The ADWR Groundwater Model Development and the Pinal Groundwater Flow Model Update, Calibration and Sensitivity Analysis

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Models present a simplification of reality

http://www.rossettiarchive.org

Mona Lisa

http://farm2.static.flickr.com

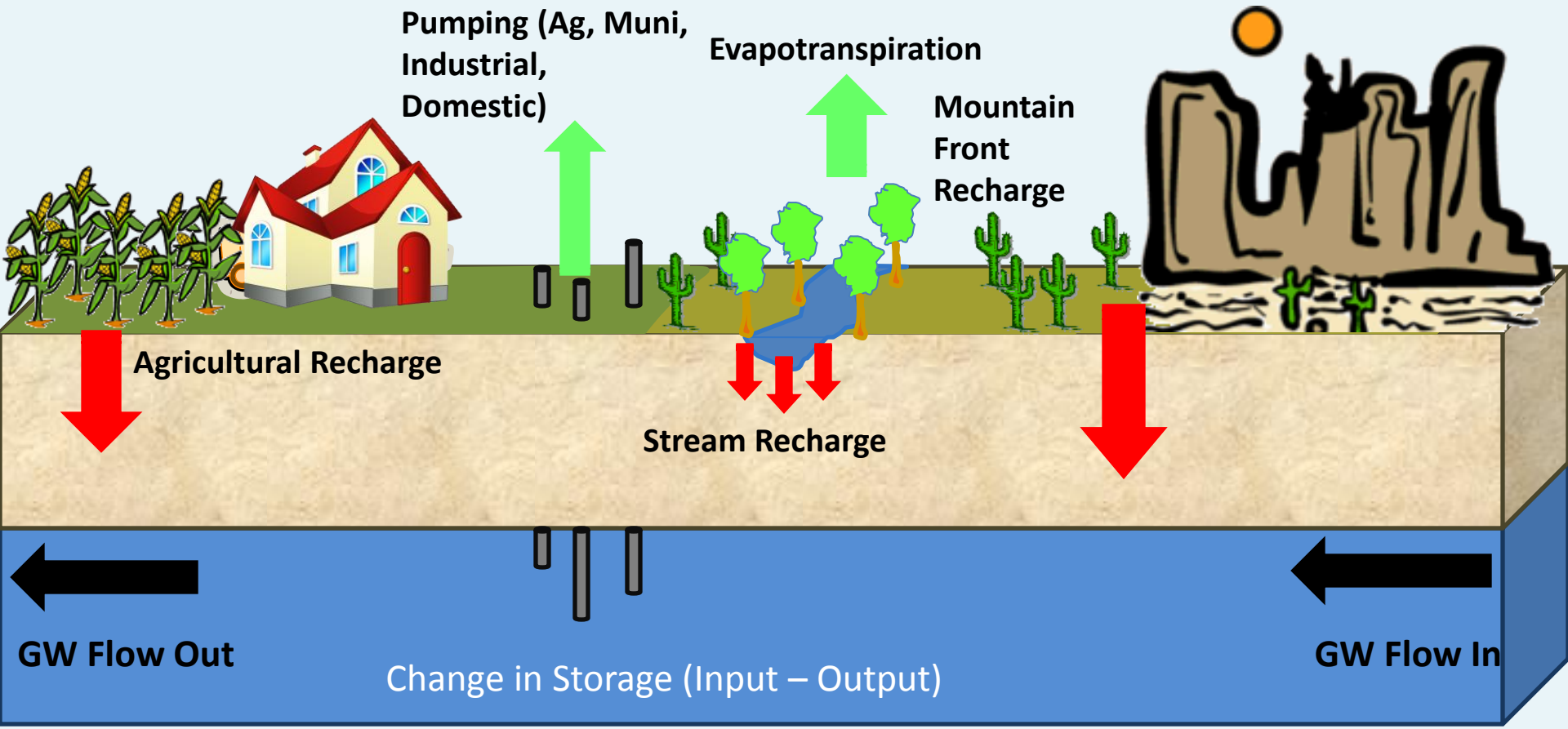
Lego Lisa

Groundwater models are computer models of groundwater flow systems.

Groundwater models are used to simulate and predict aquifer conditions.

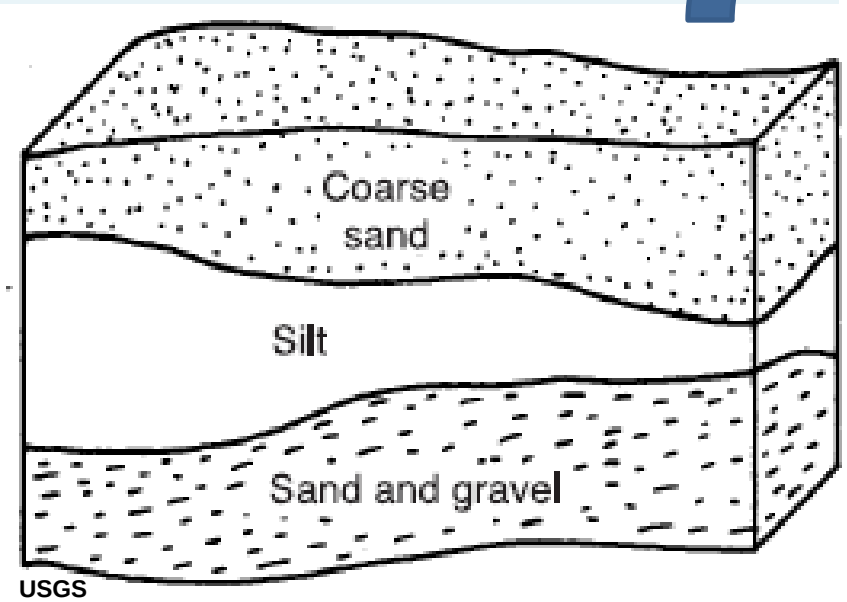
Building a Modeling – Where to Start

Modeling – Conceptual Development

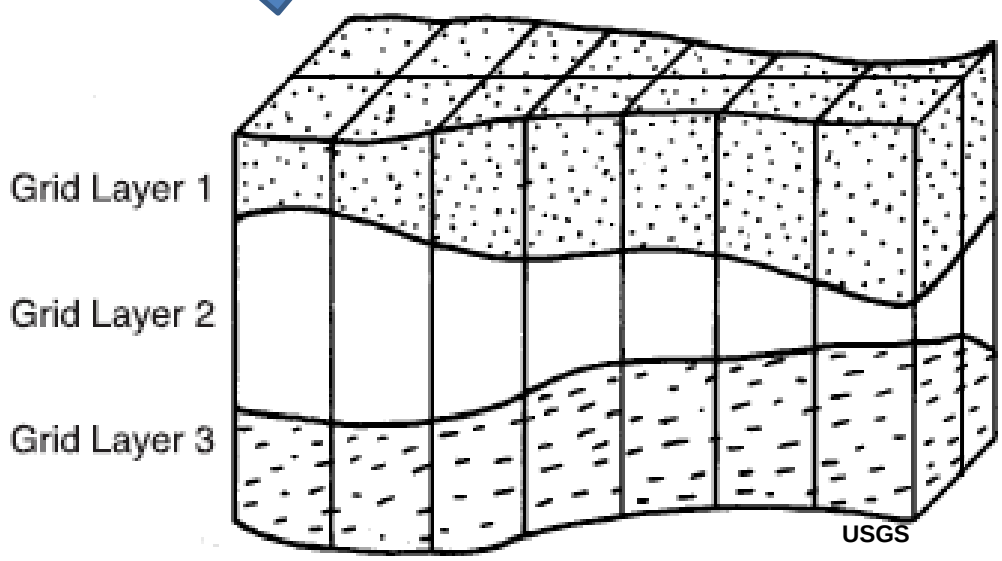


Model Setup

Translating the *Real World Landscape* into a *Model Representation*

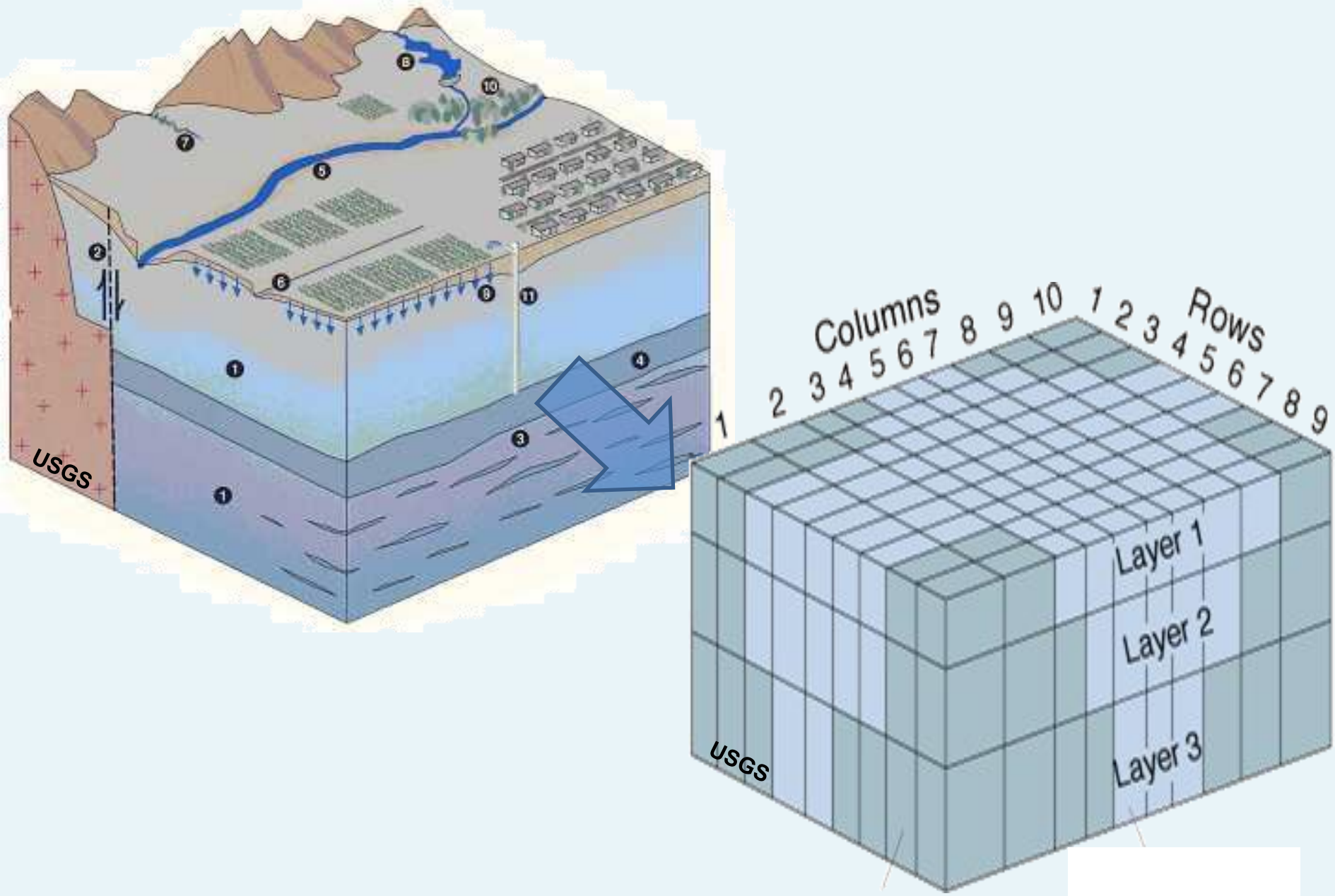


Aquifer cross section



Aquifer cross section with deformed grid superimposed

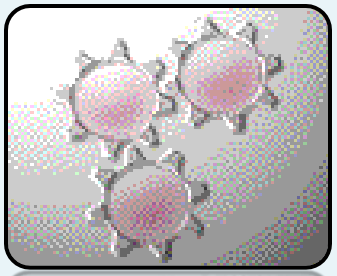
Model Setup


USGS
Columns
1 2 3 4 5 6 7 8 9 10
Rows
1 2 3 4 5 6 7 8 9
Layer 1
Layer 2
Layer 3
USGS

Modeling - MODFLOW

INPUT DATA
Recharge
Water Elevations
Geology
Pumping
Hydrologic Parameters

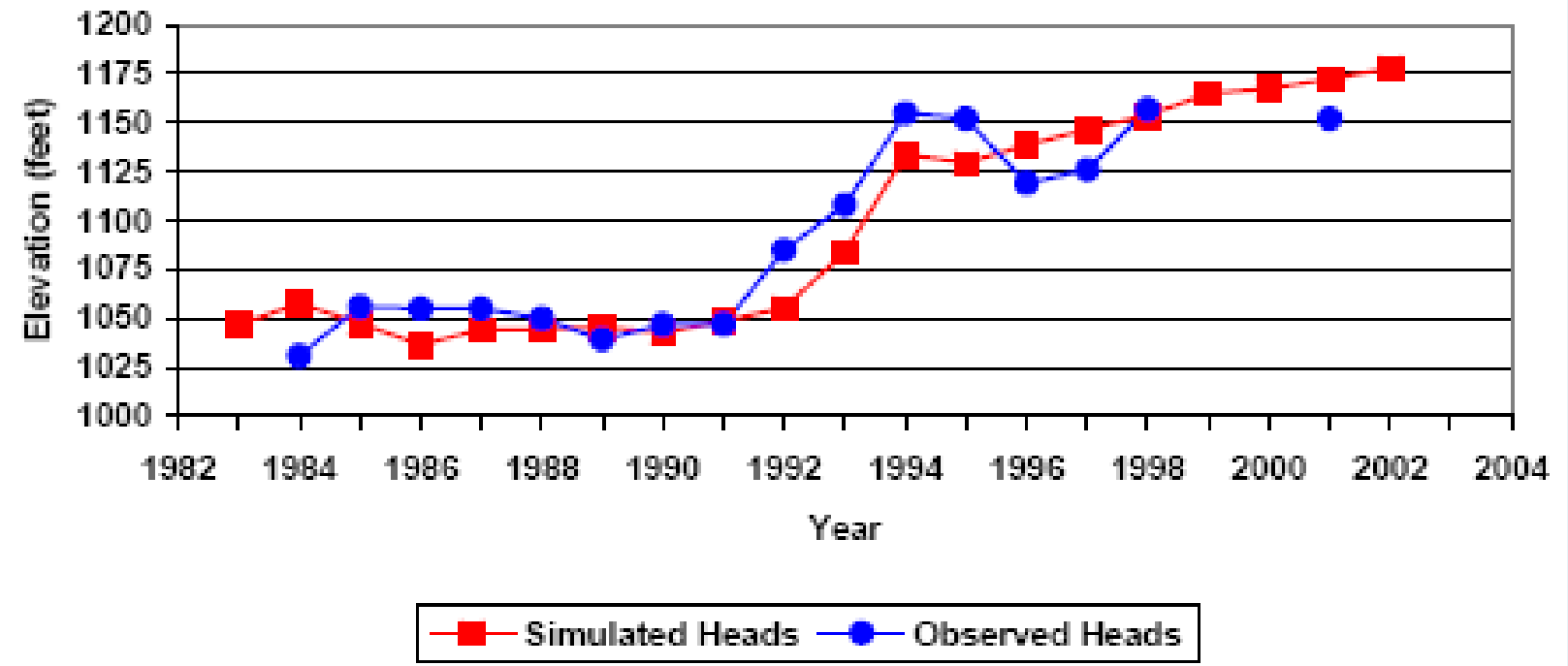
USGS
MODFLOW

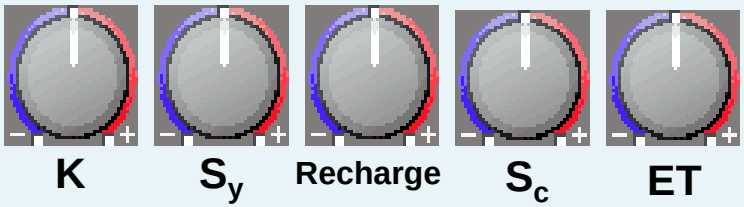


OUTPUT DATA
Water Budget
Water Elevations
Stream Flow

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]+W=S_S\frac{\partial h}{\partial t}$$

Modeling - Calibration





Input Parameter Controls

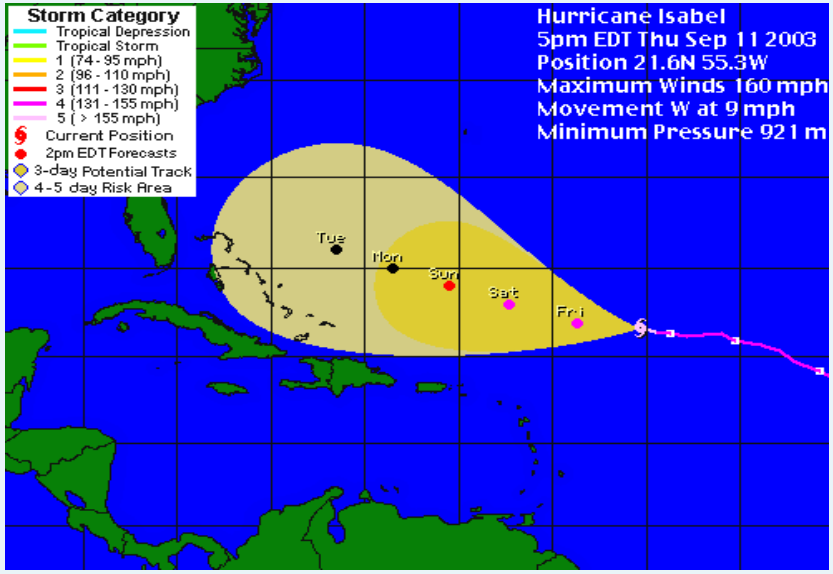
- **Calibration's intent is for the simulation to follow the observed pattern**
- Controls have set ranges
- Model can be calibrated to GW Heads, Stream Flow, GW Budget

Modeling - Projections

Important factors that affect the accuracy of groundwater model projections:

- **Suitability of the conceptual model design**
- **Quality and availability of hydrologic and geologic data used to construct and calibrate the numerical model**
- **Length of the transient calibration period**
- **Length of the projection period**
- **Accuracy of assumptions concerning future pumping and recharge**

Weather models are examples of projection uncertainty



Common Misconceptions About Models:

- ✓ Always Reliable
- ✓ One Exact Solution (non-uniqueness)
- ✓ Accurate Input Always Results in Quality Output

Recommended Approach to Modeling Studies!

Whenever possible it is useful to run multiple future scenarios to evaluate the potential range and uncertainty of projected model results !

Goals and Objectives Of the Pinal AMA Groundwater Flow Model Update

- **Create an updated groundwater model of the Pinal AMA that can be used as an analytical tool to test various water management strategies and provide technical support to regulatory programs and miscellaneous hydrologic studies**

- **Update the original Pinal AMA groundwater flow model with recent/current groundwater withdrawal and recharge information (through 2009)**

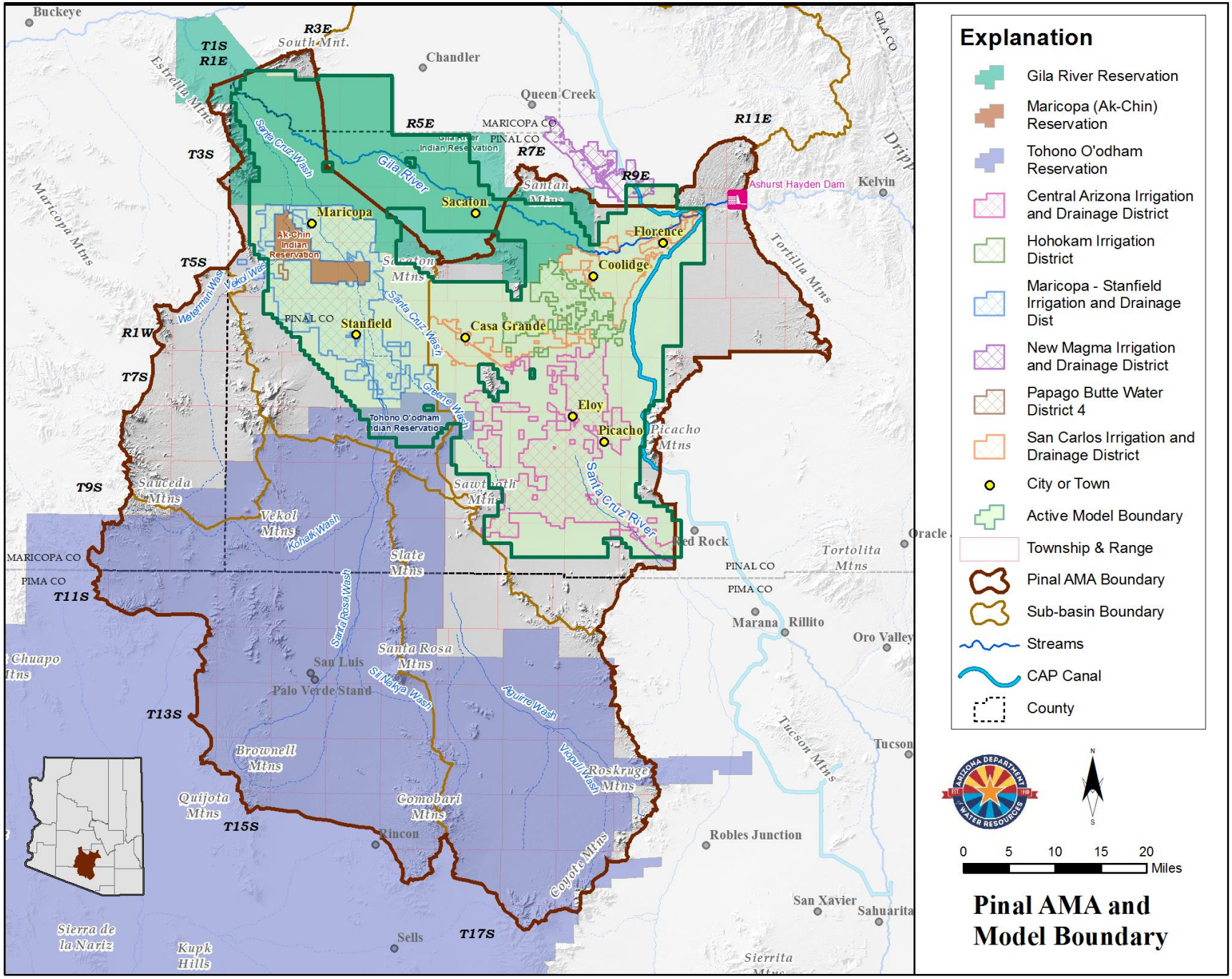
- **Eliminate "problematic" artificial boundaries, and refine grid**

- **Extend the calibration backward in time to steady-state and include the period of groundwater development in the transient model calibration**

- **Simulate "land subsidence" and "lagged" agricultural recharge**

- **Test model sensitivity to important inputs and parameters**

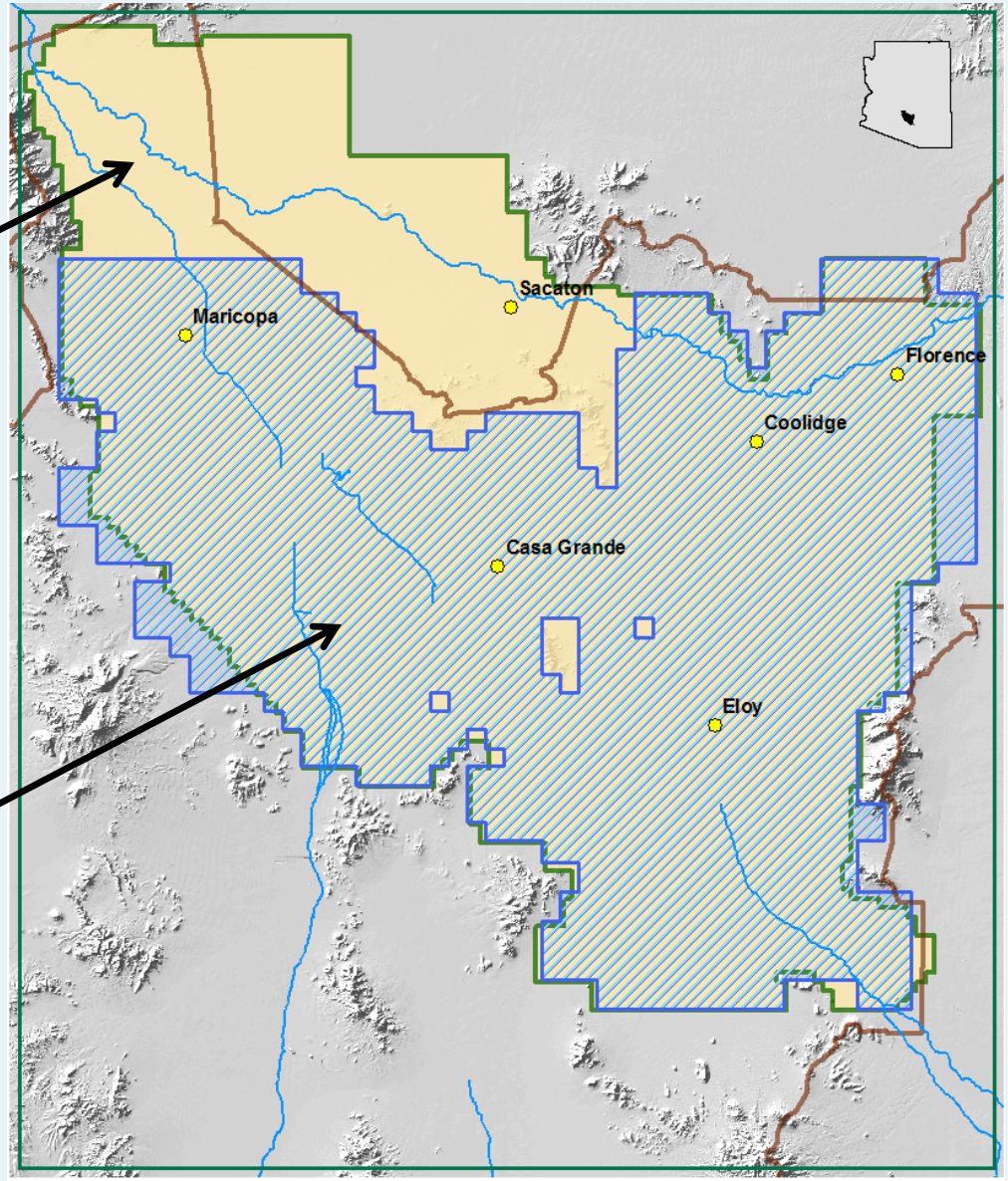
- **Test the model accuracy and suitability for future uses, recommend further improvements and updates**


Explanation
Gila River Reservation
Maricopa (Ak-Chin) Reservation
Tohono O'odham Reservation
Central Arizona Irrigation and Drainage District
Hohokam Irrigation District
Maricopa - Stanfield Irrigation and Drainage Dist
New Magma Irrigation and Drainage District
Papago Butte Water District 4
San Carlos Irrigation and Drainage District
City or Town
Active Model Boundary
Township & Range
Pinal AMA Boundary
Sub-basin Boundary
Streams
CAP Canal
County
0 5 10 15 20 Miles
Pinal AMA and Model Boundary
Buckeye
Chandler
Queen Creek
Maricopa
Sacaton
Florence
Coolidge
Stanfield
Casa Grande
Eloy
Picacho
Red Rock
Marana
Rillito
Oracle
Oro Valley
Tucson
Kelvin
Ashurst Hayden Dam
Robles Junction
San Xavier
Sahuarita
Sells
San Luis
Palo Verde Stand
Rincon
MARICOPA CO
PINAL CO
PIMA CO
GILA CO
Gila River Indian Reservation
Ak-Chin Indian Reservation
Tohono O'odham Indian Reservation
Gila River
Santa Cruz Wash
Santa Cruz River
Santa Rosa Wash
Greene Wash
Vekol Wash
Waterman Wash
Kohatk Wash
Sil Nakya Wash
Aguirre Wash
Vapul Wash
South Mnt.
Estrella Mtns
Maricopa Mtns
Santan Mtns
Sacaton Mtns
Sawtooth Mtns
Picacho Mtns
Tortilla Mtns
Tortolita Mtns
Tucson Mtns
Sauceda Mtns
Vekol Mtns
Slate Mtns
Santa Rosa Mtns
Brownell Mtns
Quijota Mtns
Comobari Mtns
Roskruge Mtns
Coyote Mtns
Chuapo Mtns
Sierra de la Nariz
Kup'k Hills
Sierrita Mtns
R3E
R5E
R7E
R9E
R11E
R1W
T1S
T3S
T5S
T7S
T9S
T11S
T13S
T15S
T17S

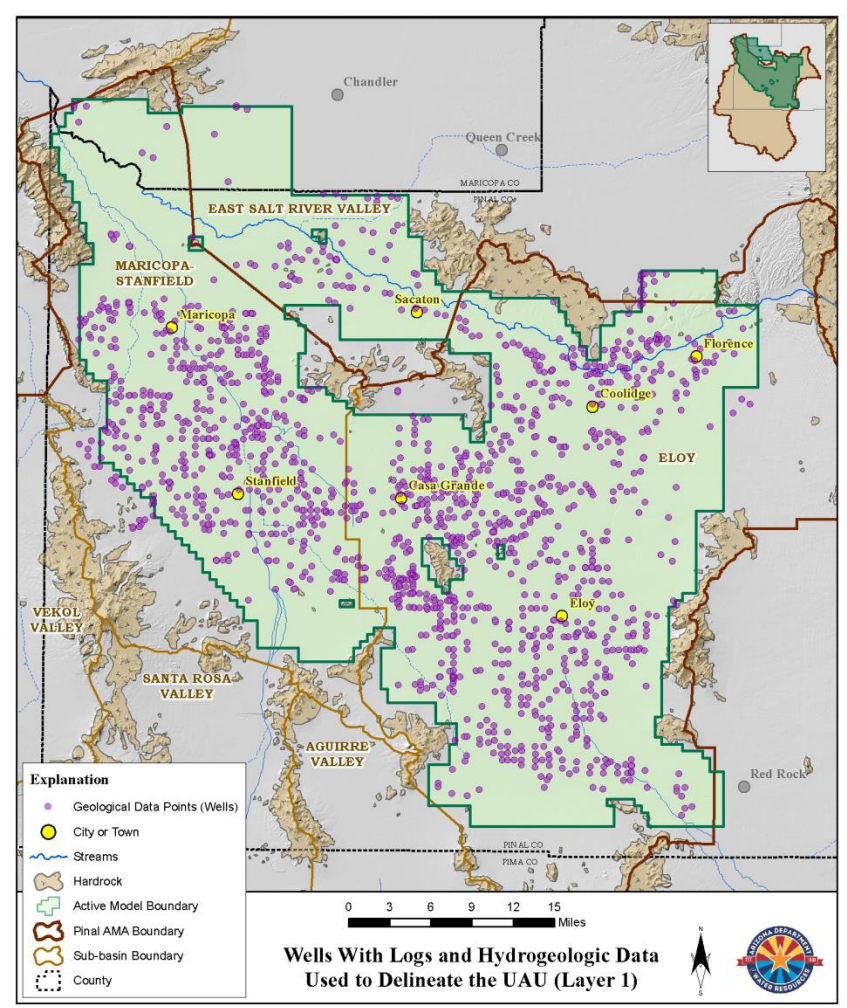
Updated Model Area

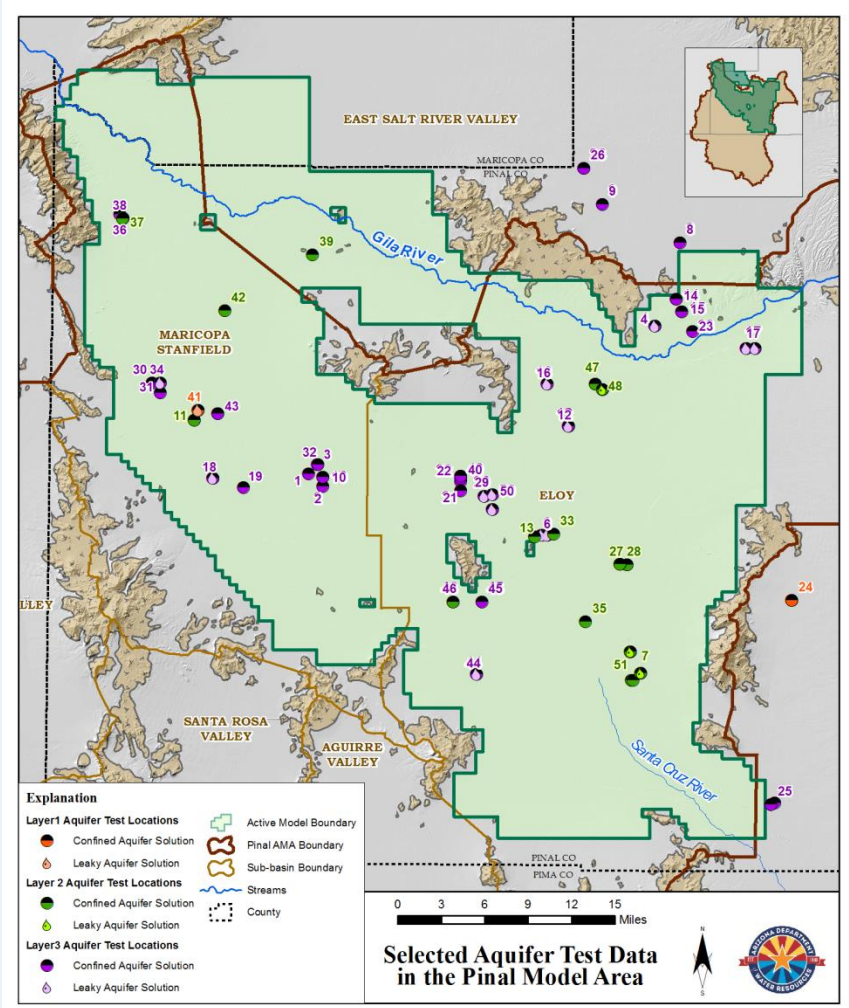
Additional Area Covered in Updated Model

Original Model Area



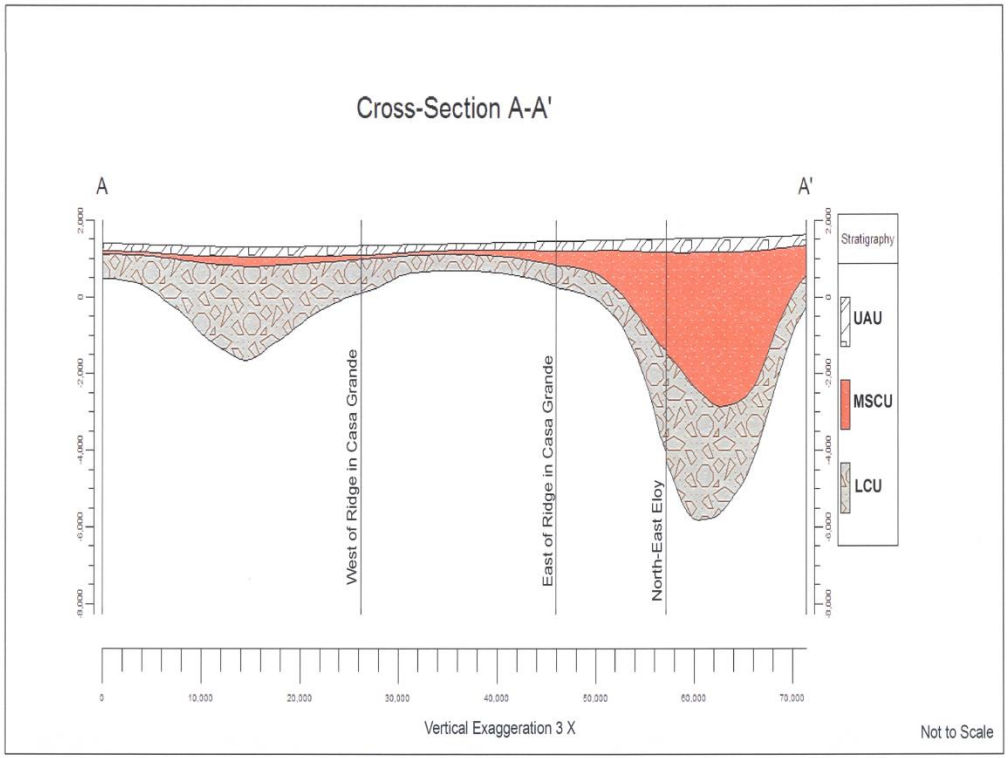
Hydrogeologic Data Analysis for Model Development

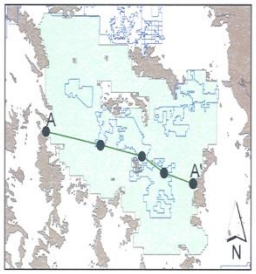




The Three Major Hydrogeologic Units Are Represented By Individual Model Layers

Figure 12





Legend
- City Boundary
- Pinal Model Boundary
- Hardrock
- Cross-Section A-A'
- Points Correspond to Cross-Section Notes

Vertical Units in Feet Above Mean Sea Level
Horizontal Units in Meters

Map showing the cross-section and location map for the east-west cross-section A-A'

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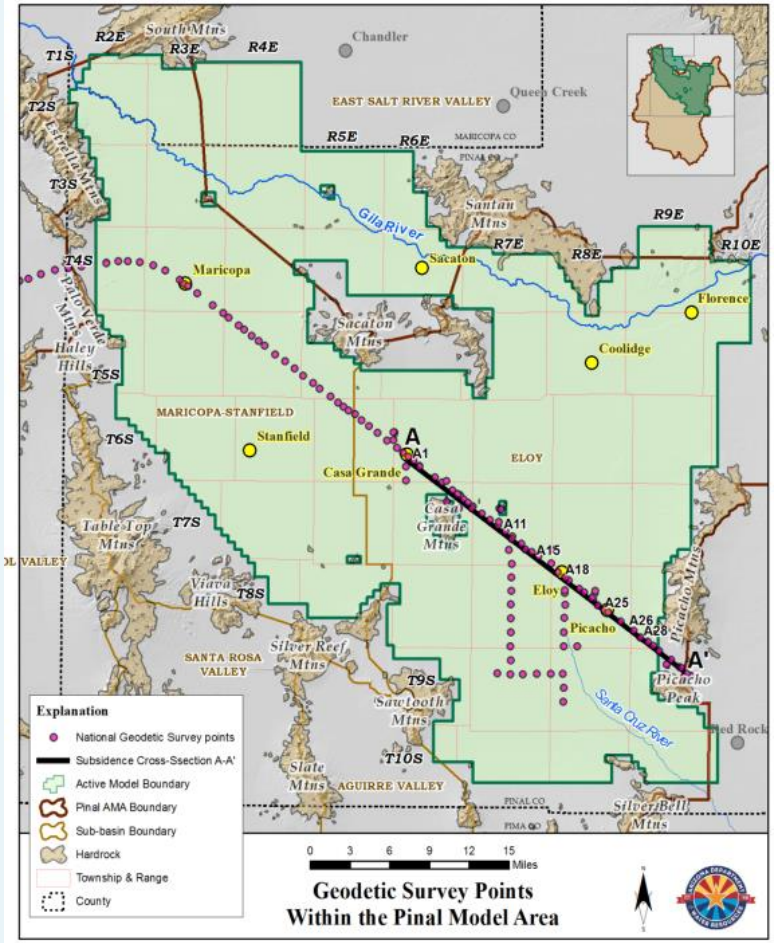
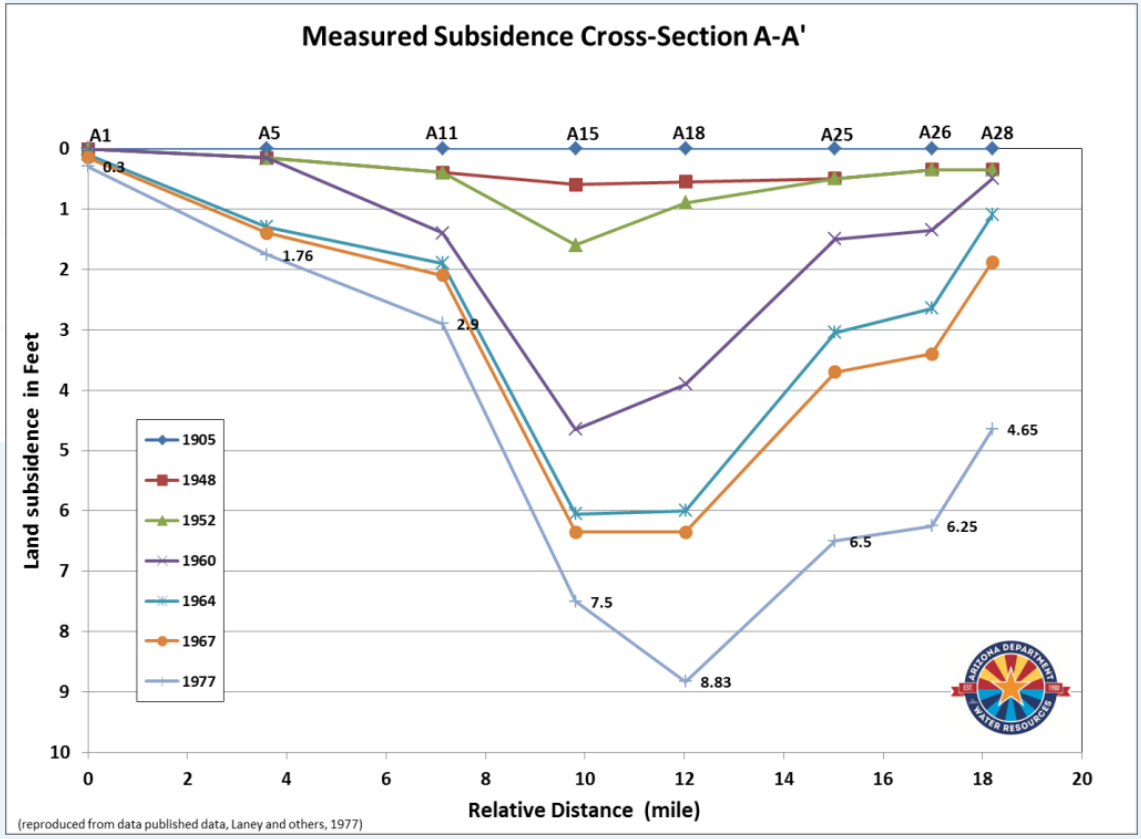
Classic Signs of Land Subsidence

Protruding Well Casings and Well Pads
in Eloy Sub-basin

Earth Fissures
SW Eloy Sub-basin

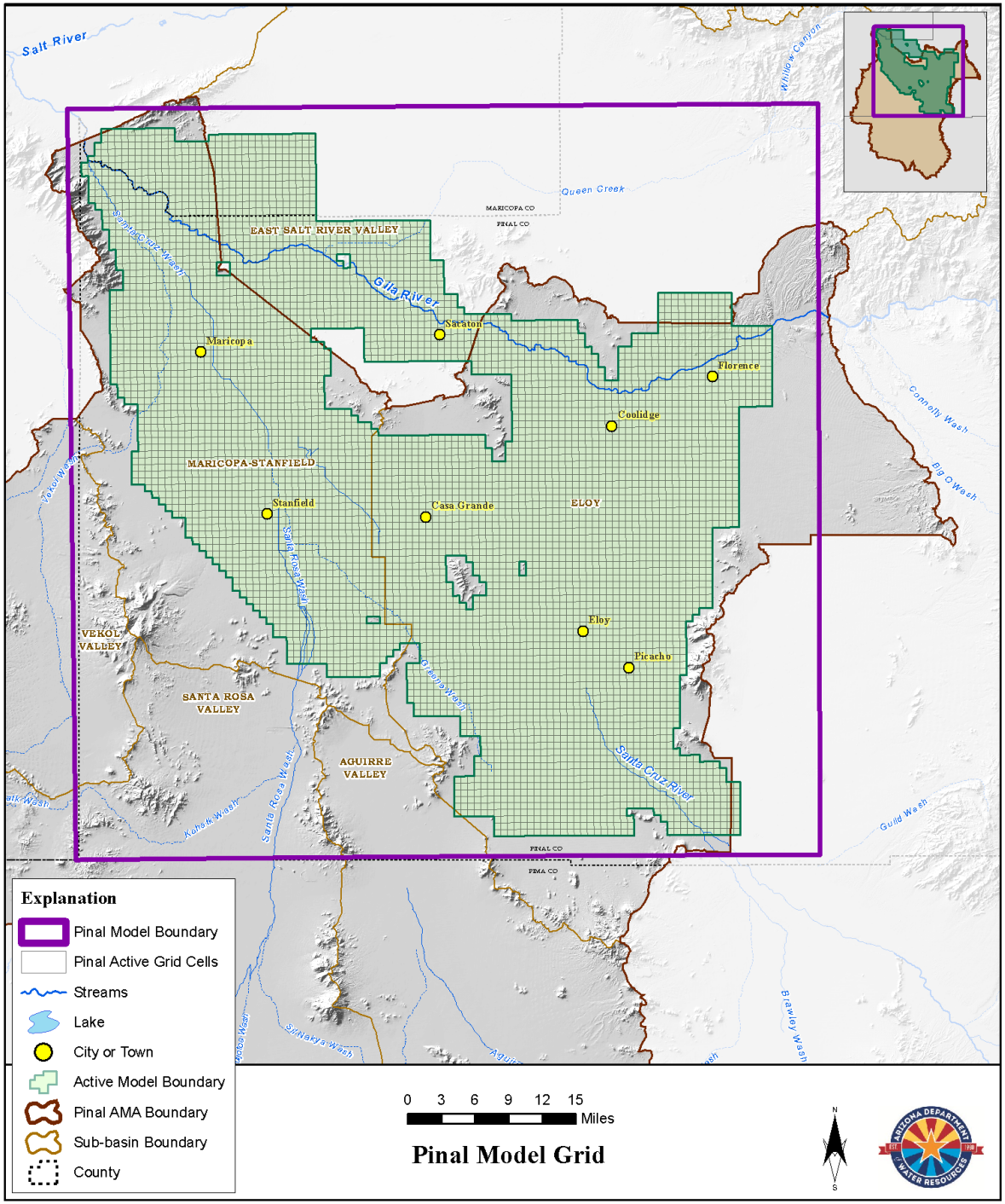
Historic Land Subsidence In the Pinal AMA

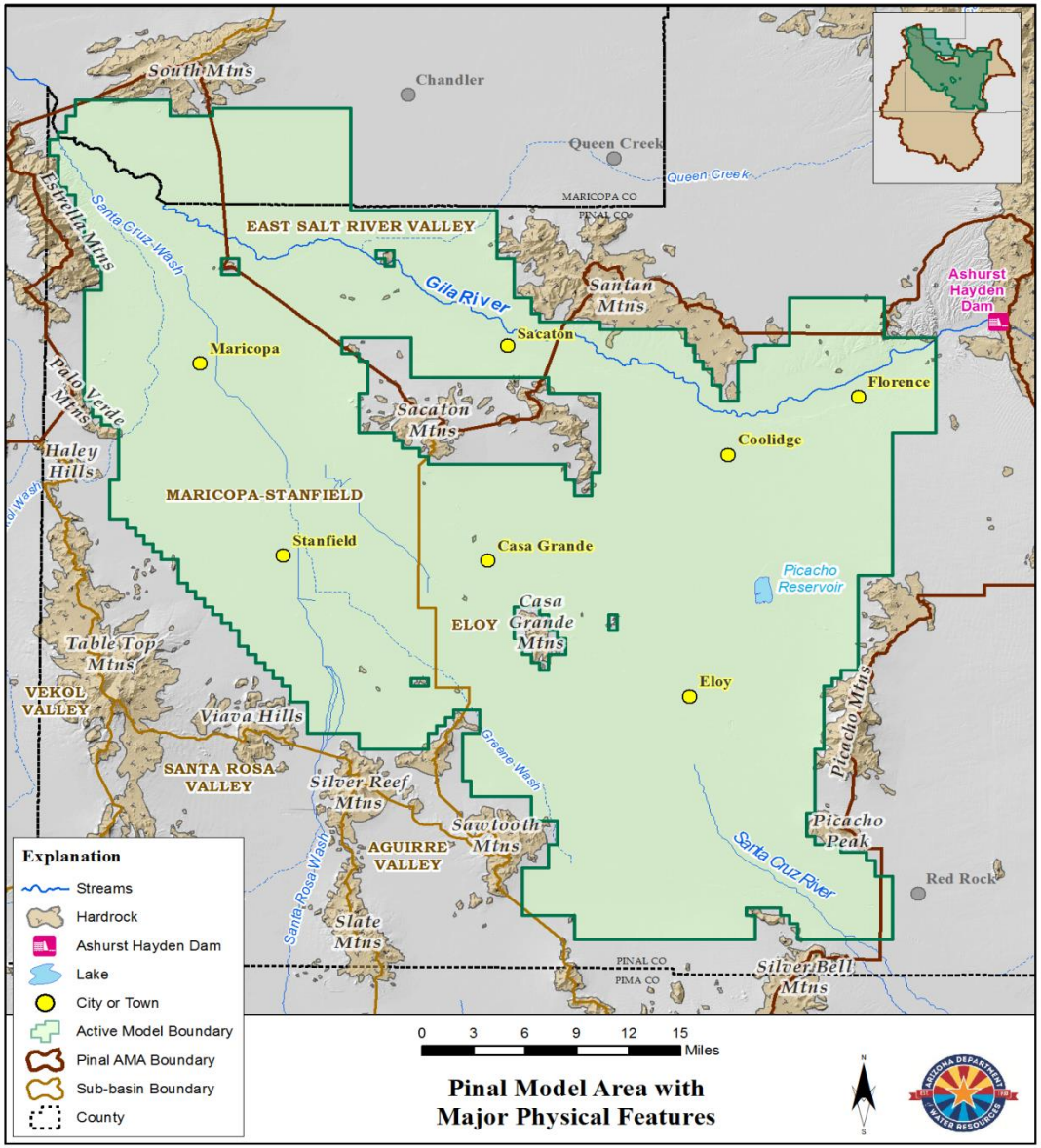




Pinal Model - Area

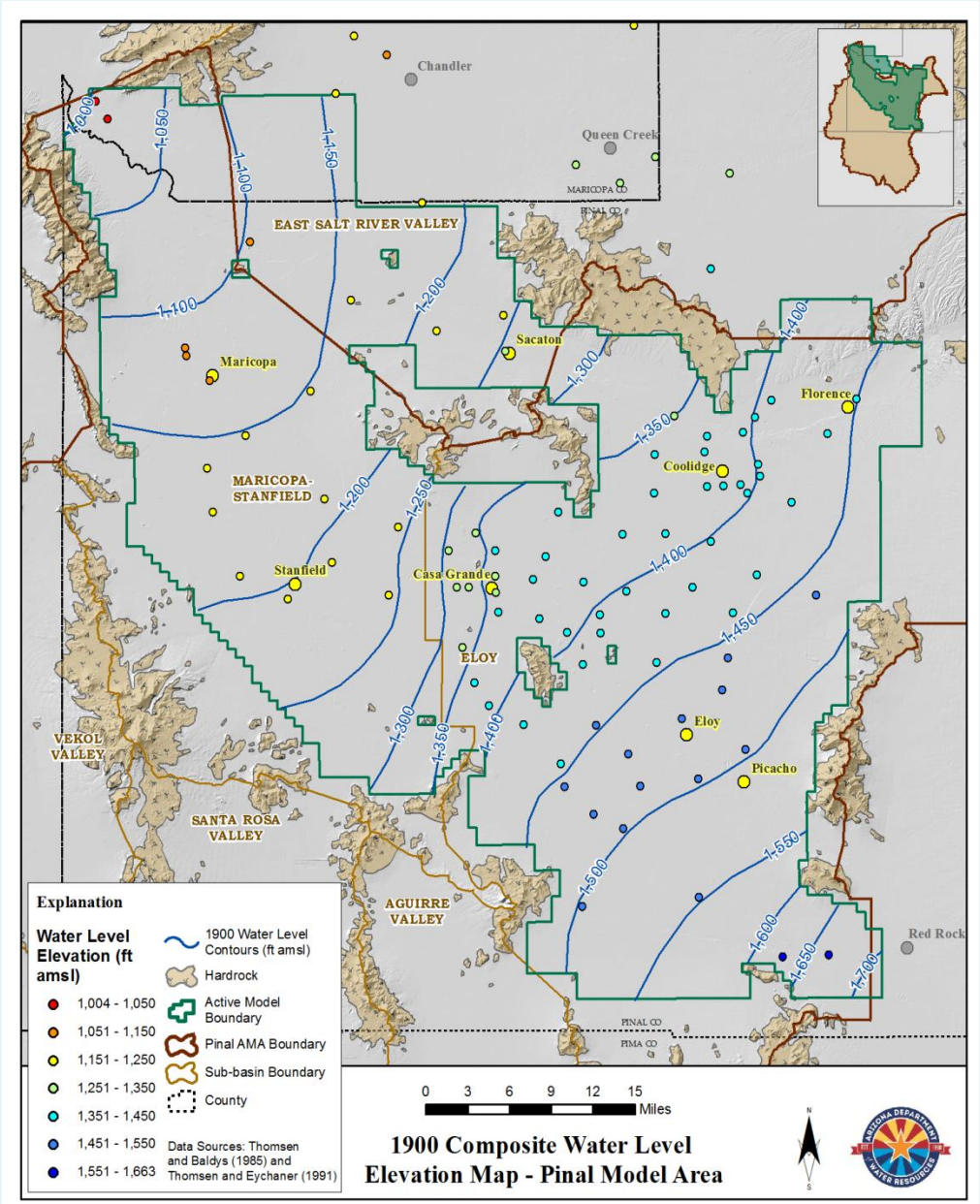
- **Active Grid**
  - **52.5 Miles by 51 Miles**
  - **Cell Size - 1/2 x 1/2 Mile**
  - **106 Rows**
  - **103 Columns**
  - **6,052 Cells**
  - **3 Model Layers**
- **Steady-State Period**
  - **Circa 1922**
- **Transient Period**
  - **1923 - 2009**

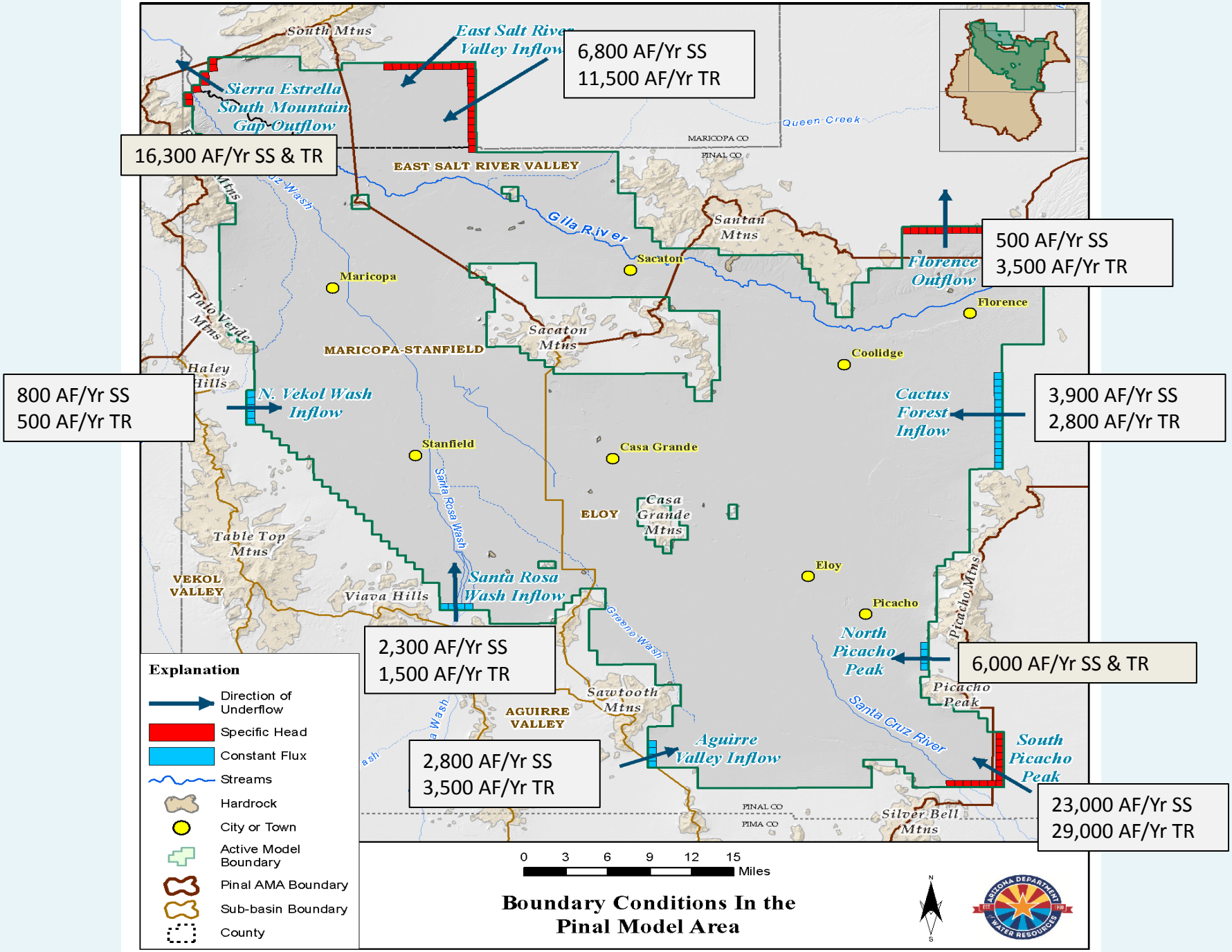




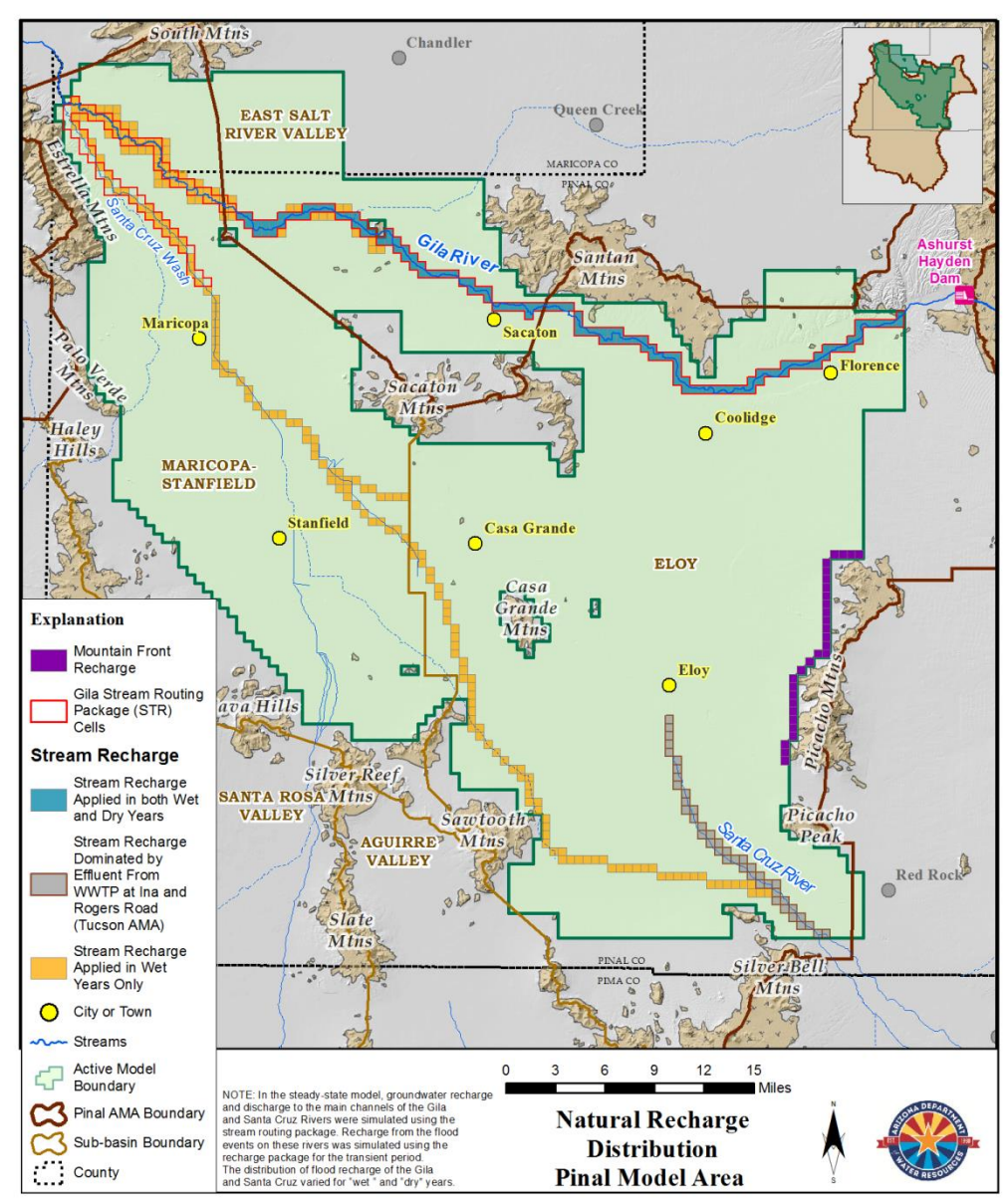
Pinal Model Area with Major Physical Features

The Steady – State System

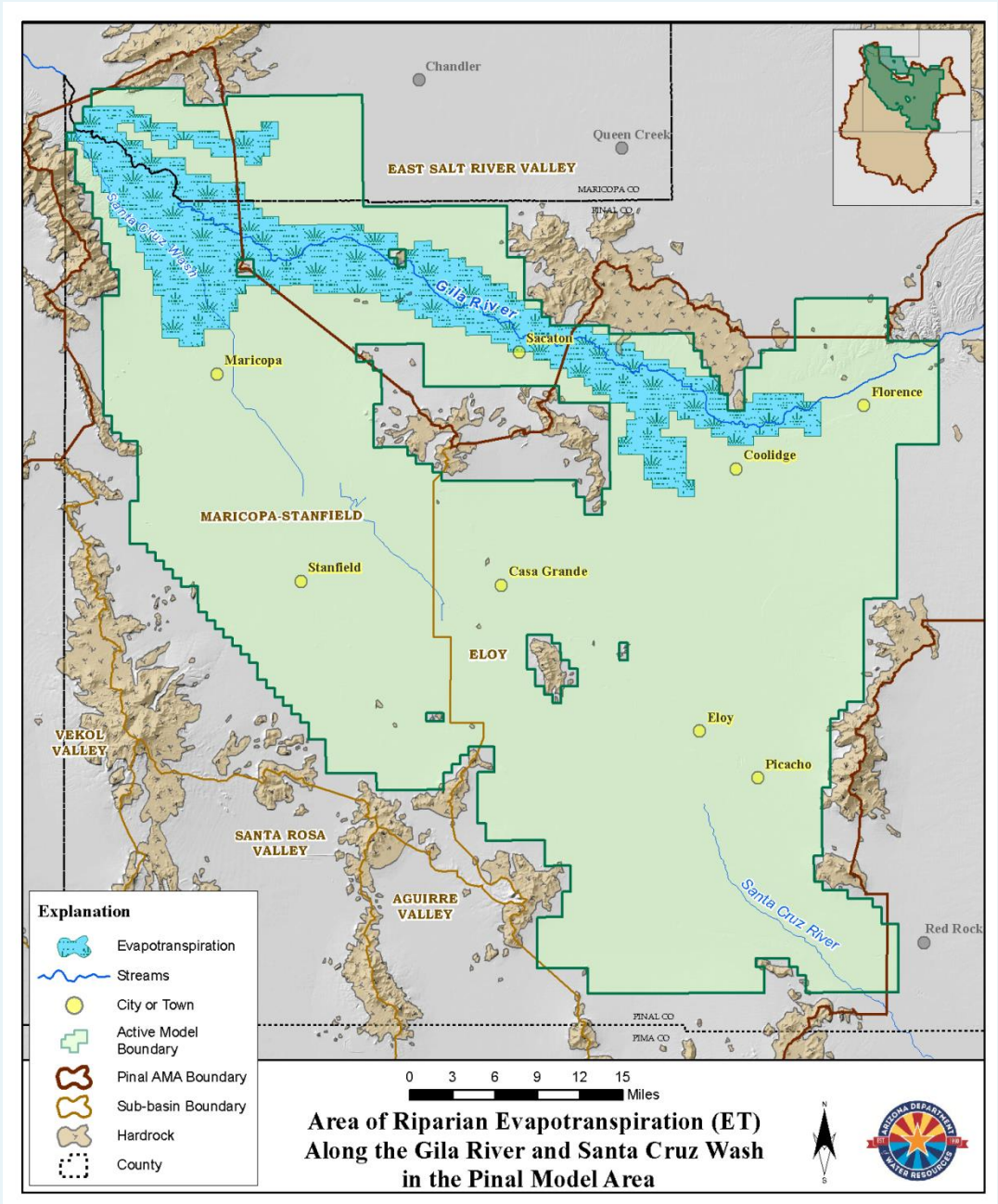



East Salt River Valley Inflow
6,800 AF/Yr SS
11,500 AF/Yr TR
Sierra Estrella South Mountain Gap Outflow
16,300 AF/Yr SS & TR
South Mtns
EAST SALT RIVER VALLEY
Queen Creek
MARICOPA CO
PINAL CO
Gila River
Santan Mtns
Sacaton
Maricopa
Florence Outflow
500 AF/Yr SS
3,500 AF/Yr TR
Florence
Sacaton Mtns
MARICOPA-STANFIELD
Coolidge
Haley Hills
N. Vekol Wash Inflow
800 AF/Yr SS
500 AF/Yr TR
Cactus Forest Inflow
3,900 AF/Yr SS
2,800 AF/Yr TR
Stanfield
Casa Grande
Santa Rosa Wash
ELOY
Casa Grande Mtns
Table Top Mtns
VEKOL VALLEY
Viava Hills
Santa Rosa Wash Inflow
Eloy
Picacho
Picacho Mtns
North Picacho Peak
6,000 AF/Yr SS & TR
2,300 AF/Yr SS
1,500 AF/Yr TR
Greene Wash
Sawtooth Mtns
AGUIRRE VALLEY
Picacho Peak
Santa Cruz River
Aguirre Valley Inflow
South Picacho Peak
2,800 AF/Yr SS
3,500 AF/Yr TR
23,000 AF/Yr SS
29,000 AF/Yr TR
Silver Bell Mtns
PINAL CO
PIMA CO
Explanation
Direction of Underflow
Specific Head
Constant Flux
Streams
Hardrock
City or Town
Active Model Boundary
Pinal AMA Boundary
Sub-basin Boundary
County
0 3 6 9 12 15 Miles
Boundary Conditions In the Pinal Model Area
ARIZONA DEPARTMENT OF WATER RESOURCES

Sources of Natural Recharge In the Pinal Model Area



Riparian Evapotranspiration Was The Major Source of Steady-State Groundwater Outflow

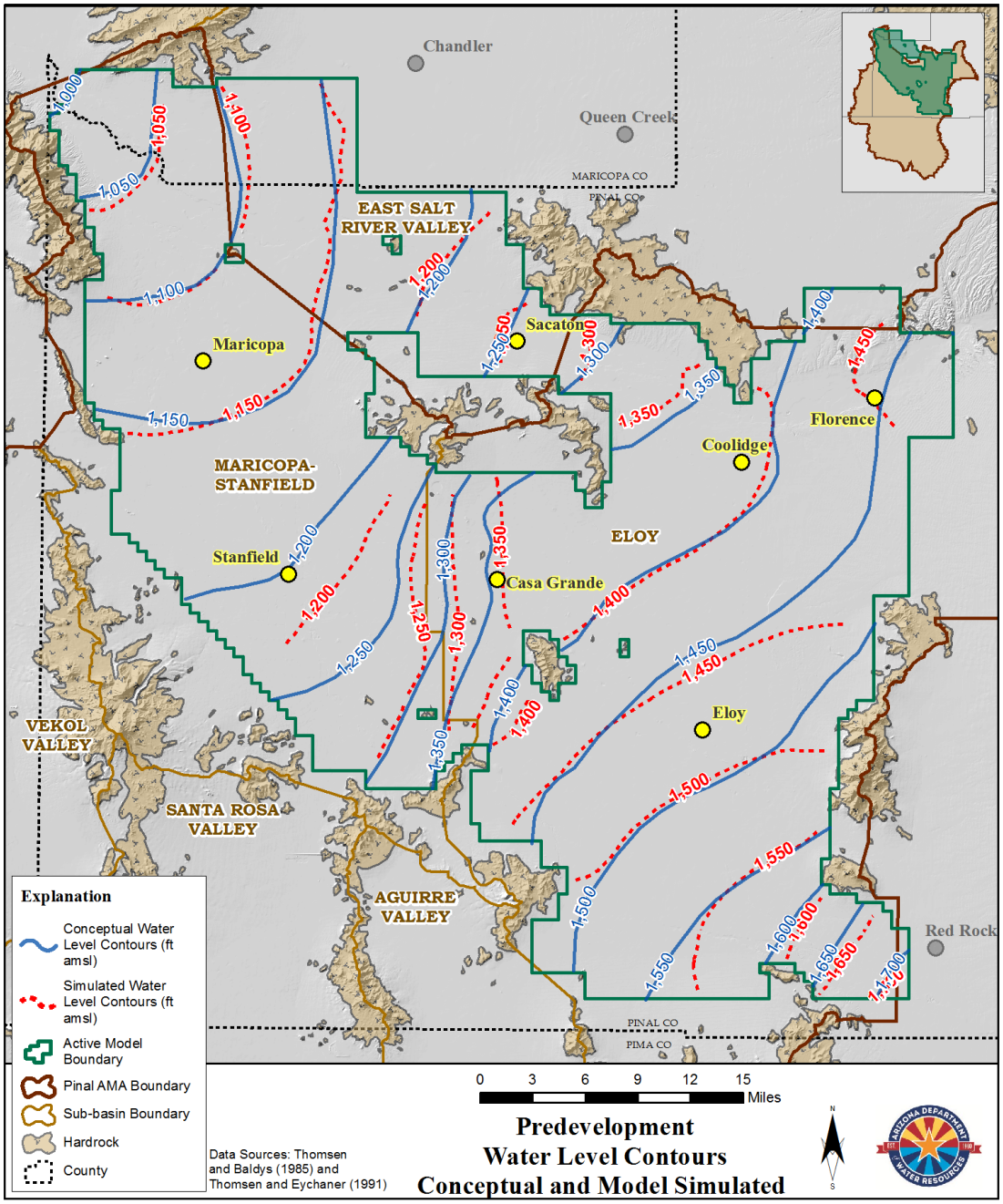


Conceptual and Simulated Steady-State Water Budgets

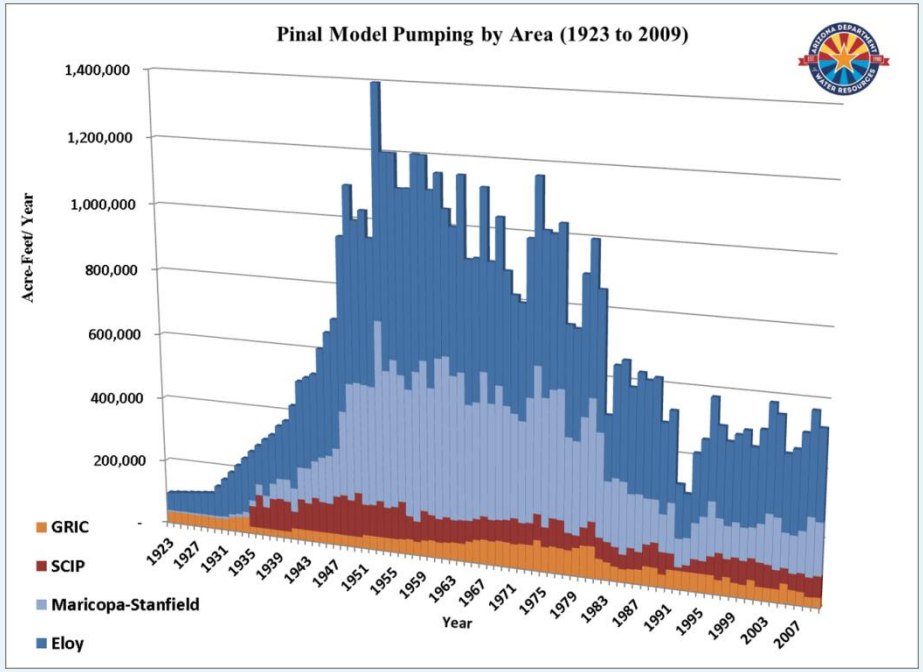
	Conceptual Steady-state Budget (AFY)	Model Simulated Steady-state Budget (Base Solution) (AFY)
Inflow		
Total Underflow	45,600	37,794
Mountain Front Recharge	500	499
Stream Infiltration recharge	94,000	92,642
Total Inflow	140,100	130,935
Outflow		
ET	97,100	95,870
Stream Discharge	21,300	20,377
Total underflow	16,800	14,688
Total Outflow	135,200	130,935

1 Components of the Conceptual Water Budget Were Estimated Independently and Therefore the Total Conceptual Steady-state Inflow and Outflow Does Not Match Exactly

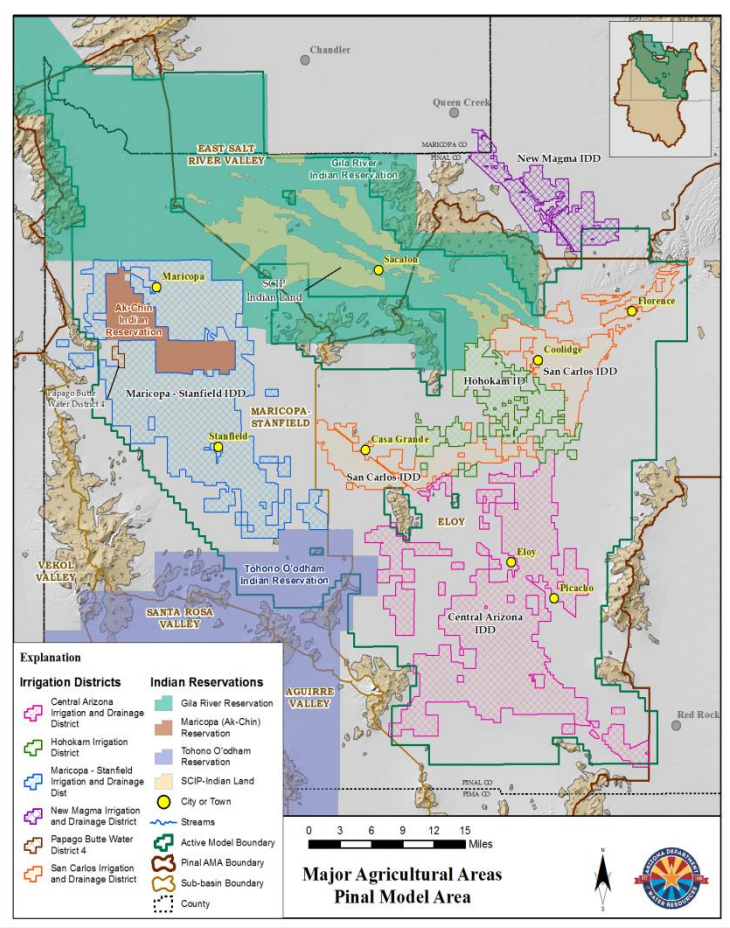
Steady-State Model Results

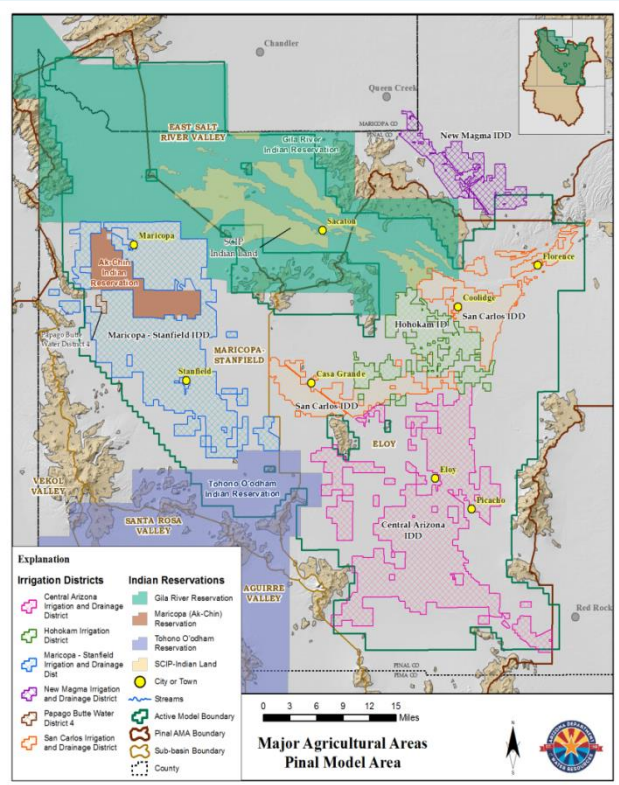


Major Irrigation Districts and Areas of Indian Agriculture, Historical Groundwater Pumping and CAP Agricultural Water Deliveries In the Pinal AMA



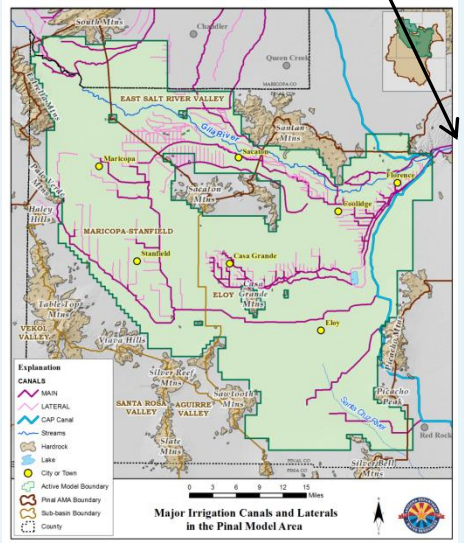
Average Annual CAP AG Water Use In The Pinal AMA (Acre-Feet)				
Irrigation District	**1988-1989**	**1990-1999**	**2000-2009**	**2010-2012**
Hohokam IDD	10,875	44,860	67,199	40,920
Central Arizona IDD	71,169	119,358	153,950	131,898
Maricopa-Stanfield IDD	153,223	150,889	150,287	133,909
GRIC-Pinal GSFs	0	0	0	155,574
San Carlos ID	0	9,542	9,210	13,172
GRIC	0	7,803	23,873	37,886
Ak-Chin	60,697	73,081	73,943	77,484
Average Annual CAP/Period	295,963	405,534	478,462	590,843
Total CAP Per Time Period	591,925	4,055,339	4,784,617	1,772,528

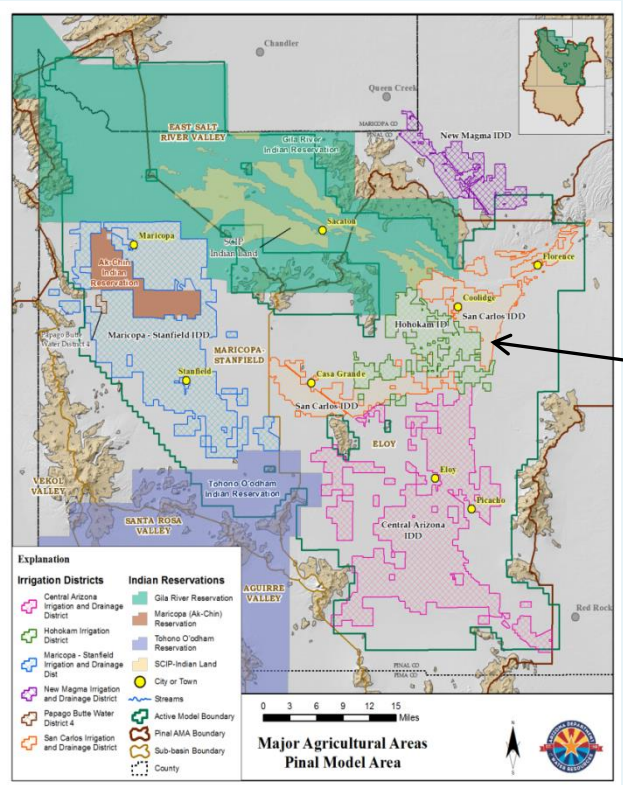




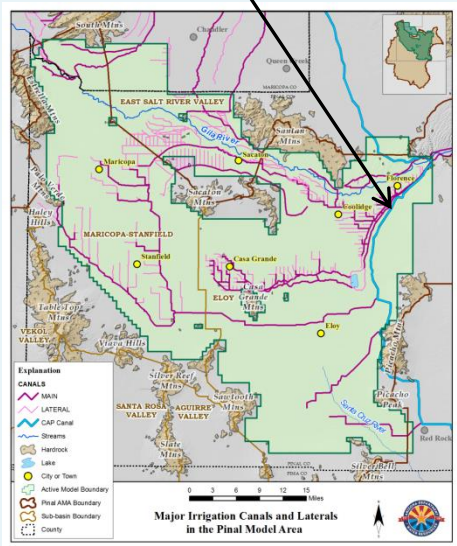
San Carlos Project Ashurst-Hayden Dam

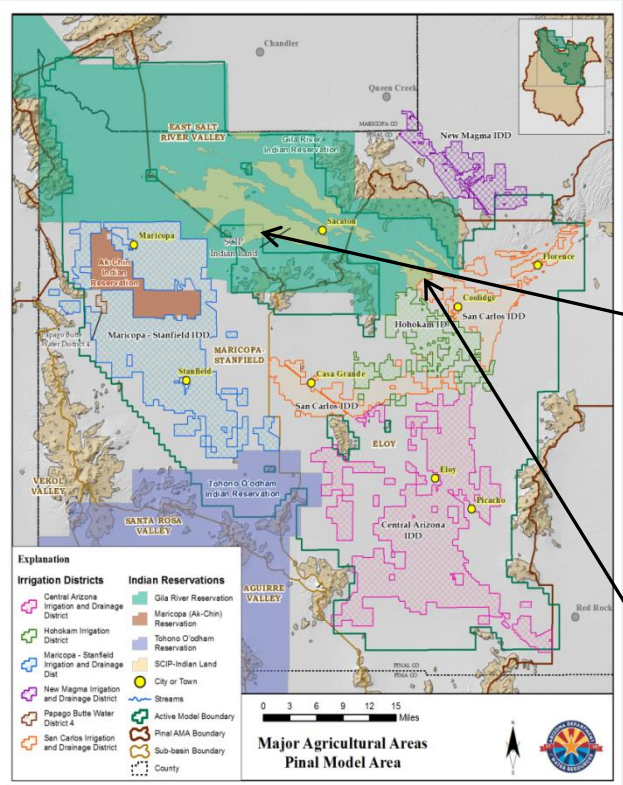
San Carlos Project
Florence- Casa Grande Canal at
Ashurst-Hayden Dam





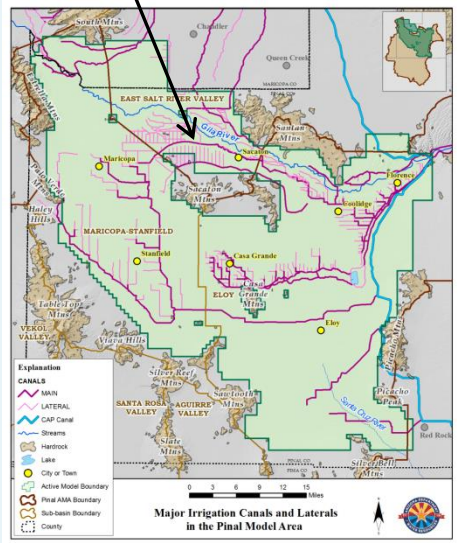
San Carlos Project Florence Canal
and Well NE Eloy Sub-basin





San Carlos Project Canal
on GRIC NW of Sacaton

Cotton Growing on San Carlos
Project Land Near Coolidge

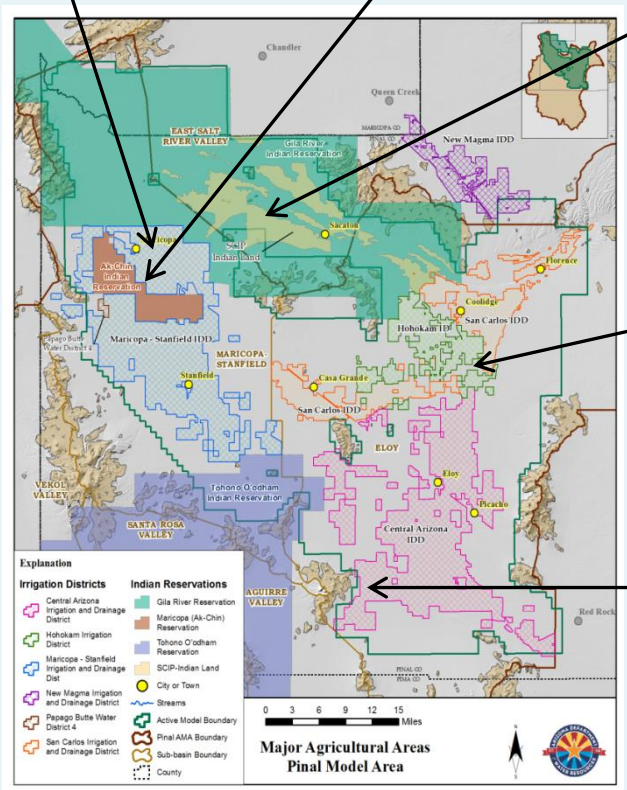


CAP Canal
Northern MSIDD

Ak-Chin Irrigated
Land in Distance

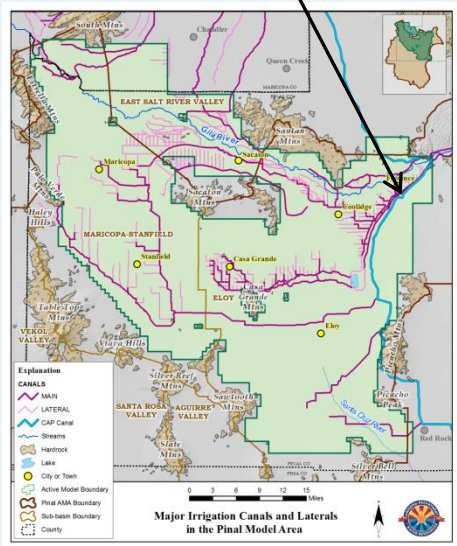
New Canal on GRIC

Central Arizona Project
Aqueduct NE Eloy Sub-basin

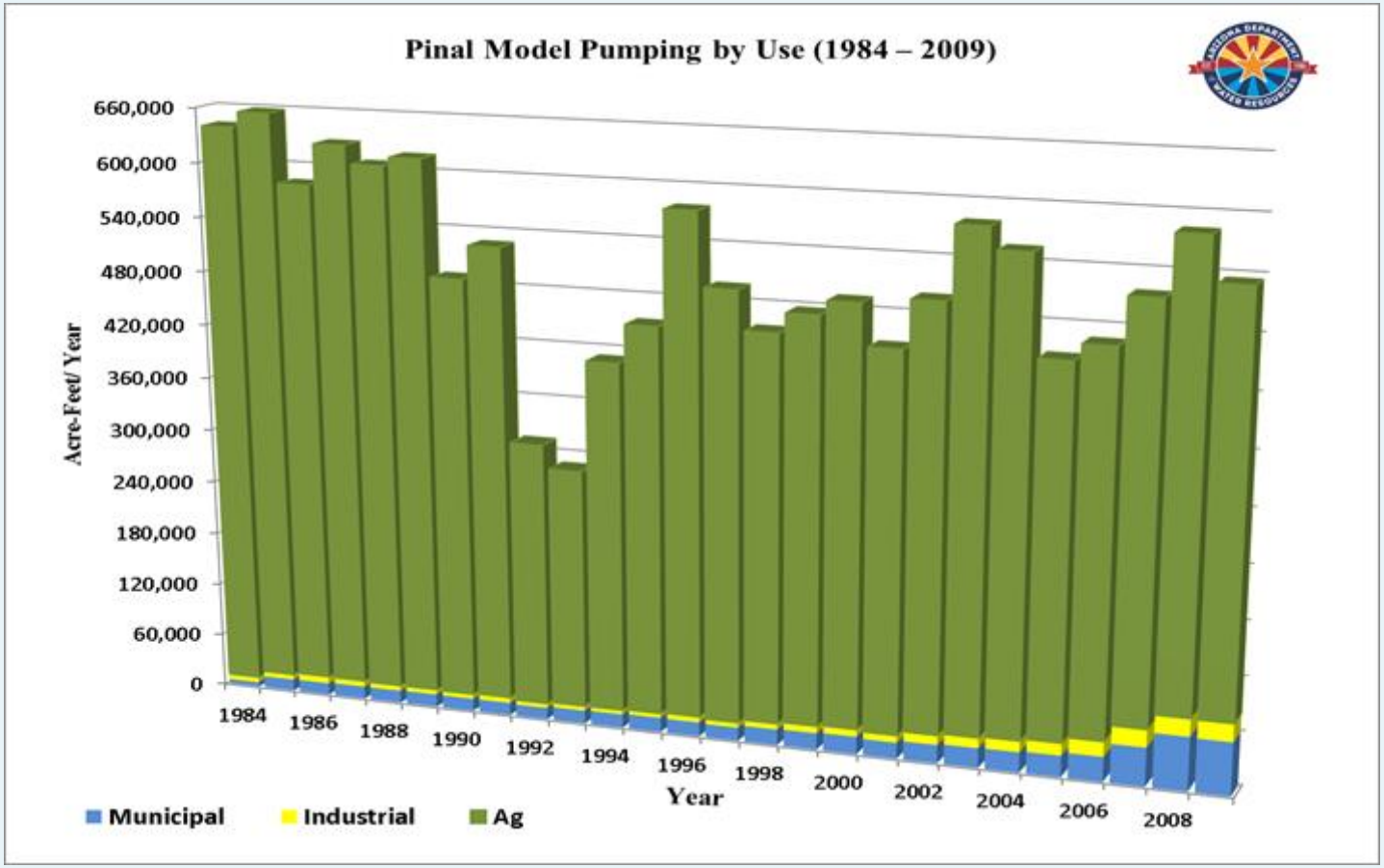


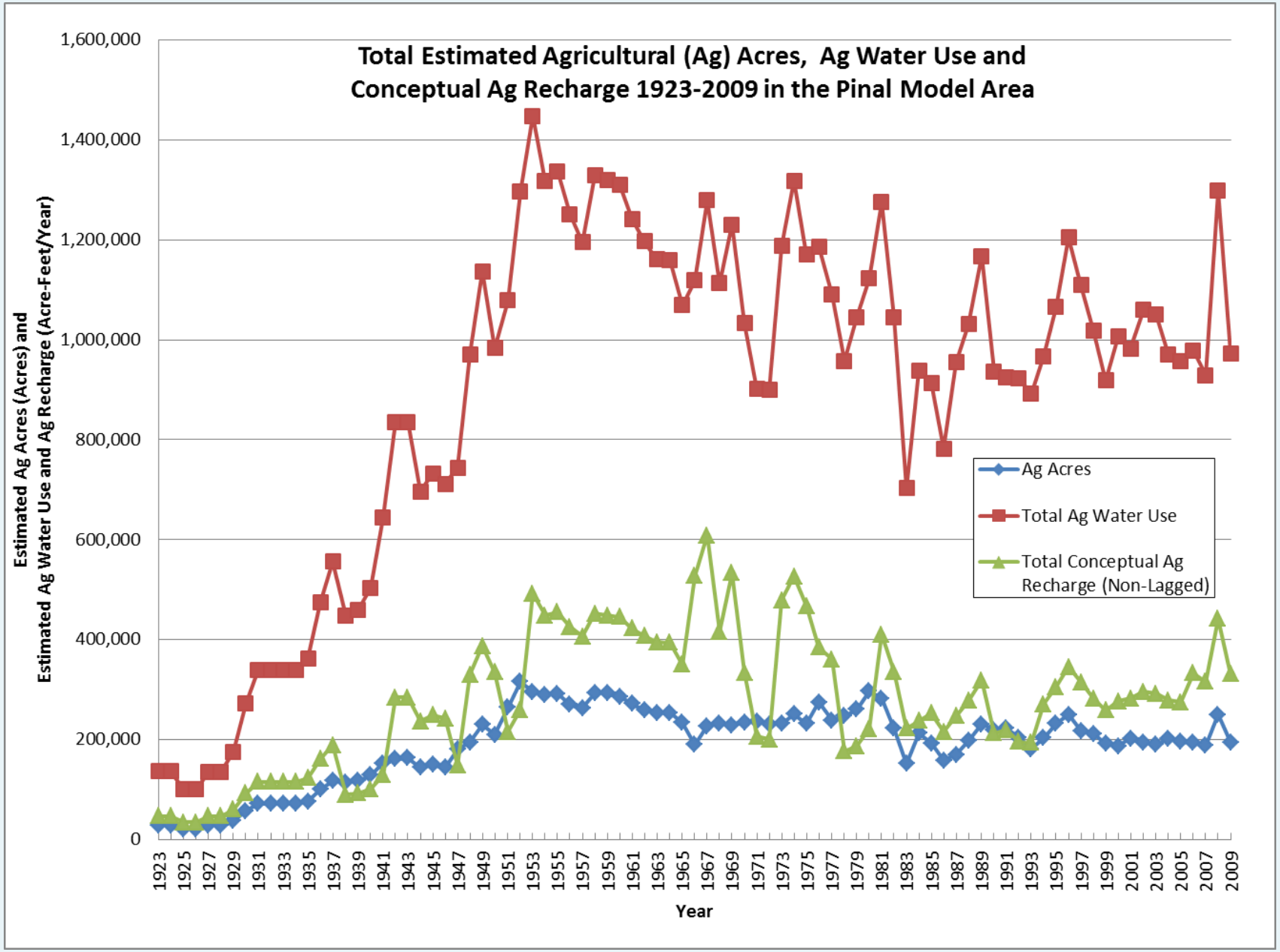
CAP Canal Hohokam IDD

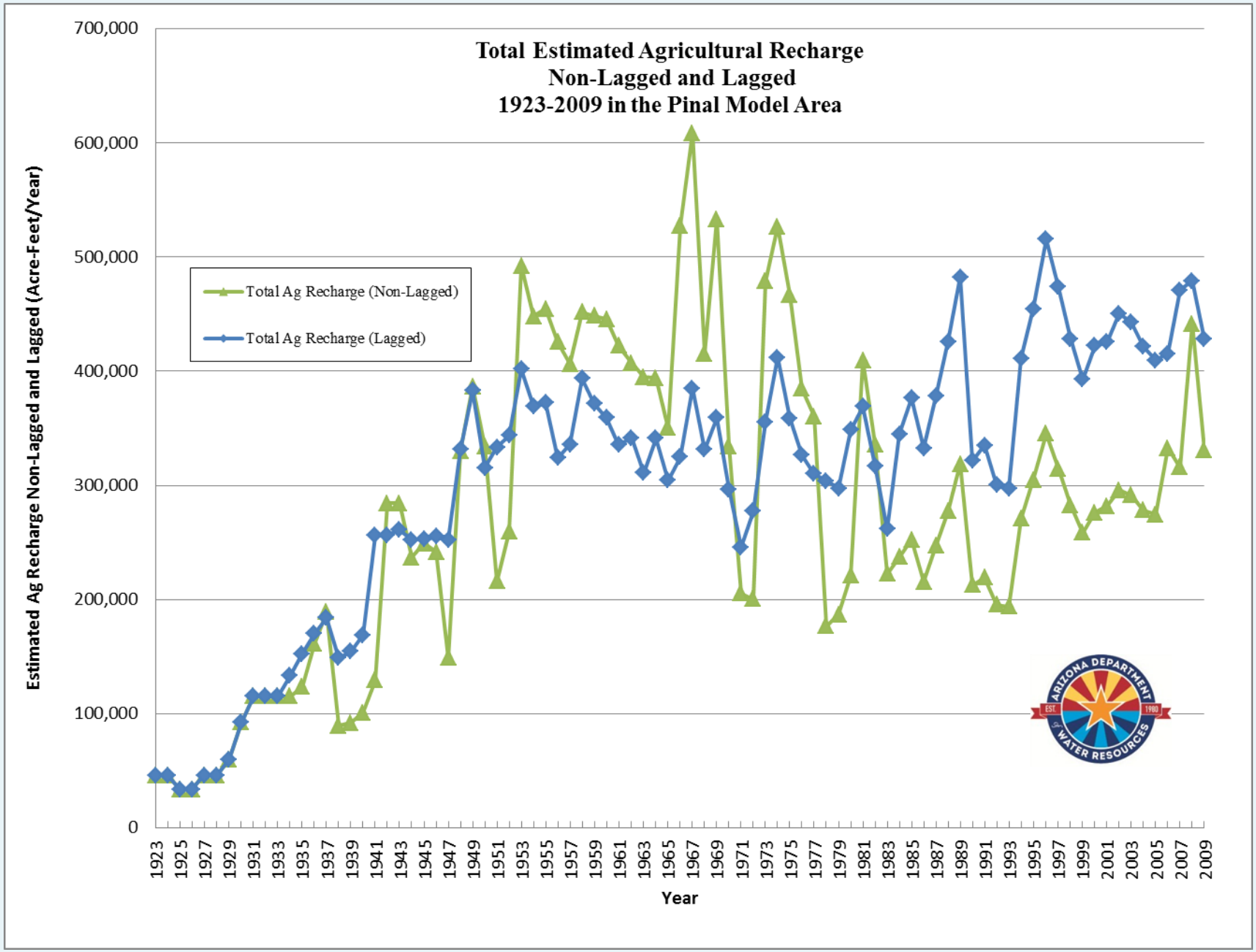
Cotton in SW CAIDD



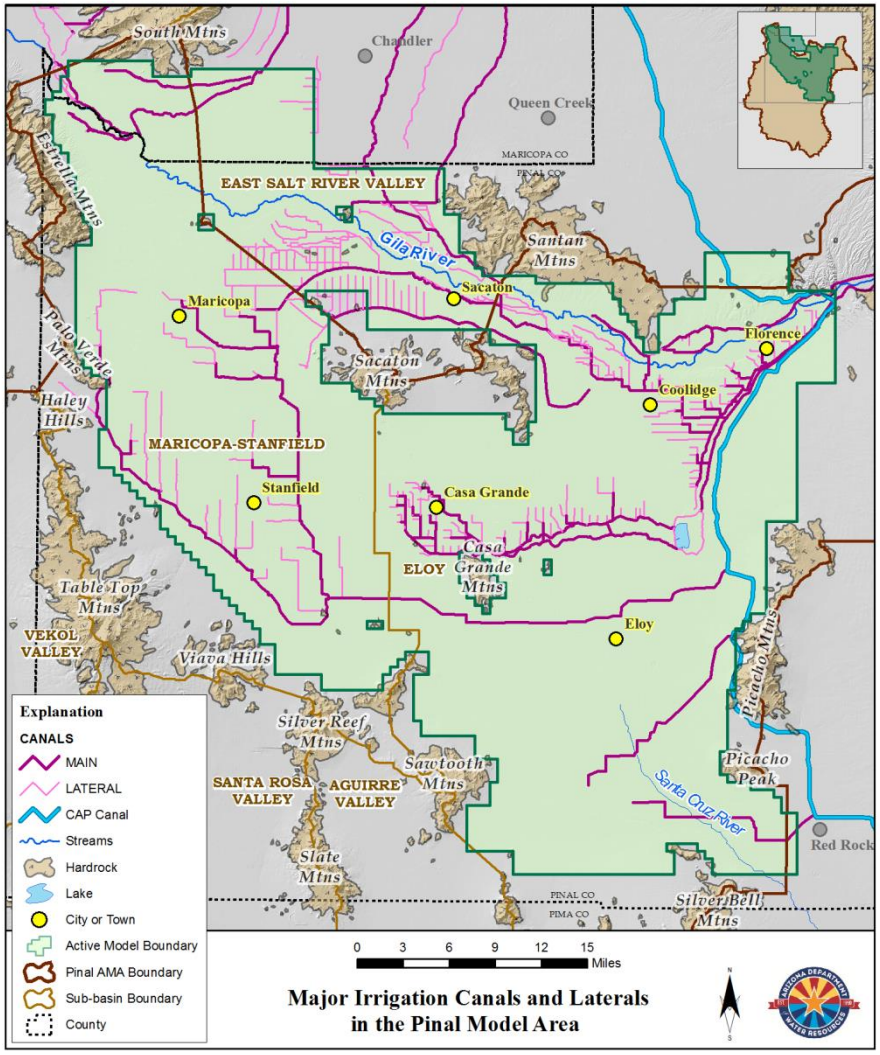
ADWR Has Received Annual Groundwater Use Data Since 1984



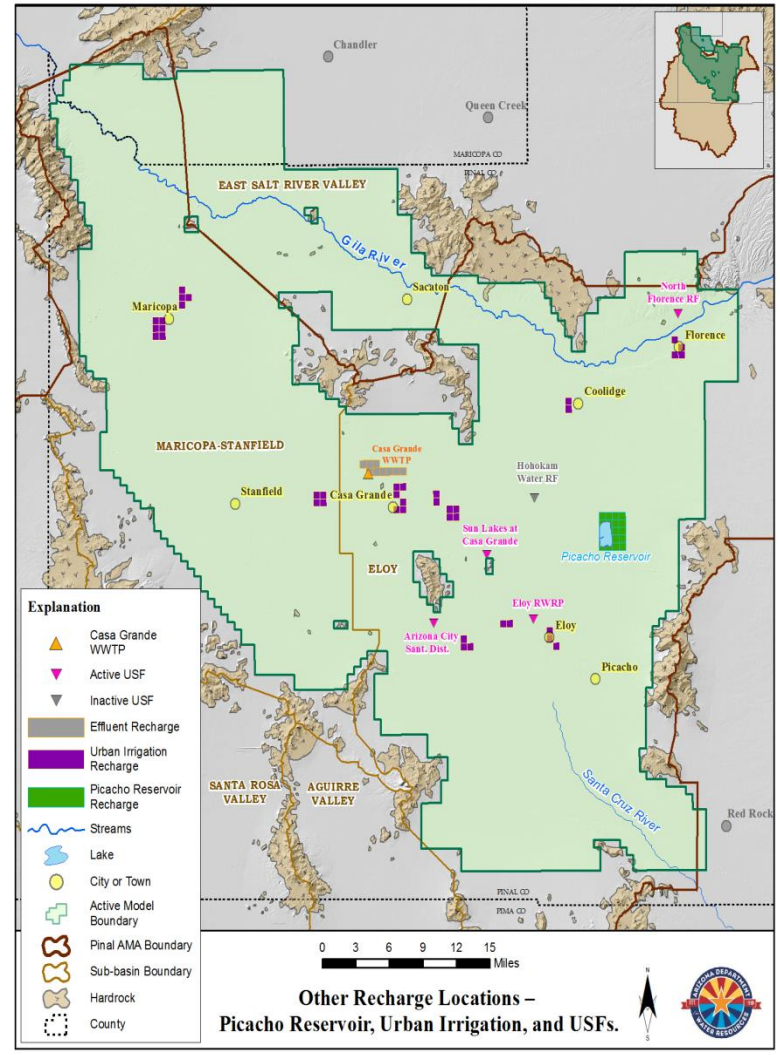

Total Estimated Agricultural (Ag) Acres, Ag Water Use and Conceptual Ag Recharge 1923-2009 in the Pinal Model Area
Estimated Ag Acres (Acres) and Estimated Ag Water Use and Ag Recharge (Acre-Feet/Year)
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
Year
Ag Acres
Total Ag Water Use
Total Conceptual Ag Recharge (Non-Lagged)


Total Estimated Agricultural Recharge
Non-Lagged and Lagged
1923-2009 in the Pinal Model Area
Total Ag Recharge (Non-Lagged)
Total Ag Recharge (Lagged)
Estimated Ag Recharge Non-Lagged and Lagged (Acre-Feet/Year)
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1923
1925
1927
1929
1931
1933
1935
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
Year
ARIZONA DEPARTMENT OF WATER RESOURCES
EST. 1980

Additional Sources of Incidental Recharge In Transient Model



Major Irrigation Canals and Laterals in the Pinal Model Area



Other Recharge Locations – Picacho Reservoir, Urban Irrigation, and USFs.

Conceptual Water Budgets For SS and Transient Periods (1923-2009)

Time	SS[2]	1923-1929	1930- 1939	1940-1949	1950-1959	1960-1969	1970-1979	1980- 1989	1990-1999	2000-2009
Inflows										
Groundwater Underflow (Total For all Model Boundaries)[1]	45,600	47,000	48,000	49,000	50,000	51,000	52,000	53,000	54,000	54,700
Agricultural Recharge (non-lagged)	0	44,600	120,800	239,100	393,600	459,000	350,200	308,000	283,000	324,700
Canal Recharge (SCIP and CAP)	0	0	66,200	89,200	72,000	95,100	114,100	170,800	125,500	95,400
Picacho Reservoir Recharge	0	0	5,400	6,700	4,800	6,000	6,000	7,300	5,100	2,500
Mountain Front Recharge	500	500	500	500	500	500	500	500	500	500
Gila River Flood Recharge	94,000	24,100	17,300	7,900	15,200	15,800	28,000	90,400	111,300	18,000
Santa Cruz River Recharge (flood and effluent from TAMA)	0	0	0	6,000	13,800	10.000	31,700	36,500	23,700	26,500
Effluent and Artificial Recharge	0	0	0	0	0	0	0	1,300	1,400	1,900
Urban Irrigation	0	0	0	0	0	0	0	800	900	1,800
Total of Estimated Inflow Components	140,100	116,200	258,200	398,400	549,900	627,410	582,500	668,600	605,400	526,000
Outflows										
Groundwater Underflow (Total For all Model Boundaries)[1,3]	16,800	17,000	17,300	17,600	17,900	18,200	18,500	18,800	19,100	19,700
Pumping	0	83,600	244,600	635,400	1,142,500	1,036,900	917,300	702,600	445,600	490,900
Evapotranspiration (Gila & Santa Cruz areas only on GRIC)[3]	97,100	64,300	29,000	23,000	23,000	23,000	23,000	23,000	23,000	23,000
Gila and Santa Cruz River Groundwater Discharge[3,4]	21,300	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total of Estimated Outflow Components	135,200	164,900	290,900	676,000	1,183,400	1,078,100	958,800	744,400	487,700	533,600

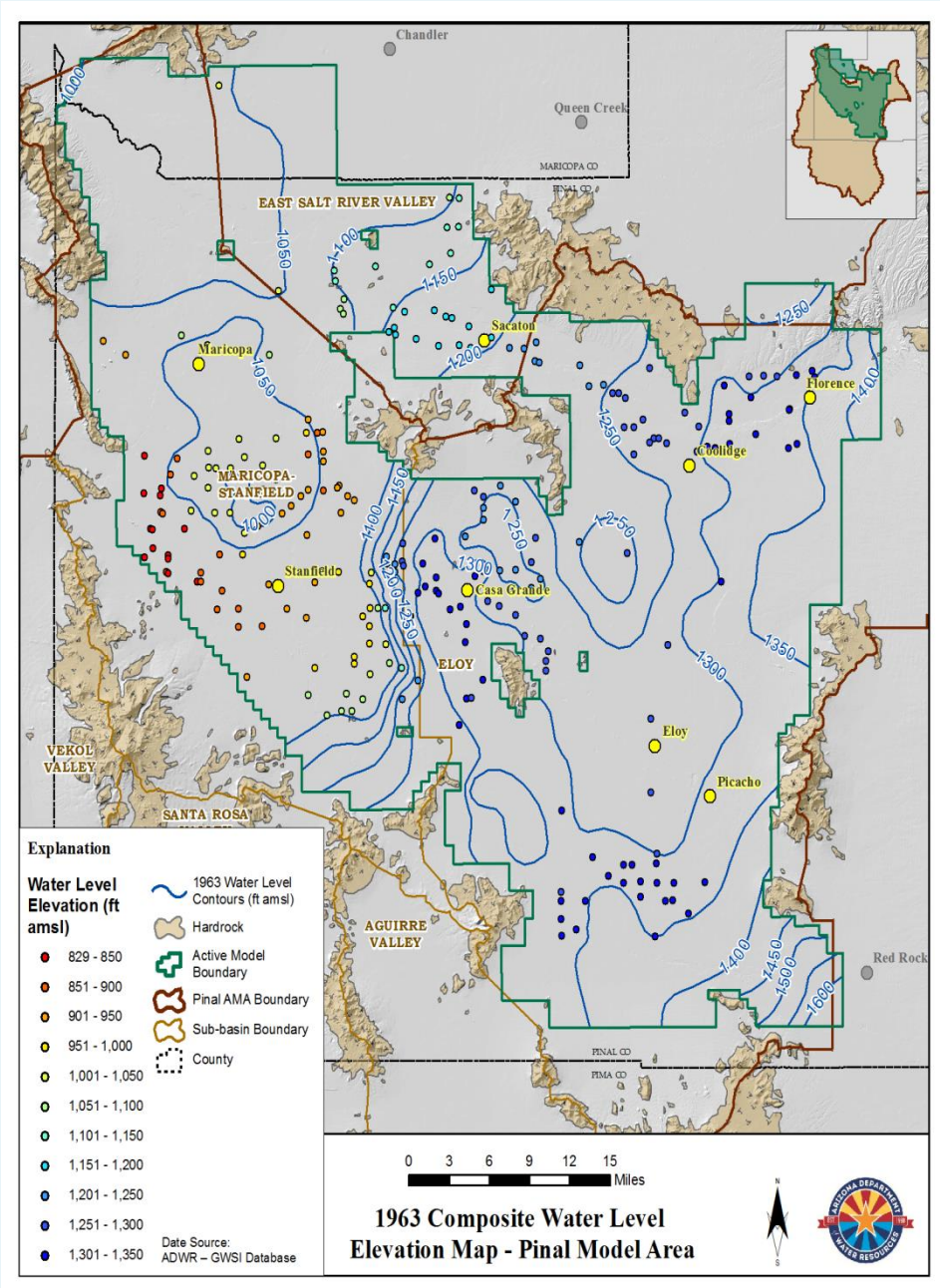
1 Estimates for periods from 1923-1999 based on interpolation between SS and 2000-2009 average rates

2 Conceptual estimates of SS Inflows and Outflows were independently developed and do not balance exactly

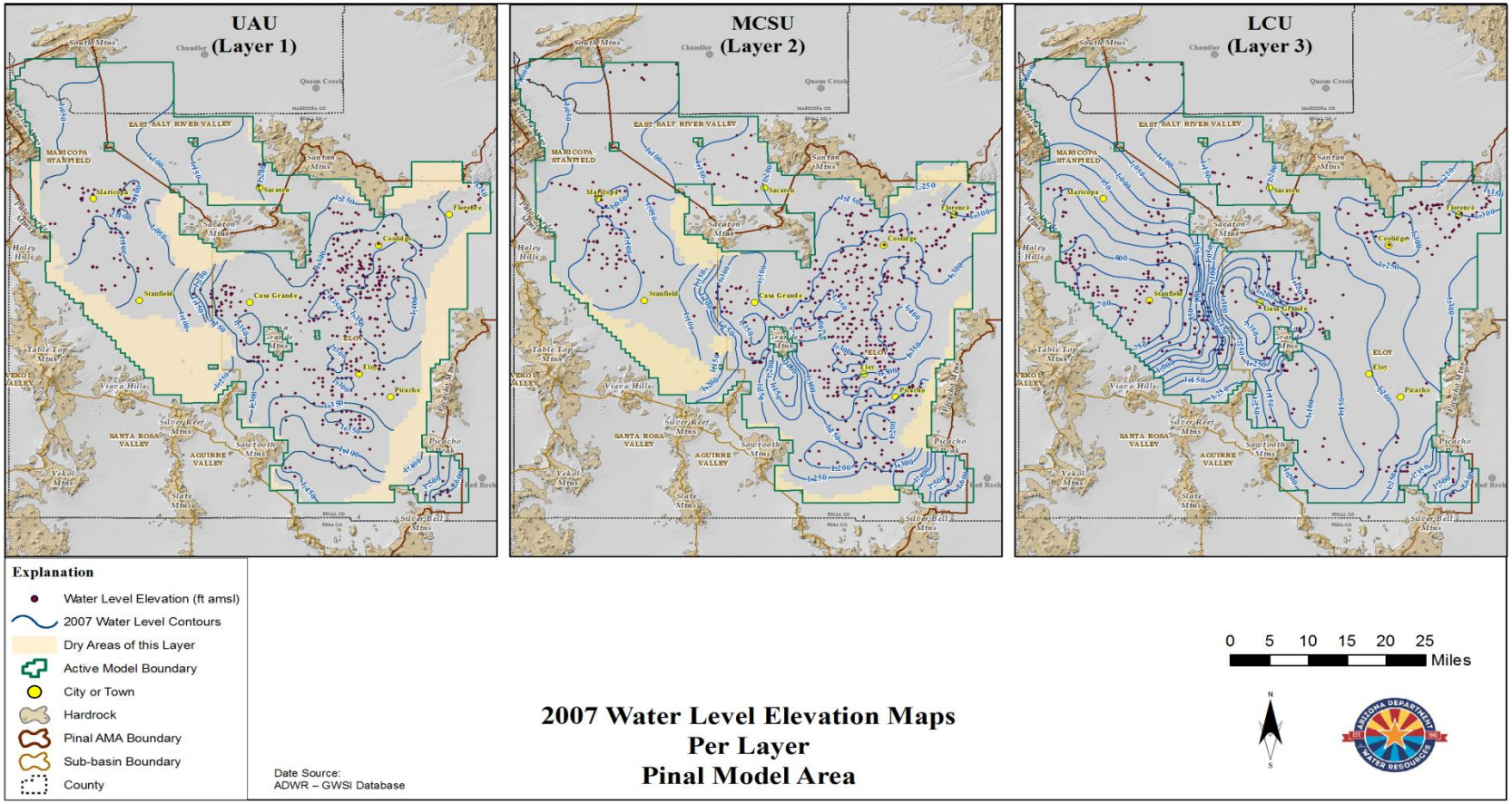
3 The close physical proximity between areas of groundwater underflow at the northwest model boundary, riparian ET and groundwater discharge to the channels of the Gila River and Santa Cruz Wash can be problematic for numerical model simulation.
Although these components of groundwater discharge may be independently estimated from available data, each component's individual simulation using a groundwater model is complicated due to their interactive head-dependency.

4 NA = Not Available. Independent estimate of this head-dependent recharge component were not made for transient calibration period

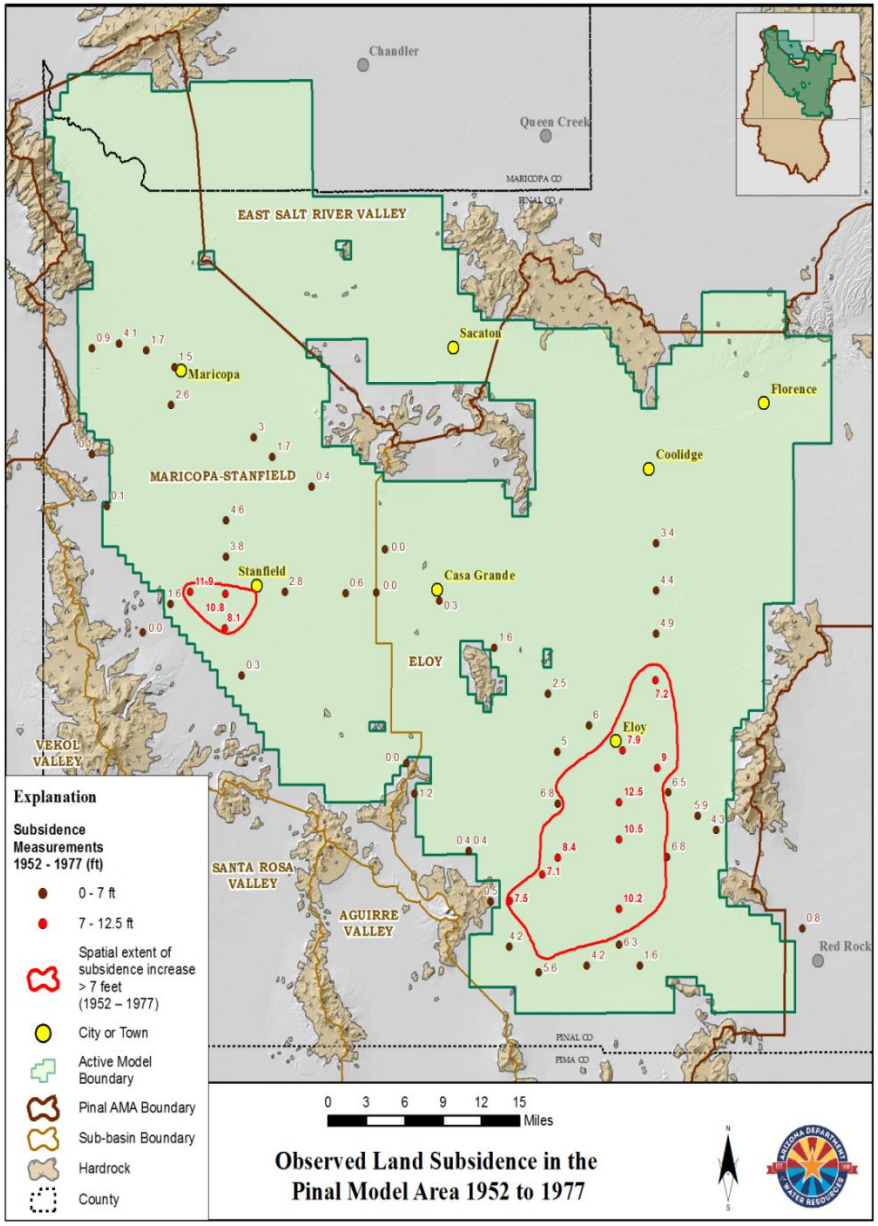
The Groundwater System Had Changed Substantially By 1963



A Very Complex Groundwater System Has Evolved By 2007



Land Subsidence Caused By Groundwater Pumping Has Impacted Large Areas of the AMA

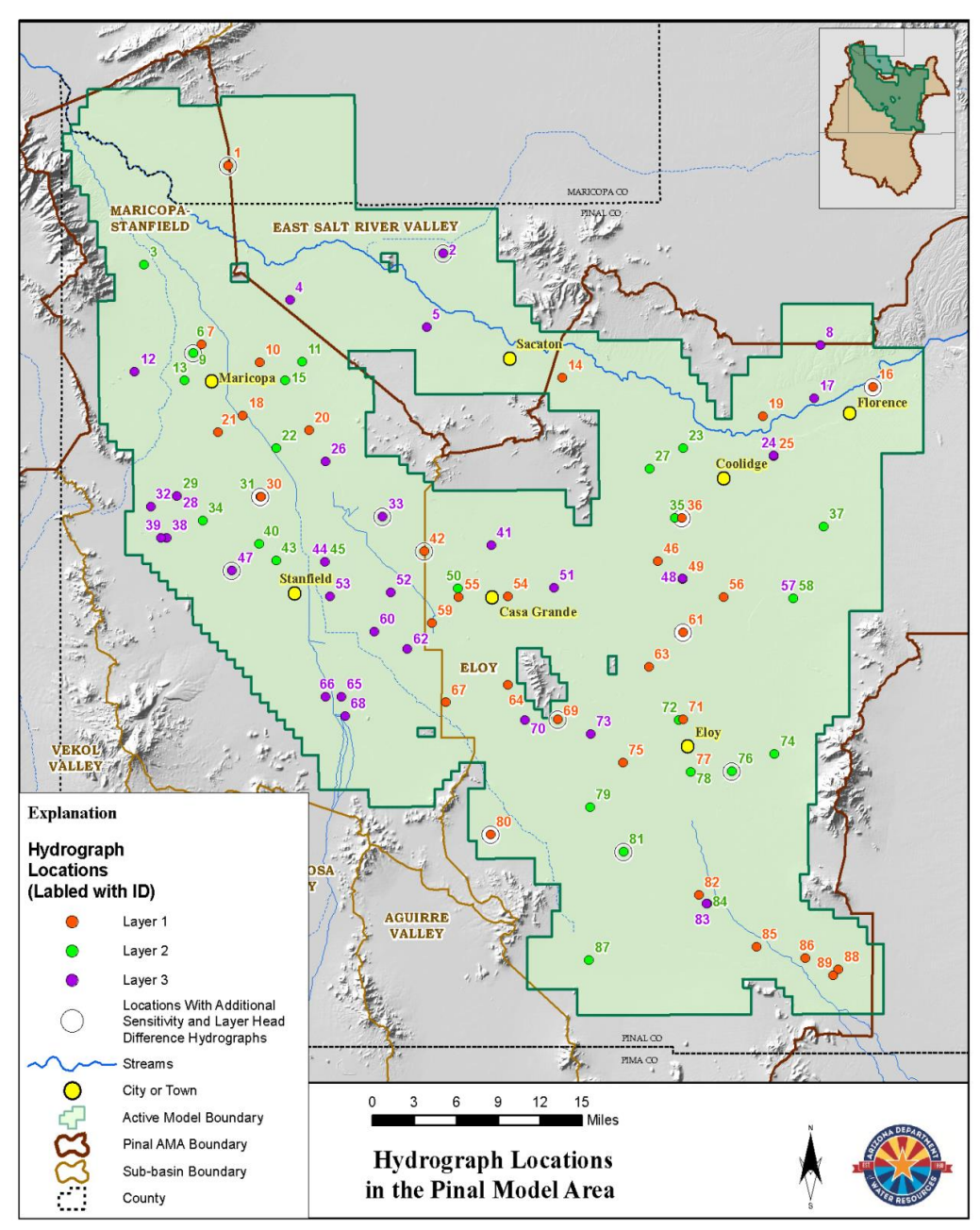


Model-Simulated Transient Water Budgets
With and Without Subsidence (SUB-SWT) Package

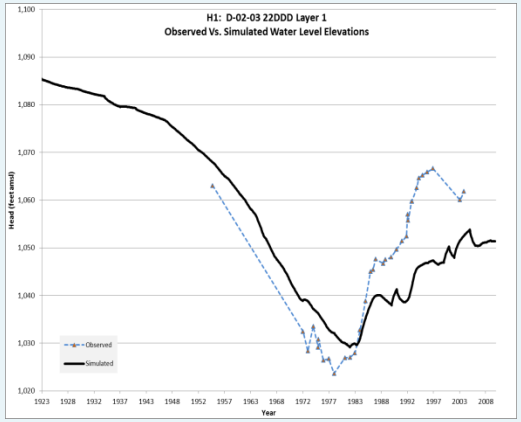
1923 - 2009 Simulated Water Budget (No SUB-SWT Simulation)	87 Year Cum. Total	Annualized Volume Over 87 Years	1923 - 2009 Simulated Water Budget (With SUB-SWT Simulation)	87 Year Cum. Total	Annualized Volume Over 87 Years	87 Year Difference (No SUB-SWT - SUB-SWT)
	AF	AFA		AF	AFA	AF
STORAGE	26,069,789	299,653	STORAGE	23,601,928	271,287	2,467,860
CONSTANT HEAD	2,742,529	31,523	CONSTANT Head	2,651,417	30,476	91,112
WELLS	1,222,018	14,046	WELLS	1,183,118	13,599	38,900
ET	0	0	ET	0	0	0
RECHARGE	39,086,318	449,268	RECHARGE	39,086,318	449,268	0
STREAM LEAKAGE	84,415	970	STREAM Leakage	105,928	1,218	-21,513
INTERBED Storage	0		INTERBED Storage	3,063,095	39,270	-3,063,095
TOTAL IN	69,203,398	795,441	TOTAL IN	69,690,083	801,035	-486,685
OUT:			OUT:			

STORAGE	9,844,526	113,155	STORAGE	9,113,814	104,756	730,713
CONSTANT HEAD	1,912,784	21,986	CONSTANT Head	2,028,463	23,315	-115,679
WELLS	55,275,482	635,350	WELLS	55,397,153	636,289	-121,671
ET	1,202,102	13,817	ET	1,278,522	14,696	-76,421
RECHARGE	0	0	RECHARGE	0	0	0
STREAM LEAKAGE	963,036	11,069	STREAM Leakage	1,038,626	11,938	-75,590
INTERBED Storage	0		INTERBED Storage	627,669	7,215	-627,669
TOTAL OUT	69,198,806	795,388	TOTAL OUT	69,483,471	890,813	2,467,860
IN - OUT	5,296	61	IN - out	206,686	2,376	-201,390
PERCENT DISCREPANCY			PERCENT Discrepancy			
Change in Storage	-16,225,262	-186,497	Change in Storage	-14,488,115	-166,503	-1,737,148
Change in Interbed Storage	0	0	Change in Interbed Storage	-2,435,426	-27,993	2,435,426
Total change in storage	-16,225,262	-186,497	Total change in storage	-16,923,540	-194,523	698,278

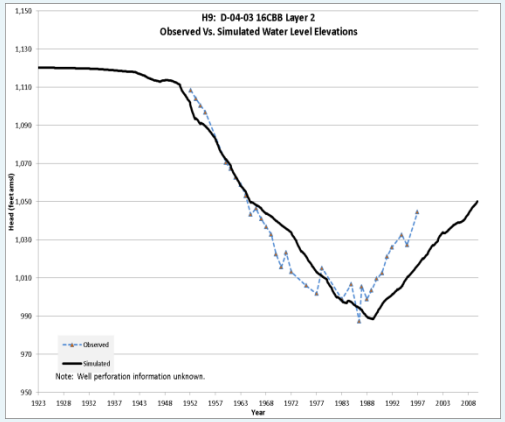
Locations of Wells Used to Evaluate the Model Calibration



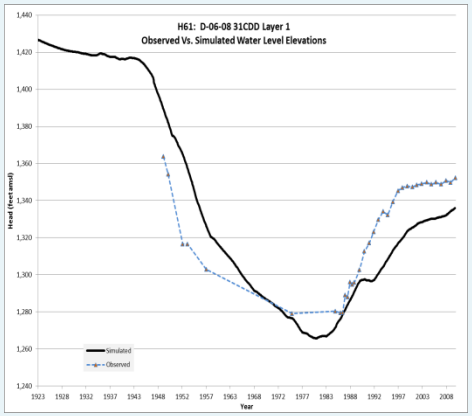
Selected Observed and Simulated Hydrographs



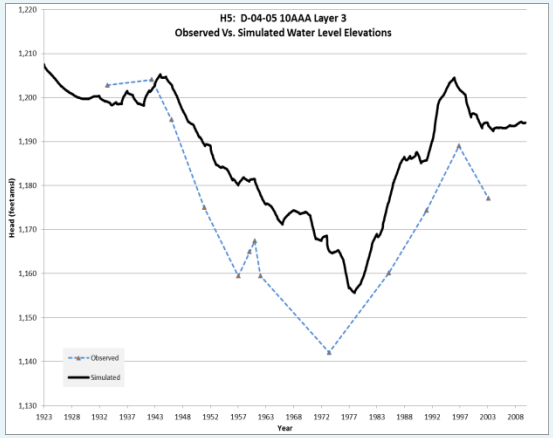
Maricopa-Stanfield Sub-basin
GRIC – Lone Butte Area



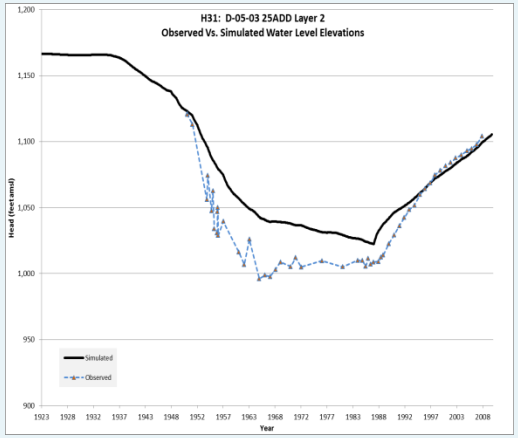
Maricopa-Stanfield Sub-basin
MSIDD Area – Near Maricopa



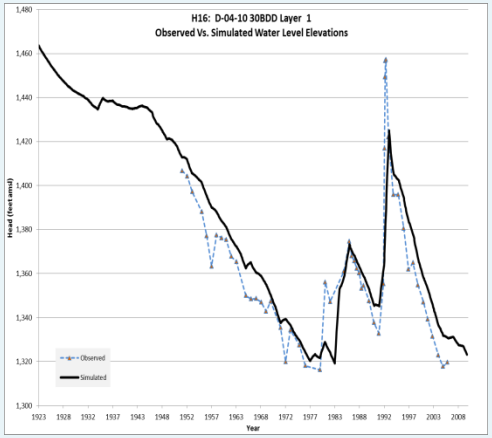
Eloy Sub-basin
SCIDD Area About 4 Miles West of Picacho Reservoir



Maricopa-Stanfield Sub-basin
GRIC/SCIP Area – about 9 Miles WNW of Sacaton

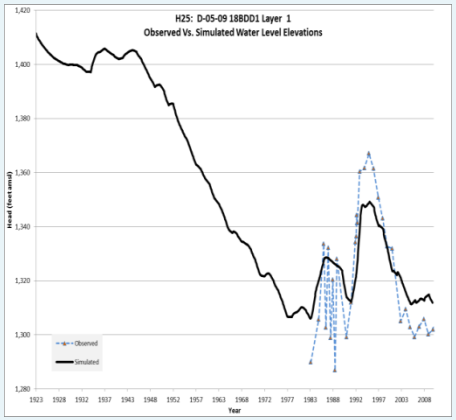


Maricopa-Stanfield Sub-basin
MSIDD/ S. Ak-Chin Area – 6 Miles NE of Stanfield

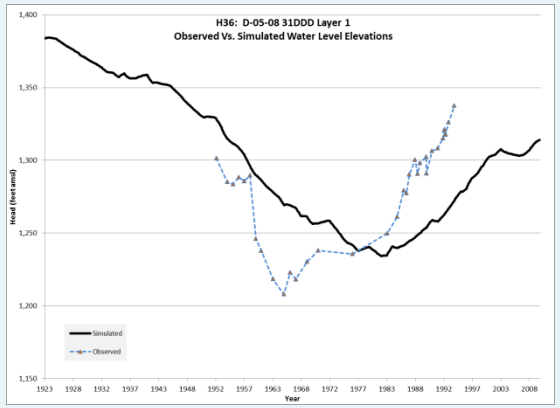


Eloy Sub-basin
SCIDD Area About 2 Miles NE of Florence

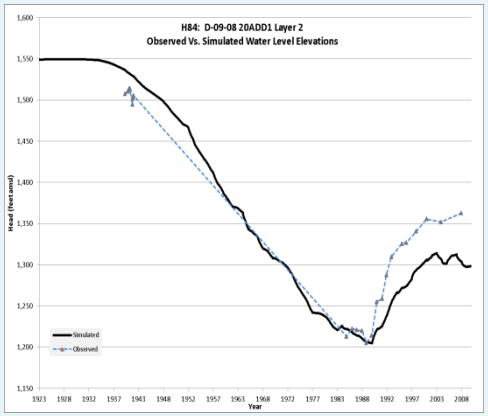
Selected Observed and Simulated Hydrographs



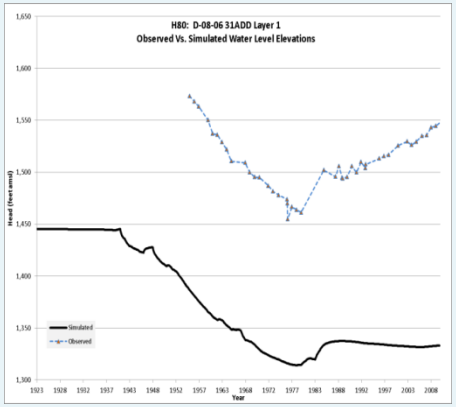
Eloy Sub-basin
SCIDD Area About 3 Miles E of Coolidge



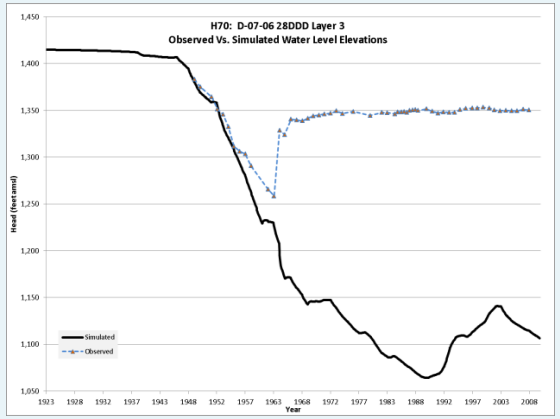
Eloy Sub-basin
Hohokam Area About 3 Miles SW of Coolidge



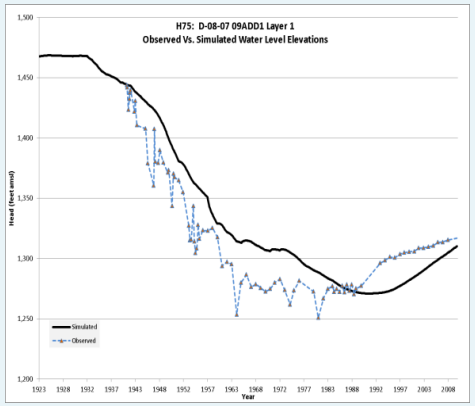
Eloy Sub-basin
CAIDD Area 2 Miles SE of Eloy



Eloy Sub-basin
Non-District Area About
10 Miles SSW of Casa Grande Mtn.

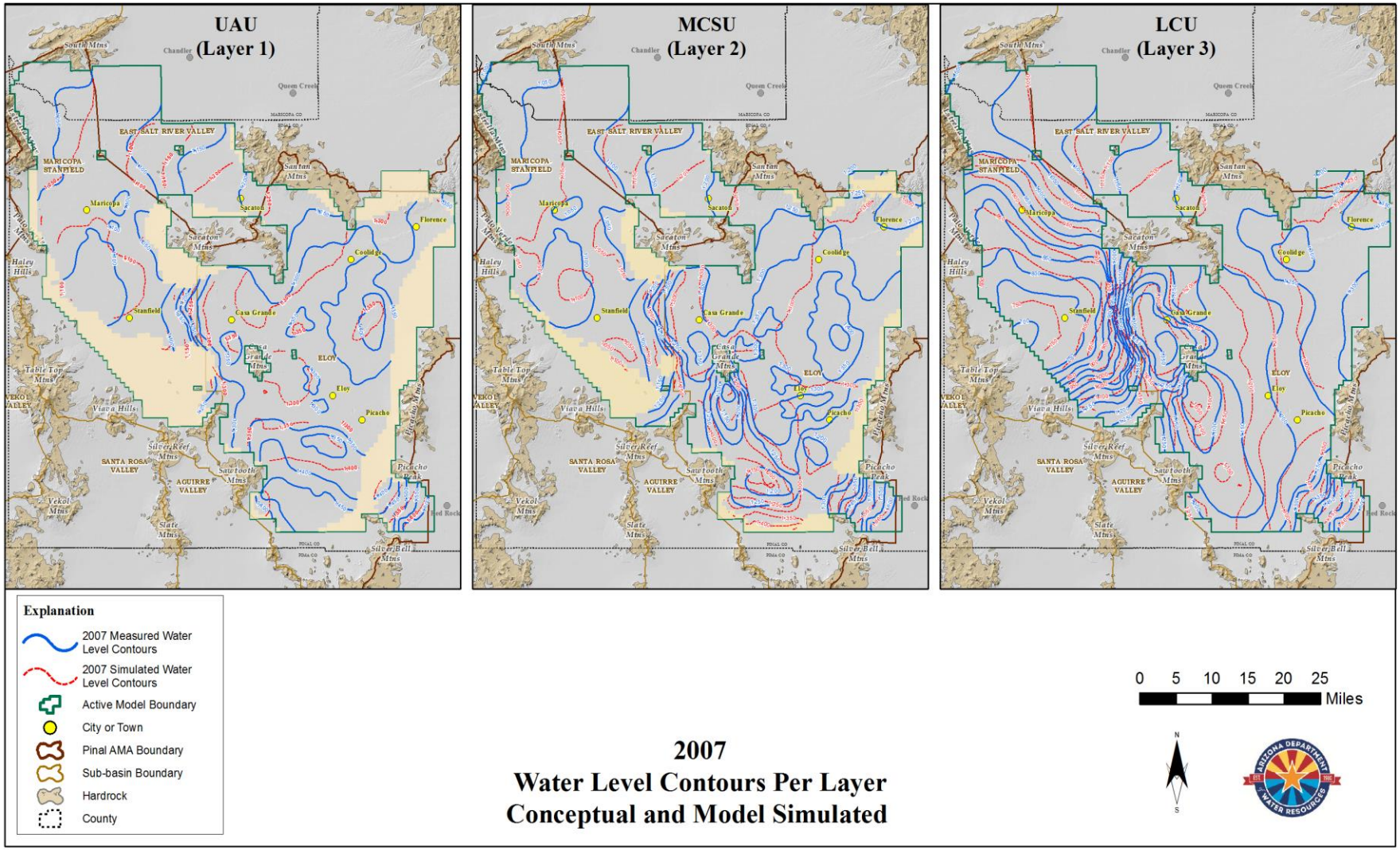


Eloy Sub-basin
Non-District Area West of Casa Grande Mtn.

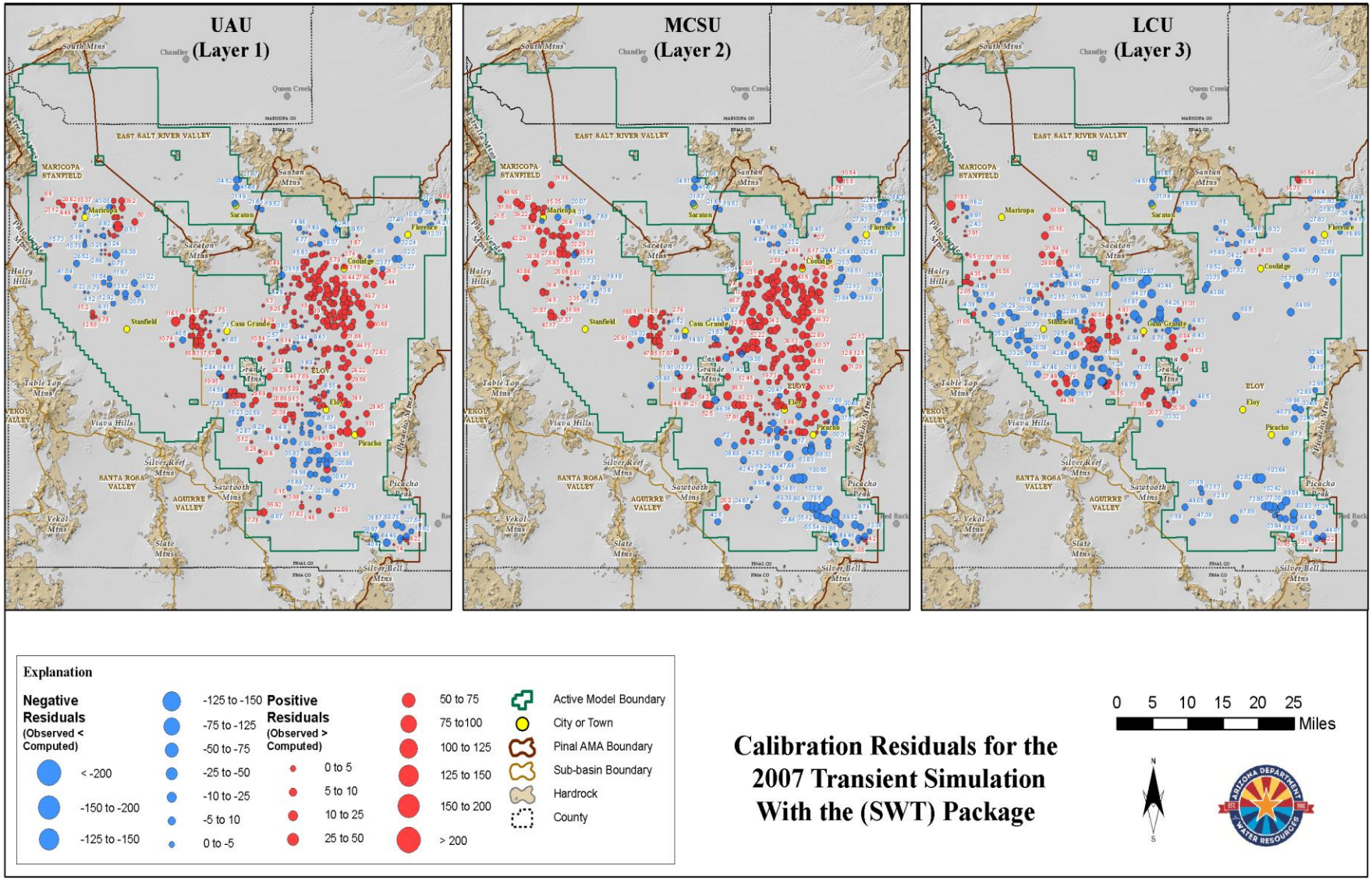


Eloy Sub-basin
E Central CAIDD Area 8 Miles E of Eloy

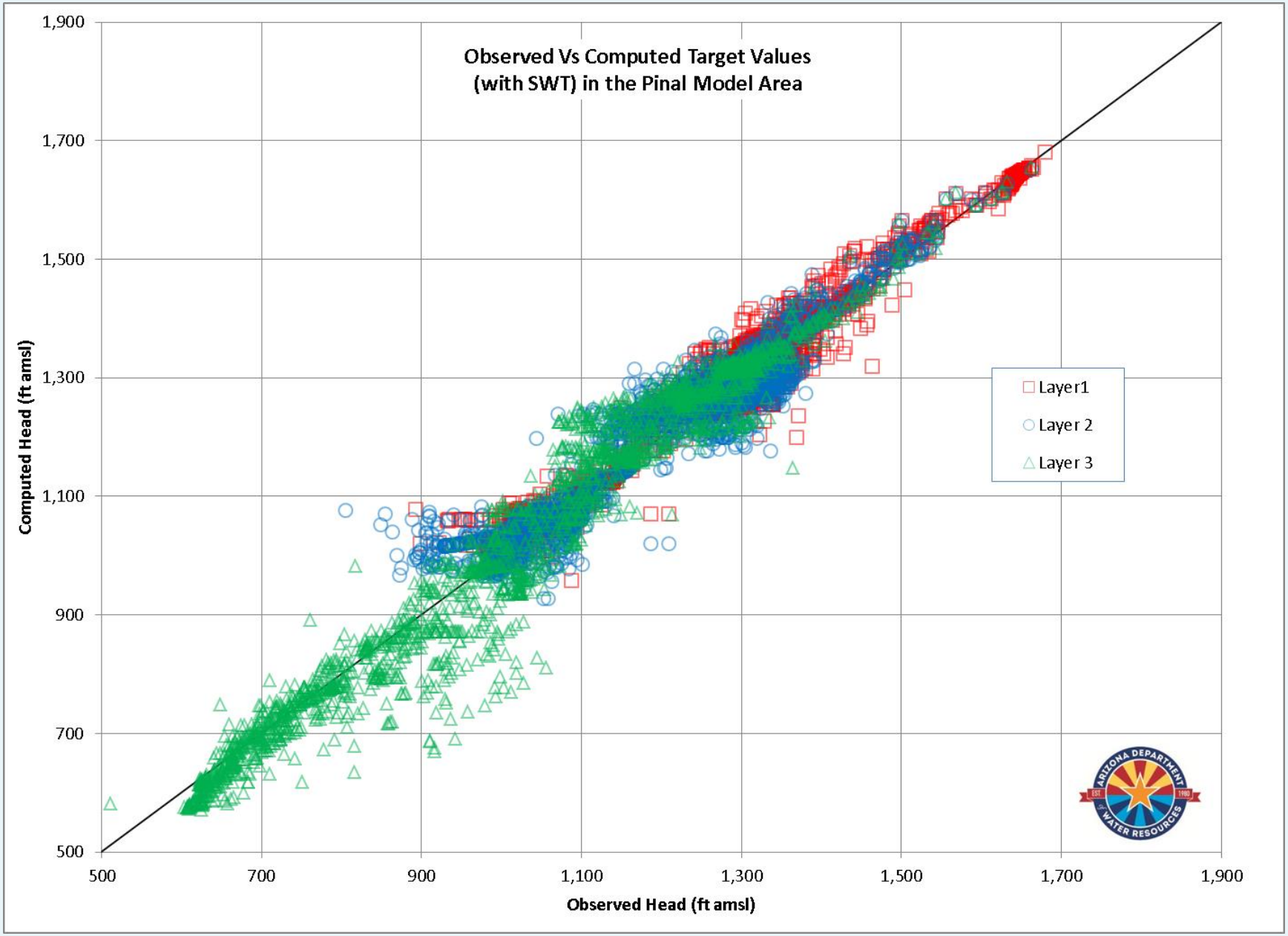
The Model Simulates the Complexities of Today's Hydrologic System



The Distribution of Model Error in 2007



Calibration Residuals for the 2007 Transient Simulation With the (SWT) Package


Observed Vs Computed Target Values
(with SWT) in the Pinal Model Area
Computed Head (ft amsl)
Observed Head (ft amsl)
1,900
1,700
1,500
1,300
1,100
900
700
500
500
700
900
1,100
1,300
1,500
1,700
1,900
Layer1
Layer 2
Layer 3
ARIZONA DEPARTMENT OF WATER RESOURCES
EST. 1980

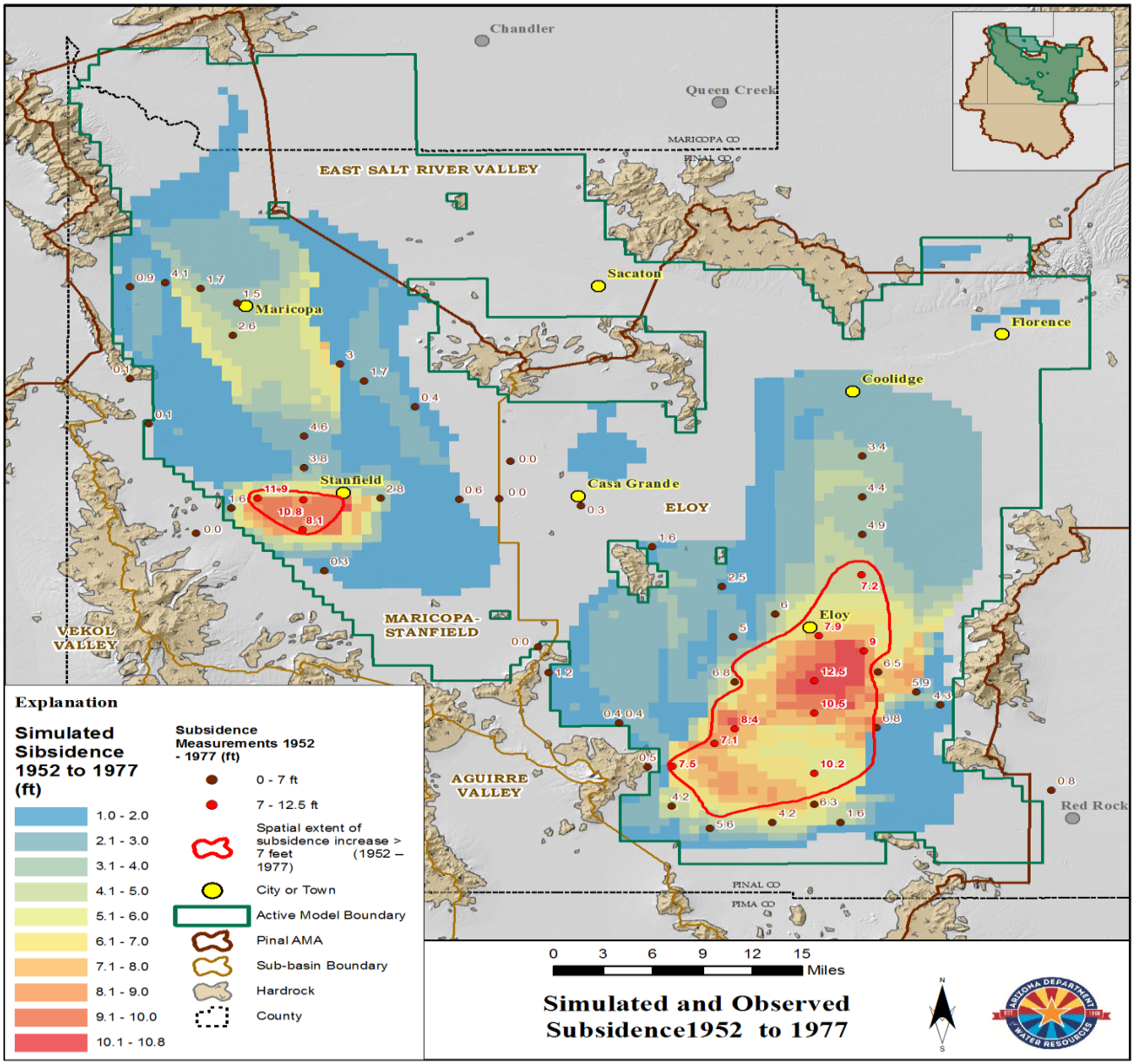
Model Error Analysis Statistics

Year	Stress Period	Number of Targets (ft)	Mean Error (ME) (ft)	Absolute Mean Error (MAE) (ft)	Standard Deviation (ft)	Minimum Residual (ft)	Maximum Residual (ft)	Root Mean Squared Error (RMSE) (ft)	RMSE as % of Total Head Change
Steady-state	1	243	4.8	8.3	11.1	-33.2	47.9	12.1	1.86%
1941	20	100	0.3	11.3	15.4	-33.4	40.4	15.4	2.83%
1952	31	143	-2.5	20.6	24.9	-54.4	79.5	25.0	4.21%
1963	42	283	-33.5	45.4	45.0	-203.4	107.5	56.1	6.97%
1976	55	152	-5.9	47.3	66.6	-272.5	223.0	66.6	7.06%
1984	63	1,561	-10.4	28.7	38.7	-184.8	189.3	40.1	4.05%
1988	67	840	0.1	35.0	48.0	-215.5	252.2	48.0	4.96%
2007	86	1,244	5.1	26.1	32.6	-107.3	166.1	33.0	3.68%
All Targets	1 ~ 88	8,031	-3.1	29.3	40.8	-272.5	252.2	40.9	3.69%

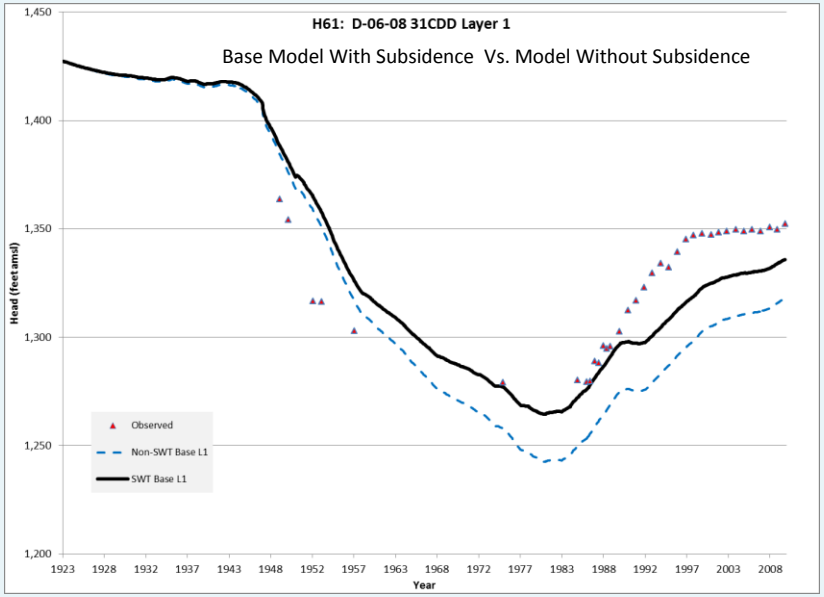
Note:

1. Head Residual = Observed Head –Model Simulated Head
2. All targets include the targets used for the selected calibration periods and the additional targets used for hydrographs in between the calibration years.

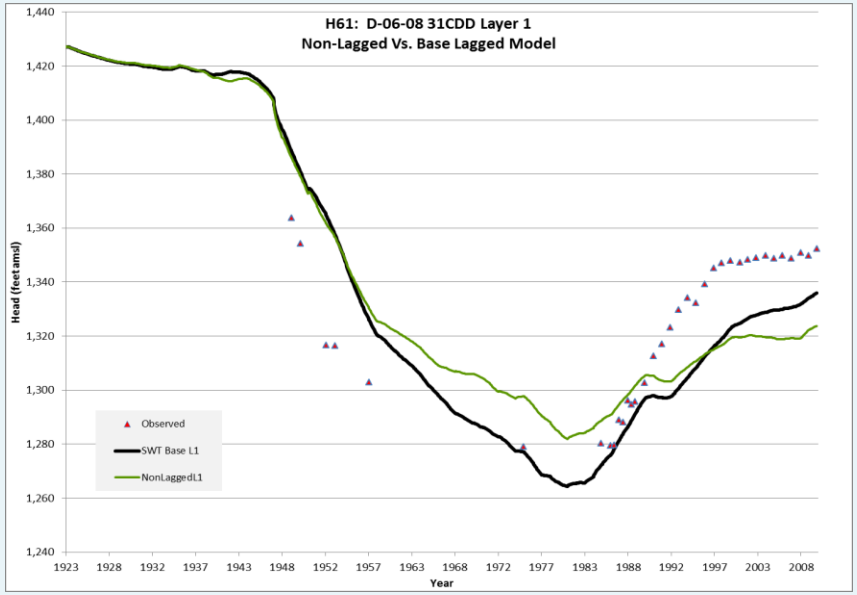
The Model Simulates the Areas of Historic Land Subsidence



Sensitivity to Subsidence



Sensitivity to "Lagged" Ag Recharge



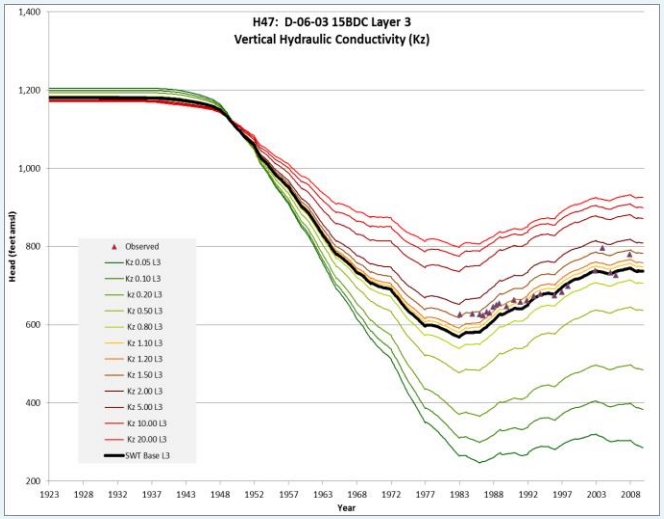
General Observations:

Simulations Without Subsidence Package Tend to Under-Simulate Observed Water Levels Compared to Simulations With Subsidence Package

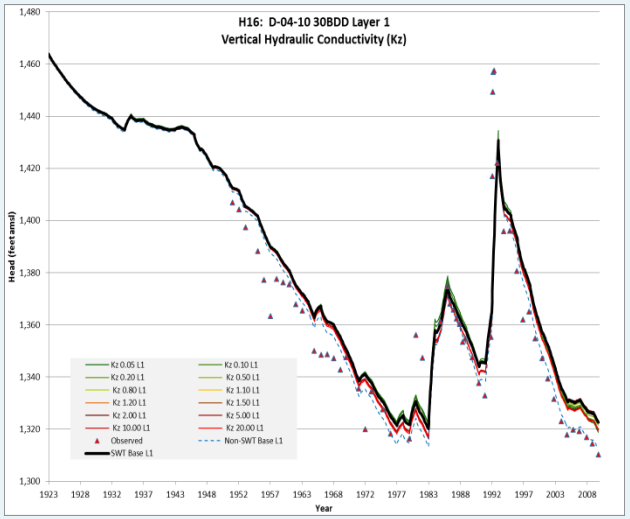
General Observations:

Simulations Without "Lagged" Ag Recharge Tend to Under-Simulate Observed Water Level Changes Compared to Simulations that "Lag" Agricultural Recharge.

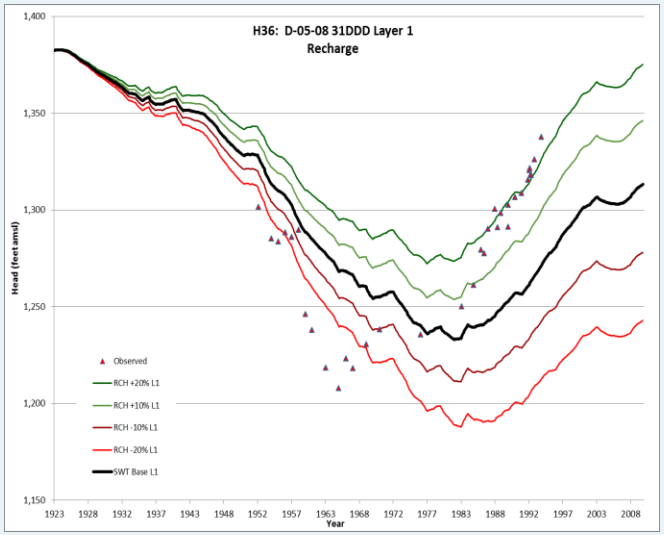
Selected Sensitivity Analysis Hydrographs



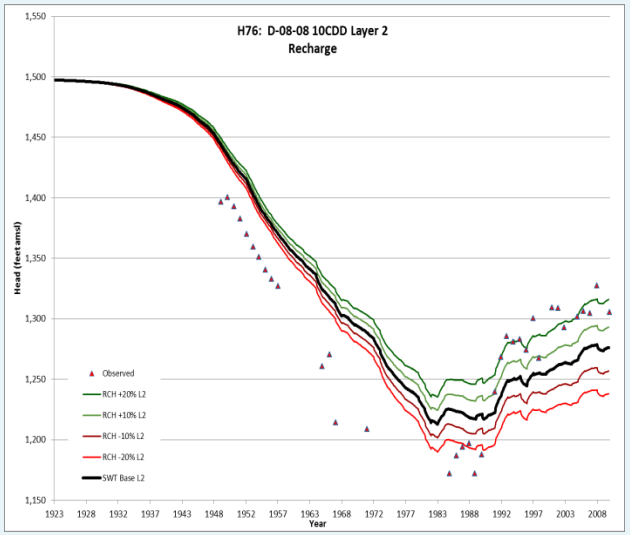
South-central Maricopa-Stanfield Sub-basin about 4 miles WNW of Stanfield



Northeast Eloy Sub-basin about 2 miles NE of Florence

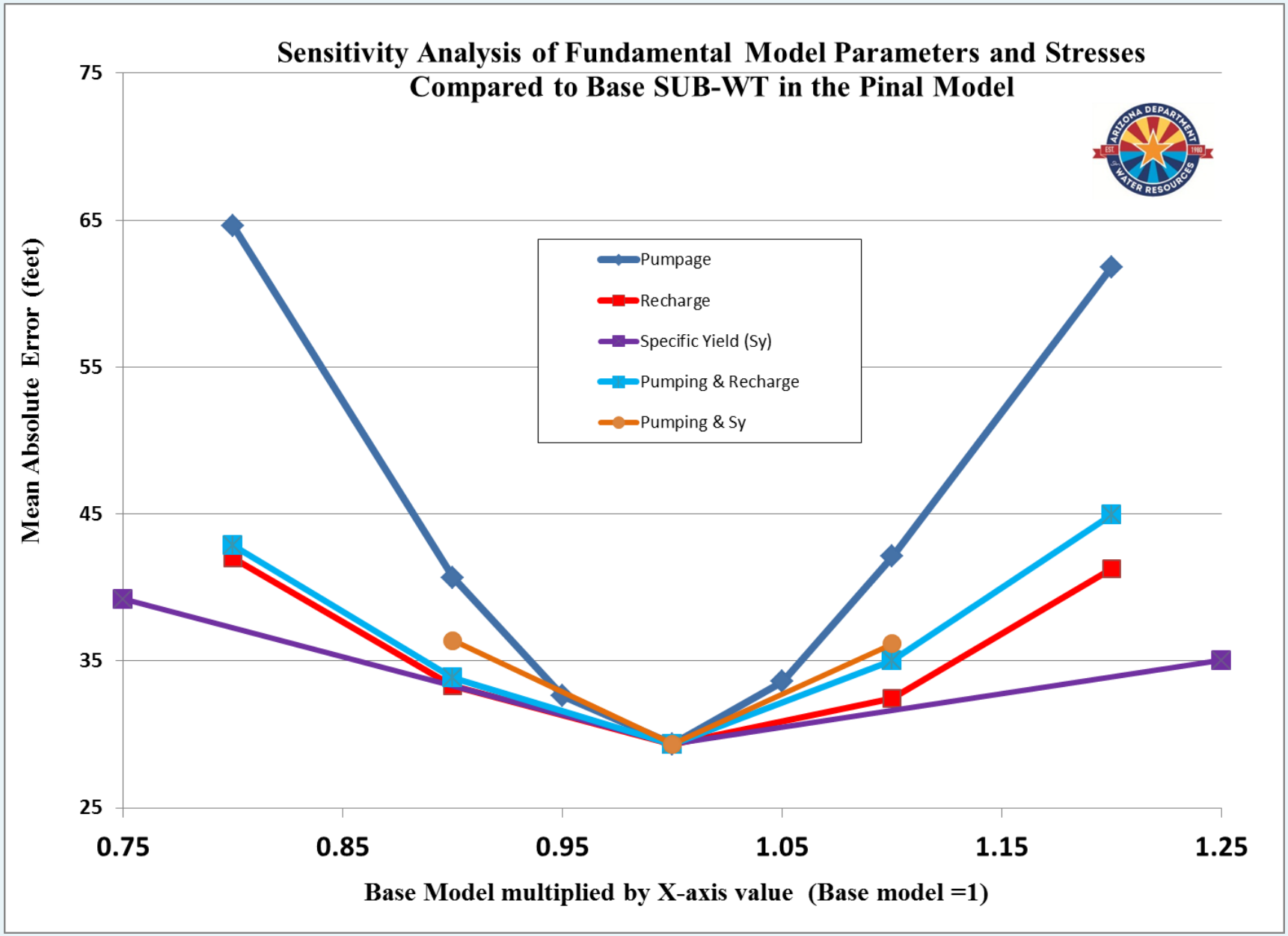


Northern Eloy Sub-basin about 3 miles SW of Coolidge



East-central Eloy Sub-basin about 3 miles SE of Eloy

The Base Model Provides the Most Accurate Solution of All Conceptual Models Tested



Recommendations On Future Data Collection, Model Updates and Calibrations

1. **Update Model Pumping and Recharge Data At Least Every 5 Years**

2. **Maintain Current GWSI Annual "Index" Line WL Measurements. Conduct Periodic WL "Sweeps" as Resources Allow.**

3. **Continued to Collect Land Subsidence Data And Analyze Using INSAR.**

4. **Continue to Conduct Periodic Microgravity Measurements For Aquifer Storage Monitoring**

5. **Continue to Improve Model Calibration In Areas of Significant Vertical Hydraulic Gradient. This may require local grid refinements in some "problematic" areas.**

6. **Further analysis and quantification of agricultural recharge and the "lagging" of simulated agricultural recharge is also advised.**

7. **A future update and analysis of riparian evapotranspiration in the model area is recommended.**

8. **Future model updates should potentially include the adaption of the Pinal AMA model to newer versions of MODFLOW such as the Newtonian (NWT) or Unstructured Grid (USG) versions.**

9. **Future model calibrations should also be based, at least in part, on automated calibration methods.**

CONCLUSIONS

- The model update has been successful in accomplishing major goals and objectives

- The model is acceptably calibrated in most areas for most purposes. However, potential uses of the model should be evaluated before the model is determined to be appropriate “as-is” for any specific use

- The model should be very useful for scenario development and testing future water management strategies

- The model is a major repository of hydrologic , geologic and water use data, and can serve as a source of valuable information for many related hydrogeoloigic studies

QUESTIONS?