Sacramento Valley																
West of Sacramento River (SRW)	1	2	320	323	1	2	328	205	1	1	259	275	2	2	352	400
Lower Sacramento Valley and Delta																
Sutter National Wildlife Refuge (SUT)	3	4	291	292	4	4	283	261	3	3	241	262	4	4	268	271
Gray Lodge Wildlife Area (GLD)	2	2	205	161	2	2	262	225	2	2	142	75	3	3	182	135
San Joaquin Valley and South Bay																
East of San Joaquin River (SJE)	1	1	-30	-28	4	3	-7	-10	0	0	-38	-34	2	2	-19	-22
West of San Joaquin River (SJE)	7	14	18	-13	4	6	6	10	8	10	-29	572	7	4	3	12
Mendota Wildlife Area (MDT)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tulare Basin																
Pixley National Wildlife Refuge (PIX)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kern National Wildlife Refuge (KER)	4	1	-16	-17	1	4	-15	-9	0	0	-22	-26	7	8	-15	-9

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
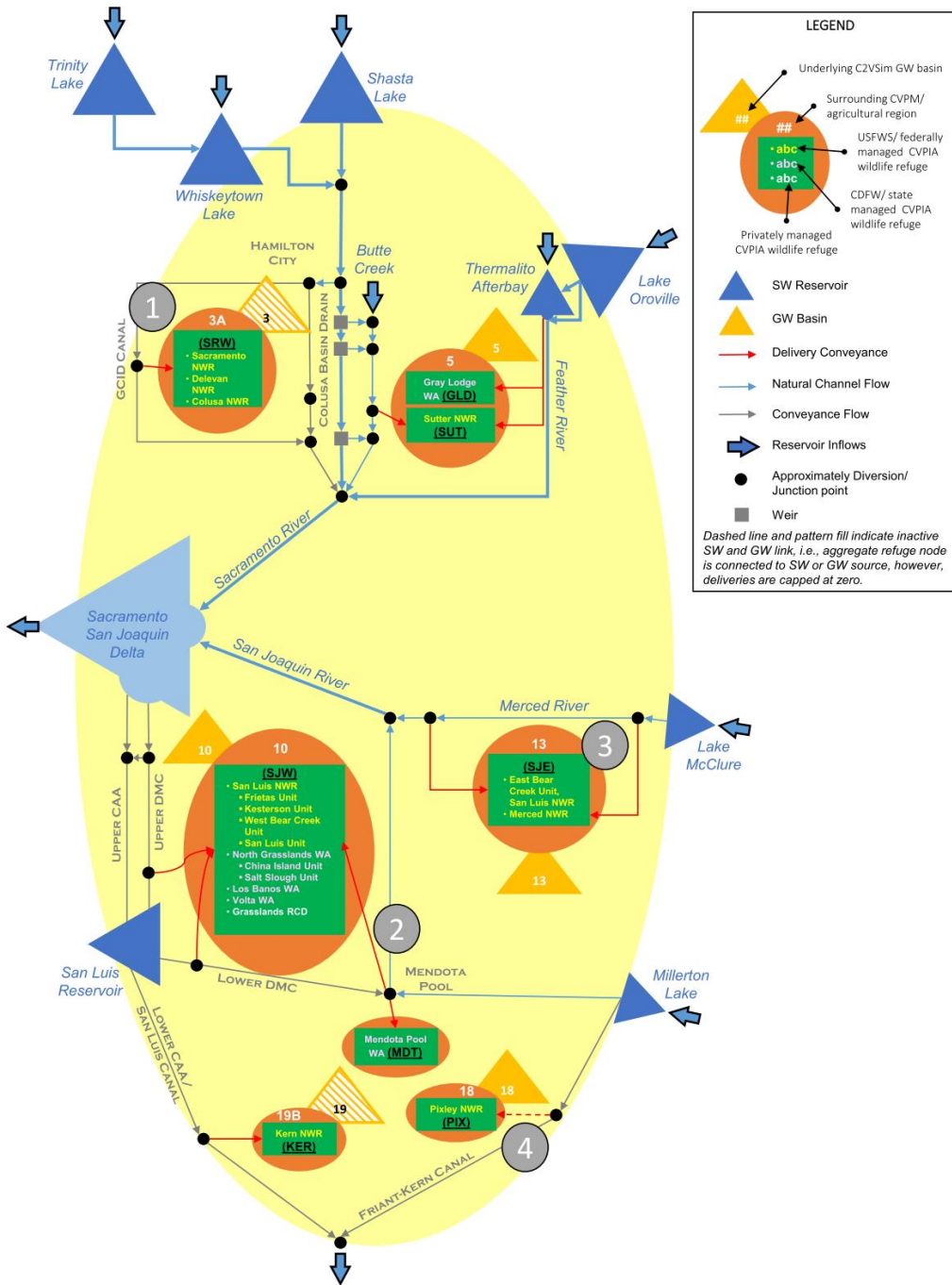**HOEC**: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)
* Opportunity cost (or Lagrange multiplier) reflects change in objective function if the capacity constraint is relaxed by one unit. Since objective function is a cost minimization function, opportunity cost represents system-wide cost of expanding conveyance capacity by one acre-foot. Negative opportunity cost represents a net benefit to the system from expanding conveyance capacity by one acre-foot.

More SW?

Opportunity cost of expanding SW deliveries ($/AF)

	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft
Upper Sacramento Valley																
West of Sacramento River (SRW)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lower Sacramento Valley and Delta																
Sutter National Wildlife Refuge (SUT)	0	0	28	27	0	0	33	45	0	0	23	27	0	0	38	42
Gray Lodge Wildlife Area (GLD)	0	0	25	25	0	0	27	25	0	0	18	20	0	0	32	32
San Joaquin Valley and South Bay																
East of San Joaquin River (SJE)	0	0	33	23	0	0	10	5	0	0	80	43	0	0	27	11
West of San Joaquin River (SJE)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mendota Wildlife Area (MDT)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tulare Basin																
Pixley National Wildlife Refuge (PIX)	-11	-8	84	291	-16	-13	16	169	-10	-1	190	437	-12	-10	13	154
Kern National Wildlife Refuge (KER)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
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* Opportunity cost (or Lagrange multiplier) reflects change in objective function if the capacity constraint is relaxed by one unit. Since objective function is a cost minimization function, opportunity cost represents system-wide cost of expanding conveyance capacity by one acre-foot. Negative opportunity cost represents a net benefit to the system from expanding conveyance capacity by one acre-foot.

Open-Market Water Trading Opportunities

Δ = Full Level 4 - Historic	
Upper Sacramento Valley	25 TAF
Lower Sacramento Valley & Delta	24 TAF
San Joaquin & South Bay	36 TAF
Tulare Basin	10 TAF

	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft
Upper Sacramento Valley	0	0	37	35	0	0	7	14	1	0	14	24	0	0	11	3
Lower Sacramento Valley & Delta	0	2	10	17	0	11	51	45	0	1	27	17	1	0	38	49
San Joaquin and South Bay	1	8	8	36	19	2	10	17	26	4	1	36	30	0	3	35
Tulare Basin	42	15	44	10	25	14	42	29	28	47	7	7	14	2	49	16
Southern California	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)

Spreadsheet Tool

- network flow model

- explore <u>demand-side</u> management objectives

- uses Linear Programming

$$Max\{HabitatAcreage\}$$

<u>Subject to</u>

WaterDemand ≤ WaterSupply

MinHabitatAcreage ≤ HabitatAcreage ≤ MaxHabitatAcreage

… and Continuity & non-Negativity constraints.

19

Limitations
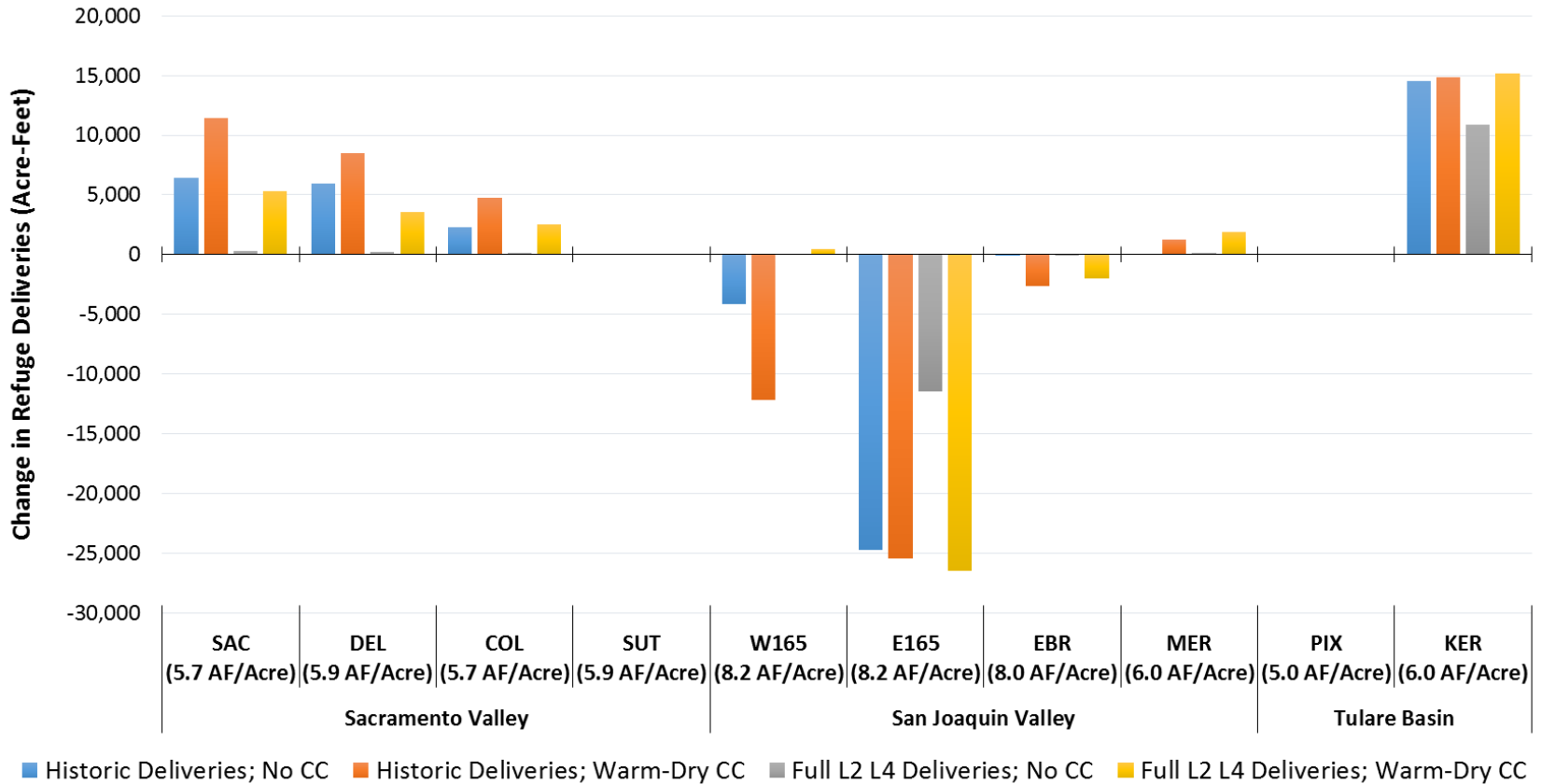
All models are wrong, but some are useful" – G.E.P. Box

- planning model

- limited data available

- missing key operational constraints

20

Inter-refuge trading?

- Σ Deliveries = ΣCVPIA Allocation

- Refuge deliveries can be more or less than CVPIA Allocations
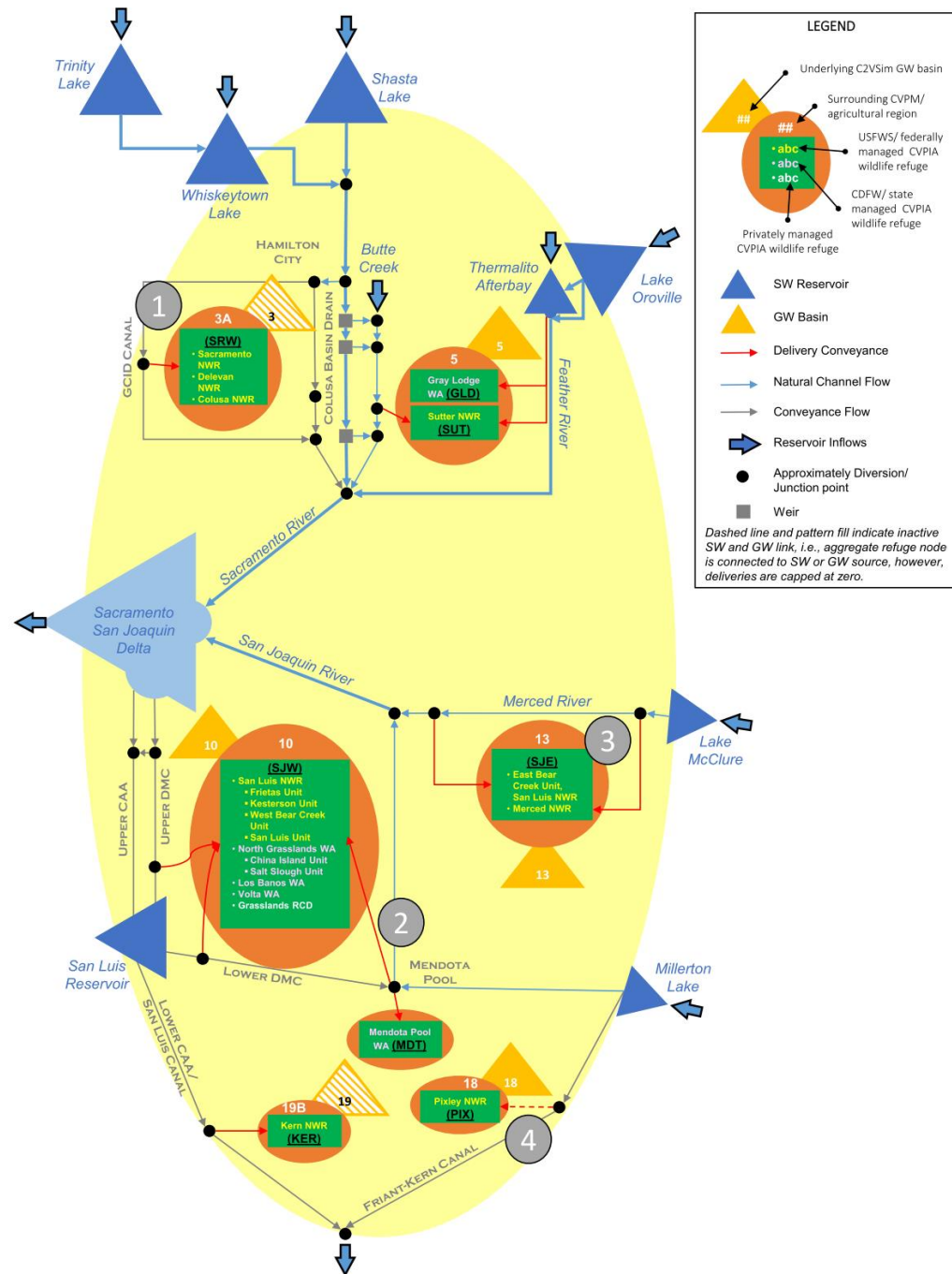
Impact of Inter-Refuge Trading on Refuge Deliveries

Optimize land-use?

- **Total acreage** for land-use type is **preserved**

- Land-use acreage **at individual refuges may be more or less** than historic operations
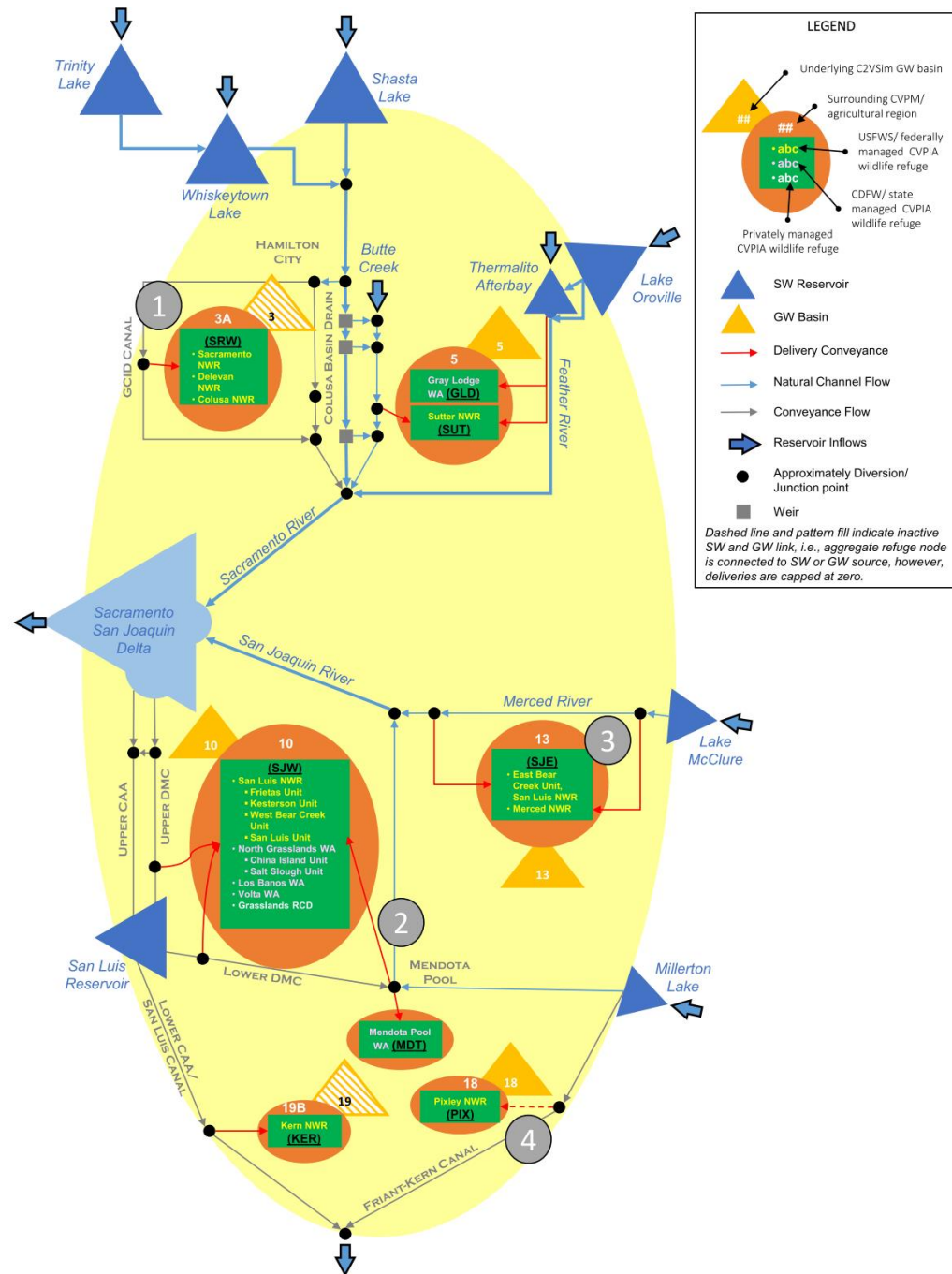
Statewide Managed Wetland Acreage: Historic vs. Optimized Operations
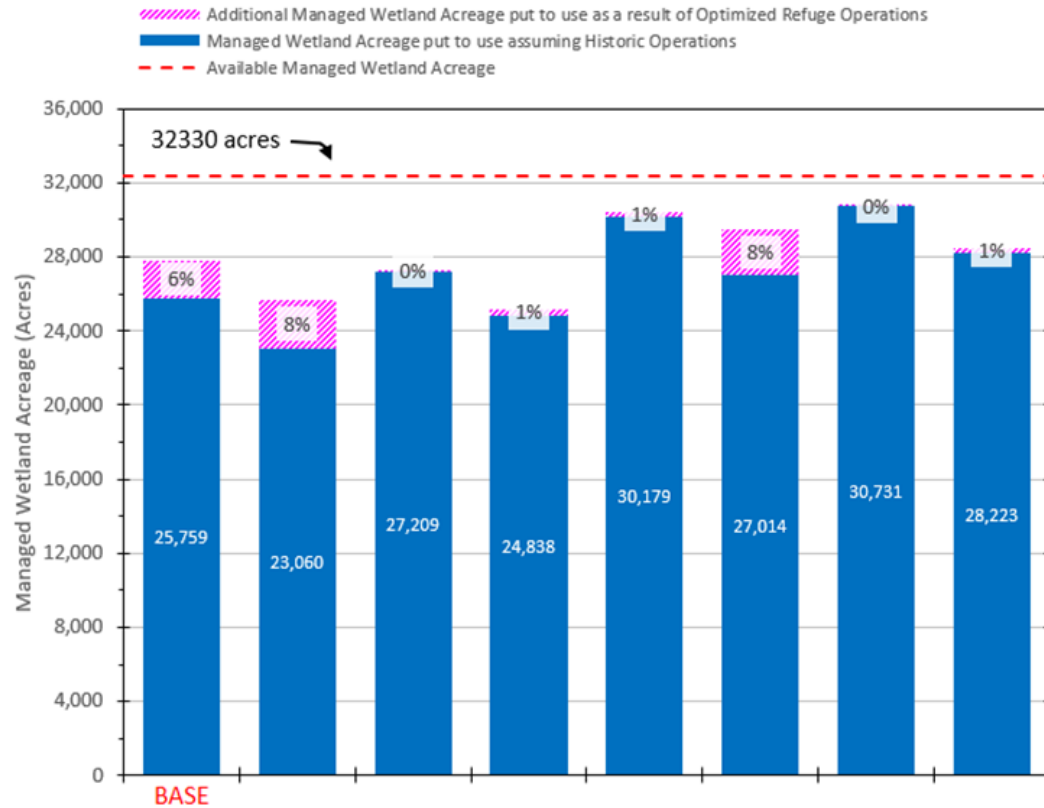
Refuge Deliveries	Historic	Historic	Historic	Historic	Full Level 2 Level 4	Full Level 2 Level 4	Full Level 2 Level 4	Full Level 2 Level 4
Climate Change	-	Warm-Dry	-	Warm-Dry	-	Warm-Dry	-	Warm-Dry
Inter-refuge Trading			✓	✓			✓	✓
% Unmanaged (Historic Operations)	20%	29%	16%	23%	7%	16%	5%	13%
% Unmanaged (Optimized Operations)	14%	21%	16%	22%	6%	9%	5%	12%

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Water Scarcity?

... and more results

Singh.Karandev@gmail.com

Thesis posted at
https://watershed.ucdavis.edu/shed/lund/ under *Former Graduate Students*

EXTRAs

CVPIA Refuge [a]	Year Established [b]	Full Level 2 [b]		Incremental Level 4 [b]	Full Level 4	
Sacramento Valley		**152,250**	**36%**	**26,750**	**179,000**	**32%**
🟡 Sacramento NWR	1937	46,400	11%	3,600	50,000	9%
🟡 Delevan NWR	1962	21,950	5%	8,050	30,000	5%
🟡 Colusa NWR	1945	25,000	6%	0	25,000	5%
🟡 Sutter NWR	1945	35,400	8%	8,600	44,000	8%
🔴 Gray Lodge WA	1931	23,500	6%	6,500	30,000	5%
San Joaquin Valley		**259,671**	**61%**	**85,745**	**345,416**	**62%**
🔴 Volta WA	1952	13,000	3%	3,000	16,000	3%
🔴 Los Banos WA	1929	16,670	4%	8,330	25,000	5%
🔴 North Grasslands WA	1990					
China Island Unit		*6,967*	*2%*	*3,483*	*10,450*	*2%*
Salt Slough Unit		*6,680*	*2%*	*3,340*	*10,020*	*2%*
🟡 San Luis NWR	1967					
Kesterson Unit		*10,000*	*2%*	*-*	*10,000*	*2%*
Freitas Unit		*5,290*	*1%*	*-*	*5,290*	*1%*
San Luis Unit		*19,000*	*4%*	*-*	*19,000*	*3%*
West Bear Creek Unit		*7,107*	*2%*	*3,603*	*10,710*	*2%*
East Bear Creek Unit		*8,863*	*2%*	*4,432*	*13,295*	*2%*
🟡 Merced NWR	1951	13,500	3%	2,500	16,000	3%
🟢 Grasslands RCD	1953	125,000	30%	55,000	180,000	32%
🔴 Mendota WA	1954	27,594	7%	2,057	29,651	5%
Tulare Basin		**11,230**	**3%**	**19,770**	**31,000**	**6%**
🟡 Pixley NWR	1959	1,280	0%	4,720	6,000	1%
🟡 Kern NWR	1960	9,950	2%	15,050	25,000	5%

[a] NWR: National Wildlife Refuge; managed by US Fish and Wildlife Service (USFWS)

WA: Wildlife Area; managed by California Department of Fish and Wildlife (CDFW)

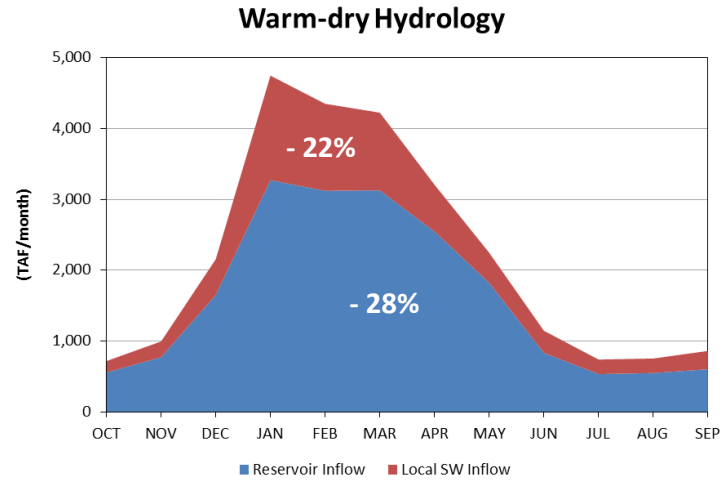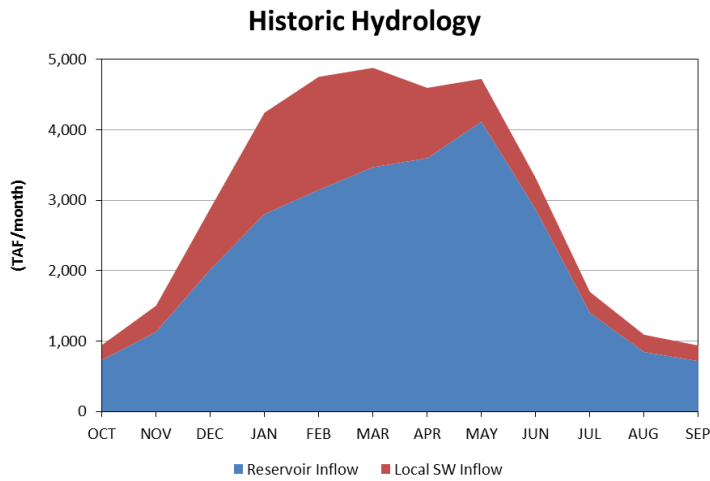RCD: Resource Conservation Districts; managed by private owners

Figure 3-11. Reservoir inflows and local surface water runoff (rim inflows)

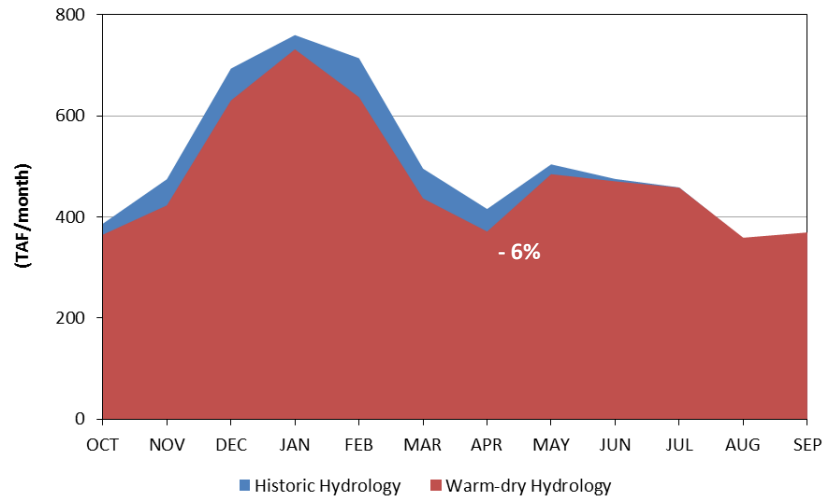Results are aggregated for all rim nodes represented in CALVIN.

Figure 3-13. Net groundwater inflows

Results are aggregated across all groundwater basins represented in CALVIN.
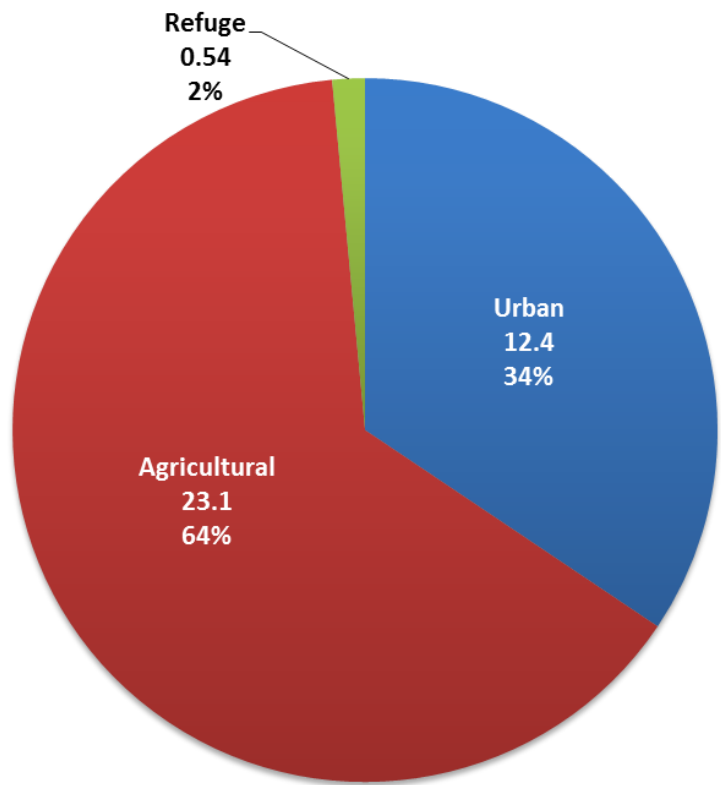
Table 3-5. Urban, agricultural and refuge demands included in CALVIN (MAF/yr)

	Urban	Agricultural	Historic Refuge Deliveries	Full Level 4 Refuge Deliveries
Upper Sacramento Valley	0.4 (3%)	2.6 (11%)	0.08 (17%)	0.1 (19%)
Lower Sacramento Valley and Delta	1.9 (15%)	4.6 (20%)	0.05 (11%)	0.07 (13%)
San Joaquin Valley and South Bay	1.7 (14%)	4.9 (21%)	0.3 (67%) ★	0.34 (62%)
Tulare Basin	1.5 (12%)	9.6 (41%) ★	0.02 (5%)	0.03 (6%)
Southern California	6.8 (55%) ★	1.4 (6%)	-	-
Statewide Total	12.4	23.1	0.45	0.54

Table 3-11. Opportunity cost* of historic refuge deliveries ($/AF)

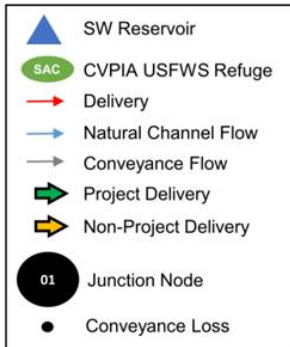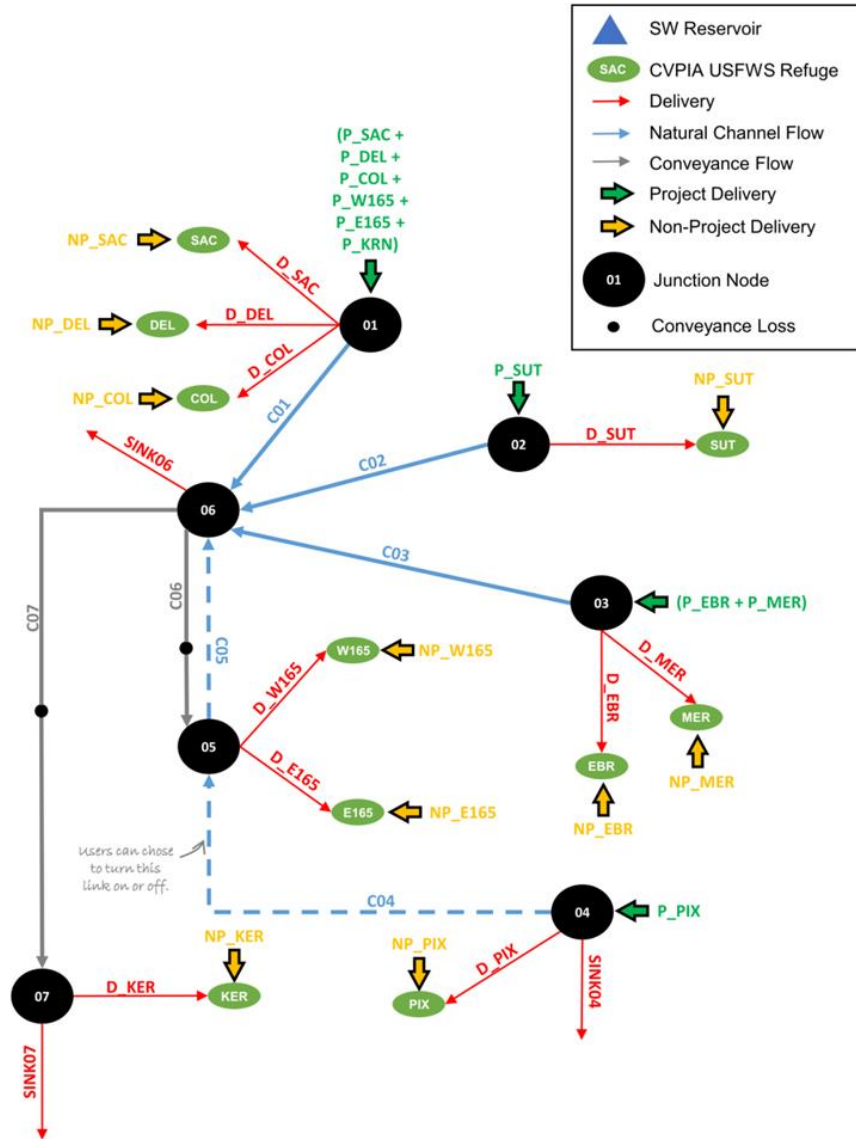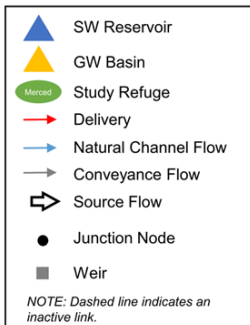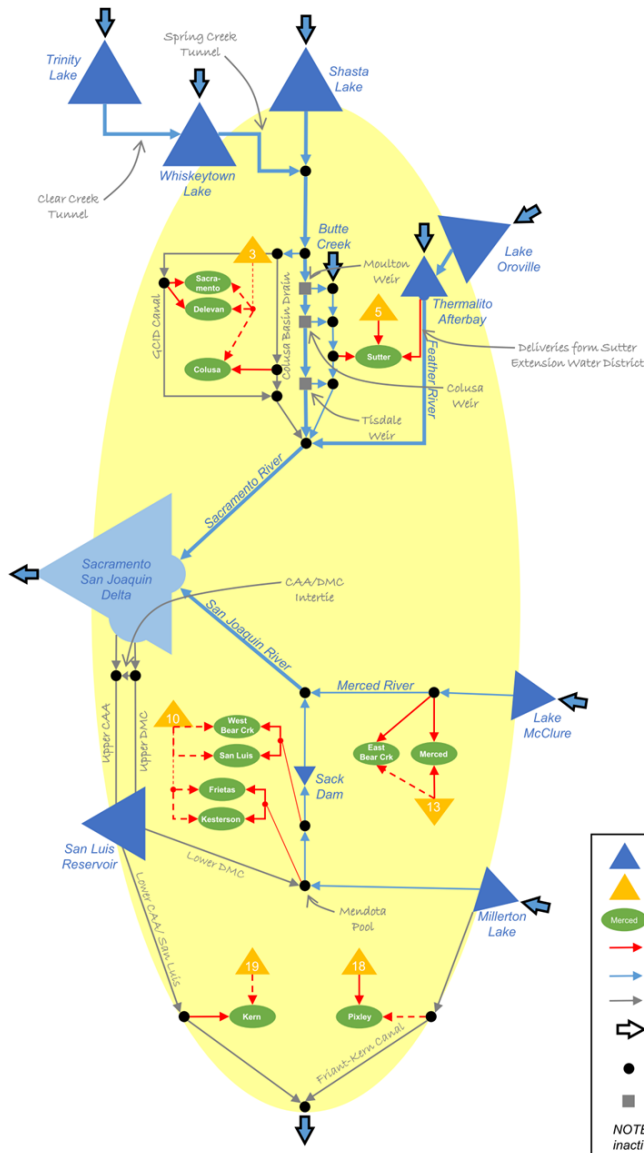|	EREC				ERIF				HOEC				HOIF			
	Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry		Historic		Warm-Dry	
	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft	With Overdraft	No Overdraft
Upper Sacramento Valley																
West of Sacramento River (SRW)	2	2	30	44	3	3	131	198	2	2	-76	-30	2	2	174	195
Lower Sacramento Valley and Delta																
Sutter National Wildlife Refuge (SUT)	2	2	289	291	2	2	327	394	1	1	195	219	2	2	353	365
Gray Lodge Wildlife Area (GLD)	4	4	292	293	4	4	283	274	3	3	242	264	4	4	268	272
San Joaquin Valley and South Bay																
East of San Joaquin River (SJE)	254	377	808	998	141	263	742	927	381	498	896	1,115	196	354	745	890
West of San Joaquin River (SJE)	235	347	708	785	130	242	576	702	370	490	821	995	182	330	637	747
Mendota Wildlife Area (MDT)	248	366	814	930	138	257	657	815	381	502	929	1,125	193	347	723	854
Tulare Basin																
Pixley National Wildlife Refuge (PIX)	339	494	926	926	223	374	926	926	499	637	926	926	273	473	926	926
Kern National Wildlife Refuge (KER)	320	464	948	1,059	187	331	769	940	491	643	1,094	1,321	255	444	851	999

EREC: Existing regulation (D-1641, 2008 USFWS BiOp and 2009 NMFS BiOp), Existing Conveyance (no Peripheral Tunnels)
ERIF: Existing regulation (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp, and BDCP Alt 2a-H3), Isolated Facility (or Peripheral Tunnels)
HOEC: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Existing Conveyance (no Peripheral Tunnels)
HOIF: High Outflow Scenario (D-1641, 2008 USFWS BiOp, 2009 NMFS BiOp and BDCP Alt 2a-H4), Isolated Facility (or Peripheral Tunnels)
* Since refuges deliveries are represented as constrained flows in CALVIN, model allocates water to refuges before delivering water to agricultural and urban water users. Opportunity cost reflects competition for water delivered to refuges; hence, qualitatively access the likelihood of waster scarcity at refuges. Negative opportunity cost represents a net benefit to the system to deliver water to the refuge.

	HISTORIC HYDROLOGY								WARM-DRY HYDROLOGY							
	Historic Refuge Deliveries				Full Level4 Refuge Deliveries				Historic Refuge Deliveries				Full Level4 Refuge Deliveries			
	No Trading		Trading		No Trading		Trading		No Trading		Trading		No Trading		Trading	
	Historic Ops	Optimized Ops	Historic Ops	Optimized Ops	Historic Ops	Optimized Ops	Historic Ops	Optimized Ops	Historic Ops	Optimized Ops	Historic Ops	Optimized Ops	Historic Ops	Optimized Ops	Historic Ops	Optimized Ops
SAC	0.17	0.16	0.12	0.00	0.01	0.01	0.12	0.00	0.16	0.21	0.12	0.00	0.16	0.04	0.11	0.00
DEL	0.17	0.20	0.12	0.00	0.17	0.01	0.12	0.00	0.15	0.21	0.12	0.00	0.15	0.04	0.11	0.00
COL	0.16	0.13	0.12	0.00	0.01	0.01	0.12	0.00	0.16	0.19	0.12	0.00	0.16	0.04	0.11	0.00
SUT	0.17	0.04	0.17	0.01	0.17	0.01	0.17	0.00	0.15	0.04	0.17	0.01	0.15	0.03	0.15	0.00
W165	0.12	0.12	0.12	0.13	0.12	0.04	0.12	0.01	0.11	0.13	0.12	0.13	0.11	0.14	0.11	0.01
E165	0.12	0.15	0.12	0.18	0.12	0.15	0.12	0.13	0.11	0.13	0.12	0.18	0.11	0.14	0.11	0.11
EBR	0.13	0.13	0.13	0.18	0.13	0.00	0.13	0.13	0.11	0.13	0.13	0.18	0.11	0.13	0.11	0.11
MER	0.17	0.04	0.14	0.07	0.17	0.03	0.13	0.00	0.15	0.04	0.14	0.07	0.15	0.04	0.11	0.00
PIX	0.20	0.24	0.20	0.29	0.20	0.00	0.20	0.00	0.18	0.21	0.20	0.29	0.18	0.21	0.18	0.18
KER	0.17	0.20	0.12	0.01	0.17	0.20	0.12	0.00	0.15	0.18	0.12	0.01	0.15	0.18	0.11	0.01

North of Delta: SAC, DEL, COL, SUT
South of Delta: W165, E165, EBR, MER, PIX, KER

<----------------------------------- Increasing Water Scarcity