ArkDSS Memorandum
Final

To: Bill Tyner and Kelley Thompson, Colorado Division of Water Resources
Brian MacPherson, Colorado Water Conservation Board

From: Wilson Water Group

Subject: Task 2.4: Development of Structure Irrigation Parameters

Date: September 28, 2020

INTRODUCTION

The Task 2.4 objective is to:

> *Review available information and determine appropriate irrigation parameters for modeled structures. Irrigation parameters include canal and lateral efficiencies, maximum irrigation application efficiencies, tailwater runoff, secondary ET losses, and average available water capacity (AWC).*

Irrigation parameter information is used in both the consumptive use (StateCU) and surface water allocation (StateMod) modeling during simulation of the water balance. Conveyance and application efficiency parameters are used to estimate the amount of water supply that is available to meet crop demands. Secondary ET losses are used to determine diverted water that is lost due to evaporation or consumption by non-crop vegetation. The tailwater runoff parameter is used to estimate the amount of non-consumed water that returns to the river via surface water flow, i.e., is not lagged back to the river through the alluvial aquifer. Soil water holding capacity (term AWC for available water capacity) is used to determine the soil reservoir volume available to store excess water deliveries and precipitation.

The purpose of this memorandum is to identify and summarize existing sources of information and recommend physical irrigation parameters for structures represented in the ArkDSS planning models. The models can be used to better understand current and future water use throughout the basin, and to investigate opportunities to meet existing shortages and future demands. However, irrigation parameter recommendations are not intended to set a precedent and should not be used as a basis for legal proceedings.

CONVEYANCE LOSS

Canal and lateral losses (conveyance losses) reflect the amount of total surface water diversions that seep into the alluvial aquifer as the water is conveyed to the irrigated fields. This loss is calculated by the models using an average efficiency factor that combines both canal and lateral losses and is applied to the total historical or simulated river diversions. Actual conveyance efficiency varies along the ditch length and throughout the irrigation season due to fluctuations in diversion rates, antecedent soil conditions, and soil types; however, an average value is considered appropriate for planning purposes in the ArkDSS effort.

Information developed for previous modeling and engineering analyses was collected, reviewed, and supplemented where necessary with industry-standard methods to develop recommendations for structures included in the modeling effort. For structures that divert for both irrigation and to fill off-channel reservoirs, a mass balance approach incorporating historical diversions and reservoir content data was also used to inform the canal and lateral loss recommendations.

Previous Conveyance Loss Estimates

Several canal and lateral efficiency studies have been completed in the Arkansas River basin, including studies developed for the Colorado vs. Kansas litigation and studies to support engineering reports for water court applications. Most of the available information is for ditches within the Hydrologic-Institutional Model (H-I Model) domain, with limited information available for other areas in the basin. Water Commissioners also provided regional estimates of canal and lateral losses during interviews completed and documented through the ArkDSS effort.

The following summarizes previously developed canal and lateral efficiency information and its applicability to the planning-level effort for the ArkDSS.

H-I Model Canal and Lateral Losses. The H-I Model is used to determine depletions and accretions to state line flow caused by ground water pumping, and replacements by simulating the hydrologic and institutional systems that occur along the Arkansas River between Pueblo and the Colorado-Kansas state line (Amended Appendix C.1, Hydrologic-Institutional Model Documentation, August 2015). The components of the surface water simulation are native stream flows, transmountain deliveries, tributary inflows, reservoir operations, and irrigation diversions. During the simulation, canal and lateral losses are applied to the irrigation diversions. Canal losses are based on a canal seepage factor and canal length. The Division of Water Resources staff indicated that canal loss was developed by:

- Estimating canal lengths from available imagery and mapping
- Compiling canal loss from previous studies in the area
- Developing a seepage factor (SEEPFC), and relationship to canal length, based on the canal lengths and available canal losses from previous studies

- Applying the seepage factor calculation to all canals in the H-I Model area
- Revising (i.e. calibrating) canal lengths over time to better fit previous or current canal loss estimates, or through H-I Model calibration.

Additional lateral losses of 7 percent are divided evenly between on-farm and off-farm losses. For purposes of developing the consumptive use analysis (StateCU) and the calibrated StateMod model, which currently allow a single value for canal efficiency, the off-farm lateral loss is additive to the canal loss percentage. The H-I Model seepage factor, canal length, canal loss, on-farm lateral loss, and total StateCU loss is presented in **Table 1**.

Table 1: Canal Loss Estimates from H-I Model

Canal	Seepage Factor (SEEPFC)	Canal Length (miles)	Canal Seepage[1]	Off-Farm Lateral Loss	Total ArkDSS Canal + Lateral Loss
Bessemer Ditch (1400533)	0.991562	18	14.1%	3.5%	17.6%
Booth-Orchard Ditch (1400591)	0.991562	6	5.0%	3.5%	8.5%
Excelsior Ditch (1400539)	0.991562	5	4.1%	3.5%	7.6%
Collier Ditch (1400538)	0.991562	3	2.5%	3.5%	6.0%
Colorado Canal (1700540)	0.991562	25	19.1%	3.5%	22.6%
Rocky Ford Highline Canal (1700542)	0.991562	41	29.3%	3.5%	32.8%
Oxford Canal (1700541)	0.991562	9	7.3%	3.5%	10.8%
Otero Canal (1700557)	0.991562	24	18.4%	3.5%	21.9%
Catlin Canal (1700552)	0.991562	18	10.4%	3.5%	13.9%
Fort Lyon Storage (1700648)	0.991562	26	19.8%		19.8%
Fort Lyon Canal (1700553)	0.991562	54	37%	3.5%	40.2%
Rocky Ford Ditch (1700558)	0.991562	8	7%	3.5%	10.1%
Holbrook Canal (1700554)	0.991562	15	12%	3.5%	15.4%
Las Animas Consolidated Ditch (1700556)	0.991562	10	8%	3.5%	11.6%
Baldwin Stubbs Ditch (1700551)[2]	n/a	n/a	n/a	n/a	n/a
Fort Bent Canal (6700610)	0.991562	15	12%	3.5%	15.4%
Keesee Ditch (6700613)	0.991562	4	3%	3.5%	6.8%
Amity Canal (6700607)	0.991562	43	31%	3.5%	34.0%
Lamar/Manvel Canal (6700614)	0.991562	12	10%	3.5%	13.2%
Hyde Ditch (6700612)	0.991562	4	3%	3.5%	6.8%
X-Y Irrigating Ditch (6700617)	0.991562	9	7%	3.5%	10.8%
Buffalo Canal (6700608)	0.991562	11	9%	3.5%	12.4%
Sisson & Stubbs Ditch No 1 (6700616)	0.991562	3	3%	3.5%	6.0%

[1] Canal Seepage = 1- SEEPFC ^ Canal Length

[2] Baldwin Stubbs Ditch diverts via a lift pump.

Discussions with water resources engineers that perform analyses for water court in the area indicate that the H-I Model canal seepage factors are generally representative of actual conditions, particularly in the Lower Arkansas River Basin closer to the state line. Although independent seepage analyses may reflect different values, the small differences support using the generally accepted H-I Model factors. Some engineers have questioned the inclusion of lateral losses and may present analyses that exclude these factors or treat them differently than used in the H-I Model. Overall, the H-I Model factors serve as the primary source of canal and lateral seepage loss information in the Lower Arkansas River Basin.

Arkansas Valley Investigation, Canal Loss Studies, 1939 – 1940 (Bureau of Reclamation, March 1942). This document reflects a summary of preliminary canal loss data and discharge records developed by the Bureau of Reclamation and provided to the Colorado Water Conservation Board. The study includes canal conditions; soil type summaries; important structures/laterals; daily canal discharge; and estimated canal losses along the Fort Lyon Canal, Colorado Canal, and Rocky Ford Highline Canal. Although informative, the canal losses in this study are not recommended for use in the ArkDSS effort because they reflect losses studied over a very limited single-year period and are representative of historical operations and conditions during the single year. Average canal losses estimated over a longer period under a variety of more current hydrological and operational conditions are more applicable to the ArkDSS effort.

Arkansas River Basin Study, Water Budget Documentation (Boyle Engineering Corporation, December 1990). This report documents the water budget results for the Arkansas River from Pueblo Reservoir to the Colorado-Kansas state line. Estimates of canal and lateral losses for diversion structures in this section of the river were analyzed as a component of the overall water budget. Boyle reviewed and compiled estimates from several sources, including from ditch company interviews. Based on this compilation, Boyle selected representative canal and lateral losses for use in the water budget analysis. The reported estimates are generally higher than losses used for the ditches in the H-I Model. As noted above, the H-I Model estimates are believed to accurately represent overall canal and ditch losses and the overlapping Boyle estimates are not recommended for the ArkDSS efforts.

Super Ditch Rotational Fallowing – Water Leasing Program, Lower Arkansas Valley Super Ditch Company (Aqua Engineering, Inc, December 2010). This report investigated the existing infrastructure, operational, and institutional components of ditch companies in the Arkansas River Valley that may be interested in participating in the Super Ditch Company. As a component of that investigation, the report summarizes estimates of canal seepage for the Rocky Ford Highline, Oxford Farmers, Otero, Catlin, Holbrook, Fort Lyon, and Bessemer

Canals. These ditches are all include in the H-I Model boundary. Although the study identified major laterals within each ditch system, additional lateral losses were not reported. The report notes that estimates of canal losses reflect losses due to seepage, phreatophytes transpiration, evaporation, and leakage through structures. In general, the study used ditch loss numbers that coincide with the H-I Model estimates. As noted above, the H-I Model estimates are believed to accurately represent canal and lateral losses; therefore, the Super Ditch estimates are not recommended for the ArkDSS efforts.

Irrigation Practices, Water Consumption and Return Flows in Colorado's Lower Arkansas River Valley (CWI No. 221, June 2012). This report stemmed from water quality and salinity concerns in the Lower Arkansas River Valley and understanding that baseline information on irrigation practices in the area is necessary prior to implementing irrigation enhancements that may improve water quality conditions. The report summarized the methods, analysis, results, and implications of an irrigation monitoring study conducted by Colorado State University (CSU) during the 2004 to 2008 irrigation season for over 60 individual farms. The report discusses transit losses as a component of the overall field water balance but does not discuss ditch-wide canal and lateral losses that may be applicable to the ArkDSS effort.

Data for Improved Water Management in Colorado's Arkansas River Basin (CWI No. 24, February 2016). This report monitored and described major hydrological and water quality features of the alluvial valley in both the Upper and Lower Arkansas River Basin. The study's "aim is to provide data both for an assessment of current conditions and to support models and decision-making for improved management of the Arkansas River Basin's water resources". In the Upper Arkansas River Basin (UARB), seepage tests were performed on the Riverside Allen, Cottonwood Maxwell, and Salida Canals. The seepage loss rates were developed using a water balance equation on small reaches of the canals during the 2009 and 2010 irrigation seasons. Although the seepage study was conducted for only a short period of time, limited seepage data has been developed for canals in the UARB area; therefore, the information is valuable to compare to general estimates of losses in the area.

Similar seepage studies were performed for ditches in the Lower Arkansas River Basin (LARB) on the Fort Lyon Canal, Rocky Ford Highline Canal, and Lamar Canal. According to the report, several seepage tests were compromised due to "moving channel bed problems"; however, the remaining tests did yield valid test results, presented as average percent loss per mile. The resulting total canal loss for these three ditches, based on the canal length information from the H-I Model accounting, and the average percent loss per mile estimates are as follows:

- 32 percent for Fort Lyon Canal (54 mile canal length)

- Between 26 and 42 percent for Rocky Ford Highline Canal (41 mile canal length)
- Between 17 and 32 percent for Lamar Canal (12 mile canal length)

The conveyance loss estimates for the Fort Lyon Canal and the Rocky Ford Highline Canal are close to the H-I Model canal seepage estimates. The Lamar Canal estimates are higher than the H-I Model estimates. As noted above, the H-I Model estimates are believed to accurately represent canal and lateral losses; therefore, the CWI No. 24 estimates for ditches included in the H-I Model boundaries are not recommended for the ArkDSS efforts.

Canal Loss Estimates from Various Decrees and Engineering Reports. Engineering reports are developed to support water court applications and often include assessments of canal and lateral losses. Although the methods and approaches used to develop these loss estimates vary (e.g. stipulated loss estimate, irrigator/ditch company interviews, seepage tests), they provide another comparison for the ArkDSS effort. Note that estimates of canal and lateral losses from the H-I Model are often used by engineers for ditches in the model area, and as such, are not included in this section. Engineering reports available to the WWG team through their modeling and water court work in the basin, and those available from the Division of Water Resources' website, were compiled and reviewed for canal and lateral loss information. Note that lateral losses were not explicitly identified in any of the reports reviewed; however, in many cases the estimates from engineering reports are the only available estimates and are believed appropriated for ArkDSS efforts.

Water Commissioner and Stakeholder Meetings (ArkDSS). As part of the ArkDSS effort, the WWG Team met with Division 2 staff, Water Commissioners, and stakeholders from federal agencies, municipalities, water conservancy districts, and irrigation districts throughout the basin. The purpose of these meetings was to obtain information and document key operational and administrative conditions in the basin. There were several topics discussed in the meetings, including canal and lateral losses. In some cases, losses were discussed as generalities across Water Districts, and others reflected losses for specific canals. In several areas, estimates from ArkDSS interviews are the only available estimates and are believed appropriated for ArkDSS efforts.

Water Balance - Development of Off-Channel Demands (ArkDSS). The ArkDSS modeling effort represents diversions to meet separate demands for canals that carry water to both irrigation and storage. Canals that carry to off-channel storage require water mass balance between diversions to storage, canal losses, reservoir evaporation, and change in storage experienced at the reservoir. An original estimate of canal loss from published data described above was assumed for the water balance analysis, then adjusted and calibrated to maintain system mass balance and represent specific ditch segments; for example from the headgate to an off-channel reservoir and from an off-channel reservoir to down-ditch irrigation. The water balance efforts are detailed in Appendix A of the ArkDSS Task 2.6 Key Reservoir Summary Memo. As appropriate, the ditch segment canal loss information is recommended for use in the ArkDSS efforts.

Conveyance Efficiency Summary and Recommendations

Table 2 provides a comparison of canal loss information from the sources listed above and the recommended model conveyance loss for each listed structure.

Table 2: Summary of Previously Developed Canal Loss Information and Model Recommendations

Canal/ WDID	H-I Model	Boyle Water Budget	Super Ditch Report	CWI No. 24	Engineering Reports	ArkDSS Interviews	ArkDSS Water Balance	Model Recommendation
Amity Canal (6700607)	30.5%	25%				29.7 – 35%[1),2)]		30.5%
Bessemer Ditch (1400533)	14.1%	20%	15%		15.1-17.6%			14.1%
Booth-Orchard Ditch (1400591)	5%	15%						5%
Buffalo Canal (6700608)	8.9%	1%						8.9%
Catlin Canal (1700552)	10.4%	20%	10%		16.5%	10%[2)]		10.4%
Champ Ditch (1100517)					0%			0%
Collier Ditch (1400538)	2.5%	15%						2.5%
Colorado Canal (1700540)	19.1%	15%				23.5 – 30%[1,2)]	25%	25%
Cottonwood & Maxwell Ditch (1100650)				31-43%				35%
Excelsior Ditch (1400539)	4.1%	15%						4.1%
Fort Bent Canal (6700610)	11.9%	20%						11.9%
Fort Lyon (1700553)	36.7%	18.24%	37%	32%		35 – 42%[1),2)]	25-41%	25% to Adobe/Horse Creek Reservoirs, 41% to Great Plains Reservoirs, 37% to Irrigation, 35.6% from Adobe/ Horse Res. to Irrigation
Fort Lyon Storage Canal (1700648)	19.8%					10 – 35%[1),2)]	25%	25%
Gomez Ditch (1600577)					20%			20%
Harrison Ditch (1100550)					20%			20%
Highland Canal (1700615)		10%						10%

Canal/ WDID	H-I Model	Boyle Water Budget	Super Ditch Report	CWI No. 24	Engineering Reports	ArkDSS Interviews	ArkDSS Water Balance	Model Recommendation
Holbrook Canal (1700554)	11.9%	18%	11-12%			24 – 25%[1),2)]	12-24%	12% to Storage 24% to Irrigation 12% from Storage
Huerfano Valley Ditch (1400657)					8.65%			9%
Hyde Ditch (6700612)	3.3%	5%						3.3%
John Flood Ditch (1900572)						10%[1)]		10%
Keesee Ditch (6700613)	3.3%	14%						3.3%
Las Animas Consolidated (1700556)	8.1%	10%				10%[2)]		8.1%
Lester & Attebery Ditch (1200512)					20%			20%
Lamar/Manvel Canal (6700614)	9.7%	23%		17-32%		20-25%[2)]		9.7%
Mexican Ditch (1600604)					7.5%			7.5%
Model Ditch (190552)						20%[1)]		20%
Montez Ditch (7900550)						20%[2)]		20%
Otero Canal (1700557)	18.4%	13%	20%					18.4%
Oxford Canal (1700541)	7.3%	15%	25%			10%[2)]		7.3%
Pleasant Valley Ditch (1200500)					20%			20%
Riverside-Allen Ditch (1100534)			36-45%					40%
Rocky Ford (1700558)	6.6%	15%			19%			6.6%
Rocky Ford Highline Canal (1700542)	29.3%	20%	13%	26-42%		20%[2)]		29.3%
Salida Ditch (1100536)				14-21%				20%

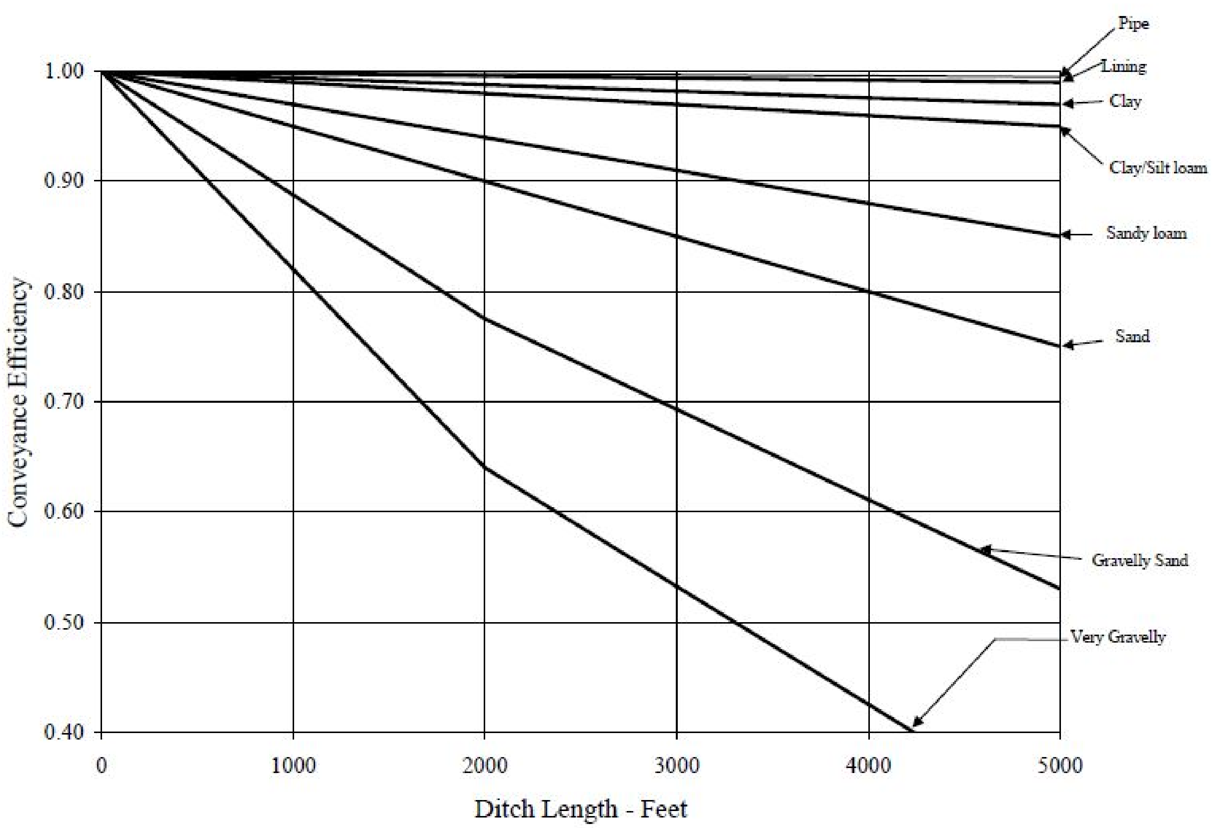
Canal/ WDID	H-I Model	Boyle Water Budget	Super Ditch Report	CWI No. 24	Engineering Reports	ArkDSS Interviews	ArkDSS Water Balance	Model Recommendation
Sisson & Stubbs Ditch No 1 (6700616)	2.5%							2.5%
Tennessee Ditch (1100503)					15%			15%
William Craig Ditch (7900511)					10%			10%
X-Y Irrigating Ditch (6700617)	7.3%	20%						7.3%
Water District 14						H-I Model[2)]		H-I Model for represented ditches
Water District 16						10%[2)]		10%
Water District 18						10% above Lucero Ditch (1800506) 20-25% below[2)]		10% ab Lucero Ditch 20% bl Lucero Ditch

1) Interview Supporting Operating Memorandum
2) Water Commissioner Meetings

Table 2 includes recommended conveyance loss for most structures that divert off the Arkansas River mainstem downstream of Pueblo Reservoir (Water Districts 14, 17, and 67). There is little information available for irrigation structures in other water districts. Industry-standard methodologies for calculating canal and lateral seepage loss, such as those recommended by National Engineering Handbook (NEH Part 623, Revised 2017) and other standard approaches, generally involve either inflow/outflow field calculations or analysis of canal length, canal geometry (cross-section), soil types, slopes, roughness factors, general condition of canal, and flow rates. Unfortunately, these parameters are not known for the all canals basin wide.

In a simplified approach, the NRCS[1] has developed conveyance efficiency (1- canal efficiency = canal loss) curves (**Figure 1**) that estimate ditch efficiency as a function of soil type and ditch length. The curves apply to ditches up to approximately one mile long. Note that these curves were extrapolated, based on ditch loss and engineering estimates to support water court cases, for the larger ditches during the South Platte Decision Support System modeling efforts where no specific canal loss information existed.

Figure 1: NRCS Canal Efficiency by Soil Type



[1] Source: NRCS Farm Irrigation Rating Index (FIRI) – A method for planning, evaluating, and improving irrigation management, June 1991, as presented by Klamm and Brenner at the 1995 ET & Irrigation Efficiency Seminar

The ArkDSS GIS coverage of ditch alignment was superimposed on SSURGO soil mapping. Ditches outside the H-I Model area are primarily comprised of a combination of Group B and C soil types as described below:

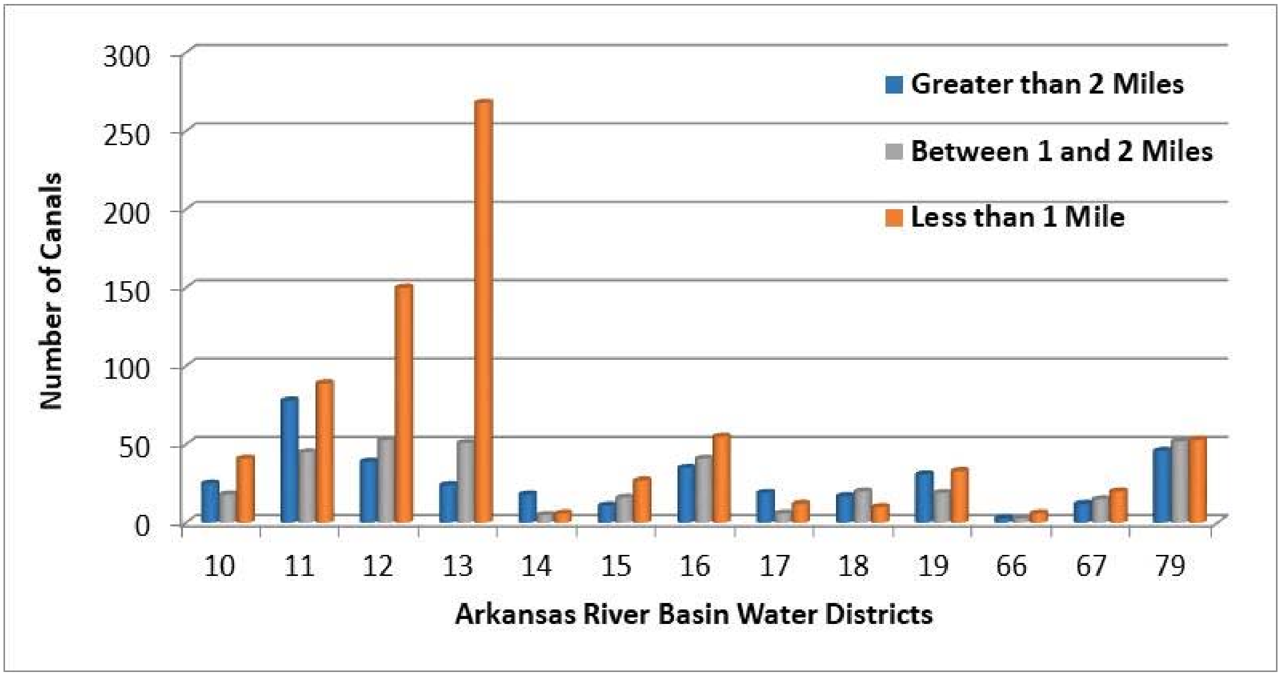
> **Group B** is silt loam or loam. It has a moderate infiltration rate when thoroughly wetted and consists chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures.
>
> **Group C** soils are sandy clay loam. They have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine structure.

As shown in **Figure 1**, a reasonable estimate of conveyance efficiency for ditches about 1 mile in length with soil Groups B (Clay/Silt loam) and C (Sandy loam) is between 85 and 90 percent (10 to 15 percent ditch loss). Information from the available water court cases and information from water commissioners indicate that 90 percent is a reasonable upper limit for ditch efficiencies for above Pueblo Reservoir and acreage on the smaller tributaries to the Arkansas basin, with efficiency decreasing with ditch length. The following general recommendations for ditches without specific information shown in Table 2 utilizes the limited available basin-wide information (canal length and soil type); while recognizing that information regarding ditch geometry, frequency of ditch maintenance, slopes, and roughness coefficients is not available.

- Canals greater than 2 miles long = 80 percent efficiency (20 percent ditch loss)
- Canals between 1 and 2 miles long = 85 percent efficiency (15 percent ditch loss)
- Canals less than 1 mile long = 90 percent efficiency (10 percent ditch loss)

For reference, **Figure 2** reflects the number of canals in each Water District, summarized by assigned ditch loss. Canal lengths were obtained from the ArkDSS GIS ditch coverage. As shown, most ditches in the upper basin and smaller tributaries (Water Districts 10, 11, 12, and 13) are less 1 mile long.

Figure 2: Canal Efficiencies by Water District



IRRIGATION APPLICATION EFFICIENCY

Losses associated with application of irrigation supplies through various irrigation practices at the farm level are generally referred to as irrigation application losses. Actual on-farm application efficiency (1 – application loss percentage) varies significantly over a field and over the irrigation season due to irrigation method, field topography, soil types, crop types, water supply, and general condition and management of irrigation systems. As such, the consumptive use and surface water modeling tools used for the ArkDSS effort allow the application efficiency to vary based on irrigation method and water supply, limited by a maximum on-farm application efficiency level. The irrigation application loss information summarized below focuses on average or maximum application efficiencies. Note that sources that discuss *system* efficiency were excluded, as system efficiency values generally combine canal and lateral losses with irrigation application losses.

Previously Developed Application Efficiency Estimates

Specific estimates of application efficiency have been studied less frequently in Arkansas River basin than canal and lateral losses, however, there have been estimates developed for the Colorado vs. Kansas litigation and for engineering reports to support water court applications. The following summarizes previously developed application efficiency information and the applicability to the planning-level effort for the ArkDSS.

H-I Model. The H-I Model, as discussed above, is used to determine depletions and accretions to state line flow caused by ground water pumping and replacements by simulating the hydrologic and institutional systems that occur along the Arkansas River between Pueblo, Colorado, and the Colorado-Kansas state line (Amended Appendix C.1, Hydrologic-Institutional Model Documentation, August 2015). During the simulation, water available to the field (i.e. river diversions less canal and lateral losses or ground water diversions) is limited by the maximum application efficiency. This factor defines the maximum amount of irrigation water available to the crop, after farm losses (including on-farm lateral losses, tailwater runoff, and deep percolation), as a percentage of farm water deliveries.

Application efficiency in the H-I Model varies based on irrigation method:

- 65 percent for flood irrigated fields under all canals listed above in **Table 1**, except flood irrigated fields under the Colorado Canal and Lamar/Manvel Canals, which are assigned a 70 percent application efficiency
- 85 percent for sprinkler irrigated fields
- 100 percent for sub-surface drip irrigated fields

Kansas v. Colorado, Report to the State of Colorado on Achievable On-Farm Efficiency, Arkansas Valley, Colorado (Franzoy, February 1996). The purpose of this report was to describe the achievable on-farm efficiency for irrigated land in the Lower Arkansas River Basin for use in the hydrological modeling supporting the Kansas v. Colorado litigation. Building on work performed by Spronk Water Engineers in 1995, the report discusses the maximum on-farm efficiency achievable for the existing physical conditions and irrigation practices, assuming a high level of management. The efficiency factors are reflective of crop types, soil types, topography, and irrigation methods. The report also stressed how important slope (topography) is in the ability to achieve higher maximum application efficiency. Maximum on-farm efficiency values are generally lower than currently used in the H-I Model (60 percent compared to 65 percent for flood), likely reflecting improvements over time. The ArkDSS modeling is intended to represent current conditions, therefore the H-I Model application efficiencies are believed to be more appropriate for the ArkDSS efforts.

Irrigation Practices, Water Consumption and Return Flows in Colorado's Lower Arkansas River Valley (CWI No. 221, June 2012). This report, as discussed above, stemmed from water quality and salinity concerns in the Lower Arkansas River Valley, and understanding that baseline information on irrigation practices in the area is necessary prior to implementing irrigation improvements that may improve water quality conditions. The report summarizes the methods, analysis, results, and implications of an irrigation monitoring study conducted by Colorado State University (CSU) during the 2004 to 2008 irrigation season on over 60 individual farms. Application efficiency ranged across the fields and across the years; 90 percent of the fields over the 2004 to 2008 period experienced application efficiencies between 35.2 and 97.8 percent. Mean application efficiency was 67.9 percent for surface/flood irrigated fields and 82 percent for sprinkler irrigated fields. These estimates are generally in agreement with the application efficiencies used in the H-I Model.

Farm Irrigation Rating Index (FIRI), 1995 ET & Irrigation Efficiency Seminar (Klamm & Brenner). The FIRI process was designed by the USDA and the NRCS as a uniform and objective method for planning irrigation water conservation measures, relying on relative ratings of different irrigation methods. FIRI itself is a product of three components: (water management) * (irrigation system) * (potential efficiency). The ArkDSS effort may be informed by the potential efficiency component of the process, which reflects maximum application efficiency for various irrigation methods (**Table 3**); which are generally in agreement with the application efficiencies used in the H-I Model.

Table 3: Potential Application Efficiencies from FIRI

Irrigation System Type	Potential Efficiency (%)
Borders	
Level or Basin	90
Graded	80
Guide	70
Contour – level	
Field Crop	70
Rice	80
Border Ditch	60
Furrow	
Level or Basin	90
Graded	75
Contour	75
Corrugations	75
Surge	85
Sub-irrigated	75

Irrigation System Type	Potential Efficiency (%)
Flood Irrigation	
Controlled	60
Uncontrolled	50
Contour Ditch	60
Sprinkler	
Big gun or boom	60
Hand or wheel line	70
Solid set (above canopy)	75
Solid set (below canopy)	80
Center-pivot	80
Center-pivot (LEPA[1])	85
Trickle	
Point Source	90
Spray emitters	85
Continuous tape	90

[1] Low Energy Precision Application (LEPA): near ground with bubblers or drag socks

Colorado High Plains Irrigation Practices Guide, Water Saving Options for Irrigators in Eastern Colorado (CWI No. 14, Spring 2004). This report is a series of informational sheets on various irrigation topics intended to inform the reader on irrigation practices that offer potential water savings at the field or farm level. Several of the information sheets discuss application efficiencies of various irrigation methods. Information Sheet No. 2: Farm Irrigation Systems includes **Table 4** outlining a variety of potential field (i.e. application) efficiencies for various irrigation systems. These estimates are generally in agreement with the application efficiencies used in the H-I Model.

Table 4: Application Efficiency Ranges from Colorado High Plains Irrigation Practices Guide

Irrigation System	Field Efficiency *(% Range)*
Surface Irrigation Systems	
Graded Furrow	50-80
w/tailwater reuse	60-90
Level Furrow	65-95
Graded Border	50-80
Level Basins	80-95
Sprinkler (non-center pivot)	
Periodic Move	60-85
Side Roll	60-85
Moving Big Gun	55-75
Lateral Move	
Spray heads w/hose feed	75-95
Spray heads w/canal feed	70-95
Center Pivot Irrigation Systems	
Impact heads w/end gun	75-90
Spray heads w/o end gun	75-95
LEPA w/o end gun	80-95
Microirrigation Systems	
Surface Drip	70-95
Subsurface Drip Irrigation (SDI)	75-95
Microsprinklers (microspray)	70-95

Application Efficiency Summary and Recommendations

It is recommended that the H-I Model maximum application efficiency numbers by irrigation method be adopted for irrigation within the H-I Model area. As noted in the Kansas v Colorado supporting information, these efficiency factors are reflective of crop types, soil types, and topography at lower elevations in the basin. These maximum efficiencies are within the range reported by previous studies (CWI No. 221 and CWI No. 14) and estimated by FIRI.

Above elevation 6,500 feet and in the Purgatoire basin below 6,500 feet, grass varieties are predominately grown for haying and cattle grazing. The fields commonly have a greater slope than fields in the lower Arkansas River Basin and maximum application efficiencies are believed to fall into the mid- to lower-range of the reported estimates from previous studies (CWI No. 221 and CWI No. 14) and FIRI. **Table 5** provides recommended maximum application efficiencies, by irrigation method, for use in ArkDSS modeling efforts.

Table 5: Recommended Maximum Application Efficiency based on Irrigation Method and Elevation

Irrigation Method	Below 6,500 feet	Above 6,500 feet[2)]
Flood	65% [1)]	60%
Sprinkler	85%	80%
Sub-Surface Drip	100%	n/a

1) Except use 70 percent for Colorado Canal and Lamar/Manvel Canals
2) Plus the Purgatoire River basin below 6,500 feet

The ArkDSS Calibration model reflects changes in irrigation method over time; therefore, maximum efficiency for ditches will correspondingly vary over time. The “baseline” ArkDSS model that will be used to compare current conditions to future changes, for example changes in demands or operations, will use current acreage and irrigation methods, and the corresponding maximum application efficiencies. Note that although drip irrigation is represented as 100 percent efficient in the H-I Model, it is common to apply excess water to leach fields at the begin or end of the irrigation season. Assuming 100 percent for planning purposes is reasonable, as it is difficult to represent the leaching practices on a field by field basis.

TAILWATER RUNOFF

Tailwater runoff refers to surface runoff resulting from crop irrigation. Tailwater runoff is represented in both the H-I Model and the ArkDSS model as returning immediately (unlagged) to the nearest drainage or river. The amount of tailwater runoff is dependent on several factors, including the distance to the nearest surface drainage, irrigation practice method, soil parameters, and topography. Tailwater factors used in the H-I Model are adjusted as necessary to reflect more efficient irrigation methods, primarily changes from flood irrigation to sprinkler or drip irrigation.

The H-I Model applies the tailwater runoff factor to water applied to the field that exceeds crop consumptive use and soil reservoir storage. StateMod, however, applies runoff factors to both inefficient field application and conveyance losses. Therefore, adjustments needed to be made to the H-I Model approach for StateMod to represent the H-I Model accounting process.

Return flows and tailwater runoff were extracted from the H-I Model results, and tailwater runoff was calculated as a percent of total return flows for each of the ditches represented in the H-I Model for the recent period 2011 through 2019. **Table 6** shows the tailwater runoff as a percent of total returns for acreage irrigated with surface water or a combination of surface and ground water, and for acreage irrigated only with ground water within the service area of each ditch. The average tailwater runoff for acreage with a surface water supply, as a percent of total return flows, is 18 percent for ditches represented in the H-I Model. The average tailwater runoff for acreage irrigated only with ground water within the H-I Model boundary is 15 percent.

Tailwater runoff as a percent of total return flows, as shown in Table 6, is often higher for ground water only acreage than for surface water irrigated acreage under the same ditch above John Martin Reservoir because there are no return flows associated with conveyance losses. However, the tailwater runoff as a percent of total return flows is generally lower for ground water only acreage than for surface water irrigated acreage under the same ditch below John Martin Reservoir. This is because the percent of ground water only acreage irrigated with sprinklers is much higher than the percent of surface water irrigated acreage served by sprinklers; and sprinkler irrigated lands experience less tailwater runoff.

Table 6: Tailwater Runoff as a Percent Total Return Flows (2011-2019)

Canal/ WDID	H-I Model Ditch Number	Surface Water Only and Commingled Acreage	Ground Water Only Acreage
Bessemer Ditch (1400533)	1	15%	17%
Booth-Orchard Ditch (1400591)	2	12%	28%
Excelsior Ditch (1400539)	3	24%	20%
Collier Ditch (1400538)	4	25%	28%
Colorado Canal (1700540)	5	19%	27%
Rocky Ford Highline Canal (1700542)	6	12%	26%
Oxford Canal (1700541)	7	15%	2%
Otero Canal (1700557)	8	17%	27%
Catlin Canal (1700552)	9	14%	10%
Fort Lyon Canal (1700553)	10	10%	17%
Rocky Ford Ditch (1700558)	11	13%	3%
Holbrook Canal (1700554)	12	17%	22%
Las Animas Consolidated Ditch (1700556)	13	18%	23%
Baldwin Stubbs Ditch (1700551)	14	28%	18%
Average Upstream of John Martin Reservoir		**17%**	**19%**
Fort Bent Canal (6700610)	15	15%	5%
Keesee Ditch (6700613)	16	20%	0%
Amity Canal (6700607)	17	12%	12%
Lamar/Manvel Canal (6700614)	18	13%	4%
Hyde Ditch (6700612)	19	22%	1%
X-Y Irrigating Ditch (6700617)	21	21%	16%
Buffalo Canal (6700608)	22	19%	26%
Sisson & Stubbs Ditch No 1 (6700616)	23	26%	0%

Canal/ WDID	H-I Model Ditch Number	Surface Water Only and Commingled Acreage	Ground Water Only Acreage
H-I Model Ground Water Only Zone 24	24	n/a	3%
Average Downstream of John Martin Reservoir		**18%**	**7%**
Average H-I Model		**18%**	**15%**

In the upper Arkansas River basin (generally higher than 6,500 feet elevation) crops are primarily flood irrigated, the irrigated fields are generally closer to the nearest drainage or river, the alluvial aquifer is not as extensive, and there is more topographic relief between the end of fields and the nearest drainage. Therefore, the percent of total unlagged runoff is estimated to be higher; 25 percent of total runoff assigned an immediate (non-lagged) runoff pattern is believed to be a reasonable estimate.

Tailwater Runoff Summary and Recommendations

It is recommended that the individual average tailwater percentages for the period 2011 through 2019 shown in **Table 6** be applied to an immediate runoff pattern for each ditch and ground water only aggregate in the H-I Model area. Ditches outside the H-I Model area below 6,500 feet elevation (primarily ditches in the Purgatoire River basin) generally irrigate pasture and hay, and likely experience slightly less tailwater runoff than row crop irrigation. Therefore, it is recommended that 15 percent of total runoff below 6,500 feet elevation outside the H-I Model boundary be assigned to an immediate (non-lagged) runoff pattern. It is recommended that 25 percent of total runoff be assigned an immediate (non-lagged) runoff pattern for irrigated acreage above 6,500 feet elevation, consistent with the approach used in the CDSS models representing the upper Colorado River tributaries.

Tailwater runoff is tied to irrigation methods in the H-I Model. The percent of immediate surface runoff has decreased slightly over time as more efficient irrigation methods have been implemented. The primary use of the SPDSS model is to compare future water use and operations against current use. Therefore, it is recommended that current levels of tailwater runoff (15 percent below elevation 6,500 and 25 percent above elevation 6,500 feet) be used for the full calibration ArkDSS Calibration model period and the full Baseline model period. Note that model calibration will focus on a subset of current years and is not expected to be impacted by this simplification.

SECONDARY ET LOSSES

Secondary ET Losses, sometimes termed incidental losses, account for diverted water that is lost due to evaporation or consumption by non-crop vegetation. The H-I Model documentation uses the term SEV defined as the "percentage of canal and lateral losses and tailwater that is consumed by evaporation or non-crop evapotranspiration". SEV has changed over time, as reflected in the **Table 7** from the H-I Model Documentation (Amended Appendix C.1). Upstream in refers to canals upstream of John Martin Reservoir and downstream refers to canals downstream of John Martin Reservoir.

Table 7: SEV Values Used in Approved Calibrations of H-I Model

Model Version	Submittal Date	Upstream	Downstream	Ft Lyon	Comments
Replacement Model	1991	25.0%	10.0%	10.0%	Recalibrated with variable monthly factors
For years 1986-1994	1996	25.0%	25.0%	25.0%	Recalibrated for Max Farm Efficiency
For years 1995-1996	1998	25.0%	25.0%	25.0%	
For years 1997-2004	2007	24.0%	11.0%	24.0%	Calibrated to original observed diversions
For 2005-2006 & subsequent years (unless changed as provided in the Decree)	2007	24.0%	11.0%	24.0%	Calibrated to revised observed diversions

Similar to the H-I Model, return flow percent factors can be reduced by the secondary evaporation percentages in the water allocation model (StateMod) and reflect a true "loss" to the system, as compared to tailwater runoff and lagged return flows that eventually accrete to the river. The H-I Model applies SEV to conveyance losses and to tailwater runoff only, not unconsumed water that lags back to the river through deep percolation. StateMod, however, applies runoff factors to inefficient field application (tailwater runoff and deep percolation) and conveyance losses. Therefore, adjustments needed to be made to the H-I Model approach for StateMod to represent the H-I Model accounting process.

Total return flows and SEV were extracted from the H-I Model results for the recent period 2011 through 2019 and SEV was calculated as a percent of total non-consumed diversions for the ditches represented in the H-I Model. **Table 8** shows the SEV as a percent of total returns for acreage irrigated with surface water or a combination of surface and ground water, and for acreage irrigated only with ground water within the service area of each ditch. As shown, the average SEV, as a percent of total non-consumed diversions is 12 percent for ditches represented in the H-I Model above John Martin Reservoir and 5 percent for ditches below John Martin Reservoir for the recent period 2010 through 2019. The differences above and below John Martin Reservoir for acreage irrigated with surface water or a combination of surface and ground water are primarily because canal and laterals are generally longer above John Martin Reservoir. The differences above and below John Martin Reservoir for acreage irrigated only with ground water supplies are because, as noted above, there is a higher percent of acreage irrigated with sprinklers below John Martin Reservoir, resulting in less tailwater runoff and associated secondary ET losses.

Table 8: Secondary ET Losses as a Percent Total Return Flows (2011-2019)

Canal/ WDID	H-I Model Ditch Number	Surface Water Only and Commingled Acreage	Ground Water Only Acreage
Bessemer Ditch (1400533)	1	12%	6%
Booth-Orchard Ditch (1400591)	2	6%	9%
Excelsior Ditch (1400539)	3	10%	8%
Collier Ditch (1400538)	4	11%	9%
Colorado Canal (1700540)	5	15%	10%
Rocky Ford Highline Canal (1700542)	6	17%	9%
Oxford Canal (1700541)	7	9%	3%
Otero Canal (1700557)	8	14%	9%
Catlin Canal (1700552)	9	10%	5%
Fort Lyon Canal (1700553)	10	19%	8%
Rocky Ford Ditch (1700558)	11	8%	2%
Holbrook Canal (1700554)	12	12%	9%
Las Animas Consolidated Ditch (1700556)	13	11%	8%
Baldwin Stubbs Ditch (1700551)	14	9%	8%
Average Upstream of John Martin Reservoir		**12%**	**7%**
Fort Bent Canal (6700610)	15	5%	2%
Keesee Ditch (6700613)	16	4%	3%
Amity Canal (6700607)	17	8%	3%
Lamar/Manvel Canal (6700614)	18	5%	1%
Hyde Ditch (6700612)	19	4%	2%
X-Y Irrigating Ditch (6700617)	21	4%	3%
Buffalo Canal (6700608)	22	6%	5%
Sisson & Stubbs Ditch No 1 (6700616)	23	4%	3%
H-I Model Ground Water Only Zone 24	24	n/a	2%

Canal/ WDID	H-I Model Ditch Number	Surface Water Only and Commingled Acreage	Ground Water Only Acreage
Average Downstream of John Martin Reservoir		**5%**	**3%**
Average H-I Model		**9%**	**6%**

Secondary ET losses from ditches and laterals are expected to be greater for longer ditches as there is more opportunity for non-crop ET and surface evaporation. As shown in Table 8, SEV is less for ground water only lands, as there is no conveyance loss component. In addition, SEV from tailwater runoff is expected to be greater in areas with higher evaporation rates (higher temperatures) and in areas with flatter topography, as tailwater has a greater opportunity to be consumed by non-crops or evaporated before it can reach the nearest drainage. No studies were found to support estimates of SEV outside the H-I Model area. Studies performed by Reclamation in the early 1970s in the Upper Colorado River basin estimated incidental loss as a percentage of crop consumptive use and are used by Reclamation in the Consumptive Uses and Losses reporting. Those incidental loss estimates range from 8 percent to 23 percent of crop consumptive use. The average incidental loss assigned to pasture grass above about 6,500 feet in the Colorado River basin tributaries in Colorado is around 10 percent of crop consumptive use. The CDSS efforts for the Colorado River transferred the 10 percent of crop consumptive use to an equivalent of 3 percent loss of return flows. Note that SEV was not included in the South Platte Decision Support System models.

Secondary ET losses are generally not included as depletions in water rights change cases or as credits against return flow obligations. Conversations were held with DWR staff regarding incidental losses outside the H-I Model and representation in the ArkDSS StateMod modeling efforts. They indicated it was not a critical component and stressed that including SEV would be inconsistent with change case approaches. Therefore, it is important to note that, as with other irrigation parameters recommended for use in the ArkDSS planning models, SEV recommendations are not intended to set a precedent and should not be used as a basis for legal proceedings. By including this secondary ET loss inside and outside the H-I Model area below 6,500 feet in the StateMod model, no precedent is being set for water rights change cases.

Secondary ET Losses Summary and Recommendations

Although SEV varies between ditches in the H-I Model, the differences are not significant and it is recommended that the average SEV of 12 percent be applied to ditches in the H-I Model above John Martin Reservoir and the average SEV of 5 percent be applied to ditches in the H-I Model below John Martin Reservoir. Likewise, the average SEV of 7 percent should be applied to ground water only acreage above John Martin Reservoir and the average SEV of 3 percent should be applied to ground water only acreage below John Martin Reservoir. For consistency in the lower elevations of the Arkansas River basin, it is recommended that ditches outside the H-I Model boundary that irrigate lands below elevation 6,500 feet, primarily ditches irrigating within the Purgatoire River Water Conservancy District, include SEV of 5 percent based on the average for the H-I Model ditches. It is recommended that SEV of 3 percent be applied to modeled ditches above 6,500 feet reflecting lower ET rates and shorter ditch lengths.

Secondary ET losses will also be applied to acreage irrigated solely by ground water, represented in the ArkDSS models as ground water aggregates. The SEV for ground water aggregates reflect losses associated with tailwater runoff only. The average SEV associated with fields irrigated solely with ground water within the H-I Model of 6 percent is recommended for application to ground water aggregates outside the H-I Model boundary.

AVAILABLE WATER CAPACITY

Available water capacity (AWC) is used to determine the volume of water than can be stored within the soil zone of irrigated fields. DWR developed a GIS layer of available water capacity using the SURGO soil mapping layer. The SURGO layer includes weighted AWC values at four different depths (24, 50, 100, and 150 cm). The weighted AWC value at 100 cm (approximately 3.3 feet) was used to represent a typical root depth for crops grown in the Arkansas River basin. Estimated root depths for crops grown in in the Arkansas River basin range from a low of about 1.6 feet for vegetables to a high of 4.9 feet for alfalfa.

Ditch-specific AWC values were calculated by area weighting the AWC value at the centroid of each individual field parcel assigned to an individual ditch or ground water aggregate based on the ArkDSS 2015 irrigated acreage assessment. If the ditch was no longer irrigating in 2015, then the most recent GIS irrigated acreage assessment was used to calculate the area weighted AWC for that ditch.