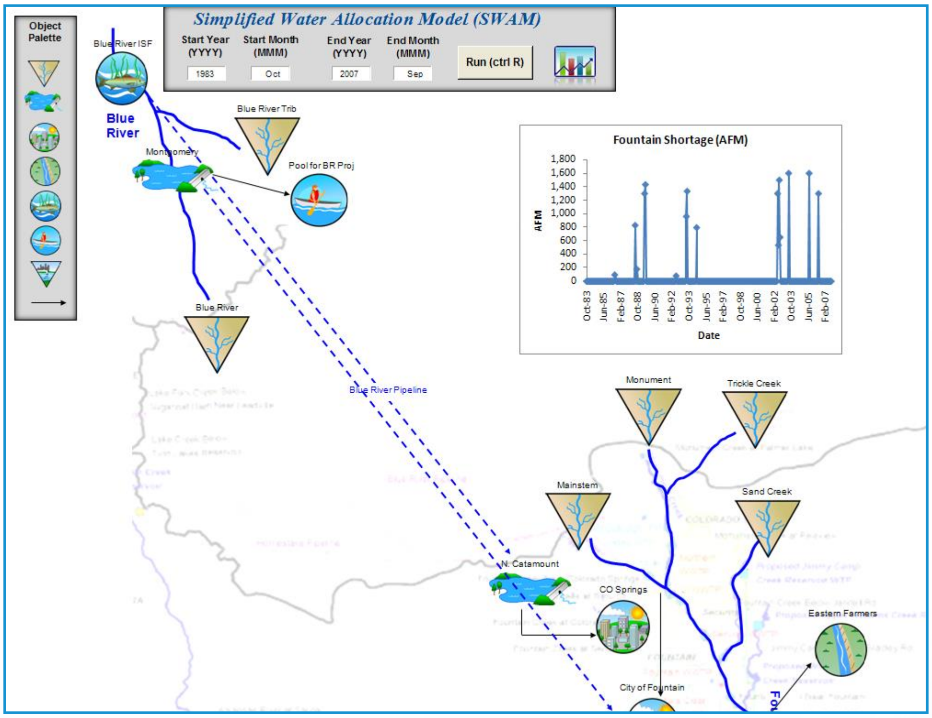
Simplified Water Allocation Model (SWAM)



VERSION 2.0
USER'S MANUAL

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Memorandum

To: *Jean Van Pelt, Southeastern Colorado Water Conservation District*

From: *Chris Kurtz, P.E. and Mark McCluskey, P.E., CDM Smith*

Date: *May 12, 2015*

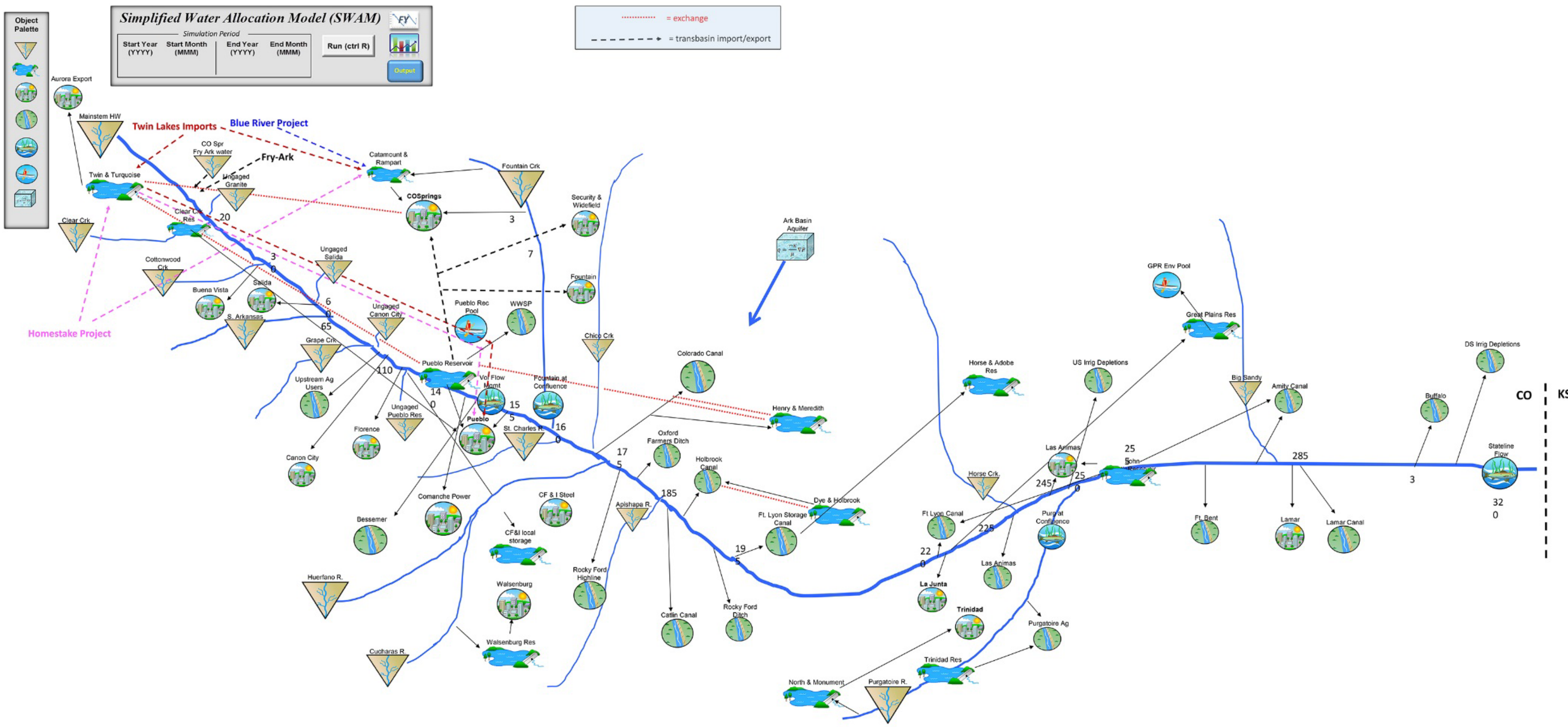
Subject: *ArkSWAM Model Documentation*

Overview

A water allocation model has been developed for the Arkansas River Basin (**Figure 1**) to support the Arkansas Basin Implementation Plan (BIP). The model spatial domain extends from the Arkansas River at Leadville flow gage in the western headwaters to the Colorado-Kansas state line in the east. It includes all major tributaries, agricultural ditch diversions, municipal and industrial (M&I) water users, and transbasin water imports. All other significant inflows and withdrawals in the basin have been represented implicitly in the model in aggregated form. The model is designed for large-scale planning studies and, more specifically, the quantification of water shortages in the basin as a result of increasing future demands. It is not designed to be a river administration or operational support tool, nor is it intended to replicate the Arkansas Basin Decision Support System (ArkDSS) that has recently completed a Feasibility Study. Consequently, there are intentional simplifications in the model, compared to the ArkDSS, to maintain its ease of use and transparency for coarser resolution planning. These simplifications include: a monthly timestep, aggregated agricultural diversions, simplified reservoir operations and accounting, and simplified representation and inclusion of water exchange and augmentation plans. That being said, the key drivers of water availability in the basin, including native hydrology, major water uses and return flows, the water rights priority system, groundwater pumping with surface returns and stream depletions, and transbasin imports, are all explicitly represented in the model. Lastly, the model is well supported by a calibration/verification exercise based on recent (1982 – 2012) river gage data.

In support of the hydrologic modeling effort a Hydrologic Modeling Technical Committee was formed whose membership includes members of the larger Arkansas Basin Roundtable. This committee focused their efforts on reviewing the model construct and calibration results. Based on the review by the committee the model was iteratively revised and enhanced to better reflect the water use and operation, as well as future regional shortages, of the Arkansas River Basin.

Figure 1 – Arkansas River BIP Water Allocation Model (ArkSWAM)



Modeling Platform

The Arkansas Basin planning model was developed using CDM Smith's Simplified Water Allocation Model (SWAM). SWAM was originally developed in 2009 to address an identified need for a networked, generalized water allocation modeling tool that could be easily and simply applied for planning studies by a wide range of end users. It has been extensively modified and enhanced since that inception. SWAM is designed to be intuitive in its use and streamlined in functionality and data requirements, while still maintaining the key elements of water allocation modeling.

SWAM is not intended to replace more complex water allocation modeling software. It is not well-suited for either operational support or water rights administration modeling. There are key constraints in the model with respect to the number of simulated water user nodes and the level of complexity available for simulating reservoir operations. Rather, SWAM was designed to complement these more complex tools by providing for efficient planning-level analyses of water supply systems. It is best suited for either analysis of focused networks or coarser resolution basin-level studies.

Like most water allocation models, SWAM calculates physically and legally available water, diversions, storage, consumption, and return flows at user-defined nodes in a networked river system. Both municipal and agricultural demands can be specified and/or calculated in the model. Legal availability of water is calculated based on prioritized water rights, downstream physical availability, and specified return flow percentages. Additional features in SWAM include easily-parameterized M&I conservation and reuse programs, agricultural land transfers, groundwater pumping, water user exchange agreements, and transbasin diversion projects. Multiple layers of complexity are available as options in SWAM to allow for easy development of a range of systems, from the very simple to the more complex.

SWAM operates on a monthly timestep over an extended continuous simulation period intended to capture a range of hydrologic conditions. The program is coded in Visual Basic object-oriented code with a Microsoft *Excel*-based interface.

Model Construction

Model Simulation Period

The Arkansas Basin SWAM model (ArkSWAM) simulates the water years 1982 – 2012. This historical period is known to include all of the current major basin operations, storage and diversion structures, and transbasin imports and is inclusive of the critical drought of the early 2000s. It is also consistent with the simulation period utilized for the SDS modeling performed as part of that project's environmental impact statement (EIS) (MWH 2007).

Tributary Objects

Tributary objects are used in SWAM to establish native flows throughout the basin. In addition to a mainstem headwater flow, multiple tributaries are included in the model in a dendritic network. These model objects are parameterized with a monthly flow time series and spatial location identifiers (e.g., confluence location). Gaged flow records were used, to the extent possible, to quantify native flows in the basin. Gages used for this purpose in the model are located above major basin operations and generally represent unimpaired flows. As described below, flow contributions from a number of ungaged subbasins were also included in the model developed using statistical estimation techniques and adjusted as part of the model calibration process. Standard hydrologic statistical methods were also employed to extend or augment gaged records, as necessary.

The following tributaries, with full or partial gaged flow records, are explicitly included in the model:

- Mainstem Headwater;
- Clear Creek;
- Cottonwood Creek;
- S. Arkansas River;
- Grape Creek;
- Fountain Creek and local runoff;
- St. Charles River;
- Chico Creek;
- Huerfano River;
- Cucharas River;
- Apishapa River;
- Horse Creek;
- Purgatoire River;
- Big Sandy Creek.

In some cases, tributary reaches are explicitly simulated in the model and include surface water user nodes along the extent of the reach. These tributary objects are parameterized with upstream (headwater) gaged flows and, in some cases, reach gains and losses (quantified as part of the calibration process) (**Table 1**). In other cases, the tributaries merely serve as point inflows to the mainstem river and are therefore parameterized using flow rates measured near the mainstem confluence. For both types of tributary objects, monthly flow records for the simulation period were either obtained directly from the United States Geological Survey (USGS) and the Division of Water Resources (DWR) gage records or were estimated using well-known statistical techniques, including area-weighting with a surrogate gage and the MOVE.2 record-filling method. The gages in this table describe inflows into the model and are generally restricted to headwater locations, upstream of any modeled water users. Additional gages, including gages further downstream, are used for model calibration as described later in this memorandum.

Table 1 – Summary of Model Tributary Objects

Tributary Object	Representative Flow Gage (USGS ID)	Drainage Area (mi^2)	Available Period of Gage Record	Statistical Extension or Record-Filling Method	Calibration Gain/Loss Factor (unitless)[1]	Mean Annual Flow (AFY)[2]
Mainstem Headwater	Arkansas River nr Leadville (07081200)	99	Oct '81 – Sep '83; May '90 – Sep '12	MOVE.2 (with 07086000 reference gage)	1	55,000
Clear Creek at Clear Crk Reservoir	Clear Creek ab Clear Crk Reservoir (07086500)	67	Oct '81 – Sep '12	none	1	49,000
S. Arkansas River at Mouth	Grape Creek nr Westcliffe (07095000) (surrogate)	201	Oct '81 – Sep '12	area-weighting, surrogate gage	1	17,000
Grape Creek at Mouth	Grape Creek nr Westcliffe (07095000)	541	Oct '81 – Sep '12	area-weighting, down to confluence	1	43,000
Fountain Crk & Local Runoff	Fountain Creek nr CO Springs (07103700) + Estimated Local Runoff[3]	102 (+ local runoff drainage)	Oct '81 – Sep '12	none	1	76,000
St. Charles River at Mouth	St. Charles River at Vineland (07108900)	474	Oct '81 – Sep '12	none	1	28,000
Chico Creek at Mouth	Chico Creek nr Avondale (07110500)	864	Mar '39 – Sep '46	mean monthly flows	35	3,900
Huerfano River Headwater	Huerfano River at Manzanares Crossing (07111000)	73	Oct '81 – Sep '87; Oct '94 – Sep '12	MOVE.2 (with 07124200 reference gage)	4	20,000
Cucharas River Headwater	Cucharas River ab Walsenburg (07114000)	56	Oct '81 – Sep '87; Oct '94 – Sep '12	MOVE.2 (with 07124200 reference gage)	1	17,000
Apishapa River at Mouth	Apishapa near Fowler (07119500)	1074	Oct '81 – Sep '12	none	1	13,000
Horse Creek at Mouth	Horse Creek nr Las Animas (07123675)	1403	Oct '79 – Sep '93	mean monthly flows	2	10,000
Purgatoire River Headwater	Purgatoire ab Madrid (07124200)	505	Oct '81 – Sep '12	none	1.75	52,000
Big Sandy Creek at Mouth	Big Sandy nr Lamar (07134100)	65	Jul '95 – Sep '12	mean monthly flows	1	13,000
Ungaged Above Granite	NA	350	NA	area-weighting (with 07086500 reference gage)	0.75	246,000

Tributary Object	Representative Flow Gage (USGS ID)	Drainage Area (mi^2)	Available Period of Gage Record	Statistical Extension or Record-Filling Method	Calibration Gain/Loss Factor (unitless)[1]	Mean Annual Flow (AFY)[2]
Ungaged Below Granite, Above Salida	NA	600	NA	area-weighting (with 07091015 reference gage)	0.75	234,000
Ungaged Below Salida, Above Canon City	NA	1120	NA	area-weighting (with 07095000 reference gage)	2	86,000
Ungaged Below Canon City, Above Pueblo Reservoir	NA	1400	NA	area-weighting (with 07099060 reference gage)	0.75	108,000

[1] Factor applied to estimated flow to represent reach gains or losses down to the confluence, quantified as part of calibration process
[2] Flow at initial point of application in model, prior to gains or losses
[3] Estimated as part of calibration process

For the Fountain Creek subbasin, upstream of Colorado Springs, stream gage data were augmented with estimates of additional flow into Colorado Springs local reservoir system. This runoff is known to be a significant source of supply for the city and is not captured in the Fountain Creek gage data. The flow augmentation was achieved by applying a uniform factor to the Fountain Creek near Colorado Springs gage data, quantified as part of the calibration process. This process was guided by downstream Fountain Creek gaged flows and independent estimates of local runoff for Colorado Springs (Colorado Springs Water Tour document).

In addition to the individual tributaries listed above, a number of ungaged tributaries were included in the model in aggregate form. Flows for these ungaged areas were estimated using area-weighting techniques applied to surrogate gages. Adjustments were made to the flow estimates as part of the calibration process. The focus of this analysis was on the ungaged headwater regions of the basin where contributions from snowmelt are likely significant. As can be seen in Table 1, these ungaged headwater tributaries constitute well over half of the total native flow in the basin as simulated in the model.

Reservoirs

The following major reservoirs are included in the model:

- Catamount and Rampart Aggregate Reservoir (offline);
- Clear Creek Reservoir (online);
- Dye and Holbrook Aggregate Reservoir (offline);
- Great Plains Aggregate Reservoir (offline);
- Henry and Meredith Aggregate Reservoir (offline);
- Horse and Adobe Aggregate Reservoir (offline);
- John Martin Reservoir (online);
- North and Monument Aggregate Reservoir (offline);
- Pueblo Reservoir (online);

- Twin and Turquoise Aggregate Reservoir (offline);
- Trinidad Reservoir (online);
- Walsenburg Reservoir (offline);

Reservoirs are parameterized according to total storage capacity, user accounts, simplified release and operational rules, and evaporation rates (**Table 2**). Table 2 describes how each reservoir is modeled, which is often a simplification of reality; some water sources and user accounts may not be included. Inflows and withdrawals from the reservoirs are dictated by activity associated with the individual water user accounts in each reservoir. Offline reservoirs divert water for storage according to physical and legal availability for individual user accounts. Online reservoirs hold inflow only to the extent legally allowed according to user account water rights and downstream senior calls. For online reservoirs, excess water not held in individual accounts, and not called by downstream users, is stored in flood control pools. The storage capacity of these pools is calculated as the difference between total user account storage and the total physical storage of the reservoir. Releases from flood control pools are defined by user-input outflow-capacity tables.

Table 2 – Modeled Reservoirs

Reservoir Name	Total Storage Capacity (AF)	Sources of Water	User Accounts	Evaporation Losses (Apr – Sep)	Prescribed Release Rules
Twin & Turquoise Aggregate	269,000	Transbasin imports	Colorado Springs, City of Pueblo, Aurora Export	0.14 – 0.28 in d^{-1}	none
Clear Creek Reservoir	11,400	Clear Creek	City of Pueblo	1% per month	none
Pueblo Reservoir	330,000	Arkansas R. mainstem & transbasin imports	City of Pueblo, Colorado Springs, City of Fountain, Lamar, Security & Widefield, Aggregate Upstream Ag Users, Winter Water Storage Program (WWSP), Pueblo Rec Pool	0.14 – 0.28 in d^{-1}	flood control pool: 0 – 5000 AFM (0 – 100% capacity)
Catamount and Rampart Aggregate	60,000	Fountain Creek, transbasin imports	Colorado Springs	1% per month	none
Walsenburg Reservoir	843	Cucharas River	Walsenburg	1% per month	none
Henry and Meredith Aggregate	300,000	Arkansas R. mainstem & transbasin imports	CO Canal, Co Canal WWSP	1% per month	none

Reservoir Name	Total Storage Capacity (AF)	Sources of Water	User Accounts	Evaporation Losses (Apr – Sep)	Prescribed Release Rules
Dye and Holbrook Aggregate	400,000	Arkansas R. mainstem & transbasin imports	Holbrook Canal, Holbrook WWSP	1% per month	none
Horse and Adobe Aggregate	200,000	Arkansas R. mainstem & transbasin imports	Fort Lyon Storage Canal, Fort Lyon Canal and Fort Lyon Storage Canal WWSP	1% per month	none
North and Monument Aggregate	5700	Purgatoire R.	City of Trinidad	1% per month	none
John Martin Reservoir	450,000	Arkansas R. mainstem	Las Animas Consolidated Ditch, Ft. Bent Canal, Amity WWSP	0.1 – 0.3 in d^{-1}	flood control pool: 0 – 70,000 AFM (0 – 100% capacity)
Aggregate Great Plains Reservoir	70,000	Arkansas R. mainstem & transbasin imports	GPR environmental pool	1% per month	none
Trinidad Reservoir	113,500	Purgatoire R.	Purgatoire Aggregate Ditch	4.7% - 7.7% per month	none

In the current model, reservoir bathymetry is defined by simplified area-capacity curves where such information is available. Monthly mean evaporation rates (inches per day) have been specified in the model based on regional values reported in the literature. In the absence of reservoir bathymetric information (smaller reservoirs only), 1 percent volumetric evaporative losses are assumed for the months of April – October, with no evaporation during the winter months. Evaporative losses for Trinidad Reservoir were calculated based on historical data.

Two nonconsumptive environmental pools are also included in the model, associated with Pueblo and the Aggregate Great Plains Reservoir. These model objects designate minimum storage levels that are maintained, to the extent possible, given physical and legal availability of water. Environmental pools are assigned a water right appropriation date in the same manner as consumptive users. This water right determines the ability of the object to divert and store water. The only losses from the environmental pools are evaporative. The Pueblo environmental pool is set at 30,000 acre-feet (AF) with a relatively senior appropriation date of 2/10/1939. The Great Plains Reservoir environmental pool is set at 21,000 AF with a largely junior appropriation date of 1/1/1990 (i.e., it only fills during wet years).

M&I Users

The following M&I water users are explicitly included in the Arkansas Basin SWAM model:

- Aurora Export.
- Buena Vista;
- Canon City;
- Colorado Fuel and Iron Company (CF&I) Steel;
- Colorado Springs;
- Comanche Generating Station;
- Florence;
- Fountain;
- La Junta;
- Lamar;
- Las Animas;
- Pueblo;
- Salida;
- Security and Widefield;
- Trinidad;
- Walsenburg.

The Pueblo M&I water user object is an aggregation of Board of Water Works Pueblo (BWWP), Pueblo West, and St. Charles Mesa Water District. Each M&I user is parameterized according to spatial location (diversions and return flows), current demand estimates, representative water rights appropriation dates, diversion rights, and source water portfolio details (including direct diversions, storage accounts, transbasin imports, and groundwater pumping) (**Table 3**). M&I users in SWAM can have multiple sources of supply used to satisfy a single set of demands in order of user-defined preferences. Sources of supply can include: direct surface diversions, surface diversions via storage accounts, and groundwater pumping.

Table 3 – Summary of M&I Water User Objects

Name	Total Demand (AFY)	Modeled Sources of Supply	Modeled Storage Accounts
Colorado Springs	114,000	• Groundwater (implicit in model) • Direct Fountain Creek + other local runoff, • Storage Fountain Creek + other local runoff • Transbasin with Pueblo Res. storage (Fryingpan-Arkansas [Fry-Ark]) • Transbasin with Catamount & Rampart storage (Blue River, Twin Lakes Reservoir and Canal Company [TLCC], and Homestake) • Exchange of transbasin return flows (to Pueblo Res.) • Exchange of Colorado Canal and Lake Meredith	• Catamount & Rampart (60,000 AF) • Twin & Turquoise (47,000 AF) • Pueblo (17,000 AF) • Henry & Meredith (27,000 AF)

Name	Total Demand (AFY)	Modeled Sources of Supply	Modeled Storage Accounts
		water (to Pueblo Res.)	
Pueblo *(includes, BWWP, Pueblo West and St. Charles Mesa Water District)*	40,000	• Direct mainstem • Storage Clear Creek • Transbasin with Twin & Turquoise storage (TLCC and Homestake) • Transbasin with Pueblo Res. storage (Fry Ark) • Exchange of transbasin return flows (to Pueblo Res.)	• Clear Creek Res. (11,400 AF) • Twin & Turquois (24,100 AF) • Pueblo Res. (54,700 AF)
Buena Vista	900	• Direct Cottonwood Creek • Groundwater	none
Salida	3,000	• Direct mainstem • Groundwater	none
Canon City	7,200	• Direct mainstem	none
Florence	2,800	• Direct mainstem	none
Security and Widefield	9,000	• Groundwater • Transbasin with Pueblo Res. storage (Fry-Ark)	• Pueblo (12,200 AF)
Fountain	5,200	• Groundwater • Transbasin with Pueblo Res. storage (Fry-Ark)	• Pueblo (7,800 AF)
EVRAZ	4,100	• Direct mainstem	• Local Storage (20,000AF)
Comanche Generating Station	10,600	• Direct mainstem (BWWP water right)	none
Walsenburg	1,000	• Storage Cucharas Riv.	• Walsenburg Res. (840 AF)
Trinidad[1]	5,100	• Storage Purgatoire Riv.	• North & Monument (5,700 AF)
Las Animas	1,000	• Groundwater	none
Lamar	2,750	• Groundwater • Transbasin with Pueblo Res. storage (Fry-Ark)	• Pueblo (1,400 AF)
La Junta	2,000	• Groundwater	none
Aurora Export	28,100	• Storage mainstem – Rocky Ford exchange • Transbasin with Twin & Turquoise Storage (Homestake)	• Twin & Turquoise (20,000 AF)

1 Modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin relative to gage location.

The model calculates both legally and physically available flow at each surface water diversion point associated with M&I water user objects. Legal availability is calculated in SWAM using the same algorithm (Modified Direct Solution Algorithm) utilized in the State of Colorado DSS and considers downstream senior calls, return flows, and diversion rights. In SWAM, the actual diverted amount is calculated as a function of physical and legal availability and demand. Monthly M&I demands are set in the model, based on the best available information, to approximately represent current demands. Monthly demand patterns are defined in the model based on model default values that follow patterns typical of M&I usage in Colorado. Water user storage accounts are assigned a "parent" reservoir, a total account capacity, and water rights (diversion and storage rights). The model attempts to maintain a full storage account, to the extent physically and legally allowable, by imparting a diversion demand on the source river in the same way that direct diversion demands are imparted. For all M&I users in the model, a uniform monthly return flow pattern is assumed based on typical indoor vs. outdoor usage patterns and consumptive use portions associated with each. No time lags have been included for return flows in this monthly timestep model.

Note that neither stream depletions nor surface water augmentation plans are explicitly included in the model M&I object portfolios, as the combination of the two represents a zero net change in the surface water budget. Also note that exchange agreements allowing the Cities of Colorado Springs and Pueblo to use their transbasin import water to extinction are included in the portfolios for these two model objects, parameterized with appropriate decree priority dates. An exchange agreement between Colorado Springs and Colorado Canal, with storage in Henry & Meredith Aggregate Reservoir, is also included as part of the water supply portfolio for the city. See *Exchanges and Flow Management Programs* for further details on modeled exchanges.

Agricultural Users

The following irrigation ditches are explicitly included in the model:

- Amity Canal;
- Bessemer Ditch;
- Buffalo Canal;
- Catlin Canal;
- Colorado Canal;
- Fort Lyon Canal;
- Ft. Bent Canal;
- Ft. Lyon Storage Canal;
- Holbrook Canal;
- Lamar Canal;
- Las Animas Consolidated Ditch;
- Oxford Farmers Ditch;
- Purgatoire Aggregate Ditch (aggregate of all ditches in Water District 19);
- Rocky Ford Ditch;
- Rocky Ford Highline;
- Upstream Aggregate Ditch (aggregation of all ditches upstream of Pueblo Res.).

The major ditches listed above comprise approximately two-thirds of the total agricultural diversion in the basin. The remaining diversions, achieved with smaller ditches and canals, were assigned, in aggregate, to the major users in the model based on relative proximity to the major diversion location. In this way, approximately 100 percent of the reported total agricultural water use is included in the model but at a coarser spatial resolution than in actual operation.

As with M&I users, agricultural users are parameterized in the model according to spatial location, demands, water rights, and source water details (**Table 4**). In the current model, agricultural user demands are set based on reported historical headgate diversions (aggregated to a representative ditch) over the simulation period (1982 – 2012) to characterize year-to-year variability. Monthly-varying diversion volumes are used to characterize the seasonality in water use. Diversions are assumed to all occur from the mainstem of the Arkansas River, except for diversions that occur in Water District 19, which are assumed to occur from the Purgatoire River (Purgatoire Aggregate Ditch). Aggregate storage accounts are included, where appropriate, based on available information (e.g., HydroBase diversion records, see *Data Sources*). For aggregate diversions where a significant portion of the diverted water is transmitted to storage prior to use, a single storage account was assigned to one of the simulated reservoirs (Table 4). Storage account capacities were initially estimated based on available data with subsequent minor adjustments as part of the calibration process. These accounts are intended to represent lumped storage available to the various diversions, and are used to overcome seasonal constraints associated with available river diversion water. WWSP storage accounts are not included in Table 4; however, WWSP is represented in ArkSwam. See Table 5 and accompanying text for more detail on WWSP storage.

Table 4 – Summary of Aggregate Agricultural Water User Objects

Name	Primary Ditch Demand (AFY)	Aggregated Demand (AFY)	Total Modeled Demand (AFY)	Representative Priority Date	Storage Accounts
Amity Canal	92,000	2,000	94,000	4/1/1893	None
Bessemer Ditch	67,000	51,000	118,000	5/1/1887	None
Buffalo Canal	23,000	34,000	57,000	10/1/1895	None
Catlin Canal	98,000	11,000	109,000	12/3/1884	None
Colorado Canal	115,000	66,000	181,000	6/9/1890	Henry & Meredith (110,000 AF)
Fort Lyon Canal	244,000	49,000	293,000	3/1/1887	None
Ft. Bent Canal	16,000	26,000	42,000	12/31/1900	John Martin (20,000 AF)
Ft. Lyon Storage Canal	43,000	0	43,000	3/1/1910	Horse & Adobe (150,000 AF)
Holbrook Canal	50,000	1,000	51,000	10/10/1903	Dye & Holbrook (150,000 AF)
Lamar Canal	41,000	0	41,000	7/16/1890	None
Las Animas Consolidated Ditch	30,000	37,000	67,000	3/13/1888	John Martin (20,000 AF)
Oxford Farmers Ditch	28,000	28,000	56,000	2/26/1887	None

Name	Primary Ditch Demand (AFY)	Aggregated Demand (AFY)	Total Modeled Demand (AFY)	Representative Priority Date	Storage Accounts
Purgatoire Aggregate Ditch	n/a	66,000	66,000	3/13/1888	Trinidad (59,000 AF)
Rocky Ford Ditch	32,000	0	32,000	5/15/1874	None
Rocky Ford Highline	117,000	0	119,000	3/7/1884	None
Upstream Aggregate Ditch	n/a	335,000	335,000	5/2/1887	Pueblo (20,000 AF)

Representative water rights appropriation dates are assigned to each of the major users listed above based on a review of the water rights of each ditch. In general, priority dates for the model were chosen based on the most senior right providing significant yield to each ditch. A uniform return flow percentage (43 percent) is assumed for all agricultural users based on average historical efficiencies reported for the basin (Southern Delivery System [SDS] report). Return flows are not lagged and are assumed to return to the river at single specified downstream locations, assigned based on visual assessment of the mapped irrigation areas associated with each major ditch.

Winter Water Storage Program

WWSP is represented in the model for participants storing in Pueblo Reservoir as well as those using off-channel storage.

The Pueblo Reservoir component of WWSP is represented in the model with a winter-only diversion (Nov – Mar) just upstream of Pueblo Reservoir and storage in the reservoir. The total annual WWSP diversion at Pueblo is set in the model at 50,000 acre-feet per year (AFY) based on recent historical recorded totals (Bureau of Reclamation [Reclamation] 2013) and a priority date of 3/1/1910.The stored water is then fully released during the growing season months (Mar - Nov). Downstream agricultural users are then able to divert additional water during the growing season equal to the amount of WWSP stored water released from Pueblo Reservoir.

Similarly, participants with WWSP storage accounts outside of Pueblo Reservoir are represented in the model with a winter-only diversion to aggregate storage accounts in either John Martin, Horse & Adobe, Henry & Meredith, or Dye & Holbrook reservoirs. Water from these accounts is then available for use during the summer months as needed.

Table 5 summarizes WWSP water rights and storage amounts. All WWSP modeled rights yield only from November through March.

Table 5 – Summary of Modeled Winter Water Storage Program Storage

Name	Winter Water Storage Program Representative Priority Date	WWSP Storage Accounts
Amity Canal	3/5/1910	John Martin (20,000 AF)
Colorado Canal	3/2/1910	Henry & Meredith (110,000 AF)
Fort Lyon Canal	3/4/1910	Horse & Adobe (50,000 AF)
Ft. Lyon Storage Canal	3/1/1910	Horse & Adobe (150,000 AF)
Holbrook Canal	3/3/1910	Dye & Holbrook (150,000 AF)
Pueblo Reservoir participants	3/1/1910	Pueblo (50,000 AF)

Transbasin Imports

Imported transbasin water is included in the model as a major source of supply for many of the M&I water users described above. Transbasin imports are simulated in the model based on historical inflows to the river basin. This approach characterizes monthly and year-to-year variability of transbasin imports over the simulation period (1982 – 2012). Imports are made available to their corresponding water users by either direct transmittal to water user storage accounts or via mainstem conveyance. As an example of the latter, Fry-Ark water utilized by Colorado Springs, Pueblo, Lamar, and downstream agricultural users is modeled as a time-varying inflow to the mainstem river at the top of the system (above Clear Creek confluence). This water flows down the mainstem and a portion is captured and stored in accounts in Pueblo Reservoir, where it is available for use by Colorado Springs and Pueblo. The Fry-Ark water owned by downstream agricultural water users is transported further downstream to aggregate agricultural diversions, as dictated by downstream water rights. In other cases, transbasin imports are simulated with a direct transmittal to a specified water user storage account (e.g., Colorado Springs Homestake, TLCC, and Blue River imports).

Major transbasin imports explicitly represented in the model, and their associated water users, are listed below (and summarized in **Table 6**):

- Homestake (Colorado Springs, Aurora Water, Pueblo);
- Blue River (Colorado Springs);
- TLCC (Colorado Springs, Pueblo);
- Fry-Ark (Colorado Springs, Pueblo, City of Fountain, Security & Widefield, Lamar, downstream agricultural users).

Table 6 – Summary of Modeled Transbasin Import Water

Name	End Users	Modeled Storage	Modeled Yield (AFY)
Homestake	Colorado Springs, Pueblo, Aurora Export	Catamount & Rampart (CO Springs), Twin & Turquoise (Pueblo)	13,000 (CO Springs) 10,600 (Aurora Export) 2,500 (Pueblo)
Blue River	Colorado Springs	Catamount & Rampart (CO Springs)	8,800 (CO Springs)
TLCC	Colorado Springs, Pueblo	Catamount & Rampart (CO Springs), Twin & Turquoise (Pueblo)	22,800 (CO Springs) 14,000 (Pueblo)
Fry-Ark	Colorado Springs, Pueblo, Fountain, Security & Widefield, Lamar, downstream ag users	Pueblo Reservoir (CO Springs, Pueblo, Fountain, Security & Widefield, Lamar)	14,500 (CO Springs) 5,000 (Pueblo) 2,200 (Fountain) 3,500 (Security & Widefield) 1,400 (Lamar) 32,000 (downstream ag users)

Exchanges and Flow Management Programs

Water exchanges in the Arkansas River Basin involve diversion and water use at one location offset by a simultaneous release of an equivalent volume at a different location. For the basin as a whole, a zero net change in river flows is realized. However, exchanges do impact the spatial distribution and timing of flows within the basin. Exchanges can also represent an important element of individual water supply portfolios in the basin. For this planning-level model, only a select number of key exchanges were explicitly included in the model (**Table 7**):

- Colorado Springs transbasin return flows;
- City of Pueblo transbasin return flows;
- Colorado Springs – Colorado Canal exchange;
- Aurora – Rocky Ford exchange.

Table 7 – Summary of Modeled Exchanges

Name	Water Users Involved	Storage	Exchange Quantity (AFY)[1]	Water Right Priority Date
CO Springs transbasin return flows	CO Springs	Twin & Turquoise	37,000	6/5/1985
Pueblo transbasin return flows	City of Pueblo	Pueblo Res.	17,000	6/5/1985
CO Springs – Colorado Canal	CO Springs, Colorado Canal	Henry & Meredith, Pueblo Res.	1,200	6/5/1985 (CO Springs), 6/10/1890 (CO Canal)
Aurora-Rocky Ford	Aurora Export	Pueblo Res.	5,700	6/5/1985

[1] Average annual volume exchanged in current model, as calculated as a function of demand and physical and legal availability

The first two listed exchanges capture the ability of these cities to use their transbasin import water (excluding Fry-Ark) to extinction. The current conditions model does not include capture and use of Fry-Ark return flows. Both are represented in the model with additional senior diversion rights set equal to their modeled, monthly-variable return flows from transbasin project water yields. For the Colorado Springs model object, water is diverted under this exchange from the mainstem headwaters and stored in Twin & Turquoise Aggregate Reservoir for as-needed use. For the Pueblo object, return flow exchange water is diverted at Pueblo Reservoir and stored in a Pueblo account for as-needed use.

The Colorado Springs - Colorado Canal exchange involves the use of Colorado Springs shares in Colorado Canal diversion water and Henry & Meredith Aggregate Reservoir storage. In the model, SWAM's water exchange functionality is utilized, within the Colorado Springs water supply portfolio (see Table 3), to divert and store downstream mainstem water in Henry & Meredith. This water is released, as needed, to offset upstream city diversions at Pueblo Reservoir.

The Aurora - Rocky Ford exchange is represented in the model using the Aurora Export M&I water user noted above (Table 7). Water is diverted to a storage account into the Twin & Turquoise reservoir model object and then utilized with typical M&I seasonal usage patterns with zero return flows (i.e., an export from the basin). While the exchange with Rocky Ford ditch is not explicitly simulated in this model, it is assumed that ample flow is available at the Rocky Ford diversion point to allow for the upstream diversion.

Lastly, the Arkansas River Flow Management program is represented in the model with an instream flow (ISF) object located on the mainstem just downstream of Pueblo Reservoir. Target flows for this object vary monthly, ranging from 100 cubic feet per second (cfs) (Dec – Feb) to 500 cfs (Jun and Jul), based on recreation and fishery needs during low flow years (Flow Management Program May 2004 Exhibit 1, commonly known as the "6-party IGA."). These ISF targets are prioritized with a decree date of 6/4/1985, which makes them just senior to the municipal exchange programs described above. In other words, if minimum downstream flow requirements are not met then the municipal exchanges described above are not allowed. The Arkansas River Flow Management object does not impact the ability of more senior water user objects to divert water.

Groundwater Pumping

A single groundwater aquifer is included in the model to provide water for M&I user pumping. Pumping in the model is currently unconstrained by groundwater hydrology (high recharge rate, no aquifer depletion). M&I groundwater supplies are included in the water user supply portfolios as appropriate.

Groundwater pumping for irrigation purposes in the basin is known to result in significant depletions of river flow. In ArkSWAM, stream depletions are represented with fully consumptive agricultural diversion objects at two different lumped locations, upstream and downstream of John Martin Reservoir. The total depletion amount is set in the model as 41,500 AFY (29,600 upstream, 11,900 downstream) based on 2014 Rule 14 plans for Lower Arkansas Water Management Association (LAWMA) downstream of John Martin Reservoir and from Arkansas Ground Water Users Association (AGWUA) and Colorado Water Protective & Development Association (CWPDA) above John Martin Reservoir. Water rights priority dates for the two lumped depletion objects are set such that they are junior to all other agricultural diversions. As noted above, neither stream depletions nor surface water augmentation plans are explicitly included in the model M&I object portfolios, as the combination of the two represents a zero net change in the surface water budget.

Data Sources

Data sources used to parameterize the model elements described above are summarized in **Table 8.** Detailed descriptions of these data sources are provided elsewhere.

Table 8 – Summary of Data Sources

Model Parameter	Data Sources
Tributary object monthly flows	USGS flow gages, statistical extension methods, geographic information system (GIS) drainage area calculations
Reservoir bathymetry	Arkansas Valley Conduit (AVC) EIS Report (Reclamation 2013)
Reservoir capacities	Abbott Report (USGS 1985)
Reservoir evaporation rates	Western Regional Climate Center (http://www.wrcc.dri.edu/)
Online reservoir outflow curves	calibration
M&I water user demands	Abbott Report (USGS 1985); CO Springs SDS Report (MWH 2007)
M&I source water details	Abbott Report (USGS 1985); ArkDSS Feasibility Study (Brown and Caldwell 2011); CO Springs Water Tour Document, Fry Ark Return Flows and Exchanges Report (MWH 2008); City of Fountain Online Bulletin (www.fountaincolorado.org); City of Security Conservation Plan (WaterMatters 2011); Buena Vista – Salida Groundwater report (USGS 2005); Aurora Water Supply Fact Book (Aurora Water 2011); phone interviews (small cities)
M&I water rights and appropriation dates	Division 2 Line Diagrams (SE CO Water Conservancy District); Abbott Report (USGS 1985); AVC EIS Report (Reclamation 2013)
Ag canal aggregation	GIS mapping of diversion location, HydroBase data: lat/long location, historical annual diversion amounts
Ag user demands	HydroBase diversion records (1982 – 2012)
Ag user storage details	HydroBase (storage flags)
Ag user diversion appropriation dates	HydroBase (assigned based on appropriation date of largest individual diversion within aggregation)
Transbasin project details (yields, storage, ownership)	HydroBase, Abbott Report (USGS 1985); Fry Ark Report (MWH 2008); CO Springs Water Tour Document; CO Springs SDS Report (MWH 2007)
Major exchange program details	AVC EIS Report, Appendix D (Reclamation 2013); Division 2 Line Diagrams (SE CO Water Conservancy District); ArkDSS Feasibility Study (Brown and Caldwell 2011)

Model Calibration

The objective of any model calibration process is to lend confidence to model predictions of future conditions by demonstrating, and refining, the model's ability to replicate past conditions. For this study, the calibration exercise sought to achieve adequate model representation of mainstem flow at selected key downstream locations (**Figure 2**), as a function of upstream headwater and tributary inputs and basin operations and water use. Calibration points were selected based on available flow gage records and to achieve sufficient spatial coverage to allow for a spatial assessment of model performance. Calibration performance metrics include: annual average flow, monthly average flow, and monthly flow percentiles. These metrics provide insight into the model's ability to simulate, respectively: the overall basin water budget, seasonality in flow and water use, and flow variability (including extreme events). Calibration adjustment parameters were primarily ungaged flow gains/losses and online reservoir outflow-capacity curves. Uncertainty associated with both sets of parameters is considered relatively high, and therefore, calibration adjustments are deemed appropriate. The calibration exercise was supported by USGS flow gage records and reported monthly reservoir storage levels for the simulation period (1982 – 2012).

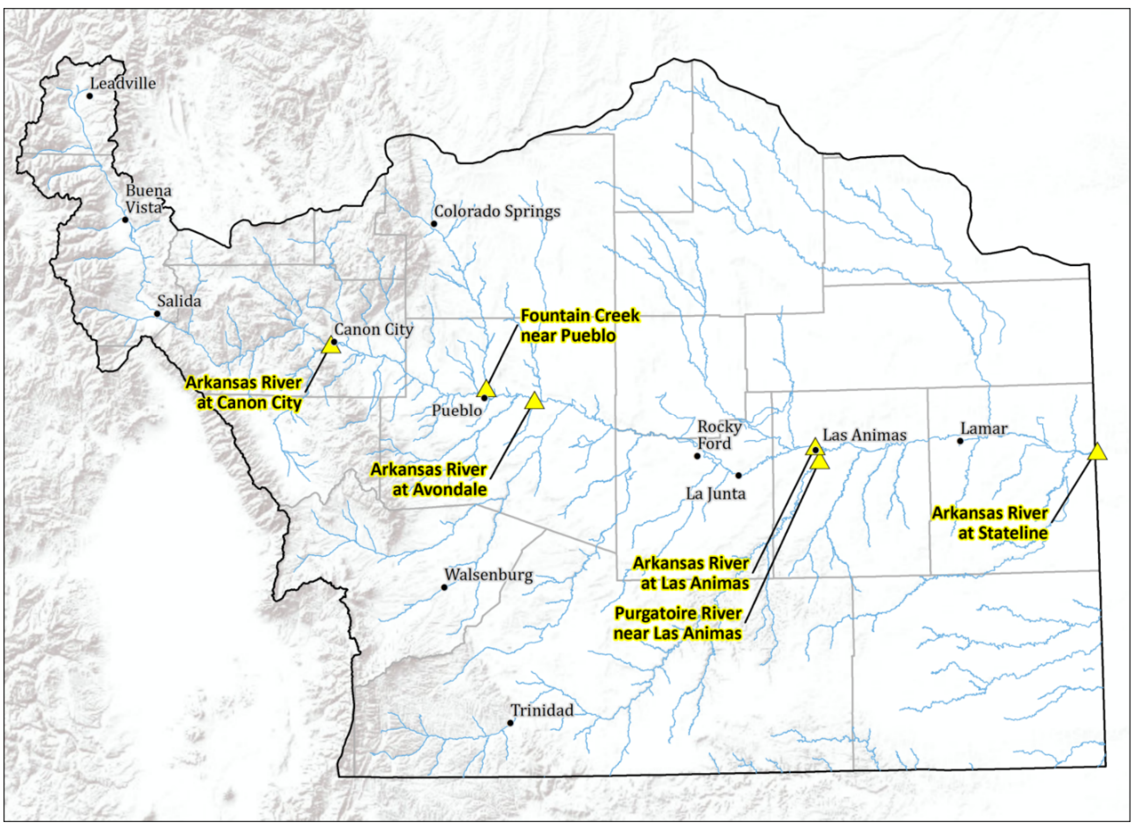


Figure 2 – Arkansas River ArkSWAM Flow Calibration Locations

Calibration results are summarized in **Table 9**, **Figure 3,** and **Figure 4**. As shown, a good agreement between modeled and measured metrics is achieved. Differences between modeled and measured annual flows are all less than 10 percent. Monthly patterns of simulated stream flow generally match the patterns observed in the gage data. Similarly, percentile plots indicate that the model does an excellent job of capturing the range of monthly flow variability observed at multiple locations throughout the basin. Results of this exercise lend confidence to the use of the model for simulating future scenarios.

Table 9 – Preliminary Calibration Results

Gage Location	Mean Measured Flow (AFY)	Mean Modeled Flow (AFY)	Percent Difference
Arkansas River at Canon City	535,000	585,000	9%
Arkansas River at Avondale	680,000	717,000	5%
Arkansas River at Las Animas	205,000	196,000	-4%
Arkansas River at Stateline	171,000	170,000	0%
Fountain Creek nr Pueblo	111,000	107,000	-4%
Purgatoire River nr Las Animas	43,000	46,000	8%

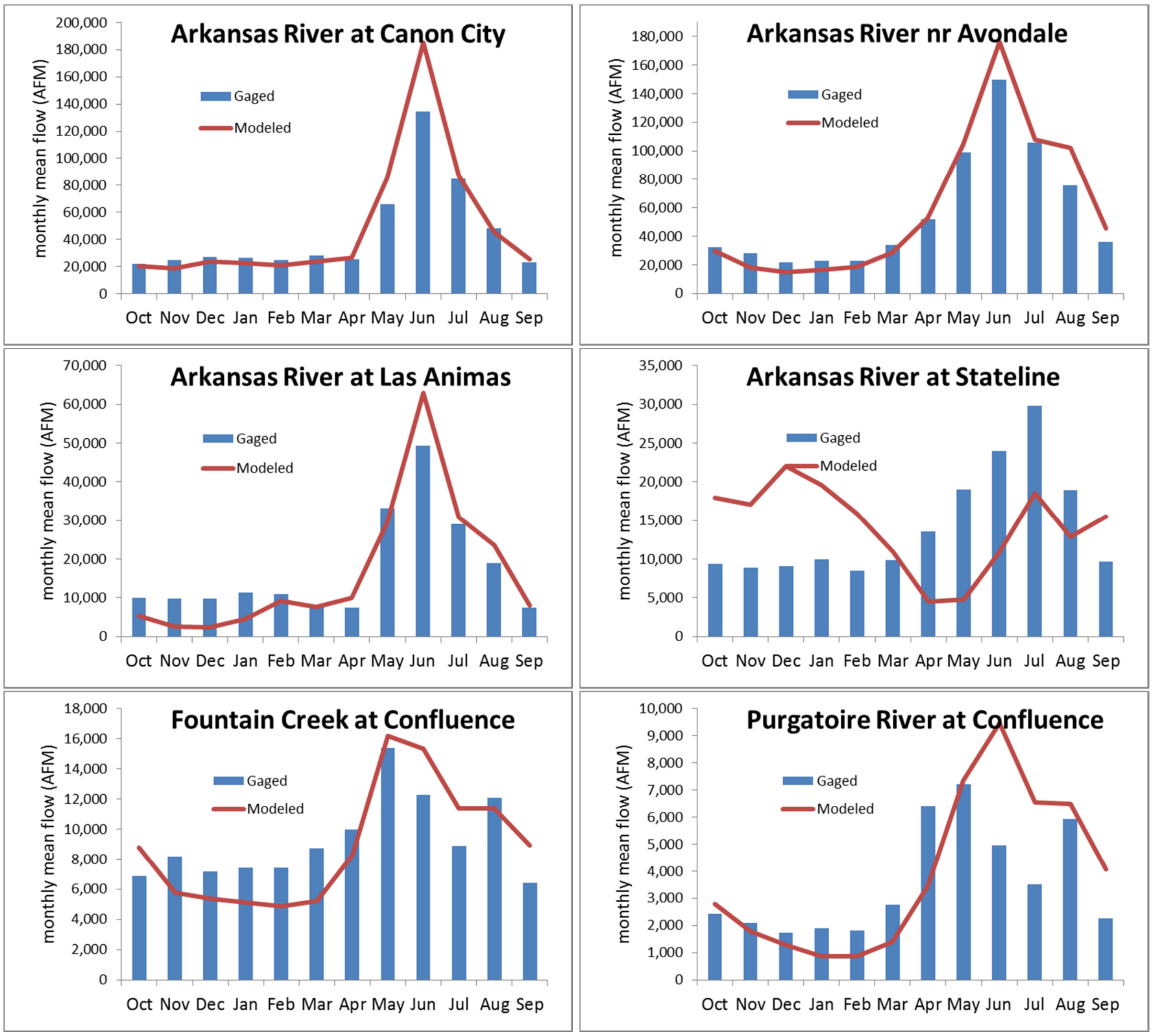


Figure 3 – Model Calibration Results, Mean Monthly Flows

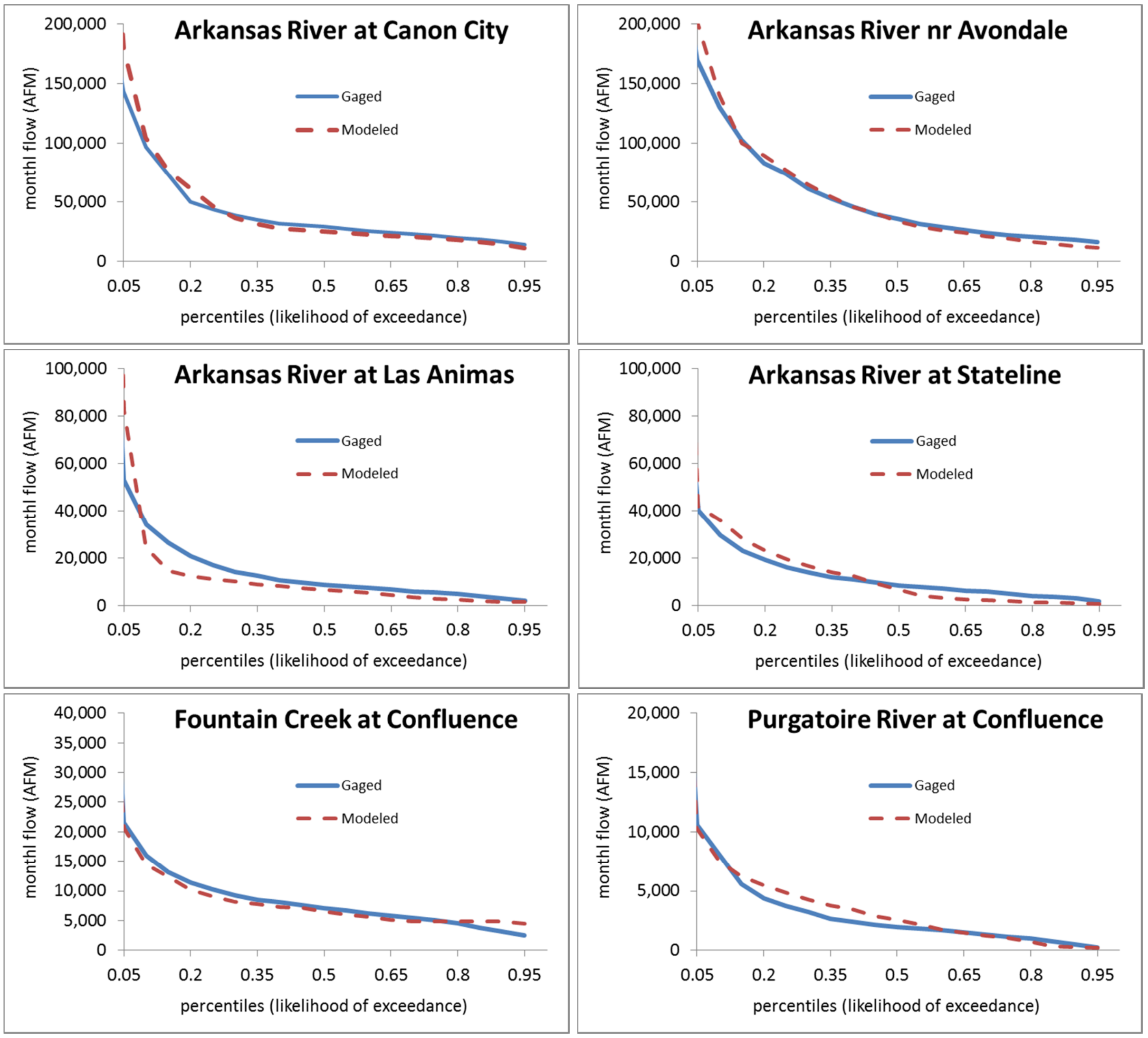


Figure 4 – Model Calibration Results, Monthly Flow Percentiles

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Memorandum

To:	*Arkansas Basin Roundtable Hydrologic Modeling Technical Committee;* *Jean Van Pelt – Southeastern Colorado Water Conservation District*,
From:	*Chris Kurtz, P.E.; Mark McCluskey, P.E.; and Alex Bowen, P.E. – CDM Smith*
Date:	*July 14, 2015*
Subject:	*ArkSWAM Model Shortage Analysis*

Overview

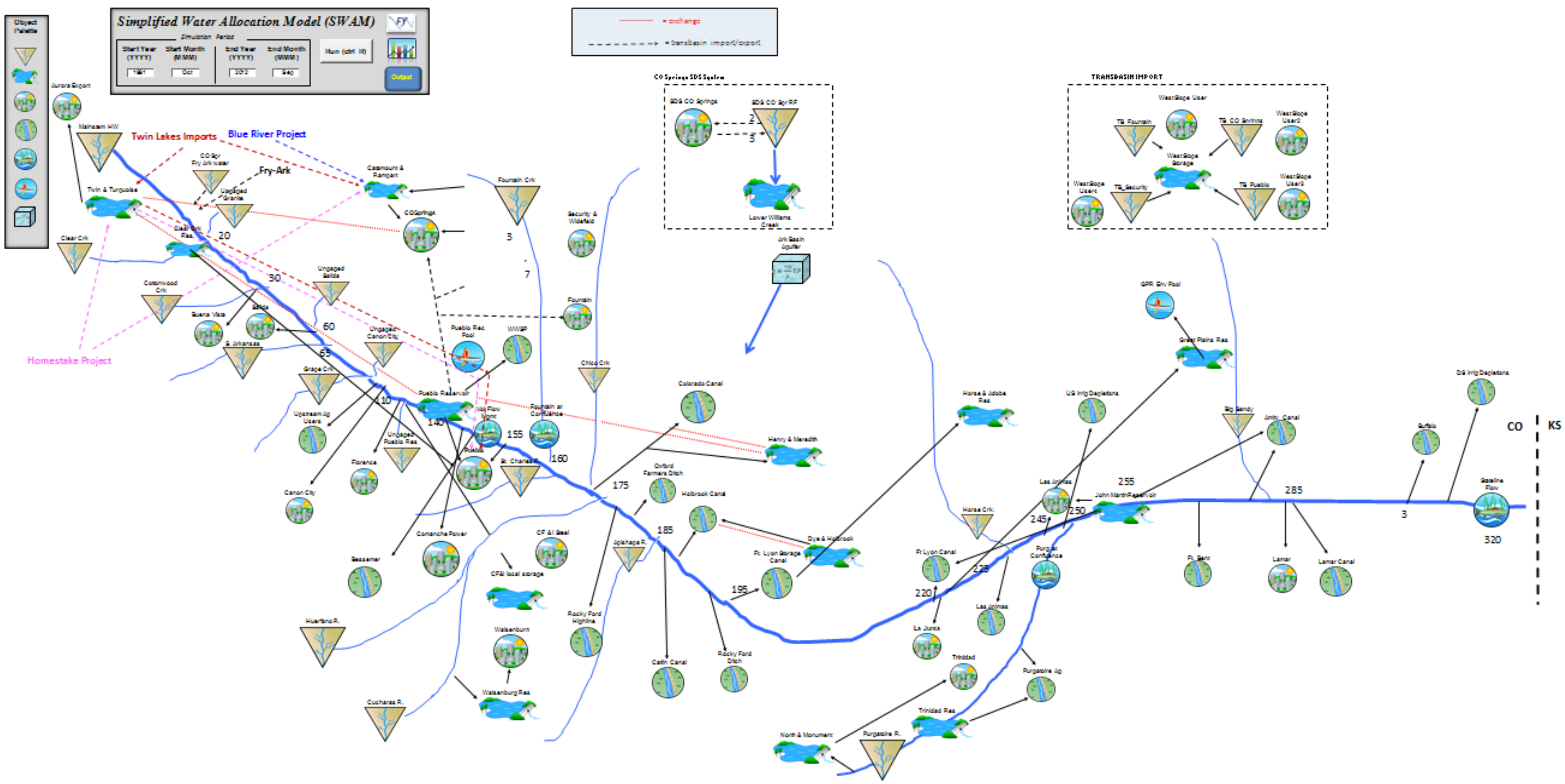
A water allocation model, known as ArkSWAM, was developed for the Arkansas River Basin to support the Arkansas Basin Implementation Plan (BIP). Initially, a model representing current conditions in the basin was developed and calibrated. Four future scenarios were then developed in order to perform an analysis capturing a range of potential shortages at a regional level for a 2050 planning horizon. This memo describes the general approach, hydrology, municipal and industrial (M&I) demand, irrigation demand, and infrastructure represented in ArkSWAM under each future conditions scenario.

The model was developed using CDM Smith's Simplified Water Allocation Model (SWAM) platform. The spatial domain of ArkSWAM extends from the Arkansas River at Leadville gage in the western headwaters to the Colorado-Kansas state line in the east. It includes all major tributaries, agricultural ditch diversions, M&I water users, and transbasin water imports. **Figure 1** shows the layout of the model network, including revisions that were made for modeling the future scenarios.

The model is simplified and is designed for large-scale planning studies. More specifically, ArkSWAM is intended to be a dynamic tool that can be used (and updated) to analyze water shortages in the basin as a result of increasing future demands. It is not designed to be a river administration or operational support tool, nor is it intended to replicate the Arkansas Basin Decision Support System (ArkDSS).

Model simplifications are required to provide useful and practical simulations of basin water resources within constraints imposed by data availability, software, budget, and schedule limitations. These simplifications include aggregation of water use nodes and/or simplified representation of legal exchange agreements or operating rules. Simplifications made for the calibrated model were carried forward into the model created for the future shortage analysis.

Figure 1 – Arkansas River BIP Water Allocation Model (ArkSWAM)



Four future scenarios have been developed to date, but other future scenarios are possible and could be developed in the future. The future scenarios used for the shortage analysis are based on the calibrated ArkSWAM model, modified to simulate a range of plausible future scenarios. Model development and calibration under current conditions and model limitations are described in detail in the May 12, 2015 memo, ArkSWAM Model Documentation.

In support of the hydrologic modeling effort, a Hydrologic Modeling Technical Committee was formed. Committee members were drawn from the larger Arkansas Basin Roundtable. During development and calibration of the current conditions model, the committee reviewed model construct and calibration results and provided input to improve the representation of water use and operations throughout the Arkansas River Basin. The committee also assisted in the development of the future scenarios definitions for the shortage analysis.

Future Scenario Development

In order to develop future scenarios, a range of assumptions and sources were considered for five primary variables that were used to define each scenario:

- **Future M&I demand** and growth rate
    - The Statewide Water Supply Initiative (SWSI) 2010 Arkansas Basin Needs Assessment Report (Colorado Water Conservation Board [CWCB] 2011) included a range of projected M&I demands, using low, medium, or high population growth projections, and high or low passive conservation estimates
- **Future irrigation demands**, including rate of loss of agricultural acreage to urbanization
    - The Needs Assessment Report included low and high estimates for acreage decreases due to urbanization
- **Future changes to environmental and recreational** uses in the basin, such as additional instream flow rights or flow augmentation programs
- **Changes in hydrology** and natural water supply availability, which may increase or decrease over time
- Rate of completion of **Identified Projects and Processes** (IPPs) to meet future water supply gaps
    - IPPs from SWSI 2010 and the BIP were reviewed to determine the likelihood of implementation and whether the concept is developed in sufficient detail to model
    - For example, IPPs identified for potential modeling included the Southern Delivery System (SDS) and planned transfers of agricultural water supplies to municipal use

The Hydrologic Modeling Technical Committee assisted with development of four unique future scenarios. Scenario definitions were selected based on a goal of establishing scenarios that were plausible and comparable to one another. **Table 1a** shows the assumptions chosen for each of these five variables in each of the four future modeling scenarios. **Table 1b** shows the same assumptions represented graphically. The symbology in **Table 1b** is also used in the modeling results figures found at the end of this memo, to quickly show the parameters. Assumptions and development of model inputs are described in further detail below.

Table 1a – Summary of Future Modeling Scenarios

Scenario	M&I Demand	Irrigation Demand	Env & Rec Demand	Hydrology	IPPs
1	Low growth; high passive conservation	Low urbanization rate; planned transfers to municipal use	Same as current conditions	Same as historical	SDS; planned transfers of agricultural water to municipal use
2	Low growth; high passive conservation	Low urbanization rate; planned transfers to municipal use	Same as current conditions	10% reduction from historical	SDS; planned transfers of agricultural water to municipal use
3	Medium growth; high passive conservation	Medium urbanization rate; planned transfers to municipal use	Same as current conditions	Same as historical	SDS; planned transfers of agricultural water to municipal use
4	Medium growth; high passive conservation	Medium urbanization rate; planned transfers to municipal use	Same as current conditions	10% reduction from historical	SDS; planned transfers of agricultural water to municipal use

Table 1b – Summary of Future Modeling Scenarios - Graphical

Scenario	M&I Demand	Irrigation Demand	Env & Rec Demand	Hydrology	IPPs
1					SDS; planned transfers of agricultural water to municipal use
2					SDS; planned transfers of agricultural water to municipal use
3					SDS; planned transfers of agricultural water to municipal use
4					SDS; planned transfers of agricultural water to municipal use

M&I Demand

Future M&I demand conditions for the Arkansas Basin are presented in the SWSI 2010 Arkansas Basin Needs Assessment Report (CWCB 2011). The projected demands from the Needs Assessment Report were reviewed for development of future demand conditions for input to ArkSWAM. As shown in **Table 1**, M&I demands are based on a "low growth" projection for Scenario 1 and Scenario 2, and a "medium growth" projection for Scenario 3 and Scenario 4. All four scenarios use the "high passive conservation" projections.

Demand projections developed for SWSI 2010, which were also used in the Needs Assessment Report, were conducted using a county-level spatial unit. However, ArkSWAM explicitly includes individual and aggregated M&I users represented as model objects. The discrepancy in spatial representation of M&I water use requires a more generalized approach to future demand allocation.

First a "delta demand" was calculated for each county as the difference between the 2010 demand levels from SWSI 2010 and the 2050 demand levels from the Arkansas Basin Needs Assessment Report. The county-level delta demands were then allocated to M&I water model user objects. Delta demands were not allocated to the two modeled self-supplied industrial objects (Comanche and Evraz), or to the Aurora Export demand, which maintained current-conditions demands for all future-conditions scenarios.

For counties containing one or more modeled municipal water user object, the delta demand was divided among those objects in proportion to the demand in the current conditions model. Counties without modeled municipal water objects were split at water district boundaries in geographic information system (GIS). Each county-water district intersection was assigned a portion of the county's delta demand in proportion to area. The delta demand from each county-water district intersection was then assigned to the nearest downstream municipal model object.

In this way, total M&I demands in the model were increased by the total M&I "delta demand" within the basin. This approach, while general, maintains an approximation of the spatial distribution of the projected growth in M&I demand and allows for the assessment of future regional water shortages using ArkSWAM. **Table 2** shows the 2050 demand for each in-basin M&I water user object within ArkSWAM for each scenario, as well as a comparison to the demand in the current conditions model. Note that the county-level approach means that each model object represents a regional demand and not only the demand of the specific municipality for which each object is named. For Scenarios 1 and 2, this approach results in an increase of in-basin M&I demand, excluding Aurora exports and self-supplied industrial users, from 194,000 acre-feet per year (AFY) to 297,000 AFY (consistent with SWSI 2010), or an increase of 53 percent. For Scenarios 3 and 4, this approach results in an increase of in-basin M&I demand from 194,000 AFY to 319,000 AFY, an increase of 64 percent.

Table 2 – Future Regional Municipal Model Object Demands, AFY

Aggregate In-Basin Municipal Model Object	Annual Demand, AFY				
	Current Conditions Model	Scenarios 1 & 2		Scenarios 3 & 4	
		Total Demand	Delta Demand	Total Demand	Delta Demand
Aurora Export	28,100	28,100	0	28,100	0
Buena Vista Area	900	4,200	3,300	4,500	3,600
Canon City Area	7,200	14,000	6,800	15,000	7,800
Colorado Springs Area	114,000	165,000	51,000	178,000	64,000
Comanche Generating Station	10,600	10,600	0	10,600	0
EVRAZ	49,400	49,400	0	49,400	0
Florence Area	2,800	5,000	2,200	5,300	2,500
Fountain Area	5,200	7,500	2,300	8,100	2,900
La Junta Area	2,000	2,400	400	2,600	600
Lamar Area	2,750	9,200	6,450	9,700	6,950
Las Animas Area	1,000	2,100	1,100	2,100	1,100
Pueblo Area	40,000	61,000	21,000	64,000	24,000
Salida Area	3,000	6,400	3,400	6,900	3,900
Security-Widefield Area	9,000	13,000	4,000	14,000	5,000
Trinidad Area	5,100	7,300	2,200	7,900	2,800
Walsenburg Area	1,000	1,800	800	2,000	1,000
Total In-Basin Municipal[1]	**194,000**	**299,000**	**105,000**	**320,000**	**126,000**
Total M&I	**282,000**	**387,000**	**105,000**	**408,000**	**126,000**

Note: values may not sum to totals due to rounding

[1] Total In-Basin Municipal does not include Aurora Export, EVRAZ, or Comanche demands

Crop Irrigation Demand

The future agricultural demand analysis from SWSI 2010 included several potential sources of reduction in future irrigated acreage. That included estimates of planned agricultural to municipal water right transfers identified as IPPs (7,200 acres) and estimates of land use conversion resulting from urbanization (between 2,300 and 3,000 acres). The SWSI 2010 agricultural projections also included unidentified (or "unplanned") agricultural to municipal transfers as a means to meet the projected 2050 M&I gap (approximately 45,000 acres). However, this assumption is not consistent with the stated future goal of preserving the existing agricultural economy within the Arkansas Basin, and unplanned transfers were not included in any of the future scenarios.

Loss of irrigated acreage was presented in SWSI 2010 at the water district level for a "low," "medium," and "high" scenario. Irrigated acreage lost to urbanization under the "medium" scenario was the average of losses under the "low" and "high" scenarios. As shown in **Table 1**, a low rate of urbanization was assumed for Scenarios 1 and 2 (low M&I demand growth), while a medium rate was assumed for Scenarios 3 and 4 (medium M&I demand growth). As documented in SWSI 2010, current irrigated acreage in the Arkansas River Basin totals 428,000. A low rate of urbanization is projected to cause a reduction of 2,360 acres by 2050, or 0.55 percent. A medium rate of urbanization is projected to cause a reduction of 2,679 acres, or 0.63 percent.

The SWSI 2010 projections were made at the water district level; however, ArkSWAM explicitly includes aggregated agricultural users represented as model objects. In addition, the SWSI 2010 projections are based on acreage, whereas the total ArkSWAM demands were based on historical diversion values. Therefore, similar to M&I demands, the discrepancies in representation of agricultural water use requires a more generalized approach to future demand allocation.

As described in the May 12, 2015 memo, irrigation demands for the current conditions model were developed based on headgate diversion data from HydroBase, including direct use as well as water conveyed to off-channel storage. The HydroBase data was aggregated to the model objects and then further processed to better represent the diversion-storage-use dynamic before being input to the model. The aggregation of HydroBase data to water users was used as a basis for distributing the reductions in demand.

To assign reductions due to urbanization to aggregate model objects, the reduction in irrigated acreage was calculated as a percentage of total acreage within each water district. The reductions by water district were then distributed to the aggregate water users in the model based on the percentage of headgate demand within each water district assigned to each modeled water user and the percentage of each water user's demand derived from each water district. The result is a percentage reduction due to urbanization for each agricultural water user within the model (a range of 0 to 6 percent).

The entire reduction from municipal transfers is expected to occur at the Bessemer Ditch in Water District 14 and was assigned to the Bessemer Ditch aggregate user. This IPP is estimated to reduce irrigated acreage by 7,200 acres, which represents about one-third of the acreage in the Bessemer aggregate object in the model. The resulting percent reduction was added to the reduction at the Bessemer Ditch aggregate user due to urbanization to determine the total demand reduction at the Bessemer Ditch aggregate user.

Finally, the percentage reductions for each water user were applied to the time-varying monthly time series from the current conditions model. The historical, time varying irrigation time series used in the current conditions model was deemed the most appropriate starting point for accounting for future reductions due to urbanization and planned transfers. Primarily, this is because it reflects impacts on irrigation diversions due to year-to-year climate variations (available precipitation, evapotranspiration). While some historical transfers and urbanization surely impacted this historical time period and thus historical diversion, a review of these occurrences found that, generally, major transfers occurred in the early portion of the simulated period or that transferred water is still diverted at the same "pre-transfer" location. Based on the approach described above, **Table 3** shows the percent reduction and total demand by water district for each model scenario. **Table 4** shows the demand and percent reduction for each agricultural model object.

Table 3 – Future Agricultural Model Demands by Water District, AFY

Water District	Current Conditions Model	Scenarios 1 & 2		Scenarios 3 & 4	
	Average Annual Demand, AFY	Average Annual Demand, AFY	Demand Reduction %	Average Annual Demand, AFY	Demand Reduction %
10	50,000	48,000	3.4%	48,000	4.2%
11	153,000	149,000	2.6%	148,000	3.3%
12	145,000	138,000	4.9%	137,000	5.6%
13	36,000	36,000	1.2%	36,000	1.4%
14	370,000	330,000	8.1%	330,000	8.1%
15	12,000	12,000	1.1%	12,000	1.3%
16	16,000	16,000	0.0%	16,000	0.0%
17	589,000	586,000	0.6%	586,000	0.6%
18	8,500	8,500	0.1%	8,500	0.2%
19	66,000	66,000	0.1%	65,000	0.2%
67	234,000	233,000	0.4%	233,000	0.5%
79	25,000	25,000	0.0%	25,000	0.0%
Total	**1,705,000**	**1,647,000**	**3.4%**	**1,644,000**	**3.5%**

Note: values may not sum to totals due to rounding

Table 4 – Future Aggregate Agricultural Model Object Demands, AFY

Aggregate Agricultural Model Object	Current Conditions Model	Scenarios 1 & 2		Scenarios 3 & 4	
	Average Annual Demand, AFY	Average Annual Demand, AFY	Demand Reduction %	Average Annual Demand, AFY	Demand Reduction %
Ag Users Above Pueblo	335,000	323,000	3.4%	321,000	4.1%
Amity Canal Area	94,000	94,000	0.4%	94,000	0.5%
Bessemer Ditch Area	119,000	77,000	34.7%	77,000	35.1%
Buffalo Canal Area	57,000	56,000	0.4%	56,000	0.5%
Catlin Canal Area	109,000	108,000	0.5%	108,000	0.6%
CO Canal Area	181,000	181,000	0.2%	181,000	0.2%
Ft Lyon Canal Area	293,000	291,000	0.6%	292,000	0.6%
Ft Lyon Storage Canal Area	43,000	42,000	0.6%	42,000	0.6%
Ft. Bent Canal Area	42,000	42,000	0.4%	42,000	0.5%
Holbrook Canal Area	51,000	51,000	0.6%	51,000	0.6%
Lamar Canal Area	41,000	41,000	0.4%	41,000	0.5%
Las Animas Ditch Area	67,000	67,000	0.6%	67,000	0.6%
Oxford Farmers Ditch Area	56,000	56,000	0.1%	56,000	0.2%
Purgatoire Ag Users Area	66,000	66,000	0.1%	65,000	0.2%
Rocky Ford Ditch Area	32,000	32,000	0.6%	32,000	0.6%
Rocky Ford Highline Area	119,000	119,000	0.1%	119,000	0.1%
Total	1,705,000	1,647,000	3.4%	1,644,000	3.5%

Note: values may not sum to totals due to rounding

Hydrology

As shown in **Table 1**, Scenarios 1 and 3 assumed no change in historical hydrologic conditions, while Scenarios 2 and 4 assumed a 10 percent reduction in natural water supply availability. Monthly inflows for 18 headwater and tributary locations within the basin were developed for the current conditions model, as described in the May 12, 2015 memo. These inflows generally represent naturalized flows of major tributaries in the basin and were initially developed based on historical gage records, and then adjusted during the calibration process. Calibrated inflows for all months and years at all 18 locations were reduced by 10 percent to create the revised hydrology for Scenarios 3 and 4. Transmountain deliveries were not adjusted for any future scenario. **Table 5** shows the annual average inflows at each modeled tributary location under each scenario. The relative location of each tributary inflow point in the model can be seen in **Figure 1**.

As described in the May 12, 2015 memo, modeling for the Trinidad municipal object is limited due to gage data availability and the location of Trinidad's North and Monument Reservoirs high up in the Purgatoire River basin. In the existing-conditions model, Trinidad has a fixed water supply. This construct allows for calculation of return flows, but may not accurately represent legal or physical availability of water supplies. The existing-conditions construct was updated to reflect the increase in demand at Trinidad under future conditions (2050 planning horizon).

In the future conditions modeling, supplies to Trinidad at North and Monument were increased to match future demands in all four scenarios. The gage above Trinidad Reservoir is used to model inflows to the Purgatoire basin. As shown in **Figure 1**, North and Monument are located above the Trinidad Reservoir gage. Therefore, the additional supplies to Trinidad were subtracted from the modeled inflows at Trinidad Reservoir to maintain overall mass balance. In this way, the total inflows to the Purgatoire Basin, including Trinidad supplies as well as flows at the Trinidad Reservoir gage, are the same in the calibrated existing-conditions model and Scenarios 1 and 3. Consistent with **Table 1**, the Trinidad Reservoir gage inflows in Scenarios 2 and 4 were reduced by an additional 10%. The total Purgatoire River gaged inflows are shown in **Table 5**.

Similar to the existing-conditions modeling, the future-conditions modeling construct for the Trinidad municipal model object may not reflect legal or physical availability. This simplified construct is acceptable for the current scope of ArkSWAM as a regional-level planning tool. However, more detail will be required in the Purgatoire basin for future, more detailed modeling efforts, including the ArkDSS model. Additional model accuracy in the Purgatoire basin will be particularly important to support review of downstream impacts due to the Trinidad Project.

Table 5 – Future Model Tributary Inflows, AFY

Tributary Object	Average Annual Flow (AFY)	
	Current Conditions, Scenarios 1 & 3	Scenarios 2 & 4
Mainstem Headwater	54,000	49,000
Fountain Crk & Local Runoff	77,000	69,000
Huerfano River Headwater	19,000	17,000
Cucharas River Headwater	16,000	15,000
Purgatoire River above Trinidad Reservoir[1]	39,300	44.000
S. Arkansas River at Mouth	16,000	14,000
Grape Creek at Mouth	43,000	39,000
Clear Creek at Clear Crk Reservoir	49,000	44,000
Cottonwood Creek at Mouth	24,000	21,000
Ungaged Above Granite	253,000	227,000
Ungaged Below Granite, Above Salida	240,000	216,000
Ungaged Below Salida, Above Canon City	88,000	79,000
Apishapa River at Mouth	12,000	11,000
St Charles River at Mouth	28,000	25,000
Ungaged Below Canon City, Above Pueblo Reservoir	110,000	99,000
Horse Creek at Mouth	9,000	8,000
Big Sandy Creek at Mouth	12,000	11,000
Chico Creek at Mouth	3,000	2,000
Total	**1,104,000**	**995,000**

Note: values may not sum to totals due to rounding
[1]Current conditions inflows: 52,000 AFY; see text for description of inflow adjustments for Trinidad model object supplies

Identified Projects and Processes

As shown in **Table 1**, two IPPs were included in the modeling: transfer of agricultural water rights for municipal use and completion of the SDS project. Transfer of agricultural water rights for municipal use was accomplished in the future conditions modeling by reducing crop irrigation demands throughout the basin, as described in the Crop Irrigation Demand section, above.

A simplified representation of SDS is explicitly included in the ArkSWAM models for scenarios 1, 2, 3, and 4. Key components of SDS represented in ArkSWAM include:

- Pueblo Reservoir storage accounts for Colorado Springs (28,000 acre feet [AF]), Fountain (15,000 AF), and Security (15,000 AF)
- Return flow storage for Colorado Springs is also included in a new model reservoir representing the Lower Williams Creek Reservoir (28,500 AF)

- An exchange between Lower Williams Creek Reservoir and Pueblo Reservoir for Colorado Springs

This simplified operation and representation of SDS in ArkSWAM was tested and compared to published results of modeled yields for the SDS system in the Final Environmental Impact Statement (USBR 2008). This comparison found that the ArkSWAM representation of SDS, though simplified, was reasonably close to published values. The Final Environmental Impact Statement estimated yield of SDS to be between 42,000 and 53,000 AFY while ArkSWAM estimated yield for SDS at 46,000 AFY.

Future Regional Shortage Analysis

ArkSWAM's model output includes physical availability of water (streamflows), legal availability of water (to identify legal constraints), reservoir storage levels, diversions, return flows, and water supply shortfalls. Output is available for locations throughout the basin on a monthly timestep. Shortages were summarized for both agricultural and municipal model objects. In addition, because the municipal model objects represent a regional future demand (see M&I Demand section above), the municipal model object shortages were disaggregated to the county level to match the SWSI 2010 spatial unit used for demand projections. Similarly, shortages from the aggregate agricultural model objects were disaggregated to the water district level to match the SWSI 2010 spatial unit used for projections of irrigated acreage reductions.

Municipal shortages are summarized in **Tables 6 through 9** and **Figures 2 through 9**. **Table 6** shows future regional shortages for municipal model objects in AFY and **Table 7** shows the same as percent of demand. **Table 8** shows future municipal shortages by county in AFY and **Table 9** shows the same as percent of demand. **Figures 2 through 5** show municipal shortages at the county level for each future scenario. **Figures 6 through 9** show municipal shortages as a percent of demand. All figures are labeled with a graphical description of the scenario, using the same icons shown in **Table 1b** and described in **Table 1a**.

Agricultural shortages are summarized in **Tables 10 through 13** and **Figures 10 through 17**. **Table 10** shows future regional shortages for agricultural model objects and **Table 11** shows the same as a percent of demand. **Table 12** shows future agricultural shortages by water district and **Table 13** shows the same as a percent of demand. **Figures 10 through 13** show agricultural shortages at the water district level for each future scenario. **Figures 14 through 17** show agricultural shortages as a percent of demand. All figures are labeled with a graphical description of the scenario, using the same icons shown in **Table 1b** and described in **Table 1a**.

Table 6 – Future Regional Municipal Model Object Shortages, AFY

Aggregate In-Basin Municipal Model Object	Average Annual Shortage, AFY			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Buena Vista Area	220	240	260	290
Canon City Area	0	0	21	21
CO Springs Area	10,000	15,000	22,000	27,000
Florence Area	0	0	1	1
Fountain Area	51	120	77	170
La Junta Area	0	0	190	190
Lamar Area	0	0	0	0
Las Animas Area	0	0	0	0
Pueblo Area	0	0	0	0
Salida Area	0	0	0	0
Security-Widefield Area	0	0	0	0
Trinidad Area[1]	95	95	97	97
Walsenburg Area	0	0	0	0
Total	**11,000**	**16,000**	**22,000**	**27,000**

Note: values may not sum to totals due to rounding

[1] As noted in the May 12, 2015 memo, modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Shortages calculated for Trinidad and Las Animas County may not reflect actual future water supply availability.

Table 7 – Future Regional Municipal Model Object Shortages, Percent

Aggregate In-Basin Municipal Model Object	Average Annual Shortage, Percent of Demand			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Buena Vista Area	5%	6%	6%	6%
Canon City Area	0%	0%	0%	0%
CO Springs Area	6%	9%	12%	15%
Florence Area	0%	0%	0%	0%
Fountain Area	1%	2%	1%	2%
La Junta Area	0%	0%	7%	7%
Lamar Area	0%	0%	0%	0%
Las Animas Area	0%	0%	0%	0%
Pueblo Area	0%	0%	0%	0%
Salida Area	0%	0%	0%	0%
Security-Widefield Area	0%	0%	0%	0%
Trinidad Area[1]	1%	1%	1%	1%
Walsenburg Area	0%	0%	0%	0%
Total	**4%**	**5%**	**7%**	**9%**

[1] As noted in the May 12, 2015 memo, modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Shortages calculated for Trinidad and Las Animas County may not reflect actual future water supply availability.

Table 8 – Future Municipal Model Shortages by County, AFY

County	Average Annual Shortage, AFY			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Baca	0	0	0	0
Bent	0	0	0	0
Chaffee	66	74	85	95
Cheyenne	0	0	0	0
Crowley	0	0	0	0
Custer	0	0	3	3
El Paso	10,000	16,000	22,000	27,000
Elbert	0	0	0	0
Fremont	0	0	19	19
Huerfano	0	0	0	0
Kiowa	0	0	0	0
Lake	150	170	170	190
Las Animas[1]	95	95	97	97
Lincoln	0	0	0	0
Otero	0	0	190	190
Prowers	0	0	0	0
Pueblo	0	0	0	0
Teller	0	0	0	0
Total	**11,000**	**16,000**	**22,000**	**27,000**

Note: values may not sum to totals due to rounding

[1] As noted in the May 12, 2015 memo, modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Shortages calculated for Trinidad and Las Animas County may not reflect actual future water supply availability.

Table 9 – Future Municipal Model Shortages by County, Percent

County	Average Annual Shortage, Percent of Demand			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Baca	0%	0%	0%	0%
Bent	0%	0%	0%	0%
Chaffee	1%	1%	1%	1%
Cheyenne	0%	0%	0%	0%
Crowley	0%	0%	0%	0%
Custer	0%	0%	0%	0%
El Paso	6%	8%	11%	13%
Elbert	0%	0%	0%	0%
Fremont	0%	0%	0%	0%
Huerfano	0%	0%	0%	0%
Kiowa	0%	0%	0%	0%
Lake	5%	6%	6%	6%
Las Animas[1]	1%	1%	1%	1%
Lincoln	0%	0%	0%	0%
Otero	0%	0%	7%	7%
Prowers	0%	0%	0%	0%
Pueblo	0%	0%	0%	0%
Teller	0%	0%	0%	0%
Total	**4%**	**5%**	**7%**	**9%**

[1] As noted in the May 12, 2015 memo, modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Shortages calculated for Trinidad and Las Animas County may not reflect actual future water supply availability.

Table 10 – Future Aggregate Agricultural Model Object Shortages, AFY

Aggregate Agricultural Model Object	Average Annual Shortage, AFY			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Ag Users Above Pueblo	28,000	41,000	28,000	41,000
Amity Canal Area	120	760	130	790
Bessemer Ditch Area	4,700	6,900	4,700	7,000
Buffalo Canal Area	0	92	0	89
Catlin Canal Area	530	670	530	680
CO Canal Area	11,000	26,000	11,000	25,000
Ft Lyon Canal Area	9,200	18,000	9,200	19,000
Ft Lyon Storage Canal Area	0	0	0	0
Ft. Bent Canal Area	0	420	0	420
Holbrook Canal Area	920	2,300	910	2,200
Lamar Canal Area	0	0	0	0
Las Animas Ditch Area	680	1,800	720	1,800
Oxford Farmers Ditch Area	270	450	310	460
Purgatoire Ag Users Area	5,300	6,500	5,400	6,600
Rocky Ford Ditch Area	0	0	0	0
Rocky Ford Highline Area	0	0	0	0
Total	**61,000**	**105,000**	**61,000**	**105,000**

Note: values may not sum to totals due to rounding

Table 11 – Future Aggregate Agricultural Model Object Shortages, Percent

Aggregate Agricultural Model Object	Average Annual Shortage, Percent of Demand			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Ag Users Above Pueblo	9%	13%	9%	13%
Amity Canal Area	0%	1%	0%	1%
Bessemer Ditch Area	6%	9%	6%	9%
Buffalo Canal Area	0%	0%	0%	0%
Catlin Canal Area	0%	1%	0%	1%
CO Canal Area	6%	14%	6%	14%
Ft Lyon Canal Area	3%	6%	3%	6%
Ft Lyon Storage Canal Area	0%	0%	0%	0%
Ft. Bent Canal Area	0%	1%	0%	1%
Holbrook Canal Area	2%	4%	2%	4%
Lamar Canal Area	0%	0%	0%	0%
Las Animas Ditch Area	1%	3%	1%	3%
Oxford Farmers Ditch Area	0%	1%	1%	1%
Purgatoire Ag Users Area	8%	10%	8%	10%
Rocky Ford Ditch Area	0%	0%	0%	0%
Rocky Ford Highline Area	0%	0%	0%	0%
Total	**4%**	**6%**	**4%**	**6%**

Table 12 – Future Agricultural Model Shortages by Water District, AFY

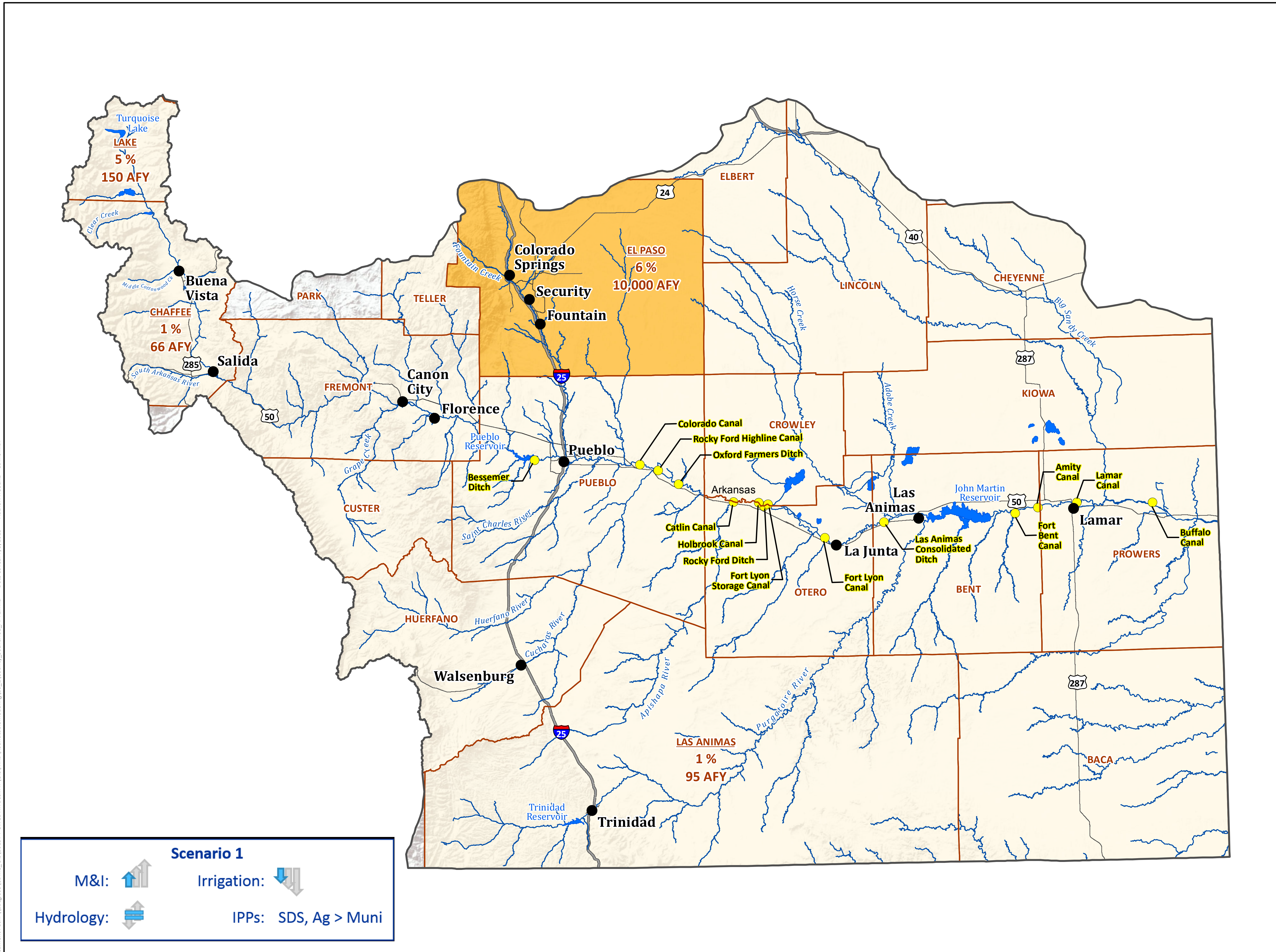
Water District	Average Annual Shortage, AFY			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
10	2,900	4,300	2,900	4,300
11	13,000	19,000	13,000	19,000
12	12,000	18,000	12,000	18,000
13	3,200	4,600	3,100	4,600
14	9,800	21,000	10,000	21,000
15	710	1,700	730	1,600
16	940	2,200	970	2,200
17	11,000	23,000	11,000	23,000
18	42	52	42	53
19	5,300	6,500	5,400	6,600
67	120	1,300	130	1,300
79	1,500	3,600	1,600	3,500
Total	**61,000**	**105,000**	**61,000**	**105,000**

Note: values may not sum to totals due to rounding

Table 13 – Future Agricultural Model Shortages by Water District, Percent

Water District	Average Annual Shortage, Percent of Demand			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
10	6%	9%	6%	9%
11	9%	13%	9%	13%
12	9%	13%	9%	13%
13	9%	13%	9%	13%
14	3%	6%	3%	6%
15	6%	14%	6%	14%
16	6%	14%	6%	14%
17	2%	4%	2%	4%
18	0%	1%	0%	1%
19	8%	10%	8%	10%
67	0%	1%	0%	1%
79	6%	14%	6%	14%
Total	**4%**	**6%**	**4%**	**6%**

Figure 2
Future Annual Average Municipal Model Shortages by County: Scenario 1 - AFY



Major Irrigation System Headgate

County Boundary

Average Annual Shortage, AFY

- < 1,000
- 1,000 to < 5,000
- 5,000 to < 10,000
- 10,000 to < 30,000

Modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Therefore, shortages calculated for Las Animas County may not reflect actual future water supply availability.

Average annual shortage is indicated on the map for each county

Park county was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles

N

COLORADO
Colorado Water Conservation Board
Department of Natural Resources

North Platte
Yampa/White/Green
South Platte
Colorado
Metro
Gunnison
Rio Grande
Arkansas
San Juan/Dolores/San Miguel

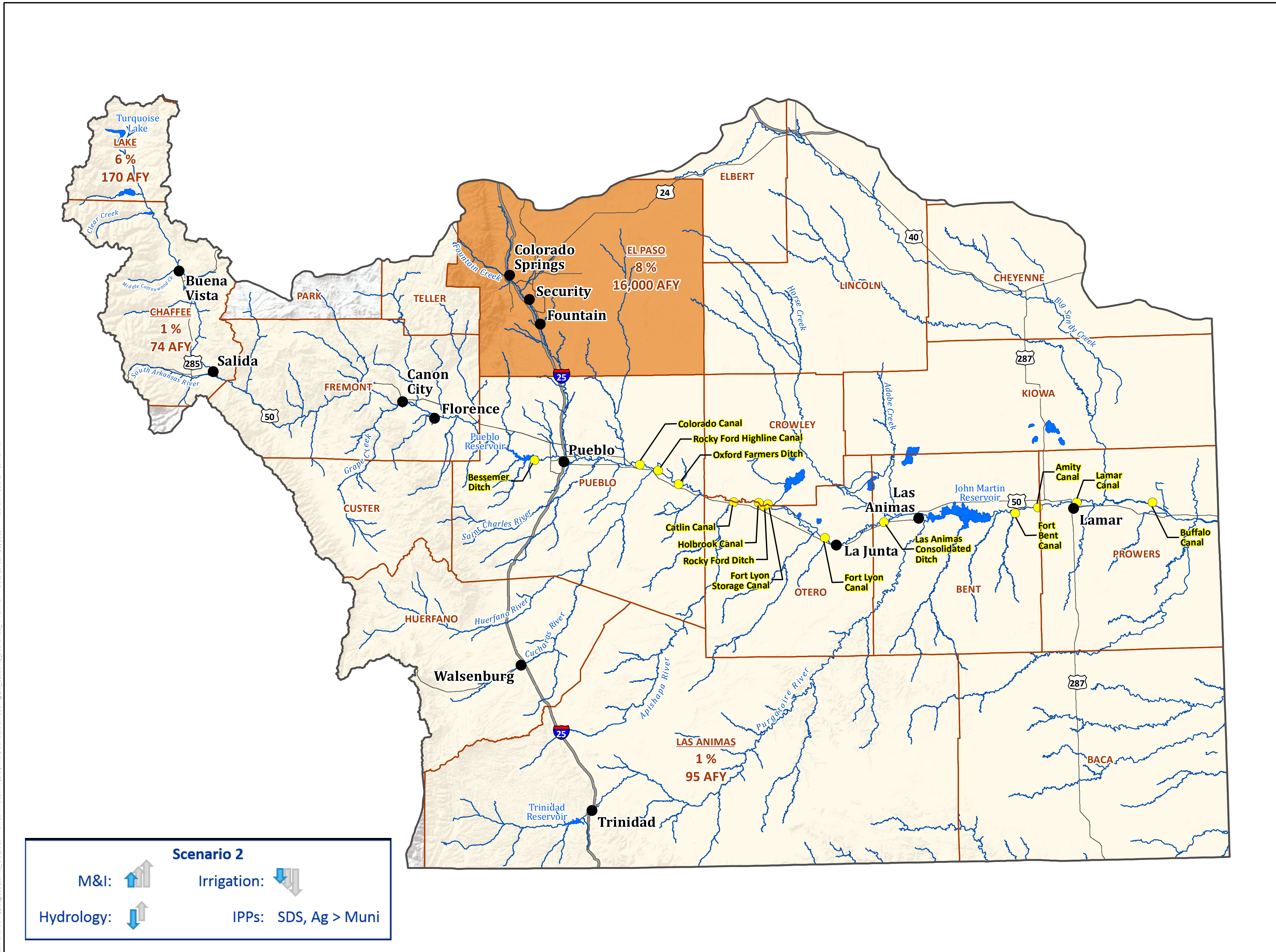


Figure 3
Future Annual Average Municipal Model Shortages by County: Scenario 2 - AFY

Major Irrigation System Headgate

County Boundary

Average Annual Shortage, AFY

- < 1,000
- 1,000 to < 5,000
- 5,000 to < 10,000
- 10,000 to < 30,000

Modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Therefore, shortages calculated for Las Animas County may not reflect actual future water supply availability.

Average annual shortage is indicated on the map for each county

Park county was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles

CDM Smith

COLORADO
Colorado Water Conservation Board
Department of Natural Resources

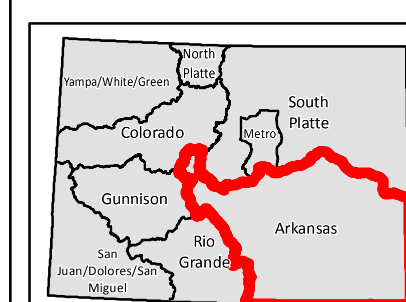
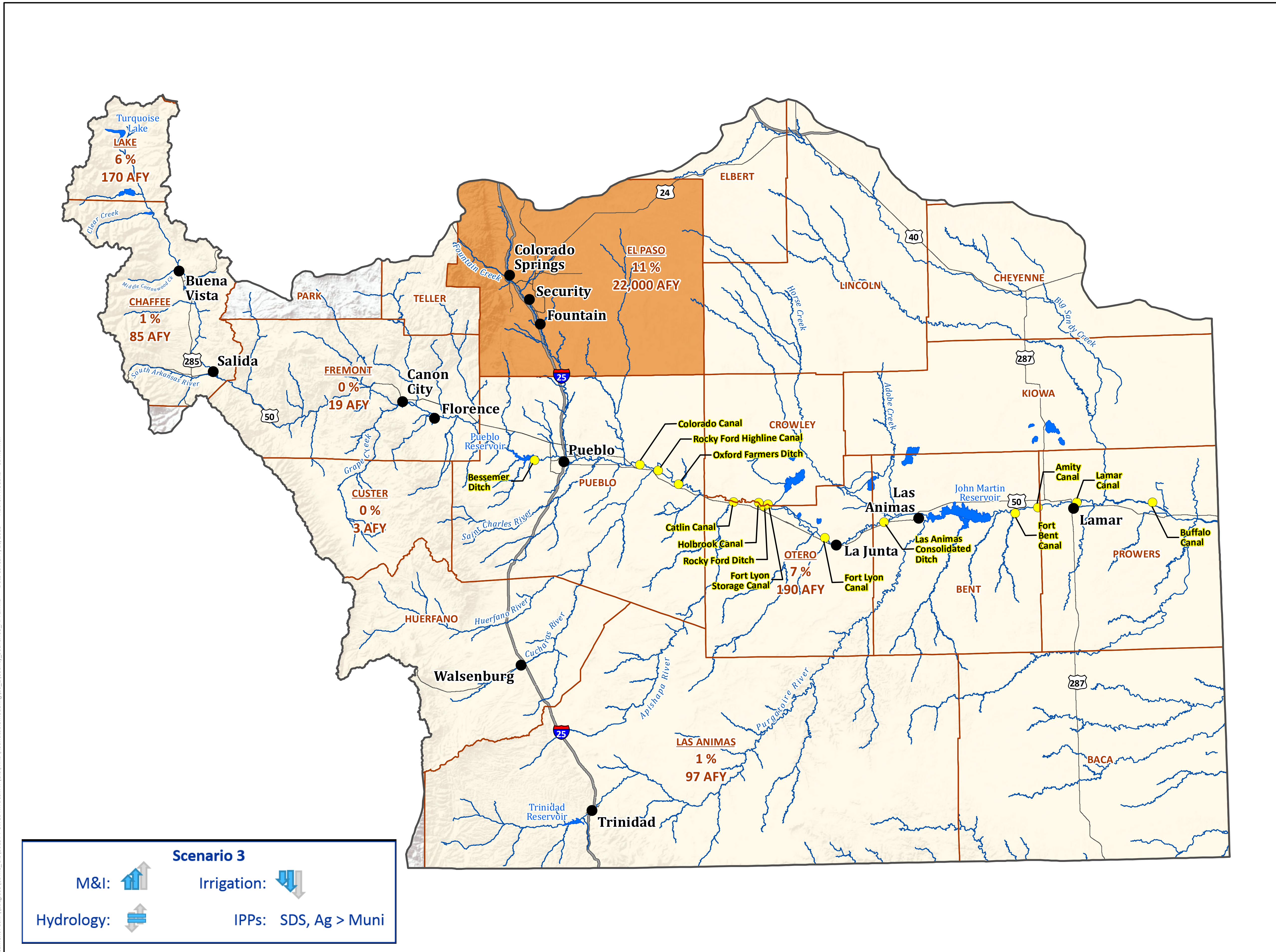


Figure 4
Future Annual Average Municipal Model Shortages by County: Scenario 3 - AFY



Major Irrigation System Headgate

County Boundary

Average Annual Shortage, AFY

- < 1,000
- 1,000 to < 5,000
- 5,000 to < 10,000
- 10,000 to < 30,000

Modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Therefore, shortages calculated for Las Animas County may not reflect actual future water supply availability.

Average annual shortage is indicated on the map for each county

Park county was not included in modeling

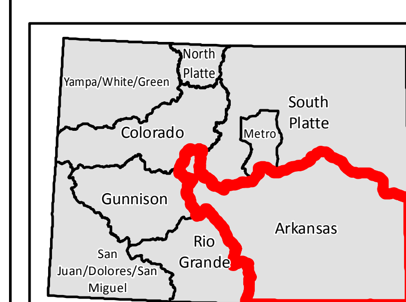
7/10/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles

CDM Smith

COLORADO
Colorado Water Conservation Board
Department of Natural Resources



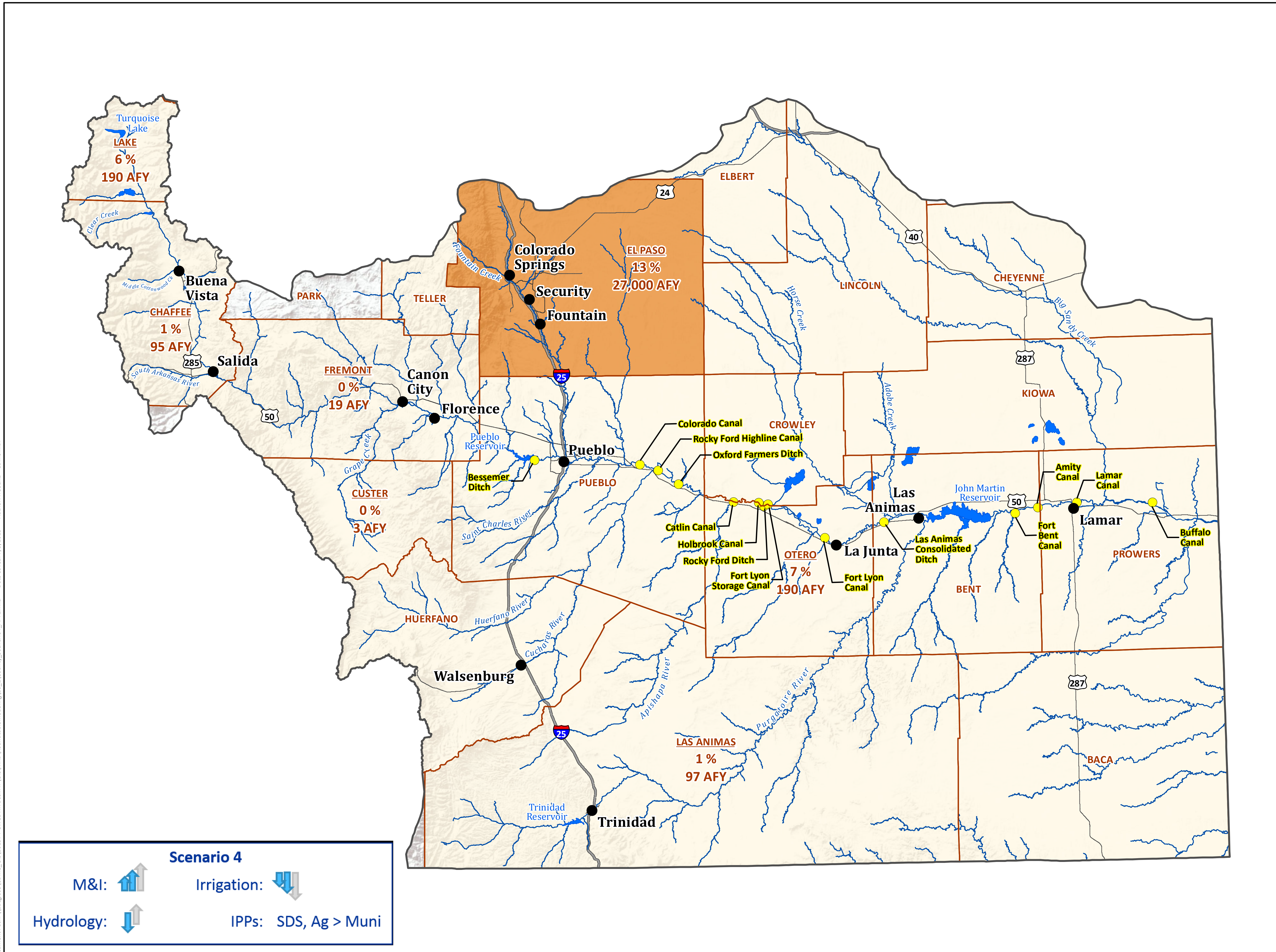


Figure 5
Future Annual Average Municipal Model Shortages by County: Scenario 4 - AFY

Major Irrigation System Headgate

County Boundary

Average Annual Shortage, AFY

- < 1,000
- 1,000 to < 5,000
- 5,000 to < 10,000
- 10,000 to < 30,000

Modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Therefore, shortages calculated for Las Animas County may not reflect actual future water supply availability.

Average annual shortage is indicated on the map for each county

Park county was not included in modeling

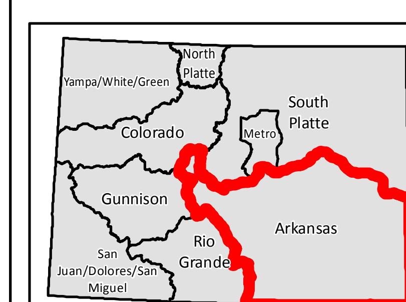
7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles

CDM Smith

COLORADO
Colorado Water Conservation Board
Department of Natural Resources



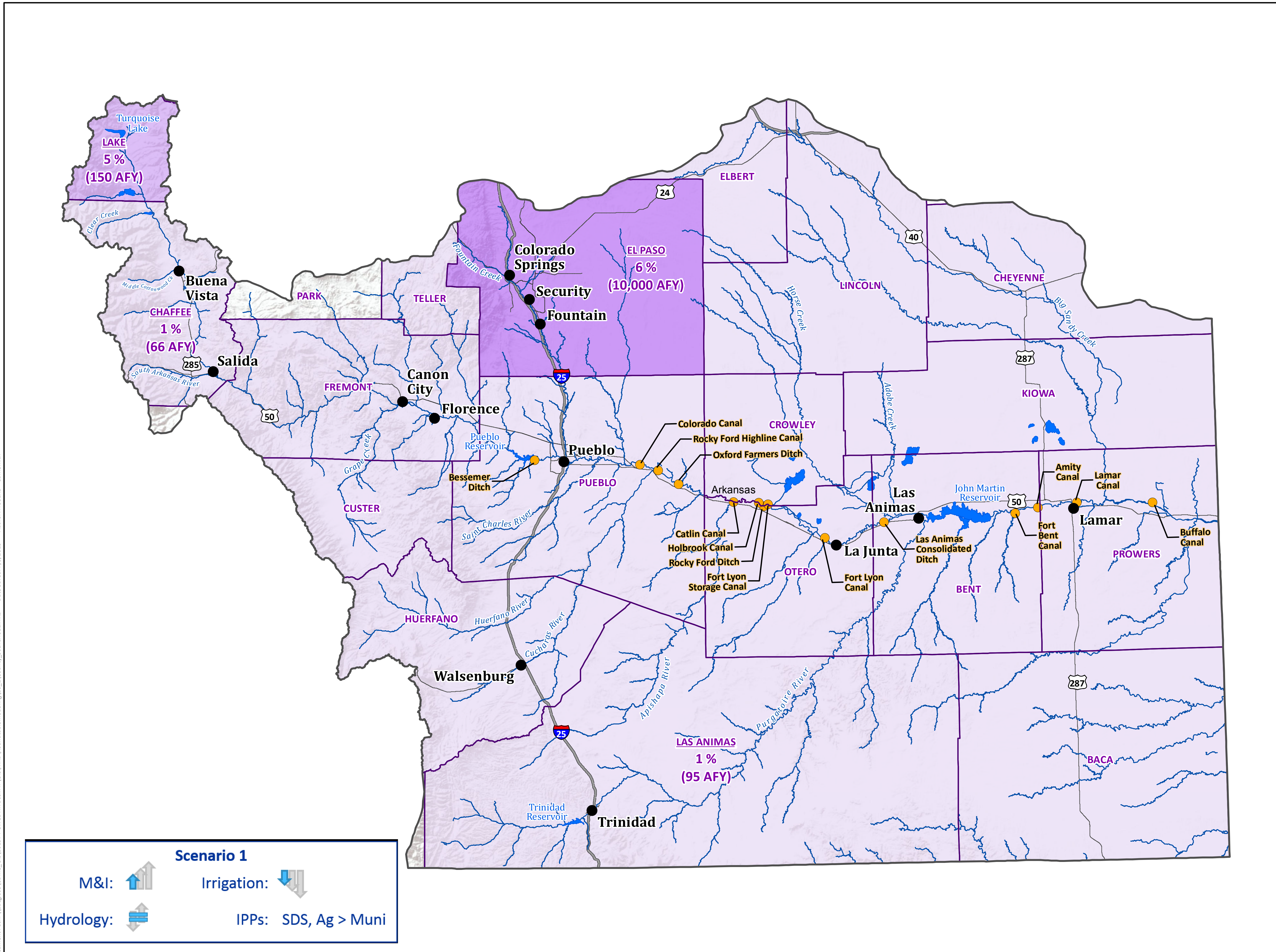


Figure 6
Future Annual Average Municipal Model Shortages by County: Scenario 1 - Percent

Major Irrigation System Headgate

County Boundary

Average Annual Shortage

No Shortage

1% to < 5%

5% to < 10%

10% to < 40%

Modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Therefore, shortages calculated for Las Animas County may not reflect actual future water supply availability.

Average annual shortage is indicated on the map for each county

Park county was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles

CDM Smith

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Colorado Water Conservation Board
Department of Natural Resources

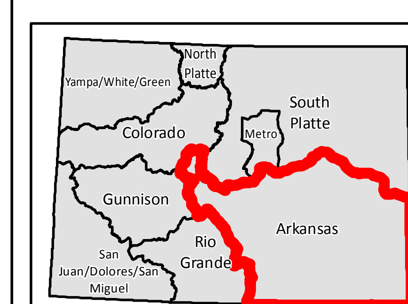
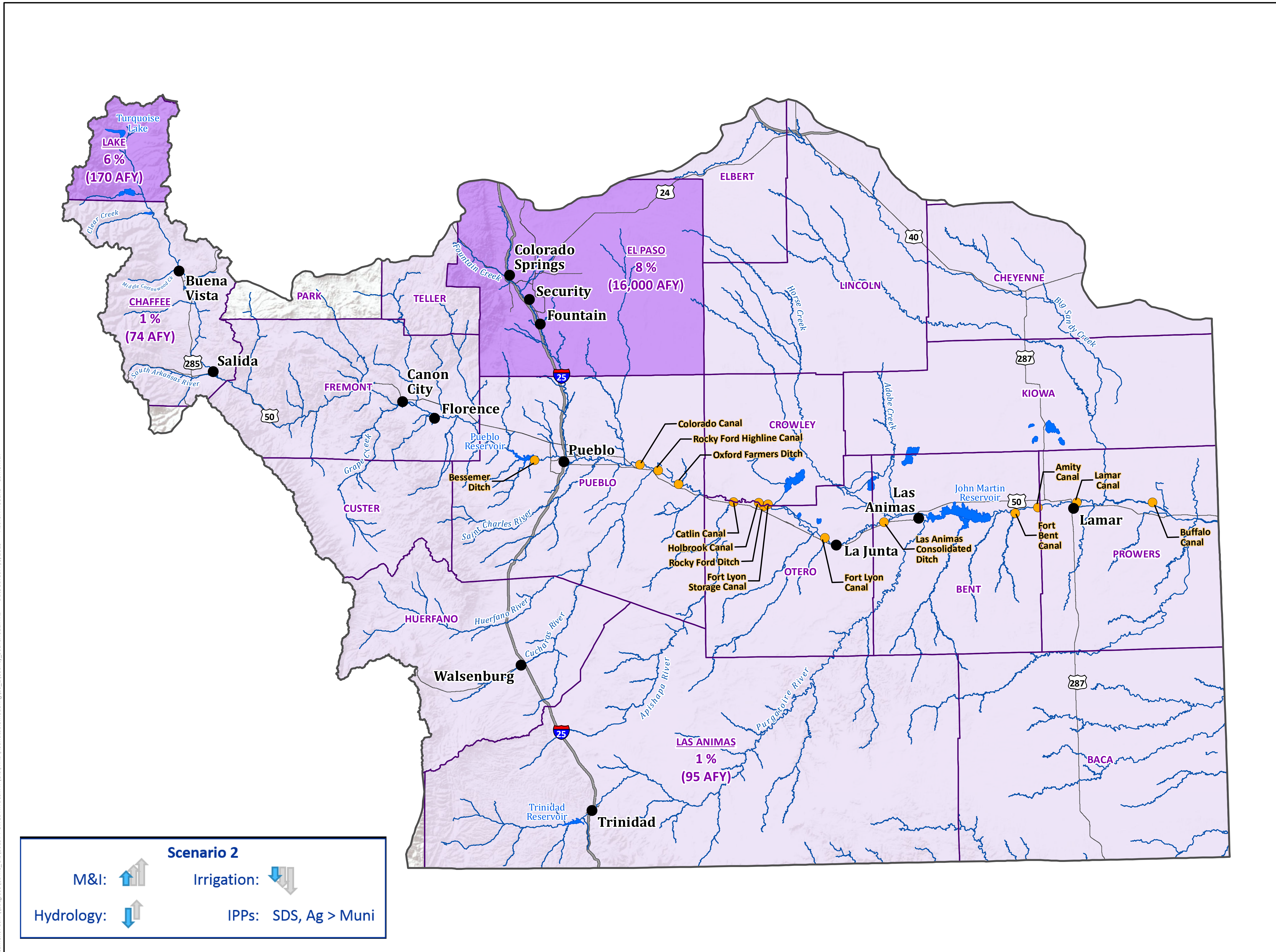


Figure 7
Future Annual Average Municipal Model Shortages by County: Scenario 2 - Percent



Major Irrigation System Headgate
County Boundary

Average Annual Shortage
- No Shortage
- 1% to < 5%
- 5% to < 10%
- 10% to < 40%

Modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Therefore, shortages calculated for Las Animas County may not reflect actual future water supply availability.

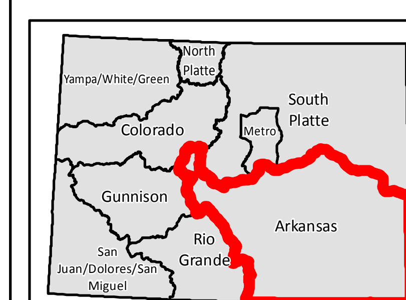
Average annual shortage is indicated on the map for each county

Park county was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles



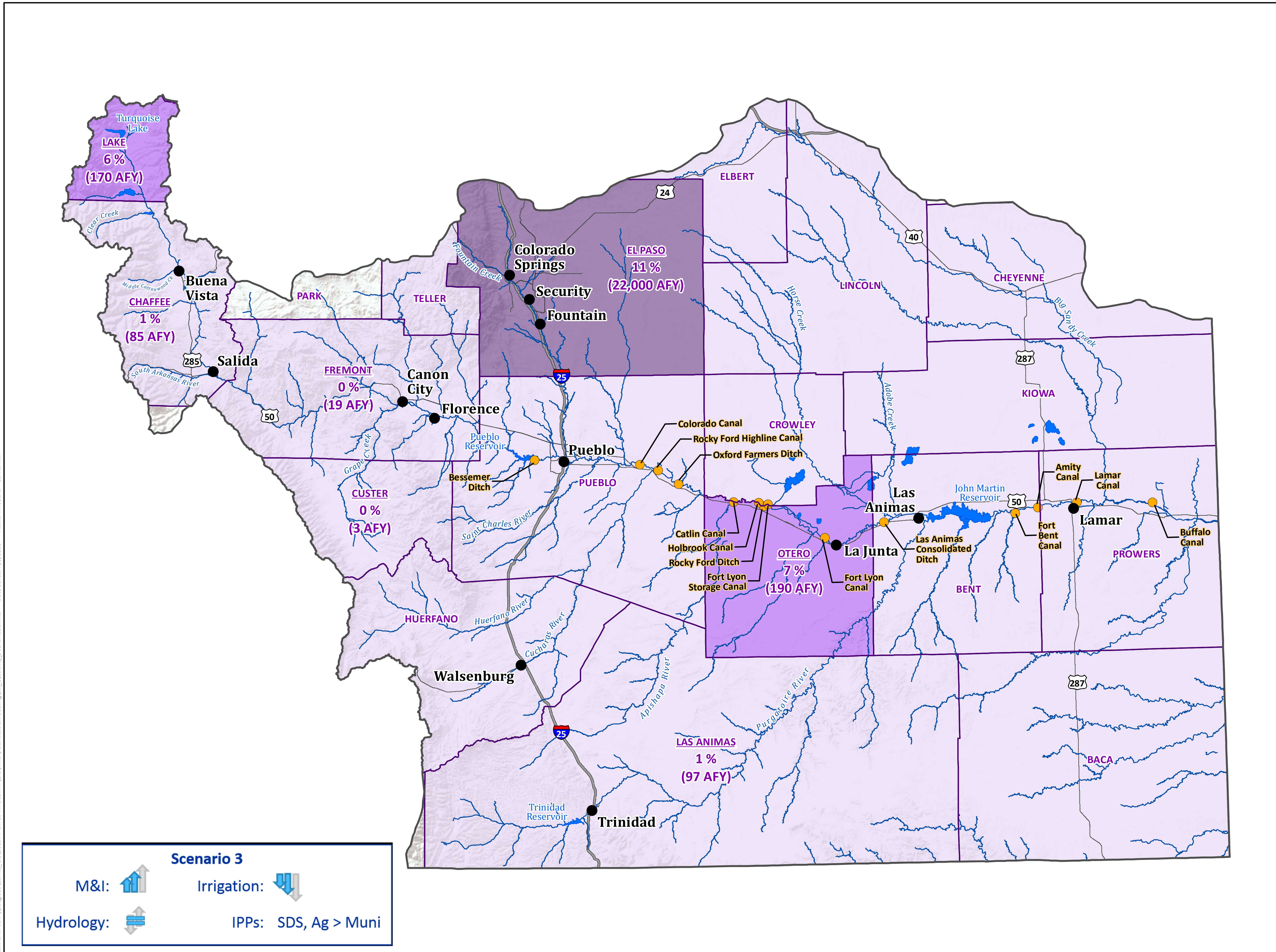


Figure 8
Future Annual Average Municipal Model Shortages by County: Scenario 3 - Percent

Major Irrigation System Headgate

County Boundary

Average Annual Shortage

- No Shortage
- 1% to < 5%
- 5% to < 10%
- 10% to < 40%

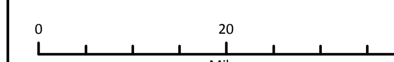
Modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Therefore, shortages calculated for Las Animas County may not reflect actual future water supply availability.

Average annual shortage is indicated on the map for each county

Park county was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA



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Department of Natural Resources

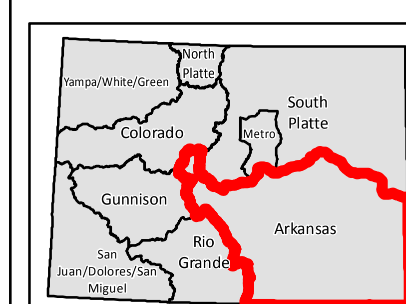
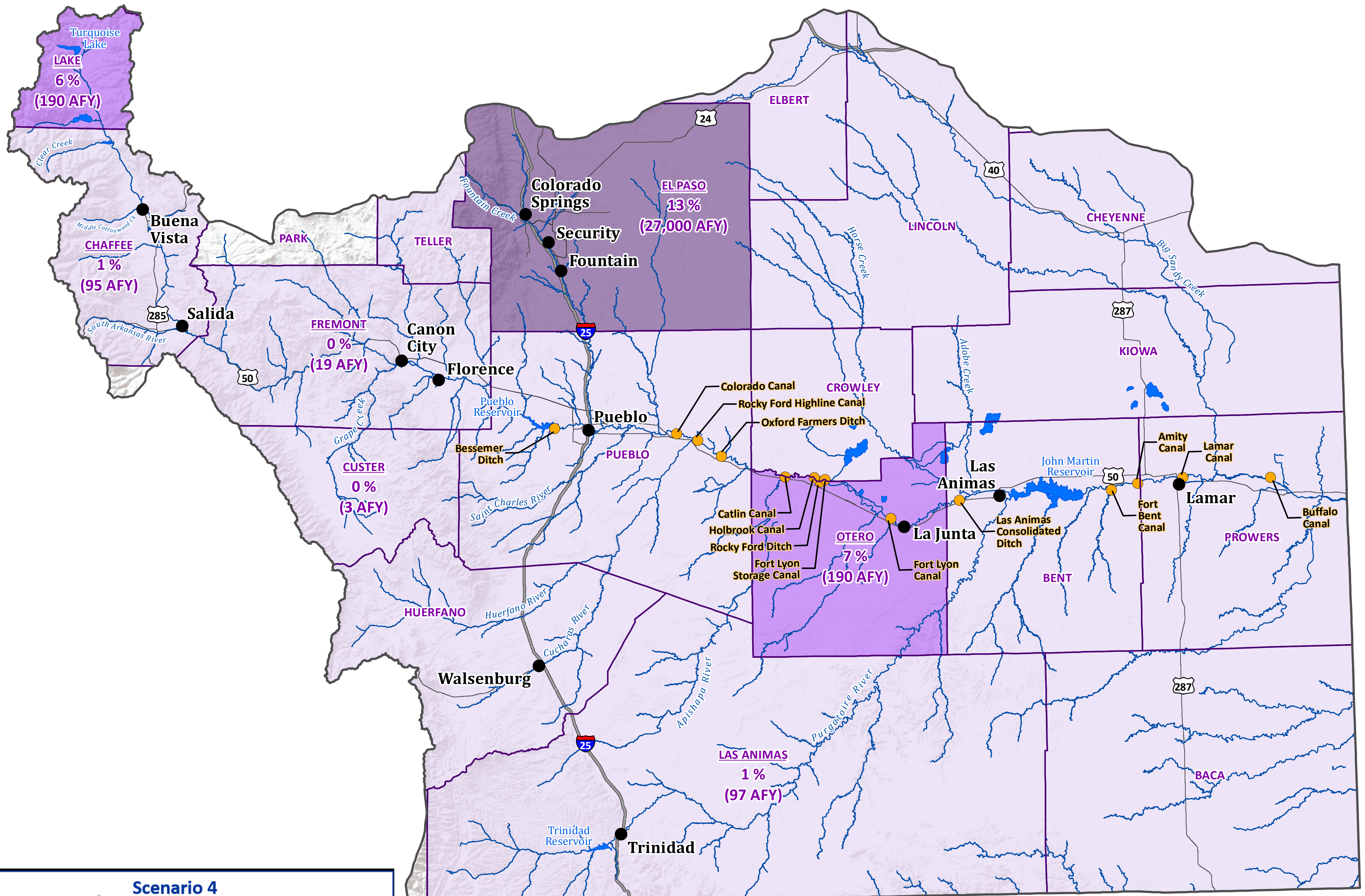


Figure 9
Future Annual Average Municipal Model Shortages by County: Scenario 4 - Percent



Scenario 4

M&I: | Irrigation:

Hydrology: | IPPs: SDS, Ag > Muni

Major Irrigation System Headgate

County Boundary

Average Annual Shortage

- No Shortage
- 1% to < 5%
- 5% to < 10%
- 10% to < 40%

Modeling of the City of Trinidad's available water supplies is limited due to the upstream location in the Purgatoire basin. Therefore, shortages calculated for Las Animas County may not reflect actual future water supply availability.

Average annual shortage is indicated on the map for each county

Park county was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40

Miles

N

CDM Smith

CO DNR COLORADO Colorado Water Conservation Board Department of Natural Resources

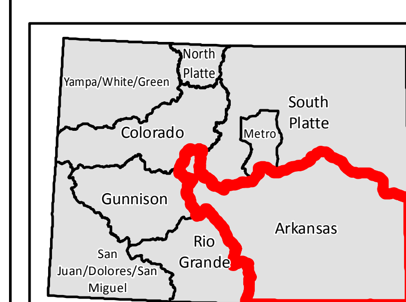
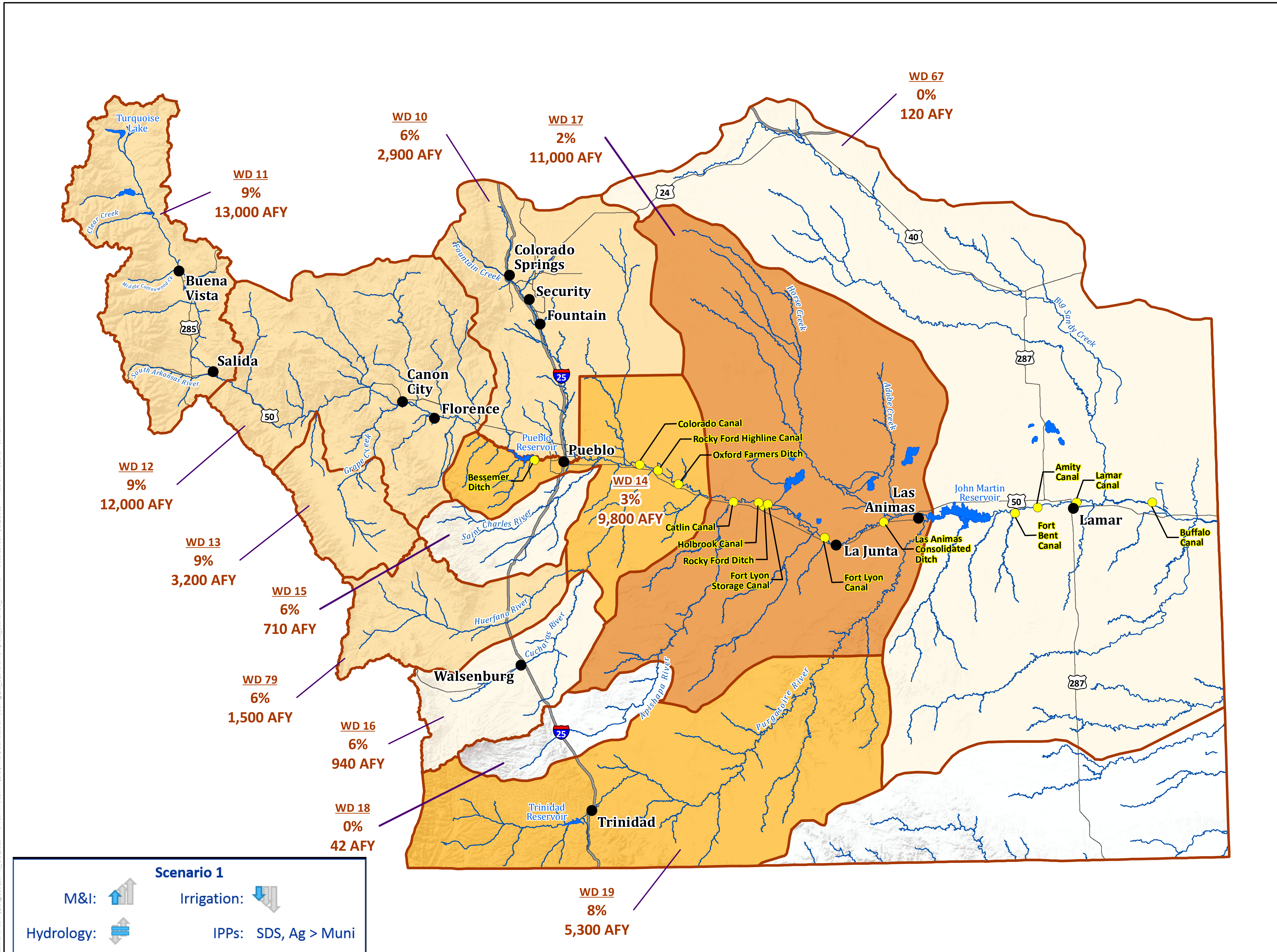


Figure 10
Future Annual Average Agricultural Model Shortages by Water District: Scenario 1-AFY



Major Irrigation System Headgate

Water District

Average Annual Shortage, AFY

< 1,000

1,000 to < 5,000

5,000 to < 10,000

10,000 to < 30,000

Average annual shortage is indicated on the map for each water district

Basin 66 was not included in modeling

7/10/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40

Miles

N

CDM Smith

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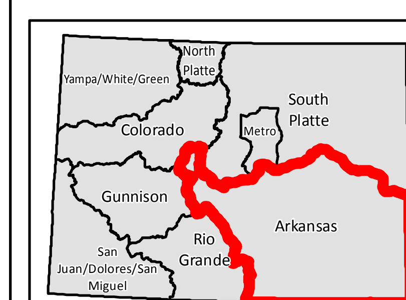
Department of Natural Resources



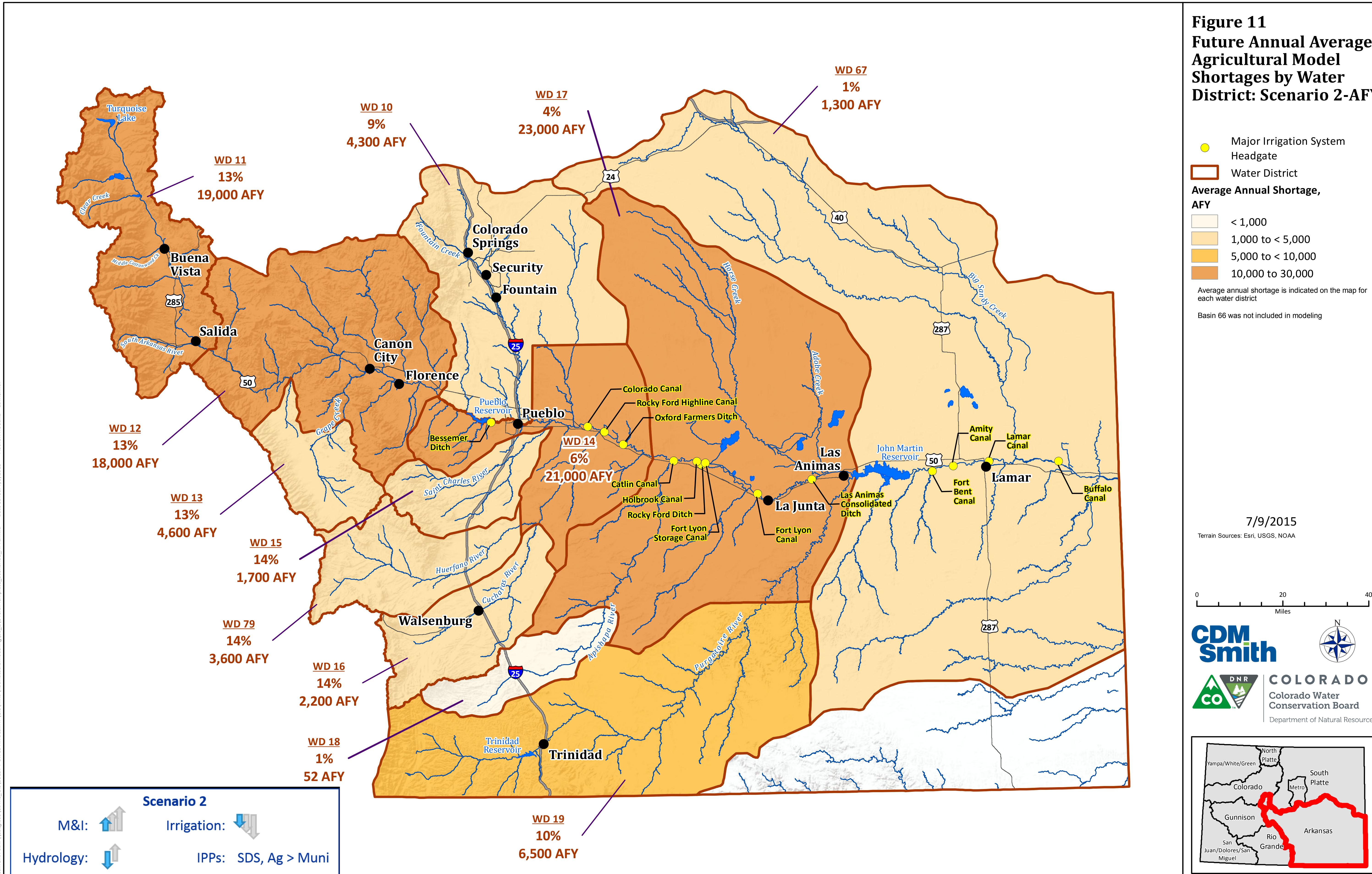
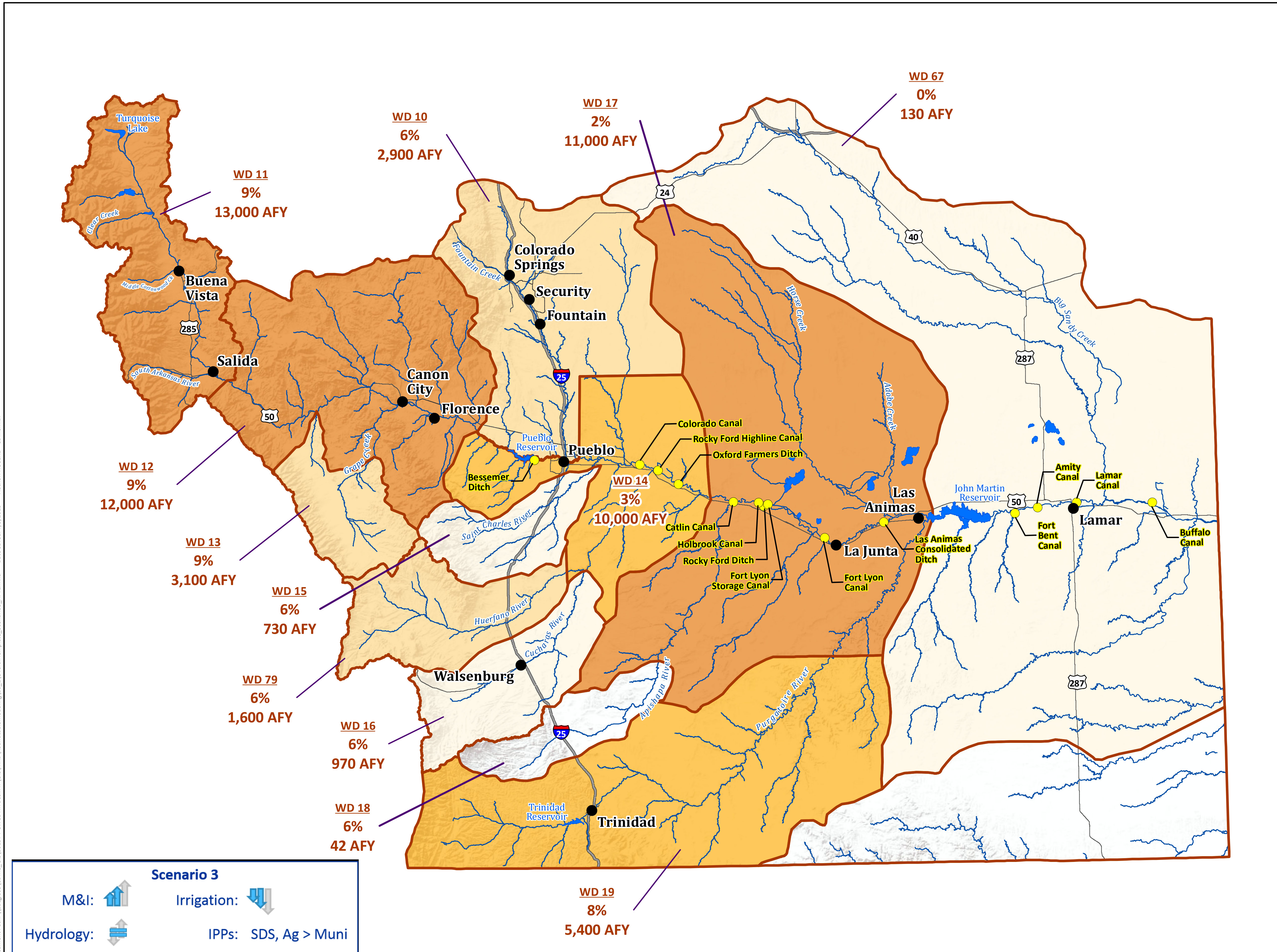


Figure 11
Future Annual Average Agricultural Model Shortages by Water District: Scenario 2-AFY

Figure 12
Future Annual Average Agricultural Model Shortages by Water District: Scenario 3-AFY



- Major Irrigation System Headgate
- Water District

Average Annual Shortage, AFY

- < 1,000
- 1,000 to < 5,000
- 5,000 to < 10,000
- 10,000 to < 30,000

Average annual shortage is indicated on the map for each water district

Basin 66 was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles

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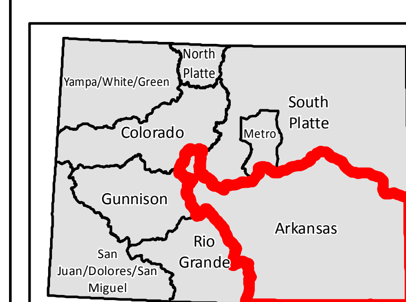
Department of Natural Resources



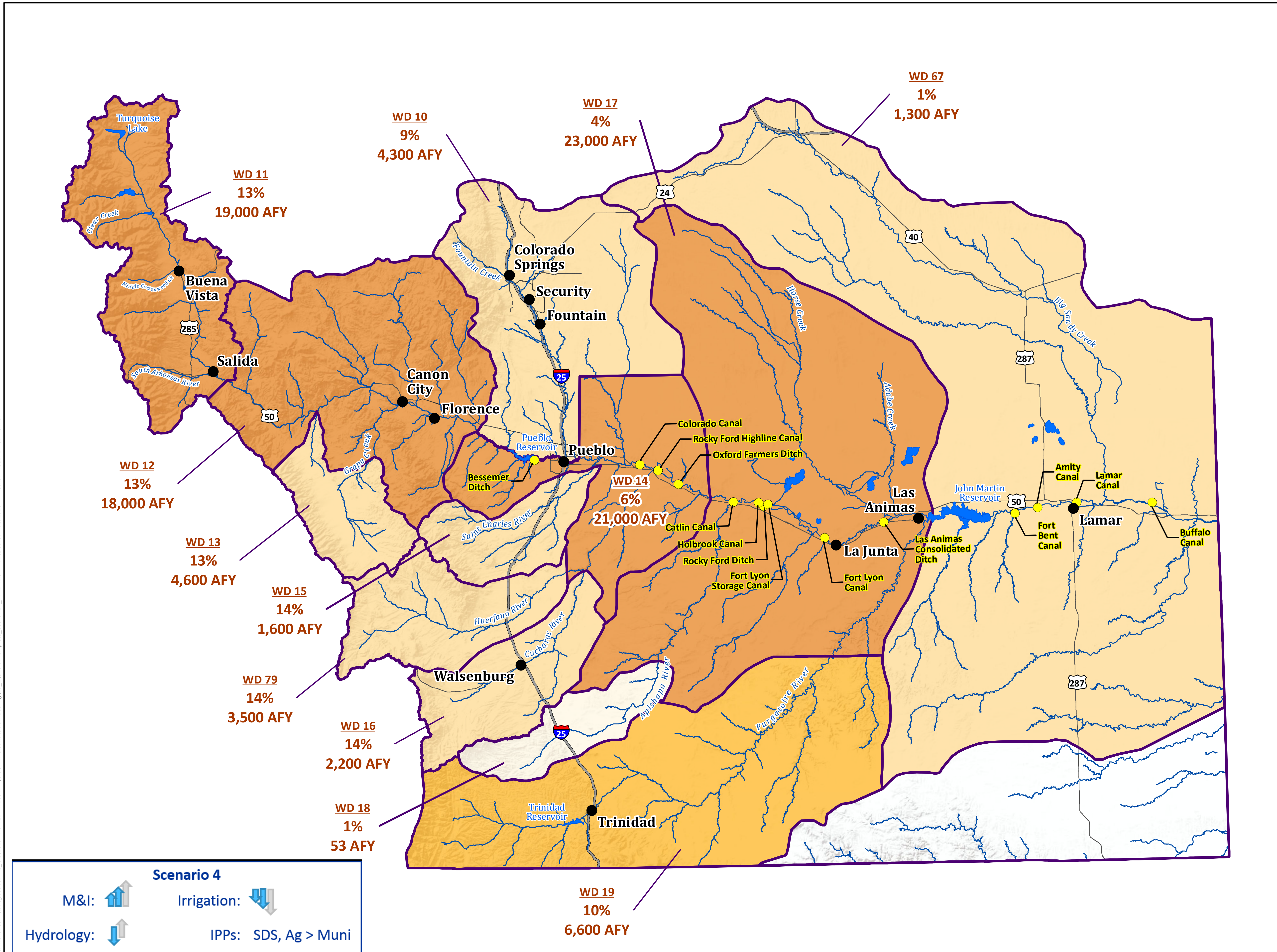


Figure 13
Future Annual Average Agricultural Model Shortages by Water District: Scenario 4-AFY

Major Irrigation System Headgate

Water District

Average Annual Shortage, AFY

< 1,000

1,000 to < 5,000

5,000 to < 10,000

10,000 to < 30,000

Average annual shortage is indicated on the map for each water district

Basin 66 was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles

CDM Smith

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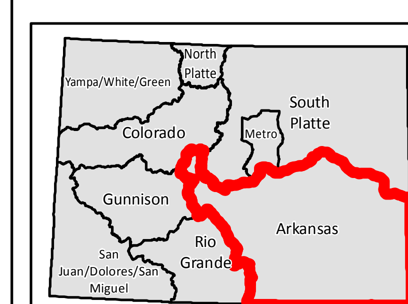
Colorado Water Conservation Board
Department of Natural Resources



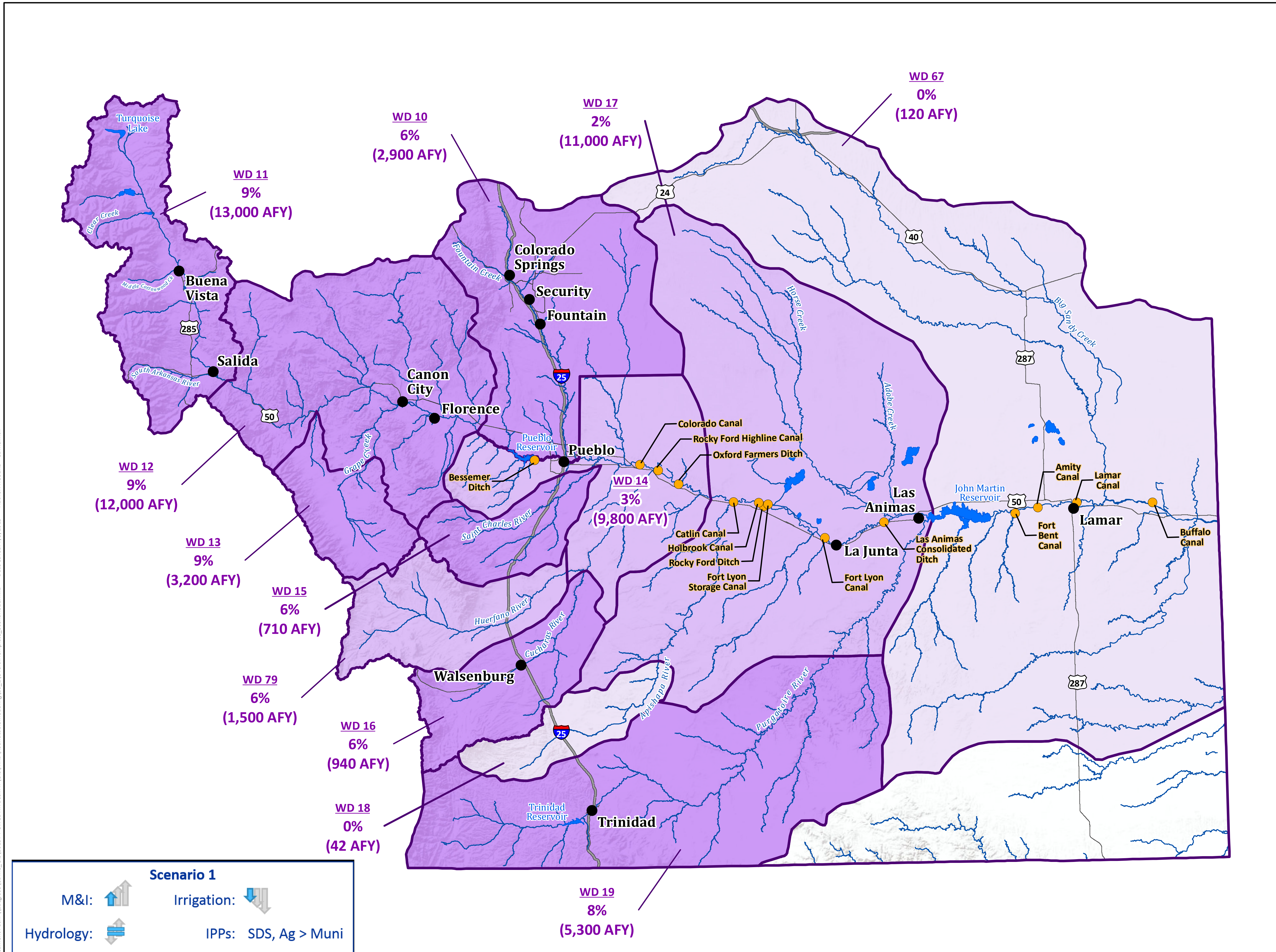


Figure 14
Future Annual Average Agricultural Model Shortages by Water District: Scenario 1 - Percent

Major Irrigation System Headgate

Water District

Average Annual Shortage

No Shortage

< 5%

5% to < 10%

10% to < 40%

Average annual shortage is indicated on the map for each water district

Basin 66 was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles

CDM Smith

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Department of Natural Resources

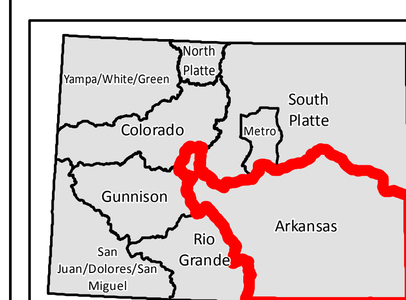
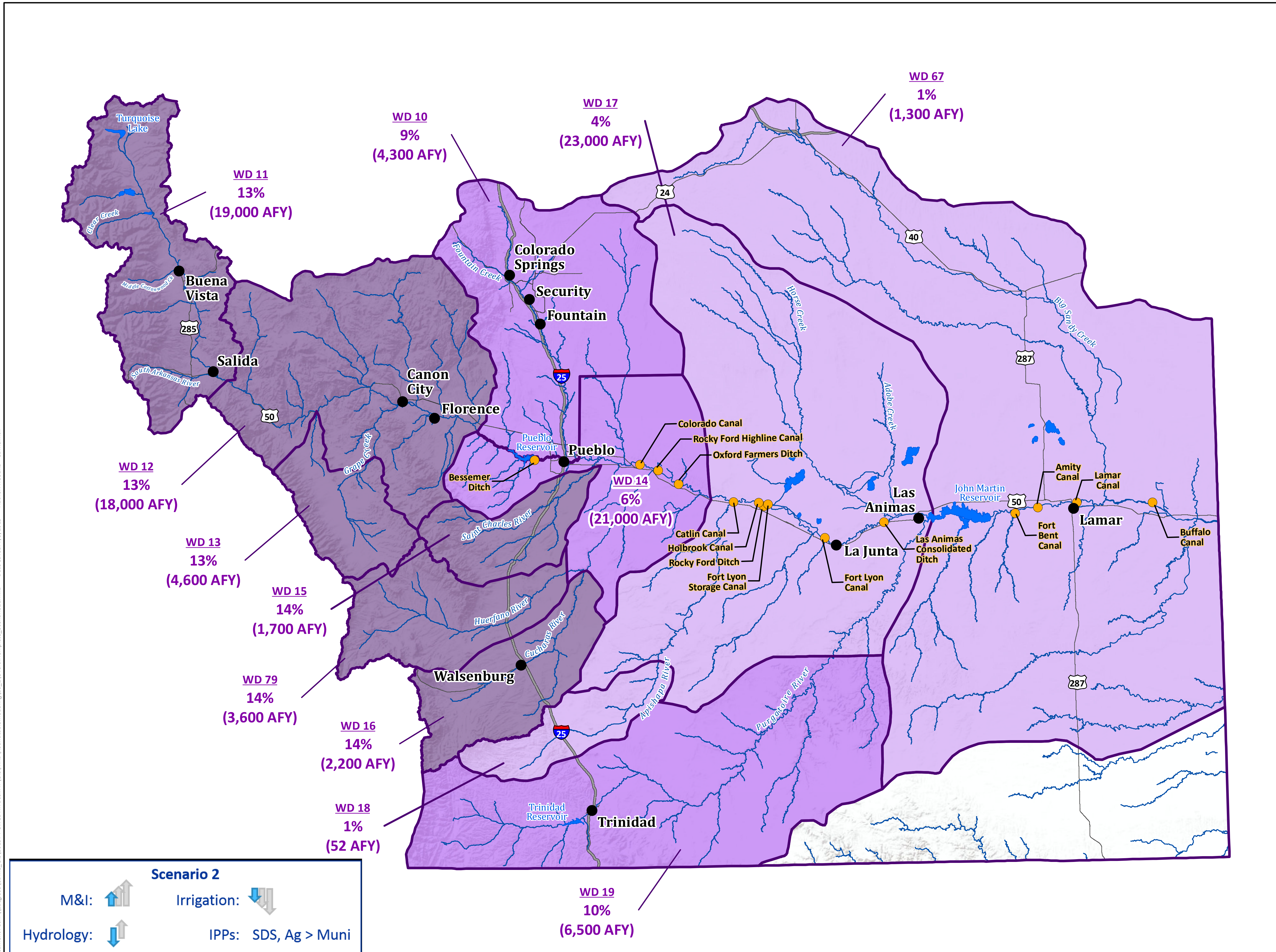


Figure 15
Future Annual Average Agricultural Model Shortages by Water District: Scenario 2 - Percent



- Major Irrigation System Headgate
- Water District

Average Annual Shortage

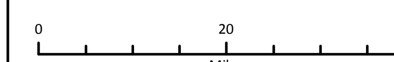
- No Shortage
- < 5%
- 5% to < 10%
- 10% to < 40%

Average annual shortage is indicated on the map for each water district

Basin 66 was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA



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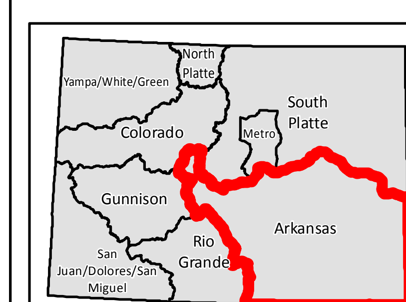
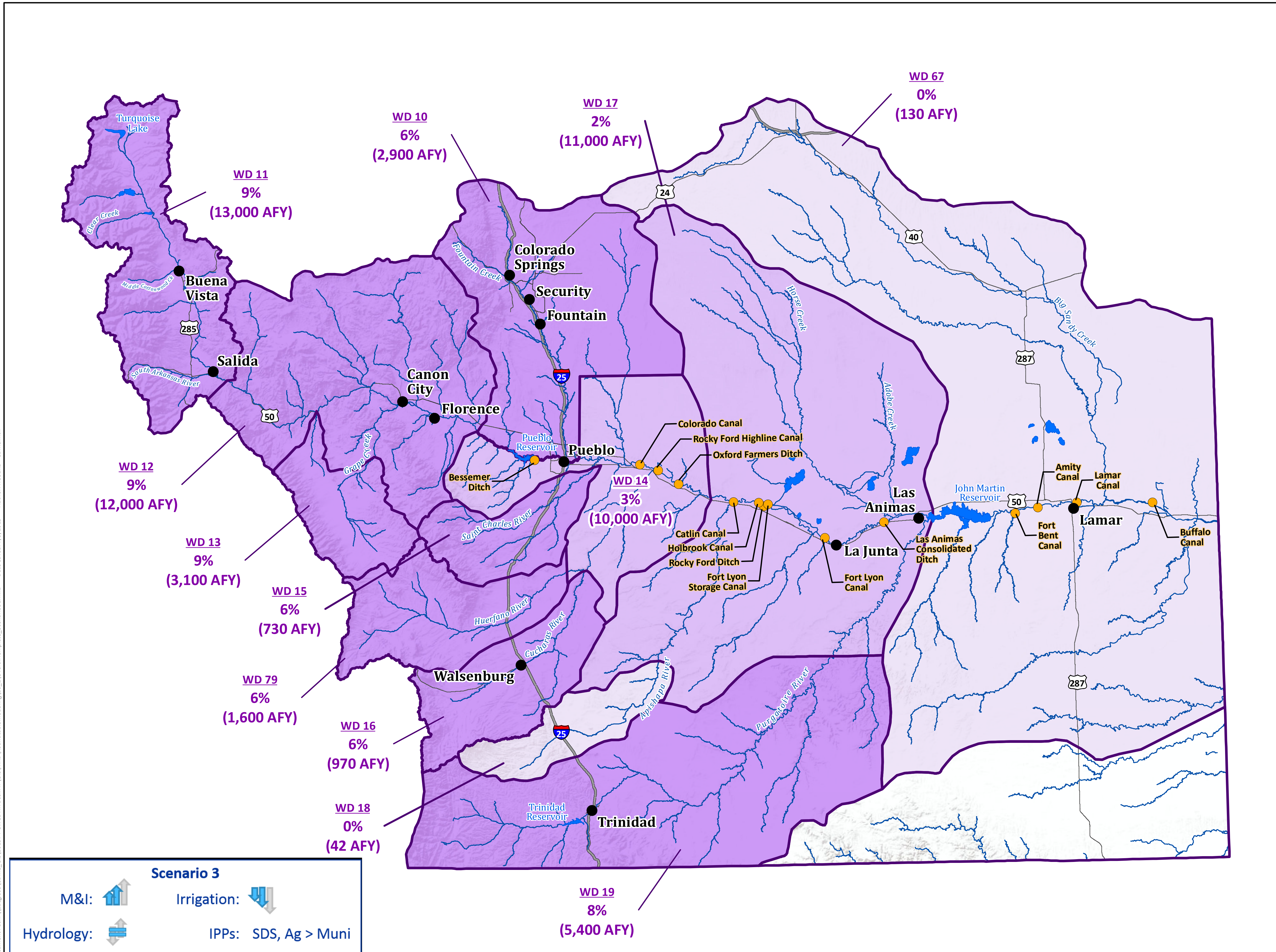


Figure 16
Future Annual Average Agricultural Model Shortages by Water District: Scenario 3 - Percent



Major Irrigation System Headgate

Water District

Average Annual Shortage

- No Shortage
- < 5%
- 5% to < 10%
- 10% to < 40%

Average annual shortage is indicated on the map for each water district

Basin 66 was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40 Miles

CDM Smith

COLORADO Colorado Water Conservation Board Department of Natural Resources

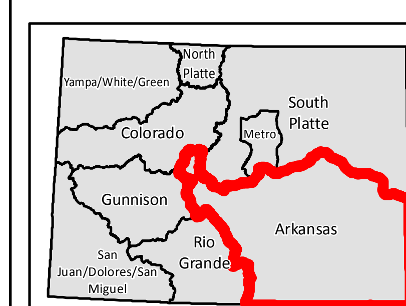
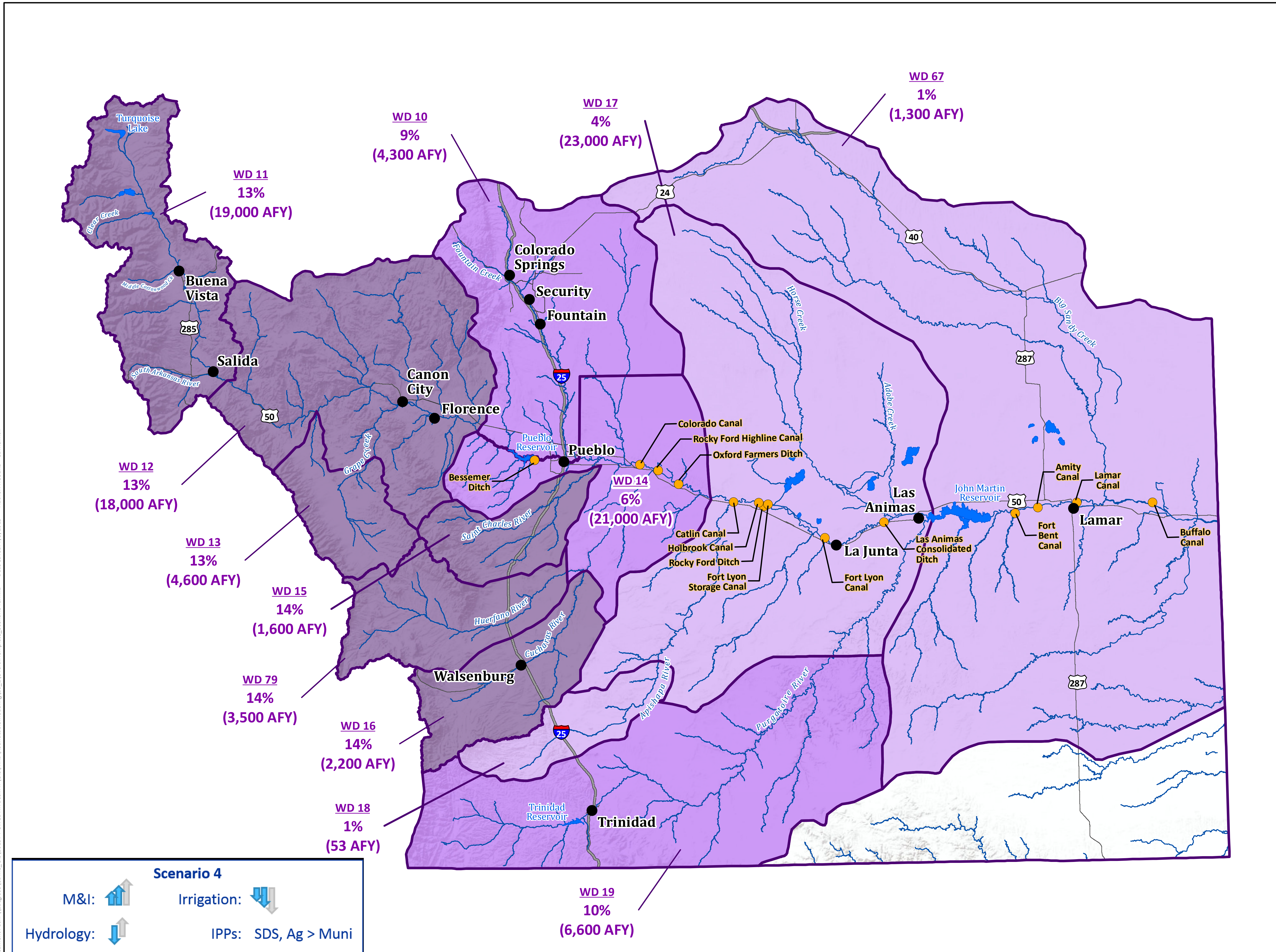


Figure 17
Future Annual Average Agricultural Model Shortages by Water District: Scenario 4 - Percent



Major Irrigation System Headgate

Water District

Average Annual Shortage

No Shortage

< 5%

5% to < 10%

10% to < 40%

Average annual shortage is indicated on the map for each water district

Basin 66 was not included in modeling

7/9/2015

Terrain Sources: Esri, USGS, NOAA

0 20 40
Miles

CDM Smith

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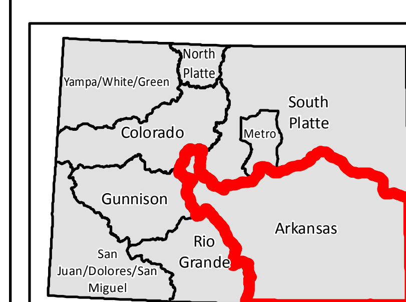
Colorado Water Conservation Board
Department of Natural Resources



Arkansas Basin Roundtable

ArkSWAM Overview

July 2015

The ArkSWAM model spatial domain extends from the Arkansas River at Leadville flow gage in the western headwaters to the Colorado-Kansas state line in the east. It includes all major tributaries, agricultural ditch diversions, municipal and industrial (M&I) water users, and transbasin water imports. All other significant inflows and withdrawals in the basin have been represented implicitly in the model in aggregated form. The model is designed for large-scale planning studies and, more specifically, the quantification of water shortages in the basin as a result of increasing future demands. It is not designed to be a river administration or operational support tool, nor is it intended to replicate the Arkansas Basin Decision Support System (ArkDSS) that has recently completed a Feasibility Study. Consequently, there are intentional simplifications in the model, compared to the ArkDSS, to maintain its ease of use and transparency for coarser resolution planning. These simplifications include: a monthly timestep, aggregated agricultural diversions, simplified reservoir operations and accounting, and simplified representation and inclusion of water exchange and augmentation plans. The key drivers of water availability in the basin, including native hydrology, major water uses and return flows, the water rights priority system, groundwater pumping with surface returns and stream depletions, and transbasin imports, are all explicitly represented in the model. Lastly, the model is well supported by a calibration/verification exercise based on recent (1982 – 2012) river gage data. Note, macros must be enabled in order for the ArkSWAM to function as intended.

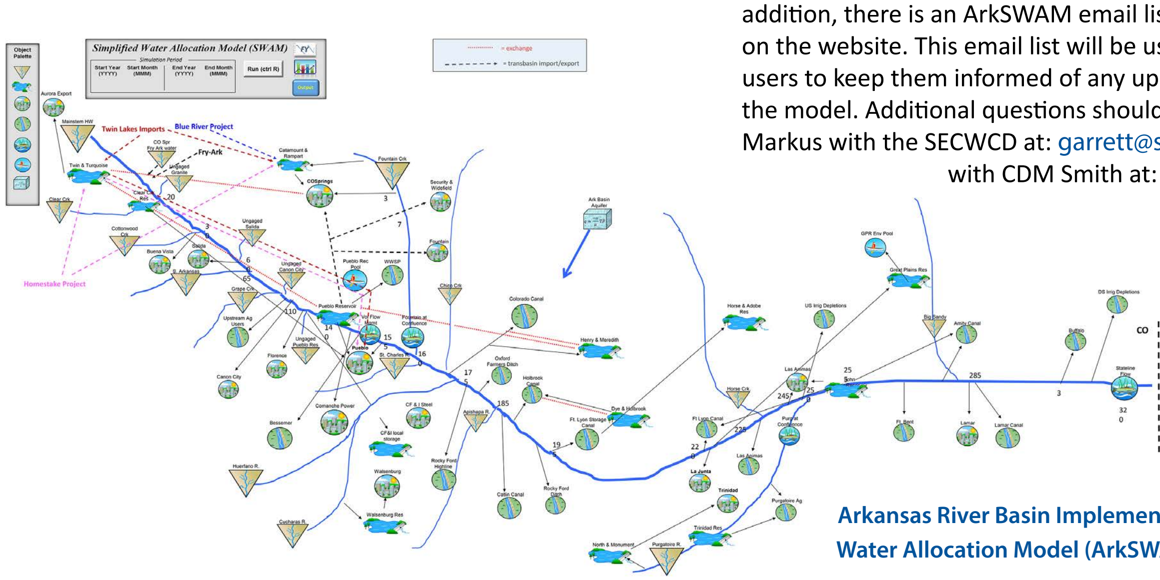
Distribution and Terms of Use

ArkSWAM was developed by CDM Smith Inc. to support the Arkansas Basin Roundtable and the April 2015 Arkansas Basin Implementation Plan. ArkSWAM was funded by a Water Supply Reserve Account grant from the Colorado Water Conservation Board (CWCB) with the Southeastern Colorado Water Conservancy District (SECWCD) as the acting fiscal agent. ***Use of ArkSWAM for any other purpose besides supporting the Arkansas Basin Roundtable is strictly prohibited.***

ArkSWAM was developed using CDM Smith's proprietary generalized Simplified Water Allocation Model (SWAM) software. SWAM was designed to be a more streamlined and user friendly alternative to more complex water allocation modeling software in use around the state. Like most water allocation models, SWAM calculates physically and legally available water, diversions, storage, consumption, and return flows at user-defined nodes (water user objects) in a networked river system. Legal availability of water is calculated based on prioritized water rights, downstream physical availability, and anticipated return flows, using the same fundamental algorithms applied in the state's water allocation decision support system (StateMod). Note that SWAM is continuously updated and enhanced. The current version of SWAM includes many new features, such as a daily timestep option, enhanced simulation of reservoir operations, and more flexible outputting options. Because of the continuous evolution and development the SWAM model, the version utilized for ArkSWAM is already outdated. For more information on the generalized SWAM software and its current version contact Tim Cox at: coxtj@cdmsmith.com or Chris Kurtz at: kurtzc@cdmsmith.com.

Documentation

ArkSWAM users are strongly encouraged to review the SWAM User Manual, the ArkSWAM Model Documentation technical memorandum (CDM Smith, May 2015), and the ArkSWAM Model Shortage Analysis (CDM Smith, July 2015). All documentation and associated models are available for download at http://www.colorado.gov/pacific/cowaterplan/arkansas-river-basin. It is strongly recommended that ArkSWAM users archive the downloaded version as "baselines" before making user specific modifications to the model (e.g., demand adjustments). In addition, there is an ArkSWAM email list signup form available on the website. This email list will be used to contact ArkSWAM users to keep them informed of any updates or news related to the model. Additional questions should be directed to Garrett Markus with the SECWCD at: garrett@secwcd.com or Chris Kurtz with CDM Smith at: kurtzc@cdmsmith.com.



Arkansas River Basin Implementation Plan
Water Allocation Model (ArkSWAM)

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Section 1

Introduction and Overview

CDM's Simplified Water Allocation Model (SWAM) was developed to address an identified need for a networked generalized water allocation modeling tool that could be easily and simply applied for planning studies by a wide range of end-users. Unlike most other water allocation software, SWAM is designed to be intuitive in its use and streamlined in functionality and data requirements, while still maintaining the key elements of water allocation modeling. SWAM was designed to provide efficient planning-level analyses of water supply systems.

Like most water allocation models, SWAM calculates physically and legally available water, diversions, storage, consumption, and return flows at user-defined nodes in a networked river system. Both municipal and agricultural demands can be specified and/or calculated in the model. Legal availability of water is calculated based on prioritized permitted withdrawals, downstream physical availability, and anticipated return flows. Additional features in SWAM include easily-parameterized municipal and industrial (M&I) conservation and reuse programs, agricultural land transfers, groundwater pumping, and transbasin diversion projects. Multiple layers of complexity are available as options in SWAM to allow for easy development of a range of systems, from the very simple to the more complex. As an example, SWAM's reservoir object can include only basic hydrology-dependent calculations (storage as a function of inflow, outflow, and evaporation) or can include operational rules of varying complexity: prescribed monthly releases, a set of prioritized monthly releases, or a set of conditional release rules (dependent on hydrology). The model user chooses the appropriate level of complexity given the modeling objectives and data availability.

SWAM operates on a monthly timestep, and the current version of the model is constrained to a total of up to eighty (80) M&I water user and eighty (80) agricultural water user nodes. The program is coded in Visual Basic with a Microsoft Excel-based interface.

Section 2

Model Description

2.1 Worksheet

The SWAM user interface is primarily comprised of a single worksheet (Figure 2-1) with drop and drag graphical features for defining and parameterizing a water supply network. On-screen representation of specific model objects, hereafter referred to as "visual objects," are created by clicking on the appropriate button in the "Object Palette" (1.). To drop and drag the created visual objects (2.), the user must first select the object by clicking on the edge of the object (hidden rectangle). Once a visual object is selected, it can be deleted using the "delete" key stroke or by right-clicking with the mouse and selecting "cut." Visual object names can be edited by single-clicking on the object label.

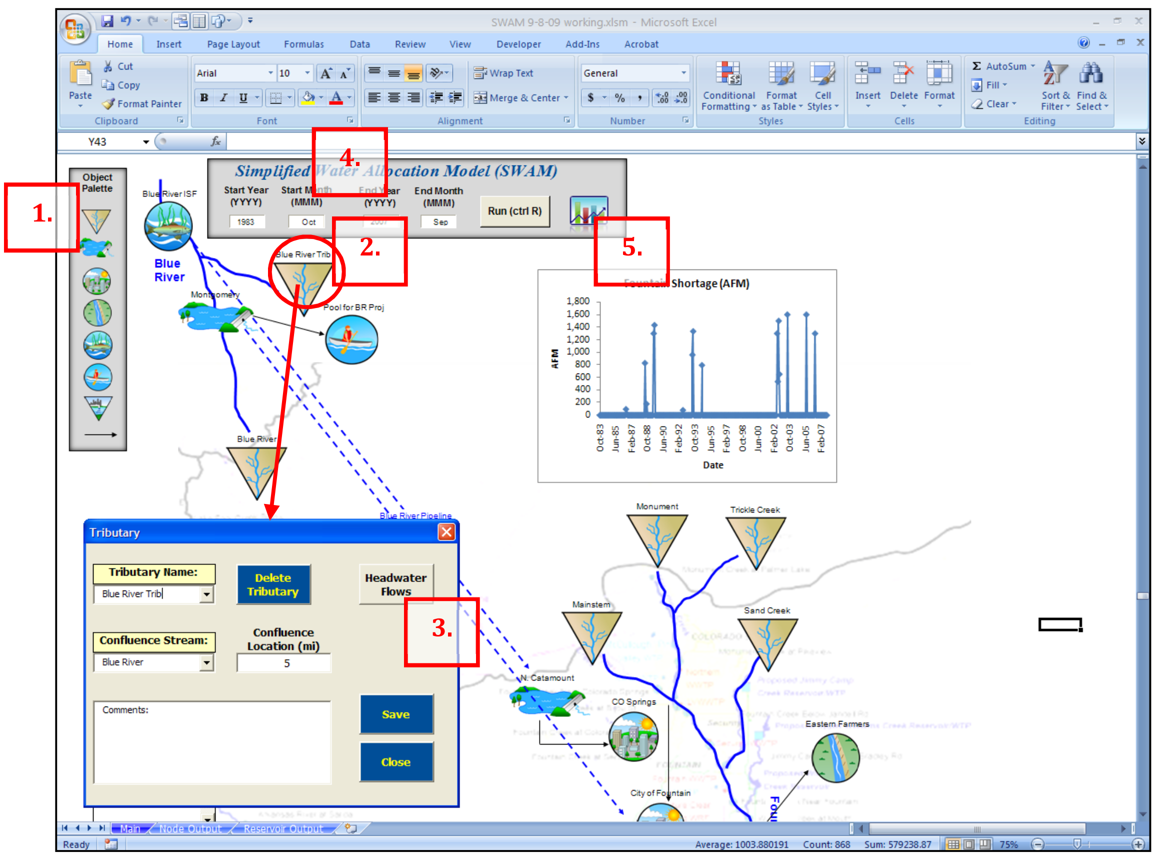


Figure 2-1. SWAM Main Screen

It is important to note that visual objects are merely placeholders and portals to the true model data objects. In other words, the model does not recognize any links between visual objects and simulated model objects (as defined below). **Consequently, deleting the visual object from the white space will not delete the actual model object.** Similarly, simply creating a visual object, as described above, will not result in inclusion of that object in the model simulation. However, that being said, creating a network of visual objects that accurately represents the simulated model objects is of great benefit to the user and is strongly advised.

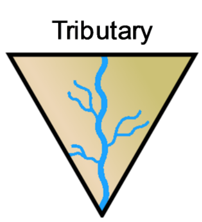
Model objects are created and deleted using the input forms (3.) accessed by clicking on the visual objects. Input forms, specific to the appropriate category of objects, must be populated and saved to create objects that are incorporated into the model simulation. Previously-created model object data are accessed using drop down menus on each of the object forms. The "Save" button must be used each time an update is made to a model object. **Simply closing the input form will not save the updates!** Specific objects and the calculations associated with these objects are described in detail below.

Also on the Main screen is the title tool bar. Here, the simulation period (start and end dates) is specified (4.) and a button for creating output graphs is available (5.). The simulation "Run" button is clicked to start a simulation. The keystroke "control-R" can also be used to start a simulation.

2.2 Model Objects

SWAM requires a user-constructed network of streams, demand nodes, and reservoirs. Each element in a constructed network is referred to as a model "object". Each object has its own set of equations and calculations in the underlying SWAM Visual Basic program (often referred to as "object-oriented" code) and its own set of user inputs (described below). In SWAM, relationships between objects are specified through the individual objects themselves, as described below. Spatial locations of objects, and the flows associated with the objects, are inferred by SWAM based on user-specified relative mile markers for each object. The actual magnitudes of these mile markers are irrelevant. Only the relative values are important, as these describe upstream (lower mile markers) and downstream (higher mile markers) positions of objects and flows. SWAM calculates stream flows at each node based on this positioning. Details of individual model objects are provided below.

2.2.1 Tributaries

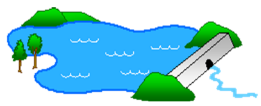


Tributary objects provide the hydrologic drivers for the entire water allocation system. SWAM requires at least one tributary object ("Mainstem") for a simulated system. The Mainstem tributary object cannot be renamed or deleted. A timeseries of monthly "headwater" flows is specified for each tributary object in the system, as well as the downstream confluence stream and the relative location (on the receiving stream) of the confluence (Table 2-1). The downstream confluence stream for the Mainstem object is set as "none".

Table 2-1. Tributary Input Parameters

Parameter Name	Units	Description
Tributary name	NA	A unique name must be assigned to each object; “Mainstem” name cannot be modified
Headwater flows	AFM	Monthly timeseries of inflows to the top of the stream
Confluence stream	NA	Name of confluence receiving stream immediately downstream of tributary (specified via a drop-down list of previously-created tributaries)
Confluence location	miles	Relative mile marker, on the receiving stream, of tributary confluence

2.2.2 Reservoirs



Reservoir objects provide for the physical storage of water. The total storage of a reservoir is generally comprised of multiple storage “accounts” associated with various water users (described below). However, the reservoir object is used to define the physical characteristics (including total capacity) of the total reservoir (Table 2-2), including spatial location, storage capacity, surface area, and evaporative (and/or seepage) losses. Monthly reservoir operating release requirements can also be specified in this object.

Evaporative losses can be specified using monthly-varying seasonal rates (inches per day or percent volume) or with a user-specified timeseries of monthly flow losses. Calculated evaporative losses are distributed to individual accounts based on relative volumes of storage in each account at the given timestep. In other words, accounts with larger stored water will realize a greater evaporative loss than accounts with less stored water.

There are two options for defining reservoir release operations in SWAM: simple and advanced. Simple reservoir release rules consist of twelve prescribed mandatory monthly releases. These releases are prioritized ahead of all water user withdrawals. Advanced reservoir release rules can be defined by the user to include up to five (5) different sets of rules governing release operations. Each of these five rules, implemented in order of priority, can consist of either prescribed monthly values (see simple rules) or “conditional” rules based on hydrologic parameter values associated with other objects in the system. Conditional rules can be specified based on storage values (AF) in either individual water user accounts or entire reservoirs, or based on headwater flow rates (AFM). For conditional releases, the user defines the targeted release volume and the conditions (e.g. >, <, = a prescribed value) that must be satisfied for the release to occur. Note that due to the numerical approach utilized in SWAM (see Section 3), for any given timestep (t), conditional releases are determined as a function of the start-of-month storage or the previous month’s (t-1) headwater flow.

Reservoir releases are distributed across individual accounts based on storage permit priority (lowest to highest priority). SWAM attempts to assign all of a regulated release to the lowest priority account. If this account is unable to meet the total release volume required (due to lack of physical availability), the model moves on to the next lowest priority account, and so on.

Reservoirs can be defined in SWAM as either “offline” or “online”. There are effectively only subtle calculation differences between the two in the model. For online reservoirs, a “flood control pool” is automatically created and handled as a water user, with unlimited physical and legal diversion capacity, in internal model calculations. This ensures that all upstream water gets routed through the online reservoir at each timestep. The size of the flood control pool is calculated internally as the difference between total reservoir capacity and the sum of individual water user accounts. When creating an online reservoir object in SWAM, the user must define how flows are released from the flood control pool via an outflow-capacity table. This type of table would typically express a direct relationship between the magnitude of monthly outflow and the reservoir volume (greater storage equates to greater outflow). In this way, by providing temporary storage and gradual release, an online reservoir smooth's out downstream hydrographs during periods of high flow.

Note that offline reservoir inflows can only be created via the "diversions" of various account-holder objects (water users, agricultural users, and recreational pools) (described below). Without user accounts, offline reservoirs will not fill with water.

Table 2-2. Reservoir Input Parameters

Parameter Name	Units	Description
Reservoir name	NA	A unique name must be assigned to each object;
Reservoir type	NA	Offline or online
Storage capacity	AF	Total physical storage capacity of reservoir
Initial storage	AF	Start of simulation initial volume of water in reservoir
Evaporation input type	NA	Monthly rates of inches per day (option 1) or percent of total volume (option 2), or user-specified timeseries of flow rates (option 3)
Evaporation rates, option 1	in. day^{-1}	Seasonal rates of evaporation (multiplied by calculated surface area, via area-capacity table, to get volumetric losses)
Evaporation rates, option 2	%	Seasonal rates of evaporation (multiplied by calculated volume to get volumetric losses)
Evaporation rates, option 3	AFM	User-defined timeseries of volumetric evaporation losses
Area-Capacity table, option 1	AF / Ac	Surface area vs. storage volume based on bathymetry of reservoir
Reservoir release receiving stream	NA	Name of receiving stream for mandatory reservoir releases
Release location	mi	Relative mile marker (on receiving stream) of reservoir releases
Monthly minimum releases	AFM	Required (regulated) minimum releases for reservoir (if applicable)
Outflow-Capacity table	AFM / % capacity	For online reservoirs only, defines outflows from flood control pool as a function of reservoir storage (percent capacity)

Advanced Release Rules:		
Advanced rules option	NA	Option button for user-specified advanced release rules, rather than simple method; allows for up to 5 different condition release rules that model attempts to meet in order of priority
User-prescribed monthly release targets	AFM	If selected, monthly minimum release targets that model attempts to satisfy at each timestep, in order of release rule priority (1 – 5)
Conditional release rules	NA	If selected, reservoir release rules that are internally determined and conditional on user-specified storage or flow conditions. Storage conditions can be associated with either total reservoir storage or a specific user account storage. Flow conditions are based on headwater flows associated with a specified tributary object. The actual release flow targets, if conditions are met, are specified by the user (AFM).
Conditional object	NA	Name of the object (water user, reservoir, or tributary) whose conditions dictate whether given release occurs
Criteria	NA	<, >, or =
Trigger value	AF or AFM	Storage or flow value threshold that triggers or activates the given release
Release target	AFM	Monthly reservoir release that is targeted if prescribed conditions are met
Release accounts	NA	Name of user account from which release is apportioned; if "all users" is selected then monthly release is apportioned across all user accounts associated with the reservoir in reverse order of storage permit priority (i.e. lowest priority loses water first)

2.2.3 Water Users

Water User

The water user object is the most generalized and versatile of the available demand node objects. It is primarily intended to represent aggregated municipal and/or industrial (M&I) water users.

On the demand side, water users are parameterized by monthly water usage requirements, including specification of indoor vs. outdoor use and consumptive vs. non-consumptive portions of each. To simplify the parameterization process, preset patterns of seasonal usage, including indoor/outdoor and consumptive/non-consumptive components, are available for typical M&I or agricultural users.

Reuse and conservation demand management options are available that reduce the net demands on water. The reuse option in SWAM assumes a one-time use only of recaptured indoor use return flows (effluent) that can only be applied toward outdoor (irrigation) demands. For conservation, SWAM allows for the use of manual monthly reductions in water use or combinations of previously-parameterized conservation program initiatives. For the latter, SWAM calculates the net final reductions in monthly usage expected for any given combination of conservation programs. The assumed reduction parameters associated with the preset option were derived based on independent analyses and experience and may not be entirely accurate for any site-specific application. However, they are included to provide for quick and easy "what if" simulations of the potential impacts of conservation.

On the supply side, multiple sources of supply (up to five) are available, including direct diversions, storage account withdrawals, and groundwater pumping. SWAM simulates the use of this water according to the preference order (1 – 5) of each source. In other words, if the entire monthly demand can be met with water from source water 1, then no water is used from other available sources (although there still may be accrual in storage accounts). Storage accounts are defined through the water user object with reference to specific reservoir objects. The ability to divert water (for direct use or into a storage account) is dependent on calculated physical and legal availability of the water at the point of diversion. Legal availability is one of the key calculations in SWAM and is based on specified permitted withdrawals and associated priority dates and the prior appropriations doctrine. This doctrine, often referred to as "first in time, first in line", recognizes earlier priority dates as higher priority in the water allocation scheme. SWAM attempts to meet the water demands of water users in order of their priority. Further details of the legal availability algorithm in SWAM are provided in Section 3. Lastly, groundwater pumping as a source of supply can be specified according to monthly pumping rates and an aquifer source (Aquifer object, see Section 2.2.7). Groundwater pumping is applied to meet water user demands at the full prescribed pumping rates, subject to aquifer storage availability (see Section 2.2.7).

Supplemental water supplies can also be specified for the given water user, namely agricultural land transfers and transbasin imports. Agricultural land transfers are simulated as steady seasonal supplies available for direct use or storage augmentation. Transbasin imports provide the user with the ability to move water from a reservoir in one river basin (source) to an account in another river basin (destination). Monthly target inflows are prescribed which define the amount of water transferred, subject to physical availability.

Note that, with respect to transbasin imports, SWAM also has the ability to directly divert (no source-side storage) from a different basin as one of the standard sources of supply for a given water user. In this case, the "transbasin import" option is not needed and the user can simply specify an out-of-basin stream as one of its sources of diverted water. However, if it is desired to move water across basins reservoir to reservoir, then the transbasin import option must be used.

Water exchange programs can be established between two water user supply accounts. Because it requires two supply accounts acting in concert, water exchanges are only available if the "multiple sources of supply" checkbox is selected. A water exchange is defined in SWAM as an agreement whereby an upstream diversion account can only divert water if a downstream partner account releases water from storage of the same amount and in the same timestep. Practically, this allows for diversion and storage to occur at the downstream location during wet periods and direct diversion to occur at the upstream location during dry periods, with no impact on downstream users (since the diversion is offset by releases from the downstream stored water). In SWAM, the downstream storage account in an exchange program can only store and release water to the stream. Water can't be used for consumption from this storage account. Diversion to the downstream storage account can only occur in timesteps where there is no release requirement (i.e. no upstream diversion) and as allowed according to standard water user supply account calculations of physically and legally available flow. For the upstream direct diversion in an exchange program, the model calculates legally and physically available flow at the node following the standard algorithms but then constrains the legally available flow to less than or equal to the total available for release from the downstream partner account. When the seasonality flag is selected (under "Water Exchange" tab), the user can specify the months in which the exchange program is active. For the selected months, upstream diversions and downstream releases can occur as described above. For months when the exchange program is not active (un-selected checkboxes), no diversions to the upstream account are allowed even if downstream storage is available for releases. Note that the downstream account in an exchange program must be assigned to the #5 preference supply account and thus is forced to be the less preferred account in the exchange partnership.

Finally, water user return flows are calculated in the model as a function of water usage and consumptive vs. non-consumptive fractions of this usage. The user must specify where these returns take place (single location or multiple locations) and whether or not the returns are lagged.

Table 2-3. Water User Input Parameters

Parameter Name	Units	Description
User name	NA	A unique name must be assigned to each object;
Multiple sources flag	NA	Flag specifying whether multiple sources of water are to be defined
Water Usage:		
Monthly use distribution	NA	Options for populating monthly usage values: with either an annual total use and preset distribution patterns (M&I or Agricultural) or manually by month
Total annual use	AFY	If either of the automated monthly distribution options are selected, then this annual total gets distributed across months according to preset distribution patterns
Monthly usage	AFM	Monthly water usage (before conservation or reuse)
% Indoor use	%	Percent of total monthly usage that is indoor (outdoor usage is calculated internally as the difference)
% CU indoor	%	Percent of total monthly indoor usage that is consumptive (no return flows) (the non-consumptive fraction is calculated internally as the difference)
% CU outdoor	%	Percent of total monthly outdoor usage that is consumptive (no return flows) (the non-consumptive fraction is calculated internally as the difference)

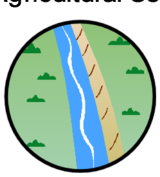
Source Water:		
Source stream	NA	Name of stream from which water is diverted
Source type	NA	Either direct diversion, via reservoir storage account, or groundwater pumping
Downstream location	mi	Relative location of diversion on source stream
Priority date	dd/mm/yyyy	Date of withdrawal permit
Ditch capacity	AFM	Physical capacity of diversion ditch
Diversion right	AFM	Uniform or monthly-varying diversion right
Reservoir name (if applicable)	NA	Name of physical reservoir in which storage account is held
Storage capacity	(AF)	Capacity of storage account
Storage right	(AFY)	Annual total cumulative diversion right associated with storage account
Water year start month	NA	Starting month for tracking annual storage right
Carry over rule	NA	Flag indicating whether stored water remaining in account at the end of the previous year counts toward the annual storage right of the following year
Monthly groundwater pumping rates	AFM	If selected, monthly groundwater pumping rates used to meet demands (subject to aquifer storage availability)
Aquifer name	NA	if selected, name of Aquifer Object that groundwater pumping draws from
Return Flows:		
Locations option	NA	All return flows to a single location or return flows spread out over multiple locations
Receiving stream	NA	Name of receiving stream for return flows
Location	mi	Relative mile marker on receiving stream for location(s) of return flow discharge to the stream
Lag	months	Lag (if any) associated with return flows, relative to month of water use
% of Return flow (for multiple locations only)	%	Percent of total return flow, for given month, that is discharged at each location (sum across locations must equal 100% for each month)

Conservation: (optional)		
Manual vs. preset option	NA	Manual option requires user inputs of monthly water usage reductions (indoor and outdoor), while preset option uses assumed parameters associated with various selected conservation mechanisms to calculate net monthly usage reductions
Indoor/outdoor reduction	%	Percent reduction in water use, by month
% CU indoor/outdoor	%	Percent of indoor/outdoor reduction that is consumptive; these parameters are used for internal calculations of adjustments to overall consumptive use after conservation is applied
Drought-only flag	NA	Flag indicating whether conservation is activated only during user-defined drought conditions
Min-res volume (for drought-only conservation)	%	Percentage of water user storage capacity (for each source water account) that, when reached, triggers conservation
% of pop. (preset option only)	%	Percentage of service area population that is participating in given conservation activity
Reuse: (optional)		
% recapture	%	Percentage of indoor use effluent that gets recaptured for outdoor reuse
Graywater recycling flag	NA	Flag indicating whether to simulate graywater recycling
Ag Transfer (optional)		
Ag lands retired	acres	Total area of agricultural land involved in transfer
Annual CU	AF/acre	Average annual consumptive use of crops in retired ag lands
Irrigation efficiency	%	Amount of water consumed divided by amount of water diverted at farm headgate, expressed as %
Monthly distribution of supply	%	Percentage of annual total water delivery provided by month

Transbasin import: (optional)		
Implicit vs. explicit option	NA	Implicit transbasin imports do not simulate water at the source. Rather, the specified monthly volumes are assumed to be available at every timestep and are simply added to the specified water user account. Explicit transbasin imports explicitly simulate diversions and storage within the source basin and require specification of the source reservoir and account. For explicit imports, the monthly targeted imports may not always be met as they are subject to water availability.
Source reservoir (explicit only)	NA	Name of reservoir in source basin that imports draw from
Source account (explicit only)	NA	Name of account in source reservoir that imports draw from
Target inflow	AFM	Desired monthly import flow for transbasin project
Conveyance loss (explicit only)	%	Percent loss associated with transbasin import
Destination account	NA	Source water account number that transbasin import water is placed (augments existing source water)
Water exchange (optional)		
Upstream diversion account	NA	Account number associated with the upstream diversion component of the exchange program
Downstream release account	NA	Account number associated with the downstream storage and release component of the exchange program. Note that currently the model requires that this be Source Water 5 account)
Seasonal water exchange flag	NA	Flag indicating that exchange program is seasonal (as specified by monthly on/off flags). Note that for months where the exchange is not allowed (monthly flag unchecked), no diversions are permitted by upstream diversion account, but downstream storage account can divert and fill storage according to associated withdrawal permit.

2.2.4 Agricultural Users

Agricultural User



The primary difference between this object and the water user object (described above) is the way in which water usage (demand) is calculated or input. The agricultural user object allows for explicit calculation of water demands associated with crop agriculture. Monthly stream demands are calculated as a function of calculated monthly evapo-transpiration (ET) rates, irrigated acreage, and irrigation and conveyance efficiencies. ET rates are calculated using the well-known Blaney Criddle (or Modified Blaney Criddle) equations as a function of crop type, effective mean monthly precipitation, monthly mean temperature, field elevation, latitude, and crop-specific coefficients. Details of these

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calculations are provided in Section 3. Crop coefficients for seven crop types (corn, wheat, alfalfa, pasture, potatoes, grain, and beans) have been pre-set in the model. However, these coefficients are easily modified by the user. Additionally, a user-defined crop type is available.

Agricultural user demands can also be hard-entered by the modeler as a monthly timeseries. These need to be entered for the full period of simulation. This feature may be useful when historical diversion flows are known at a particular node and no changes to that node are simulated. *Since the water user object does not allow for direct user inputs of a timeseries of demands, the agricultural user object must be used for this type of node representation (even if not strictly an agricultural node).*

As with the generalized water user object, up to five different source water accounts may be utilized for any given agricultural user. Each of these can either use water directly from the source stream (direct diversion), from a reservoir account, or from groundwater pumping. These sources of water are modeled in the same manner described above for the Water User object. Transbasin imports are also available to supplement an agricultural user's local sources.

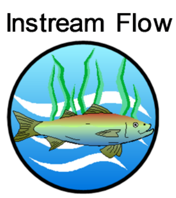
Return flow percentages are either calculated within the model interface (if demands are calculated) as a function of irrigation efficiency and ditch loss, or are directly input by the user (if demands are input). If calculated, water returned to the stream is equal to the water lost during conveyance (ditch loss) plus the water lost due to irrigation inefficiencies and over-watering. Return flow locations (up to five different locations) are specified by the user in the same manner as the water user object (above).

Table 2-4. Agricultural User Input Parameters

Parameter Name	Units	Description
User name	NA	A unique name must be assigned to each object;
Multiple sources flag	NA	Flag specifying whether multiple sources of water are to be defined
Water Usage:		
Blaney Criddle ET option	NA	Original Blaney Criddle (U = KF) or SCS modified equation (includes extra climatic factor)
Irrigated acres	acres	Area of land to be irrigated associated with given node
Ditch loss	%	Percent of headgate diversion water that gets lost (e.g. via leakage) during conveyance to fields
Irrigation efficiency	%	Represents all on-field losses of water, including excess application, leakage, and evaporation
Elevation	ft (absl)	Approximate elevation of irrigated acreage
Latitude	degrees	Approximate latitude of irrigated acreage (used for calculating daylight hours in given month)
Crop factors (Kc)	unitless	Empirical factors used in Blaney Criddle equations specific to crop type and growth stage

Duration of growth stage	days	User-defined (or pre-set) number of days in given growth stage; used for applying the crop factors (Kc)
% of total acreage	%	For each crop type, the percent of the total node irrigated acreage used for growing given crop
Start month	NA	Growing season starting month for given crop (note that duration of growing season is defined by growth stage durations described above)
Temp	°F	mean monthly temperature
Precip	inches	mean monthly precipitation
Source Water:		
(see water user object)		

2.2.5 Instream Flow Objects



Instream flow objects allow for the prioritization of stream flows to meet environmental or recreational goals. Monthly flow rights are specified along with a priority date associated with those rights. Maintaining the target flows then becomes a priority over junior diversion rights. If flow targets are not achieved, a "shortage" is calculated and reported by the model. Instream flow objects are also useful for explicitly tracking and reporting stream flows at specific points in the network. If an instream flow object is to be used merely for outputting stream flows, then the priority date should be set such that it does not impact other water users in the system.

Table 2-5. Instream Flow Object Input Parameters

Parameter Name	Units	Description
Instream Flow name	NA	A unique name must be assigned to each object;
Target stream	NA	Name of stream associated with instream flow target
Downstream location	mi	Relative location of instream flow on source stream
Priority date	dd/mm/yyyy	Date of withdrawal permit
Flow right	AFM	Monthly-variable or constant instream flow right

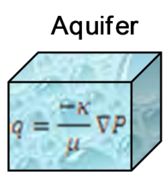
2.2.6 Recreation Pool Objects

Recreation pool objects are used to prioritize the maintenance of a reservoir pool. In other words, water is diverted as needed and as available to maintain a user-specified volume of water in a given reservoir. Often this water might be for recreational purposes, such as boating, fishing, or swimming. The pool target might also be for hydropower purposes. Generally, the only losses associated with a recreation pool are evaporative. In some cases, regulated reservoir releases are also drawn from the recreation pool, depending on the assigned priority of the pool. See discussion on the distribution of reservoir evaporative losses and regulated releases in Section 2.2.2. Note that a recreation pool can only be created for an existing reservoir (which needs to be created first).

Table 2-6. Recreation Pool Object Input Parameters

Parameter Name	Units	Description
Reservoir name	NA	A rec pool may only be added for an existing reservoir (only 1 rec pool per reservoir allowed)
Source stream	NA	Name of stream from which water is diverted
Downstream location	mi	Relative location of rec pool diversion on source stream
Priority date	dd/mm/yyyy	Date of withdrawal permit
Pool volume	AF	Target volume of recreation pool

2.2.7 Aquifer Objects



Aquifer objects are used to track groundwater storage as subject to pumping by single or multiple users (water users and/or ag users). Storage calculations are performed at each timestep as a function of: total groundwater pumping associated with the aquifer (calculated), monthly aquifer recharge rates (prescribed), and initial aquifer storage (prescribed). Aquifer objects are simulated as a fully contained and lumped storage vessel. Any upgradient or lateral inflows or downgradient lateral outflows are neglected.

In addition to tracking groundwater storage, aquifer objects can be used to estimate water table drawdown, at up to five (5) different monitoring well locations, as a function of aggregate pumping rates and aquifer hydraulic properties. Drawdown calculations are only available for confined aquifers. Aquifer drawdown is calculating using a polynomial approximation to the Theis Equation (Abramowtz and Stegun, 1968). Application of the equation has been extended in SWAM to handle time-variable pumping rates. The equation assumes a homogeneous isotropic confined aquifer and fully penetrating wells. It also assumes that the aquifer is infinite in radial extent. Aquifer hydraulic properties are defined according to user-prescribed storativity and transmissivity values. Drawdown is calculated at each simulation timestep for up to five specified “monitoring well” locations. The locations are parameterized according to a table of user-defined radial distances between monitoring well and pumping well (or wellfield). The impacts of each water user or ag user pumping well /wellfield are included in the cumulative drawdown calculations.

2.3 Model Output

Monthly output for all model nodes are written to the “Node Output” worksheet in SWAM. Brief descriptions of each output parameter are provided below. For water user or agricultural user objects with multiple sources of water, SWAM provides detailed output for each source account as well as the totals for the object.

- <u>Physically available (AFM):</u> This is the physical stream flow just upstream of the point of diversion. Physical availability is calculated as a function of upstream headwater flows, node diversions, and node return flows.

- Legally available (AFM): This is the total flow that can legally be diverted at the point of diversion. As discussed elsewhere, legal availability is calculated in SWAM as a function of downstream priority demands, node monthly diversion and annual storage rights, and physical flows in the system. Note that in times of surplus water, SWAM reports the non-limiting legal availability as the physical availability + node return flow.

- Diverted (AFM): This is the actual amount diverted for the given node. It is generally the smaller of physical availability, legal availability, and desired diversion total. Note that the “desired diversion total” here refers to the net usage demand plus any storage make-up water to fill available capacity (e.g. make-up for evaporative or release losses).

- Storage (AF): This is the node storage account volume (if applicable) at the end of the given timestep. This value is calculated as a function of diverted flow (inflow) and demand withdrawals, account evaporative losses, and account regulated releases (outflows). The actual volume resides in the associated “parent” reservoir.

- GW Pumping (AFM): Monthly groundwater pumping rates by the user associated with the given node (if applicable).

- Demand (AFM): This is the net water usage demand on the stream for the given node at the given timestep. Demand is calculated as a function of user-input (or calculated) monthly usage values and reuse and conservation impacts (if applicable).

- Shortage (AFM): This is the monthly shortfall in water supply and represents the difference between demand and demand met. Demands are met through both direct diversion water and storage account withdrawals. In the case of instream flow objects, shortages are simply the difference between the instream flow target and the actual physical flow at the node. For recreation pools, the reported shortage reflects the difference between targeted rec pool volume and actual pool volume.

- Return Flow (AFM): This is the monthly returns to the stream after node usage. These are calculated in SWAM as a function of user-input consumptive use percentages, actual demand met, and reuse considerations (if applicable). Note that if the node return flow lag is > 0, then reported return flows reflect the calculations associated with the timestep at t - lag.

- Release (AFM): This is the monthly storage regulated release associated with the node storage account (if applicable). As discussed in Section 2.2.2, total reservoir regulated releases are distributed by the model across individual storage accounts according to permitted withdrawal priority (lowest to highest priority). These releases decrease storage account volume and are unavailable for node use.

Output specific to reservoir objects are provided in the “Reservoir Output” worksheet. These output are described below.

- Storage (AF): This is the total volume of water in the physical reservoir at the end of the given timestep. This volume is inclusive of all of the individual user accounts and, if applicable, the recreation pool associated with the reservoir. This value is calculated as a function of total inflows to the reservoir (“diversions” to storage by various accounts) and total outflows from the reservoir (evaporation + regulated releases + user withdrawals).

- Excess Volume (AF): Currently, this output variable only reflects the result of specifying an initial reservoir volume that exceeds the sum of all account capacities held by the reservoir. It is water that is not "owned" by any of the child accounts of the reservoir and is included in the output only to provide for complete water balances during the early timesteps of a simulation (when initial conditions are impacting calculations).
- Overflow (AFM): Currently, the output variable is provided only to resolve water balances in the case of the sum of individual account storage capacities exceeding total reservoir physical storage capacity. Since this situation is technically user-input error, the overflow output parameter should be used for debugging purposes only. Note that since SWAM does not explicitly simulate online reservoirs, flood overflows (spills) are implicitly reflected in the stream flows that bypass the model reservoir object.
- Release (AFM): This is the total reservoir regulated release for the given timestep. In most cases (unless there is excess volume) this value will be the sum of the individual account releases provided in the "Node Output" worksheet.

Output specific to aquifer objects are provided in the "Aquifer Output" worksheet. These output are described below.

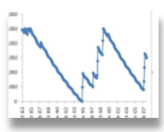
- Storage (AF): This is the total volume of water stored in the aquifer at the end of the given timestep. This value is calculated as a function of aggregate groundwater pumping rates by all users associated with the aquifer, specified aquifer recharge rates, and a specified initial storage value.
- Recharge (AFM): This is an output of the input values specified by the user on the aquifer input form and represents total monthly recharge to the aquifer.
- Total Pumping (AFM): These are the total pumping withdrawals from the aquifer, representing the sum of all water user and ag user pumping for the given timestep.
- Drawdown 1 – 5 (ft): Water table drawdown levels at given timestep for monitoring well locations 1 – 5 (defined by user), calculated as a function of pumping rates and aquifer hydraulics using the Theis analytical solution.

Note that neither the "Node Output" nor the "Reservoir Output" worksheets should ever be deleted by the user (the model won't know where to place output)!

In addition to the raw timeseries output data described above, graphical output summaries can easily be created on the "Main" page using the "Output Plotting" control button (below).

Lastly, an option (button shown below) is available in SWAM to output timeseries data to an external text file rather than to the output worksheets. This is provided as a means of greatly reducing simulation run times for larger, more complex models. Text file outputting can only be for a single user-specified node. Therefore the model must be run multiple times to generate text file output for all nodes (still may save simulation time for larger models). Normal worksheet outputting can be done for all nodes during a single simulation or, for improved efficiency, for a single targeted node.

2.4 Reservoir Firm Yield Calculations



In addition to the normal water allocation simulation mode described above, SWAM contains an alternative simulation option whereby automated firm yield calculations are performed for a specified reservoir object. Under this simulation, full outputting of network parameters is not provided. Instead, only final firm yield values are provided. Firm yields are calculated through internal simulation iterations of the full networked system with adjustments made to targeted reservoir water user demands until the firm yield is identified. For these purposes, firm yield is defined as the minimum annual reservoir demand that can be sustained throughout the period of simulation. The model iterates until zero storage in the targeted reservoir account is exactly achieved during the simulated critical drought period. Firm yields are calculated for a specified reservoir user account and are a function of tributary flows, monthly demand patterns, reservoir evaporation rates, and higher priority demands (either upstream or downstream) in the simulated system.

Firm yield calculations can be performed in SWAM for multiple "alternative hydrology" input data sets. Users can prescribe multiple monthly timeseries sets of upstream tributary flows with the model calculating, in "batch" mode, firm yields for each hydrologic scenario. These alternative hydrologies might represent, for example, various climate change forecasts derived from Global Climate Model (GCM) projections. Two sets of hydrology projections can be prescribed, each with up to ten (10) different data sets. This format was implemented in recognition of a common approach to climate change modeling whereby separation is maintained between groups of projections specific to assumed greenhouse gas emission scenarios. For example, a user might prescribe a set of ten hydrologic projections developed for the A2 (worst case) greenhouse gas emission scenario and another ten for the B1 (best case) emission scenario. Model simulations are performed independently for each group. Output from the batch mode simulation are provided in the form of a table of firm yield values. Output can also be summarized by the model in probability (normal) distribution functions fitted to the output data. This type of summary provides quantification of the levels of model consensus across scenarios and is often useful for planning decision-making.

Section 3

Technical Documentation

This section provides detailed descriptions of the fundamental equations and algorithms employed by SWAM.

3.1 Diversions

For every timestep, t, diversions are calculated for each node as a function of physical availability, legal availability, net user demand, and physical diversion capacity. Within each timestep, these calculations are performed in order of node ranking by withdrawal permit (highest priority to lowest priority). The overall equation for calculating node diversions can be written as:

$$Q_{div} = \min\left(Q_{phys}, Q_{avail}, demand, capacity\right) \qquad (3\text{-}1)$$

Where Qphys = physically available water at point of diversion, Qavail = legally available water at point of diversion, demand = net demand on stream by node, and capacity = physical (ditch) capacity of diversion.

Physical availability at any given node is calculated as a function of upstream tributary flows, node diversions and return flows, and reservoir regulated releases. This calculation can be written as:

$$Q_{phys}^{i} = \sum_{j=i-1}^{j=0} Q_{HW}^{j} - Q_{div}^{j} + Q_{RF}^{j} + Q_{release}^{j} \qquad (3\text{-}2)$$

Where index i designates the relative downstream position of the node and j designates the upstream locations of tributary inflows, node diversions, node return flows, and reservoir releases.

Legal availability is calculated for each node, again in descending order of priority, as a function of monthly diversion right, annual storage right (if applicable), downstream priority demands, return flows, and downstream physical availability. This calculation follows the algorithm used in the State of Colorado's StateMod model ("Direct Solution Algorithm"). The first step in the algorithm is calculating the minimum flow left in the river at all downstream nodes after priority water users have diverted their allowable amount. This step can be written as:

$$Q_{avail'}^{i} = \min\left([Q_{phys}^{i+1} - Q_{div}^{i+1}], [Q_{phys}^{i+2} - Q_{div}^{i+2}], [Q_{phys}^{i+3} - Q_{div}^{i+3}], \ldots [Q_{phys}^{i+n} - Q_{div}^{i+n}\right) \qquad (3\text{-}3)$$

Where i refers to the relative downstream position of the node and n = number of downstream nodes. Because of the order of node calculations, only higher priority downstream users will have non-zero Qdiv values in this equation.

The second step in the calculation of legally available flow is the recognition of the availability of return flow from the given node to downstream users. An adjustment is made to the previously calculated Qavail to account for these return flow "credits":

$$Q^i_{avail''} = \frac{Q^i_{avail'}}{1-\%RFi} \quad (3\text{-}4)$$

Where % RFi = percent return flow at node i. This step essentially allows for the diversion of additional water due to recognition of the return flows on that diversion that can then be used to satisfy downstream priority users.

The final steps in the calculation of legally available flow are checks against the node's monthly diversion right and annual storage right, both user input. The model constrains the legally available flow to the less of the monthly diversion right and the previously calculated Qavail. It also ensures that the total cumulative diversion for the given water year does not exceed the user-specified annual storage right (if applicable). This can be written as:

$$Q^i_{avail} = \min(Q^i_{avail''}, diversion\ right, \Delta storage\ right) \quad (3\text{-}5)$$

Where *Δstorage right* = the remaining "cap" space in the annual storage right allotment (annual storage right – total water year cumulative diversion to-date).

The demand at each node is calculated as a function of the available storage space in a reservoir account (if applicable) and the actual water usage for a given timestep. For a water user or agricultural user with a storage account, the model first attempts to meet water usage demands with stored water, then looks to the available stream water to make up the difference and replenish storage. This can be written as:

$$demand^i = storage\ gap + \Delta S^i \quad (3\text{-}6)$$

Where demand = the demand on source stream at given timestep for node i, storage gap = timestep demand - storage water withdrawal (see Section 3.2), and ΔS = available storage space (capacity – S) in account for node i after withdrawals.

Finally, as described in Equation 3-1, the model considers the physical capacity of the diversion structure, i.e. ditch or pipeline. This is simply a user-specified value that may or may not be constraining, depending on the other terms in the equation.

3.2 Water Users

The water user calculation module (WaterUserCalc) is called twice within each simulation timestep. The first call is prior to the calculation of diversions (described above). During this call, initial storage calculations are performed with all available storage used to meet node demands as needed. If there is not enough storage to meet the total demand, the "storage gap" is carried over to the calculation of stream diversion demands (Equation 3-6, above). The available storage space (ΔS) is also calculated in this first iteration and carried through to the stream diversion demand calculations. The second call to the water user calculation module incorporates the stream diversion and updates storage values, node shortages, and return flows. WaterUserCalc also includes calculation of various optional supply and demand management alternatives, including conservation, reuse, agricultural transfers, transbasin imports, and water exchanges.

Key equations associated with the water user object include calculations of storage, shortages, return flows, and the dynamics of multiple source accounts with a single water user (and single set of demands). Water user storage is calculated as a function of diversions, withdrawals, evaporation, and releases using the standard water balance equation:

$$\frac{dS}{dt} = inflow - outflow \tag{3-7}$$

In SWAM, the numerical solution to this equation looks like:

$$S_i^t = S_i^{t-1} + diversion_i^t - demand_i^t - evap_i^t - release_i^t \tag{3-8}$$

where Sit = storage volume at time t, diversion = stream diversion (= 0 for first call to WaterUserCalc), demand = demand for storage water to meet water user needs, evap = reservoir evaporation credited to storage account (see Section 3.4), and release = mandatory storage account release to fulfill reservoir release obligations or exchange program offset requirement.

In SWAM, Equation 3-8 is first applied using the full water user demand. If the demand exceeds the available storage (after mandatory releases and evaporation), then the result will be a negative storage value (Sit < 0). In this case, the model sets the storage to 0 and assigns the difference (the negative storage) to the "storage gap" variable used in Equation 3-6, for the 1st call to WaterUserCalc, or to the final node shortage, for the 2nd call to WaterUserCalc.

Water user return flows are calculated according to:

$$RF_i^t = (1 - \%CU) * demandMet \tag{3-9}$$

Where RFit = return flow volume for given timestep, %CU = percent consumptive use associated with the water user demand, and demandMet = the actual demand met by storage water + diversion water.

When a water user includes multiple sources of water (see Section 2.2.3), SWAM calculates each account as if a stand-alone water user object. These calculations proceed in order of source account preference. SWAM attempts to meet all water user demands using the 1st preference source account, before moving to the 2nd, and so-on. Residual demands (shortages) are carried over from one account to the next account by setting the demand variable of the next preferred account to the residual demand (shortage) of the previous account. Timestep iterations are performed with these adjusted demands until either the total original demand is met, or all sources of supply are exhausted. An illustrative example is provided below.

<u>Example of Multiple Source Account Distribution of Demands, For Timestep t:</u>

Original total demand = 100 AF

Iteration 1:

Account #1 demand = 100 AF

Account #2 demand = 0 AF

Account #3 demand = 0 AF

Account #1 supply (storage + diversion) = 50 AF

Total Shortage = 50 AF

Iteration 2:

Account #1 demand = 50 AF

Account #2 demand = 50 AF

Account #3 demand = 0 AF

Account #2 supply (storage + diversion) = 25 AF

Total Shortage = 25 AF

Iteration 3:

Account #1 demand = 50 AF

Account #2 demand = 25 AF

Account #3 demand = 25 AF

Account #3 supply (storage + diversion) = 20 AF

Total Final Shortage = 5 AF

End Iterations.

3.3 Agricultural Users

Agricultural users are handled as water users in SWAM and utilize the same code. Differences compared to standard (M&I) water users are:

- Ag User return flow percentages are used directly within the WaterUserCalc module, rather than percent consumptive use (see Equation 3-9). As described in Section 2.2.4, these percentages are either user-defined or calculated within the user-interface as a function of irrigation efficiency and ditch losses.
- Demands can either be user-specified (full timeseries) or calculated within the user-interface according to the Blaney-Criddle equation (modified or original) for crop ET.

Return flow calculation:

$$\%RF = \%ditchLoss + (100 - \%ditchLoss) * \%irrEffic \qquad (3\text{-}10)$$

where *%ditchLoss* = ditch loss percentage and *%irrEffic* = irrigation efficiency.

Ag demand calculation (Blaney Criddle):

$$u = kt * kc * f \qquad (3\text{-}11)$$

$$kt = \max(0.0173 * T - 0.314, 0.3);\ Modified\ Blaney\ Criddle \qquad (3\text{-}12)$$

or

$kt = 1;\ Original\ Blaney - Criddle$

kc = WF_1*kc_1(t) + WF_2*kc_2(t) + WF_3*kc_3(t) +….. (3-13)

$$WF_i = \frac{A_i}{A} \qquad (3\text{-}14)$$

and

$$demand = \frac{u}{12} * A - \frac{P_{eff}}{12} * A \qquad (3\text{-}15)$$

where u = crop ET (inches), kt = climate factor for modified Blaney-Criddle equation, kc = aggregate crop factor that is calculated as a weighted average of user-defined crop-specific factors that vary according to growing season stage, T = mean air temperature, f = temperature and daylight factor, A = total irrigated acreage, A_i = irrigated acreage for crop type i, and P_{eff} = effective precipitation (inches).

3.4 Reservoirs

Reservoir objects are comprised of single or multiple water user storage accounts. The primary purposes of the Reservoir object calculations are to aggregate account storage values for outputting and to calculate reservoir evaporation and releases and distribute these losses across appropriate user accounts. Specific account storage calculations are described in Section 2.2. Reservoir object calculations are performed at the start of each simulation timestep (in the sub-routine "ResCalc"). Start of month total reservoir storage is calculated as the sum of all relevant user account storage values calculated in the previous timestep (see Equations 3-7 and 3-8). Evaporation and release calculations are linearized in SWAM by formulating as a function of start-of-month reservoir storage only. This is an approximation, but is deemed adequate for this planning level model.

Evaporation losses are calculated as a function of user-defined monthly rates (in mo-1) and start-of-month surface area, or as a function of user-defined monthly percent volumetric losses and start-of-month storage. Alternatively a timeseries of monthly evaporation losses (AFM) can be prescribed by the user. As an example, the former can be written as:

$$evap^t = evapRate^t * area^{t-1} \quad , \qquad (3\text{-}16)$$

where evapt = evaporation loss (AFM) at timestep t, evapRatet = prescribed monthly loss rate corresponding to timestep t, and areat-1 = reservoir surface area at start of timestep t (or end of timestep t-1).

As described previously (Section 2.2), calculated evaporative losses are distributed to individual accounts based on relative volumes of storage in each account at the given timestep. In other words, accounts with larger stored water will realize a greater evaporative loss than accounts with less stored water. This distribution occurs within the Reservoir object module at the start of the given timestep.

Similar to evaporation losses, reservoir releases are either calculated as a function of start-of-month hydrologic conditions or are prescribed by the user as mandatory monthly release volumes. For the latter, the model releases the prescribed amount as available in storage (after evaporation losses). For the former, "advanced" reservoir release rules, the model calculates release requirements as a function of downstream hydrologic conditions. These conditions equate to those calculated in the previous timestep (start-of-month storage or previous month flow).

Reservoir releases are distributed across individual accounts based on storage permit priority (lowest to highest priority). SWAM attempts to assign all of a regulated release to the lowest priority account. If this account is unable to meet the total release volume required (due to lack of physical availability), the model moves on to the next lowest priority account, and so on.

Since allocation of evaporation and release losses to individual user accounts is performed at the start of each timestep, these values are incorporated into subsequent water user water balance calculations.

For online reservoirs, flood control pool outflows are calculated as a function of start-of-month reservoir storage and user-defined outflow-capacity tables. Like releases, flood control pool outflows are calculated after evaporation calculations for each timestep. Therefore storage volumes used to calculate outflows equate to start-of-month values minus evaporation losses for the current month. Note that flood control pool outflows are included in the total release volume required to satisfy prescribed monthly release requirements. In other words, if a prescribed mandatory monthly release is 10,000 AFM, and 5000 AFM is calculated for the flood control pool outflow, then only an additional 5000 AFM is required to satisfy the release requirement.

3.5 Instream Flow Objects

Instream flow objects are handled as non-consumptive water user objects (Section 3.2) in the model. Instream flow objects impart a monthly demand on the system, parameterized according to a permit and priority date, but all allocated flows are 100% immediately returned to the system and no water storage occurs. In this way, no flow depletions occur while still imparting a flow demand. Internally, calculations follow those described for water user objects above but with storage set to zero, return flow percentages set to 100%, and return flow location set to the same as the point of diversion.

3.6 Recreation Pools

As above, recreation pools are included in the model calculations as non-consumptive water user objects. Reservoir recreation pool object demands are calculated as the difference between the specified rec pool target volume and the actual pool volume at the start of the timestep. Water usage for the rec pool object is set to zero. Consequently, the only losses of water for a rec pool object are evaporation. As with any water user object, rec pools are parameterized with a storage permit priority date. The rec pool permitted withdrawal volume is set internally so that it is non-limiting (106 AFY). Water therefore gets allocated to a rec pool based on its priority date and the pool demand (difference between target and beginning of timestep volume).

3.7 Aquifer Objects

Aquifer storage is calculated via a standard storage water balance:

$$\frac{dS}{dt} = inflow - outflow \qquad (3\text{-}7)$$

In SWAM, the numerical solution to this equation looks like:

$$S_i^t = S_i^{t-1} + recharge_i^t - \sum_{j=1}^{n} GWpumping^t$$

where i = aquifer index, S = storage at end of given timestep, recharge = monthly aquifer recharge rate, j = index for all water users that pump from aquifer i, n = number of water users that pump from aquifer i. Groundwater pumping rates are calculated internally for each water user or ag user object as a function of demands and availability and priority of other sources of supply.

Aquifer drawdown is calculated using a polynomial expansion of the Theis equation. The Theis equation can be written as:

$$s = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

where s = drawdown (change in hydraulic head at a point in space as a function of cumulative impacts from pumping since the start of pumping), u = dimensionless time parameter, Q = pumping rate, T = aquifer transmissivity (L^2/t), S = aquifer storativity (unitless), r = distance from the pumping well to the drawdown observation point, t = time since pumping began, and W(u) is the well function. In SWAM, the well function (W(u)) is approximated by a multi-term polynomial presented in Abramowtz and Stegun (1968). SWAM applies convolution principles to calculate the combined impacts of multiple pumping wells, in different locations, with time-variable pumping rates.

3.8 Reuse

Reuse is a demand management option for water user objects. In SWAM, the only form of reuse explicitly available under this option is direct recapture of indoor usage return flows (wastewater treatment plant effluent). When this option is selected by the user, net monthly water demand is adjusted at each timestep according to:

$$demand^t = total\_usage^t - total\_indoor\_usage^t * (1 - \%CU) * \%reuse$$

where %reuse = a user-specified percentage of indoor return flows that gets recaptured for reuse and %CU = percent consumptive use associated with the indoor usage. Return flows from a water user implementing reuse are also reduced accordingly.

3.9 Conservation

A net monthly conservation percentage is calculated at each timestep as parameterized by the model user. This percentage corresponds to a percent reduction in water usage. Different percentages are calculated for indoor use versus outdoor use. The percentages are applied according to:

$$totalUsage^t = indoor\_usage^t * \left(1 - \%Cons^{in}\right) + outdoor\_usage^t * (1 - \%Cons^{out})$$

where %Consin = monthly percent conservation reduction in indoor water usage at timestep t, and %Consout = monthly percent conservation reduction in outdoor water usage at timestep t.

3.10 Transbasin Imports

Transbasin import water gets added to the total supply portfolio of a water user at each timestep. Import water is calculated as a function of specified transbasin delivery targets, source water availability, and conveyance losses (if any). In SWAM, transbasin water automatically gets added to the total supply of the assigned water user, regardless of demand. If a surplus in supply in a given month results, the surplus is returned to the river. In other words, transbasin import water, if designated by the water user, represents a continuous additional water source for a modeled basin.

3.11 Agricultural Transfers

As with transbasin imports, agricultural transfers are simulated in SWAM as supplemental sources of supply for a given water user. Ag transfer water deliveries are calculated as a function of user-defined irrigated acreage that gets retired, the irrigation consumptive use associated with the acreage, irrigation efficiency, and a monthly distribution of irrigation demands. As above, ag transfer water, when selected by the user, represents a continuous source of supply to the water user, and ultimately the modeled surface water basin, independent of demand.

3.12 Groundwater Pumping

Groundwater pumping is available as a source of supply for water user and agricultural user objects in SWAM. Groundwater supply is calculated in the model as a function of user-specified target pumping rates, net demand for groundwater, and aquifer storage availability. A key difference between groundwater as a source of supply and the supplemental supplies described above is that groundwater pumping is constrained by demand at each timestep. In other words, groundwater will not be pumped if there is not a need for it in a given simulation month.

Groundwater pumping return flows are included in the calculation of total surface water returns from a given water user.

3.13 Water Exchanges

Water exchange programs can be established between two water user supply accounts. Because it requires two supply accounts acting in concert, water exchanges are only available if the “multiple sources of supply” checkbox is selected. A water exchange is defined in SWAM as an agreement whereby an upstream diversion account can only divert water if a downstream partner account releases water from storage of the same amount and in the same timestep. Practically, this allows for diversion and storage to occur at the downstream location during wet periods and direct diversion to occur at the upstream location during dry periods, with no impact on downstream users (since the diversion is offset by releases from the downstream stored water). In SWAM, the downstream storage account in an exchange program can only store and release water to the stream. Water can’t be used for consumption from this storage account. Diversion to the downstream storage account can only occur in timesteps where there is no release requirement (i.e. no upstream diversion) and as allowed according to standard water user supply account calculations of physically and legally available flow. For the upstream direct diversion in an exchange program, the model calculates legally and physically available flow at the node following the standard algorithms but then constrains the legally available flow to less than or equal to the total available for release from the downstream partner account. When the seasonality flag is selected (under “Water Exchange” tab), the user can specify the months in which the exchange program is active. For the selected months, upstream diversions and downstream releases can occur as described above. For months when the exchange program is not active (un-selected checkboxes), no diversions to the upstream account are allowed even if downstream storage is available for releases. Note that the downstream account in an exchange program must be assigned to the #5 preference supply account and thus is forced to be the less preferred account in the exchange partnership.

Section 4
References

Abramowtz and Stegun 1968. Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables. 7th Edition. United States Department of Commerce.

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