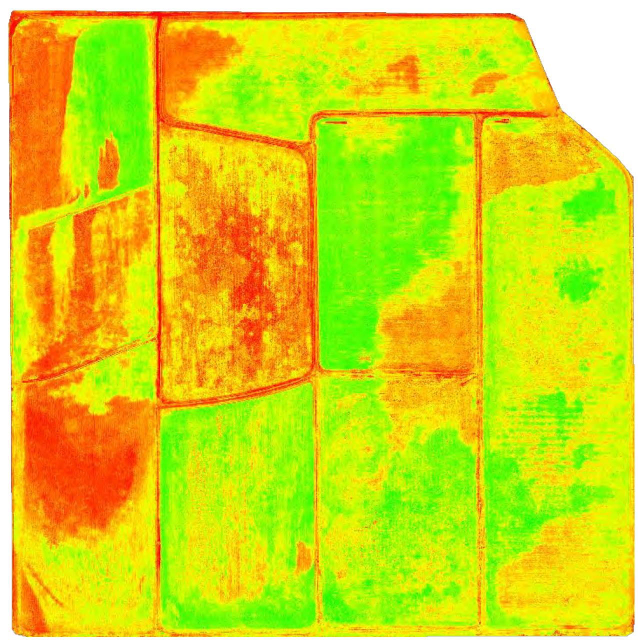
Phase Two Tailwater Return Flow Study on the Fort Lyon Canal



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Executive Summary

The relative lack of variation amongst Maximum Farm Efficiency (MFE) values between water-long ditches and water-short ditches has been viewed as a deficiency of the Hydrologic Institutional (HI) Model. In Kansas v. Colorado testimony concerning on-farm efficiency, Colorado cited deficit irrigation and tailwater reuse as two factors that justified its argument that higher MFE values should be implemented in the HI Model for water-short ditches, such as the Fort Lyon, Amity, Colorado, Holbrook, and Otero canals.

MFE, as used in the HI Model, is a function of on-farm ditch loss (FDL), tailwater fraction (TWF), and initial deep percolation fraction (DPF) and is defined as:

$$MFE = 100\% - FDL\% - TWF\% - DPF\%$$

For the Fort Lyon Canal, MFE, FDL, and TWF have assigned values of 65%, 3.5%, and 9.65% respectively in the HI Model. DPF has a resulting value of 21.9%.

The objectives of this study are as follows:

1) Generate high-quality data on tailwater and irrigation efficiency.

2) Evaluate results to determine potential for Phase Three to support possible integration into the HI Model and the Irrigation System Analysis Model (ISAM).

3) Support a potential increase in the transferrable yield of Fort Lyon shares.

Tasks included as part of these objectives include the following:

1) Continue tailwater monitoring on participating fields in the McClave Drain Study Area for two additional years. Irrigation and tailwater data collection began in 2015 in the McClave Drain Study Area where the Fort Lyon Canal share ratio is typically 1 share per acre.

2) Select farms from an upstream region of the Fort Lyon Canal (where the canal share ratio is typically 2 shares per acre) for two years of irrigation and tailwater monitoring.

3) Conduct irrigation application efficiency data collection on one to three fields in the McClave Drain Study Area for one season including field measurement of efficiency parameters and multispectral aerial imaging.

Results and Conclusions:

Continued irrigation monitoring for calculation of TWF values was conducted on approximately 2000 acres in the McClave Drain study area in 2017 and 2018. The average measured yearly TWFs for the McClave study area during 2017 and 2018 were 4.58% and 5.58% respectively compared to a value of 9.65% used in the HI and ISAM models. Irrigation monitoring for TWF calculation was conducted on 500 acres in the Las Animas area (where share to acre ratio is twice as high) during 2018 and 2019. TWF values for the Las Animas study area were 15.66% and 9.67% respectively compared to a value of 9.65% used in the HI and ISAM models.

Collection of field data for use in the calculation of MFE was performed during 2019 on seven fields within a single farm in the McClave Drain study area. Field data collected included irrigation performance characteristics (cutoff, advance, recession times), diversion and tailwater amounts, irrigated acreage and distribution, initial soil moisture content, infiltration rates and rainfall amounts. Average MFE values for 2019 (considered an average water supply year) was 65.4% compared to 65% in the HI and ISAM models. Further modeling of MFE using irrigation diversion, precipitation, and potential ET data from 2012 (a low water diversion year) yielded an MFE value of 74.6% (nearly 10% higher than HI and ISAM models).

Multispectral crop imaging was performed on seven fields within a single farm during 2019 using an unmanned aerial vehicle (UAV) and multispectral camera capable of capturing simultaneous images in the Near-Infrared (NIR), Blue, Green, Red, and Red Edge reflectance bands. Soil moisture data was collected using soil moisture sensors buried at 1 ft, 2ft, 3ft, and 4ft depths at 10 locations across the farm. Each soil moisture station was equipped with a wireless data logging system. The goal of the study was to determine whether a numerical correlation exists between soil moisture content (and ultimately crop consumptive use) and any spectral reflectance index. While multispectral crop imaging provided a useful tool in which to assess overall crop health as well as generalized soil moisture conditions, it failed to yield correlations high enough to use in the calculation of MFE.

Based on meetings with Colorado Division of Water Resources personnel, A Phase Three study could prove beneficial in establishing trends of higher farm efficiencies in low water supply scenarios and should be further explored with the possibility of creating an adjustable MFE value in the HI and ISAM models based on water supply and/or soil moisture values. A third phase of study would most likely focus on irrigation set characteristics (set advance, recession, and cutoff times) and infiltration data over a much larger study area. It may also include additional tailwater data collection on farms with higher share to acre ratios.

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I. Background and Introduction

I.a. Models and Flood Irrigation

The Hydrologic Institutional (HI) model is used to assess compliance of the Arkansas River Compact between Colorado and Kansas. This model utilizes monthly canal diversions, crop evapotranspiration (ET), and precipitation measurements from irrigated farm land in the Arkansas River Valley east of Pueblo, CO, along with several canal-specific factors to estimate total Arkansas River flows at the Colorado/Kansas state line.

The Irrigations Systems Analysis Model (ISAM) is used by the Colorado Division of Water Resources in the administration of compact-related rules to estimate depletions/accretions to the Arkansas River within Colorado caused by irrigation improvements that have the potential to alter return flow patterns to the river, such as lining of off-farm earthen ditches and conversion from flood irrigation to sprinkler systems. The ISAM model replicates the monthly consumptive use and soil moisture accounting of the HI Model and therefore utilizes HI Model canal-specific parameters and factors. Some of the canal-specific factors utilized in the two models include:

- Canal Seepage Loss
- Off-Farm Lateral Loss
- Tailwater Fraction
- On-Farm Ditch Loss
- Maximum Farm Efficiency
- Deep Percolation Fraction
- Secondary Evapotranspiration Loss
- Available Water Capacity
- Crop Root Zone Depth.

The Maximum Farm Efficiency (MFE) factor as used in the HI and ISAM Models acts as an upper limit to the percentage of irrigation water applied to a crop that can be consumed by the crop. This limit is used in the soil-water budgeting procedure to account for the non-uniform distribution of irrigation water associated with flood irrigation practices. The MFE factor was adjusted in initial versions of the HI Model developed prior to the final Kansas v. Colorado decree, and because state line depletions are particularly sensitive to the value of this factor, it is often the subject of debate amongst irrigation experts.

During the typical flood irrigation process, irrigation water is diverted from the Arkansas River by canal companies through earthen canals to farmers who then divert water from the canal through a headgate structure to their farms. For farms immediately adjacent to the canal, irrigation water is usually diverted from the canal directly onto the farm. For farms not adjacent to the canal, irrigation water is transported via a private or shared off-farm lateral to the farm. Off-farm laterals can be constructed of plastic pipe, concrete channel, or earthen channel. Once irrigation water arrives at the farm, it is delivered to individual fields through earthen ditch, concrete ditch, or pipe. At the field, irrigation water is applied using gated pipe, concrete ditch (with cutouts or siphon tubes), or earthen ditch (with cutouts or siphon tubes).

Flood irrigation is characterized by “sets” in which water is applied to a single section of the field - generally encompassing a specific number of cutouts, siphon tubes, or gates applying water - at any one time. A single set is typically allowed to distribute water onto a field section for a certain number of hours or until the advancing water front reaches the tail end of the field (set duration). At this point, water leaves the field area and contributes to the irrigation supply of adjacent fields or is conveyed back to the river system through a tributary. Once a set is finished, a new set is made, either by moving check dams upstream (or downstream) in the ditch to new cutouts or by opening a new set of gates (in gated pipe irrigation systems). Flood irrigation sets often start at one end of the field and are moved toward the opposite end until the field is completely irrigated.

The HI and ISAM Models account for the inefficiencies of flood irrigation through the factors listed previously. On a farm-scale analysis, the tailwater fraction, deep percolation fraction, on-farm ditch loss, and maximum farm efficiency are used within the water-budget process to determine the amount of water consumed by a crop and the amount that can potentially return to the river system.

The MFE Factor has been the subject of debate, not only because of its effect on state line depletions but also because of: 1) the difficulty in measuring the value across entire canal systems and 2) the differences in definition among experts. In the HI and ISAM Models, MFE is the maximum amount of field application made available for crop use over each canal system on a monthly basis. MFE values for flood irrigation on canals within the HI Model domain have been assigned values of 65% to 70%.

From a modeling perspective, MFE is a function of on-farm ditch loss (FDL), tailwater fraction (TWF), and deep percolation fraction (DPF) and defined in the HI Model as:

$$MFE = 100\% - FDL\% - TWF\% - DPF\%$$

where:

$$FDL = \frac{On\ Farm\ Ditch\ Loss\ Amount}{Amount\ Delivered\ to\ Farm}$$

$$TWF = \frac{Tailwater\ Amount}{Applied\ Amount}$$

$$DPF = \frac{Deep\ Percolation\ Amount}{Applied\ Amount}$$

with FDL, TWF, and DPF considered on a canal-wide basis with a monthly time step.

TWF is generally a function of management practices (including set size and set duration) and water sediment loads (clearer water tends to advance more slowly across a field producing less tailwater). TWF has an assigned value of 9.65% in the HI Model while FDL is assigned a value of 3.5%.

DPF is also influenced by the same factors as TWF as well as crop rooting depth and soil-water content within the crop root zone prior to irrigation. DPF is not assigned an explicit value in the HI Model, but for the Ft Lyon Canal is 21.9% based on the assigned MFE of 65%. In the HI Model, irrigation application exceeding the amount required for crop consumption or soil storage (within the crop root zone) is assumed to deep percolate.

In Kansas v. Colorado testimony concerning on-farm efficiency, Colorado cited deficit irrigation and tailwater reuse as two factors that justified its argument that higher MFE values should be implemented in the HI Model for water-short ditches such as the Fort Lyon, Amity, Colorado, Holbrook, and Otero canals. Deficit irrigation is the practice of applying an irrigation supply that is less than the amount required by a crop for optimum yield. The primary irrigation practice that differs between full-irrigation and deficit irrigation scenarios is set duration. During deficit irrigation, set durations are often shortened resulting in less tailwater and less total infiltrated amount over an irrigated area. This scenario also tends to reduce deep percolation losses and increase irrigation efficiency.

Tailwater reuse is the practice of controlling and reapplying tailwater either through mechanical means such as tailwater ponds and pumps or simply utilizing down gradient ditches to distribute tailwater as a supply for other fields, farms, or even canals. Tailwater reuse has the potential to cause an increase in irrigation efficiency over the entire tailwater production/reuse area depending on the amount of tailwater reused and the soil-water content in the crop root zone before tailwater application. Because of the relationship between TWF and MFE, field observation of TWF values lower than previously estimated could signify that MFE values are underestimated in the HI and ISAM Models.

I.b. Goals of the Study

Estimates of MFE and TWF as used in the HI Model are the result of several field trips taken through the area by experts from Kansas and Colorado during 1996[1]. These field trips yielded opinions on achievable irrigation efficiencies through observations of soil types, field slopes, tailwater, tailwater reuse, and MFE. Soil types and general field slope data were confirmed with Natural Resource Conservation Service (formerly Soil Conservation Service) data. Tailwater, tailwater reuse, and MFE opinions, however, appear to have been estimated through visual inspection only.

The objectives of this study are as follows:

1) Generate high-quality data on tailwater and irrigation efficiency.

2) Evaluate results to determine potential for Phase Three to support possible integration into the HI Model and the ISAM.

3) Support a potential increase in the transferrable yield of Fort Lyon shares.

[1]Littleworth, A. Second Report, Kansas vs. Colorado, U.S. Supreme Court, Section VI. September 1997

II. Study Areas

II.a. Site Selection

The relative lack of variation amongst MFE values between water-long ditches and water-short ditches has been viewed as a deficiency in the HI Model. The Fort Lyon Canal, which irrigates approximately 94,000 acres, is the largest canal in Colorado and is oftentimes considered a water-short system. Water is typically delivered to shareholders on a rotational basis using 48 hour "runs" beginning at the top of the canal near La Junta and moving downstream near Lamar before starting over. Table 1 illustrates the variation in annual Fort Lyon Canal water supplies, number of runs, and precipitation from 2017 through 2019.

Table 1: Recent Fort Lyon Canal Water Supply and Precipitation

Year	[1]FLCC Water Supply (ac ft)	[1]FLCC #Runs	[1,2]FLCC Precipitation (in)
2017	250,682	51	21.39
2018	191,594	22	13.12
2019	219,417	28	11.69

[1]From 2017, 2018, and 2019 Annual Reports of the Officers of the Fort Lyon Canal Company and www.flcc.net
[2]Average of Lamar and Las Animas rainfall measurements, FLCC

Over the last 18 years, the Fort Lyon Canal system has experienced a substantial conversion from flood irrigation acreage to center-pivot sprinkler irrigated acreage. Currently, about 20,000 acres under this system utilize sprinkler irrigation. This transition has left few large sections of irrigated farm ground under the Fort Lyon Canal that utilize traditional flood irrigation practices that involve tailwater reuse and multiple farmers. Field selection for inclusion in the study was based on the following criteria:

- ✓ Irrigated using flood method (earthen ditch, concrete ditch, gated pipe)
- ✓ Multiple tenants farming within single block of irrigated farm ground
- ✓ Ability to accurately measure diversion and tailwater flows
- ✓ Landowner/tenant cooperation.

Figure 1: Location of the Fort Lyon Canal in Colorado

The study areas selected for this project encompass about 2,000 flood irrigated acres near the town of McClave (the same study area evaluated during Phase One of this project) and 500 flood irrigated acres near the town of Las Animas in Bent County, Colorado. Farm ground within the study areas is owned by 11 different landowners and actively farmed by 8 different tenants who each granted permission to allow research activities to be conducted on their farms.

Figure 2: Location of the Study Areas on the Fort Lyon Canal

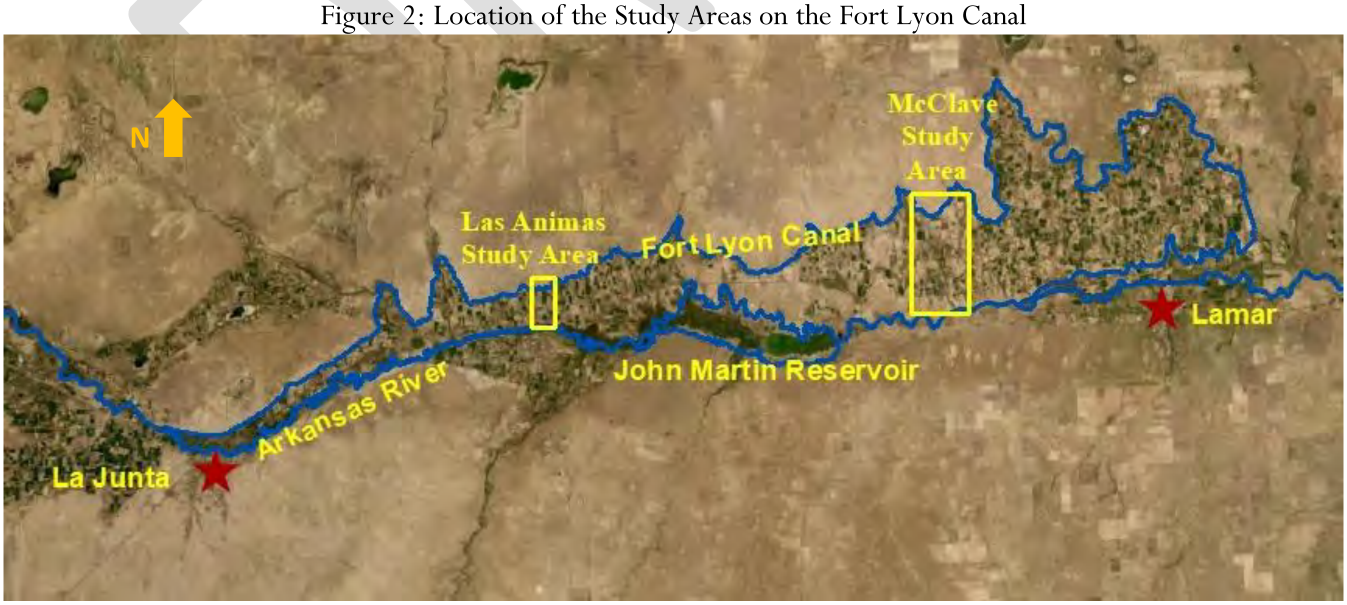
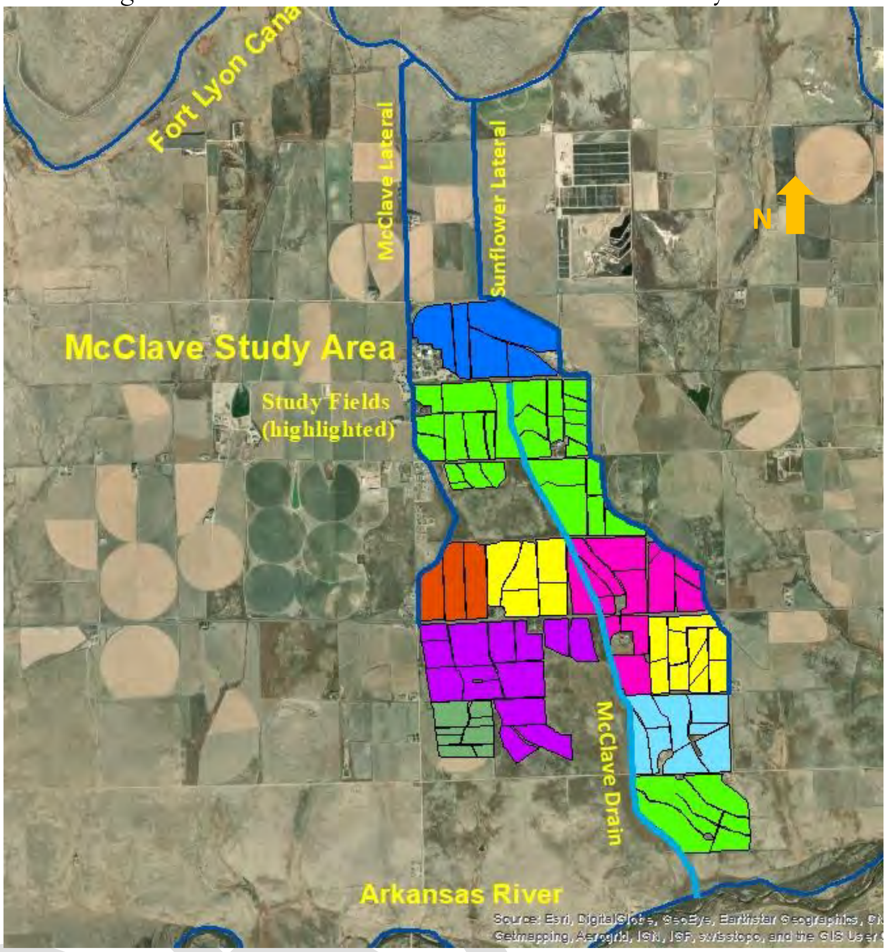
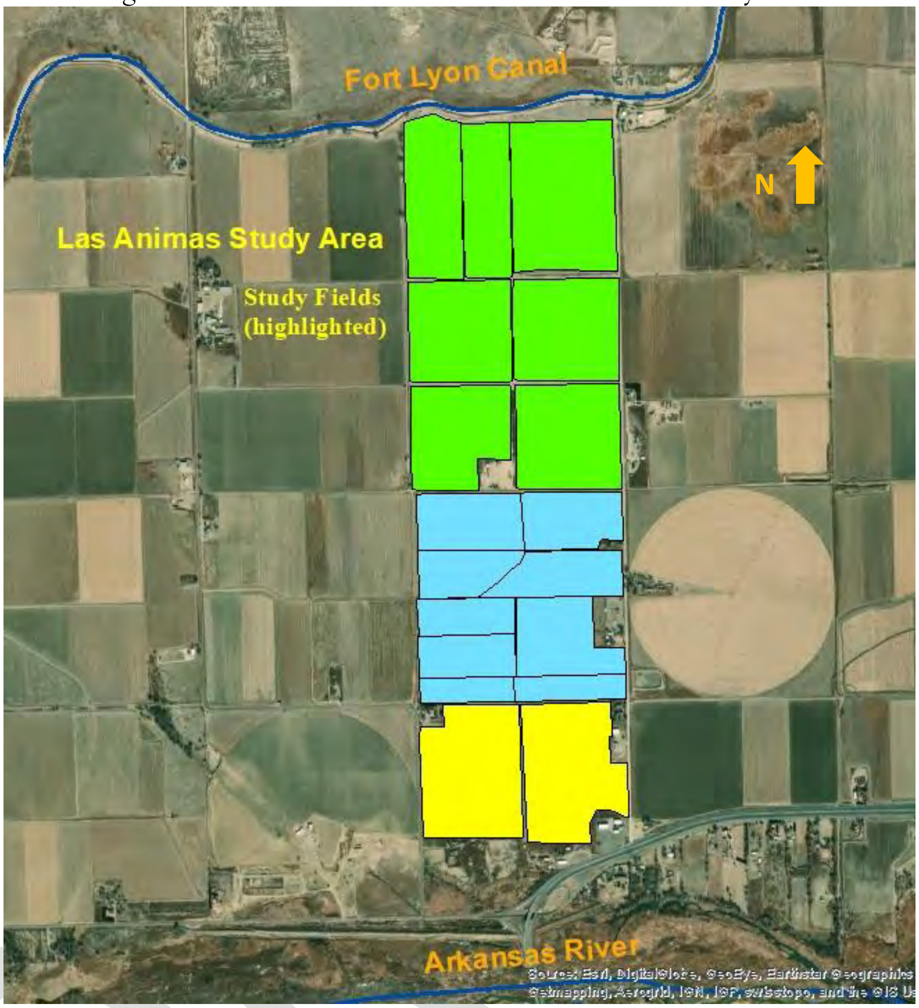


Figure 3: Location of Farms within the McClave Study Area



Irrigation supply for the McClave study area is diverted from the Fort Lyon Canal through two lateral ditches – the McClave Lateral and the Sunflower Lateral – which follow ridge lines on the western and eastern boundaries of the study area respectively. The McClave Drain channel dissects the study area from north to south and carries any tailwater return flows, groundwater seep, and precipitation runoff back to the Arkansas River.

Figure 4: Location of Farms within the Las Animas Study Area



Irrigation supply for the Las Animas study area is diverted from the Fort Lyon Canal through two headgates approximately 2 miles north of the Arkansas River at Las Animas. Tailwater ditches carry any tailwater return flows, groundwater seep, and precipitation runoff back to the Arkansas River.

Farm identification for the study was based on whether irrigation supply was derived from the McClave Lateral (denoted with letter M in the study farm naming convention), the Sunflower Lateral (denoted with letter S), or the Fort Lyon Canal near Las Animas (denoted with the letters LA) and the order in which the farm diverted water from the lateral or canal (numbered 1 through 5).

II.b. Study Area Characteristics

Soil types within the McClave study area are predominantly Rocky Ford clay loams while soil types within the Las Animas study area are mostly Rocky Ford and Numa clay loams.

Table 2: Soil Types in the McClave Study Area

NRCS-WSS Dominant Soil Types in McClave Study Area			
Soil Symbol	**Soil Name**	**Acres in Study Area**	**% of Study Area**
RfB	Rocky Ford clay loam, 1 to 3 percent slopes	1465.1	54.22%
RfA	Rocky Ford clay loam, 0 to 1 percent slopes	730.9	27.05%
NmB	Numa clay loam, 1 to 3 percent slopes	224.5	8.31%
NmA	Numa clay loam, 0 to 1 percent slopes	146.2	5.41%
RkB	Rocky Ford loam, wet, 1 to 3 percent slopes	58.7	2.17%
RkA	Rocky Ford clay loam, wet, 0 to 1 percent slopes	32.1	1.19%
Ca	Cascajo soils and gravelly land	17.8	0.66%
MeC	Minnequa loam, 1 to 5 percent slopes	16.0	0.59%
ToC	Travessilla-Olney sandy loam, 1 to 9 percent slopes	8.9	0.33%
HaC	Harvey loam, 1 to 9 percent slopes	1.4	0.05%
WlB	Wilid silt loam, 0 to 3 percent slopes	0.6	0.02%
NuB	Numa clay loam, wet, 0 to 3 percent slopes	0.1	0.00%

Table 3: Soil Types in the Las Animas Study Area

NRCS-WSS Dominant Soil Types in Las Animas Study Area			
Soil Symbol	**Soil Name**	**Acres in Study Area**	**% of Study Area**
MeB	Minnequa loam, dry, 1 to 5 percent slopes	4.9	0.90%
NmA	Numa clay loam, 0 to 1 percent slopes	43.3	8.00%
NmB	Numa clay loam, 1 to 3 percent slopes	203.4	37.70%
NuB	Numa clay loam, wet, 0 to 3 percent slopes	40.1	7.40%
NvB	Numa clay loam, sand substratum, 0 to 3% slopes	3.1	0.60%
RfA	Rocky Ford clay loam, 0 to 1 percent slopes	212.8	39.40%
RfB	Rocky Ford clay loam, 1 to 3 percent slopes	32.7	6.10%

Source: NRCS Web Soil Survey

Irrigated field gradients within the McClave study area vary from about 0.67% to 3.57% with an average of 1.36%. Field slopes west of the McClave Drain channel tend to follow downward gradients to the south and east while fields east of the channel tend to follow downward slopes to the south and west. Field slopes in the Las Animas study area vary from 0.68% to 1.74% with an average of 0.97%. Field slopes in the Las Animas study area follow a consistent gradient to the southeast.

Table 4: Topography Statistics for McClave Study Area

[1]Topography Statistics for McClave Study Area	
Average Gradient across Study Area	1.36%
Highest Gradient in Study Area	3.57%
Farm ID with Highest Gradient	M2
Lowest Gradient in Study Area	0.67%
Farm ID with Lowest Gradient	M1

Table 5: Topography Statistics for Las Animas Study Area

[1]Topography Statistics for Las Animas Study Area	
Average Gradient across Study Area	0.97%
Highest Gradient in Study Area	1.74%
Farm ID with Highest Gradient	LA1
Lowest Gradient in Study Area	0.68%
Farm ID with Lowest Gradient	LA2

[1]Gradients measured only on irrigated ground in the study area
Source: USA Topo maps

Crops grown within the McClave and Las Animas study areas are predominantly alfalfa but also include winter wheat, grain sorghum, corn, oats, and forage sorghum.

Table 6: Crop Type Distribution by Year for Study Areas

2017 McClave Crop Type	Sum of Acres	% of Total Acres
ALFALFA	**1082**	**62%**
SORGHUM (ALL)	**335**	**19%**
Other	**174**	**10%**
WHEAT	**70**	**4%**
CORN (GRAIN)	**52**	**3%**
OATS	**39**	**2%**
TOTAL	**2127**	**100%**

2018 McClave Crop Type	Sum of Acres	% of Total Acres
ALFALFA	**1079**	**62%**
Other	**356**	**20%**
SORGHUM (ALL)	**140**	**8%**
CORN (GRAIN)	**126**	**7%**
WHEAT	**50**	**3%**
TOTAL	**1751***	**100%**

*Appr. 376 ac dried up in McClave Study Area after 2017

2018 Las Animas Crop Type	Sum of Acres	% of Total Acres
ALFALFA	**285**	**57%**
CORN (GRAIN)	**132**	**26%**
Other	**84**	**17%**
TOTAL	**501**	**100%**

2019 Las Animas Crop Type	Sum of Acres	% of Total Acres
ALFALFA	**240**	**48%**
OATS	**176**	**35%**
SORGHUM (ALL)	**46**	**9%**
Other	**39**	**8%**
TOTAL	**501**	**100%**

Earthen ditches are the predominant irrigation conveyance method utilized in the McClave Drain study area while the Las Animas study area is characterized by more efficient conveyance methods including underground pipe, gated pipe and concrete ditch.

Table 7: Length of Irrigation Conveyance/Distribution Systems in McClave and Las Animas Study Areas

		Earthen Ditch	Concrete Ditch	Gated Pipe	Underground Pipe
McClave Study Area	Length (mi)	28.81	2.26	0.46	2.43
	% of Total	85%	7%	1%	7%
Las Animas Study Area	Length (mi)	1.69	0.62	1.5	2.05
	% of Total	29%	11%	26%	34%

Source: ArcMap 10.3

III. Tailwater Return Flow Measurements and Results

III.a. Flow Measurement Stations

TWF is defined as the ratio of tailwater amount to the application amount and can be applied on a field-level, farm-level, or canal-wide basis. Tailwater reuse has historically been a common practice in the study area and includes reuse from field to field within an individual farm as well as from one farm to another. In order to account for tailwater reuse within the study area as a whole, tailwater measurement stations were installed at all surface water field exit points where tailwater return flows were expected to occur[2]. Tailwater flumes were sized based upon expected tailwater flow rates; this was determined in part by the number of canal shares associated with each farm along with communicated prior experience from the farmers.

Table 8: Flow Measurement Stations

Station ID	Installation Date	Flume Type	Throat Width (in)	Measurement Type	Farms Measured	Date Verified	% Error
MCDIV1[1]	4/16/2015	Parshall	48	Diversion	M1,M2,M3,M3B,M4,M5		
MCDIV2	4/15/2015	Parshall	48	Diversion	M1,M2,M3,M3B,M4,M5	10/1/2015	0.2%
MCDIV3[2]	5/13/2015	Parshall	36	Diversion	M3,M3B,M4,M5	7/28/2015	-2.1%
SUNDIV1[1]	4/16/2015	Parshall	36	Diversion	S1,S2,S3,S4		
SUNDIV2	5/11/2015	Parshall	36	Diversion	S1,S2,S3,S4	8/16/2015	2.2%
SUNDIV3	5/29/2015	Parshall	36	Diversion	S2,S3	7/9/2015	-4.3%
TWM1	4/17/2015	Parshall	9	Tailwater	M1	8/11/2015	0.7%
TWM2A	4/21/2015	Cutthroat	12	Tailwater	M2	4/7/2017	0.0%
TWM2B	5/18/2015	Cutthroat	12	Tailwater	M2	10/12/2015	0.0%
TWM2C	4/20/2015	Parshall	6	Tailwater	M2	9/16/2015	-1.7%
TWM3	6/16/2015	Parshall	9	Tailwater	M3,M3B	10/3/2017	-4.3%
TWM4	4/23/2015	Cutthroat	8	Tailwater	M4,M5	5/1/2016	4.5%
TWM4B	10/9/2015	Cutthroat	8	Tailwater	M4	10/12/2015	-3.6%
TWS1A	6/17/2015	Parshall	9	Tailwater	S1	8/7/2015	-0.9%
TWS1B	6/17/2015	Cutthroat	12	Tailwater	S1	7/31/2015	3.4%
TWS1C[5]	6/18/2015	Cutthroat	8	Tailwater	S1		
TWS1D[5]	7/29/2016	Parshall	9	Tailwater	S1		
TWS2[3]	4/25/2015	Cutthroat	12	Tailwater	S2,S3	8/6/2015	-4.6%
TWS2[4]	8/21/2015	Parshall	18	Tailwater	S2,S3	8/29/2015	-4.9%
TWS3	4/24/2015	Parshall	9	Tailwater	S3	9/24/2015	-3.9%
TWS4[5]	5/3/2016	Cutthroat	8	Tailwater	S4		
LADIV84	4/25/2018	Parshall	24	Diversion	LA2, LA3	8/2/2018	4.5%
LADIV85	4/26/2018	Parshall	24	Diversion	LA1	8/2/2018	
TWLA123	4/22/2018	Parshall	18	Tailwater	LA1, LA2, LA3	8/5/2018	0.0%
TWLA3A	4/28/2018	Parshall	12	Tailwater	LA3	8/20/2018	-4.7%
TWLA3B[5]	4/29/2018	Parshall	9	Tailwater	LA3		

[1]FLCC flume; unable to verify consistent flume shift; data discarded.

[2]Removed after 2015 irrigation season due to sediment problems; data not used due to submerged conditions during several irrigation events.

[3]Removed after 2015 Run #19 due to higher than anticipated tailwater flowrate.

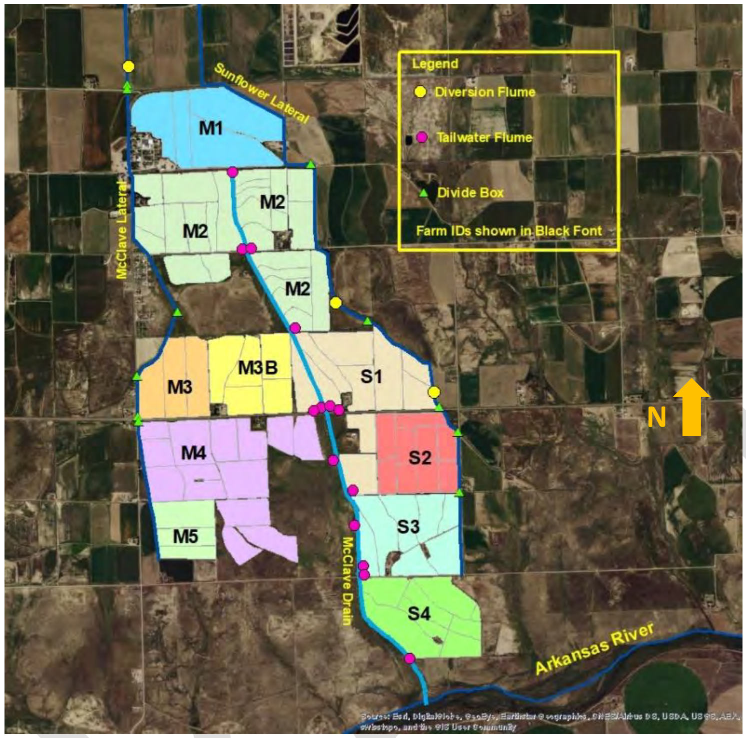
[4]Installed prior to 2015 Run #20.

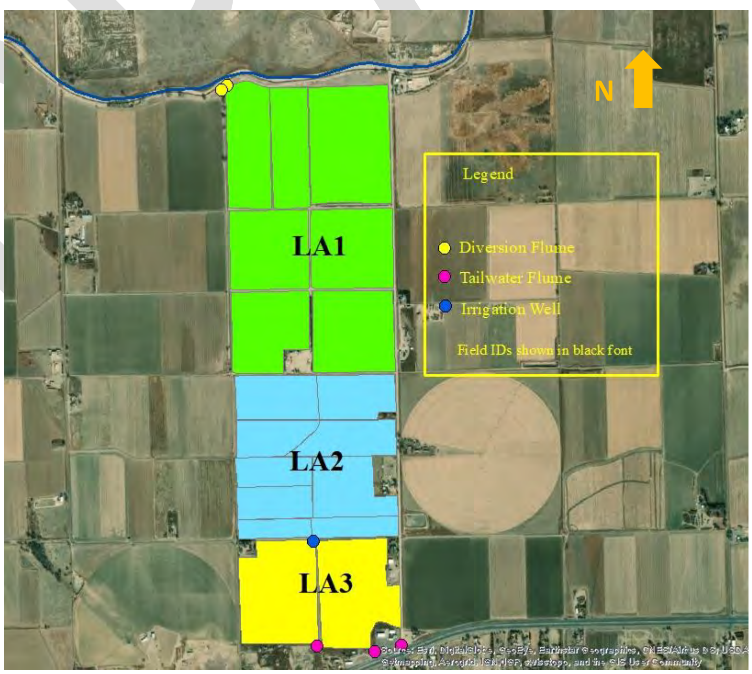
[5]Infrequent tailwater runoff; not present during tailwater and unable to test accuracy

[2]Interviews with farmers prior to beginning the study provided locations of tailwater entry points and expected tailwater flow rates.

In the McClave Drain study area, irrigation application amounts were derived from diversion measurement flumes located in the McClave and Sunflower Laterals. Diversion flumes measured total lateral flow rate prior to division and distribution to individual farms. In the Las Animas study area, Parshall flumes located immediately downstream of headgates were used to measure diversion flow rates onto farms.

Figure 5: Location of Flow Measurement Structures within McClave and Las Animas Study Areas





Each diversion and tailwater measurement station included a flume, stilling well with equipment box, and Sutron® Stage Discharge Recorder (SDR) with solar panel and battery.

Figure 6: Diversion Flume

Figure 7: Tailwater Flume

Flumes were installed according to Colorado Division of Water Resources publication "Standard Operating Procedures: Discharge Measurement at Parshall Flumes." Flume measurement accuracy was checked using a USGS Pygmy Current Meter in combination with AquaCalc Pro Plus Stream Flow Computer (JBS Instruments).

III.b. Lateral Divide Boxes

Lateral divide boxes are water regulation structures that serve the purpose of dividing off-farm lateral flows into the appropriate flow rates for diversion to individual farms.

Figure 8: Divide Box

Divide boxes are typically constructed of a concrete floor and walls with a divide wall located in the channel parallel to water flow. The length of each section adjacent to the divide wall is proportional to the number of shares passing through that section. The bottom four rows of Table 7 summarize the proportion of flow that each farm receives through flumes MCDIV2, SUNDIV2, LADIV84, and LADIV85. These values are determined through dimensional analysis of each divide box within the two study areas.

Table 9: Divide Box Diversion Splits

Flume	MCDIV2	MCDIV2	MCDIV2	MCDIV2	MCDIV2	MCDIV2	MCDIV2	MCDIV2	SUNDIV2	SUNDIV2	SUNDIV2	SUNDIV2	SUNDIV2	SUNDIV2	LADIV85	LADIV84	LADIV84	TOTAL
Farm ID	**M1**	**M2**	**M3**	**M3B**	**M4**	**M5**	**PT**	**ITI**	**S1**	**S2**	**S3**	**S4**	**RT**	**BN**	**LA1**	**LA2**	**LA3**	
Divide Box ID																		
MCBOX1	40%	40%	60%	60%	60%	60%	60%	60%										
MCBOX2	43%	57%																
MCBOX3			0%	16%	84%	84%	84%	84%										
MCBOX4					71%	71%	71%	29%										
MCBOX5					68%	68%	32%											
MCBOX6					72%	28%												
SUNBOX2									32%	68%	68%	68%	68%	68%				
SUNBOX3										41%	59%	59%	59%	59%				
SUNBOX4											51%	51%	25%	25%				
SUNBOX5											29%	71%						
LADIV84																70%	30%	
LADIV85															100%			
% of MCDIV2 Diversions	17%	23%	0%	10%	18%	7%	11%	14%										100%
% of SUNDIV2 Diversions									32%	28%	6%	15%	10%	10%				100%
% of LADIV84 Diversions																70%	30%	100%
% of LADIV85 Diversions															100%			100%

PT, ITI, RT, BN are farms that divert water from McClave or Sunflower Laterals that are not included in study.

Lateral divide boxes are founded on the assumption that flow depth and velocity are uniform throughout the entire divide box cross section. Several divide box cross-sections were analyzed using a USGS pygmy current meter and AquaCalc Pro Plus Stream Flow Computer to check flow velocity distribution. Non-uniform lateral velocity profiles were accounted for by applying a weighted flow fraction through each divide section.

Table 10: Divide Box Velocity

	[1]Left Channel Width (in)	[1]Left Channel Velocity (ft/s)	[1]Left Channel Velocity Weighted Fraction of Flow through Box	[1]Left Channel Farm IDs	[1]Right Channel Width (in)	[1]Right Channel Velocity (ft/s)	[1]Right Channel Velocity Weighted Fraction of Flow through Box	[1]Right Channel Farm IDs	Total Box Width (in)	Total Velocity (ft/s)
Divide Box ID										
MCBOX1	63.00	2.68	0.92	M1,M2	81.00	3.08	1.06	M3,M3B,M4, M5,PT,ITI	144.00	2.91
MCBOX2	47.25	1.81	0.99	M1	60.75	1.84	1.01	M2	108.00	1.83
MCBOX3	23.25	2.06	0.92	M3B	109.25	2.28	1.02	M4,M5,PT,ITI, M3B(toPT)	132.50	2.24
MCBOX4	81.00	1.00	1.00	M4,M5,PT, M3B	32.50	1.00	1.00	ITI	113.50	1.00
MCBOX5	72.00	2.04	0.98	M4,M5	31.00	2.18	1.05	PT	103.00	2.08
MCBOX6	49.00	2.43	1.03	M4	21.00	2.18	0.93	M5	70.00	2.36
SUNBOX2	132.00	1.00	1.00	S2,S3,S4,RT, BN	61.00	1.00	1.00	S1	193.00	1.00
SUNBOX3	50.50	2.11	0.98	S3,S4,RT,BN	34.00	2.19	1.02	S2	84.50	2.14
SUNBOX4	38.00	1.00	1.00	RT,BN	39.00	1.00	1.00	S3,S4	77.00	1.00
SUNBOX5	52.00	1.00	1.00	S4	21.13	1.00	1.00	S3	73.13	1.00

[1]Looking downstream through divide box.
PT, ITI, RT, BN are farms that divert water from McClave or Sunflower Laterals that are not included in study.
2018

III.c. Irrigation Ditch Seepage Losses

In order to calculate TWF, it is necessary to know the amount of irrigation water applied at the field. The Moritz[3] equation was used to estimate ditch seepage losses between diversion measurement stations (located in off-farm laterals) and each field.

Moritz equation:

$$S = 0.2 * C * \left(\frac{Q}{V}\right)^{1/2}$$

where:
S = ditch seepage loss (cfs/mi)
C = saturated hydraulic conductivity (ft/day)
Q = flow rate in ditch (cfs)
V = flow velocity in ditch (ft/s)

Field measurements of ditch cross-sectional dimensions were collected at 217 points within the study areas and included on-farm ditches as well as off-farm laterals.

[3]Source: Department of Interior, Bureau of Reclamation, Design Standards No. 3, Canals and Related Structures

Figure 9: Cross-Section Dimension Point Map for Farm M4

Lateral cross-sectional profiles were observed as rectangular in shape while on-farm ditch cross sections were assumed trapezoidal with equal side lengths. Saturated hydraulic conductivity values were determined for each cross-section measurement point using NRCS Web Soil Survey data. For on-farm ditches, *Q* was calculated by dividing diversion volumes on each farm per run (48 hours long) and selecting the median value over the entire season. This process yielded a median *Q* value for each farm per year. For off-farm laterals, *Q* was calculated by subtracting divide box splits for each lateral segment from diversion measurement station data. Average flow velocity, *V*, was calculated by a combination of Manning's Equation and Mass Balance:

Manning's Equation:

$$V = \left(\frac{1.486}{n}\right) * R^{\frac{2}{3}} * S^{\frac{1}{2}}$$

where

n = Manning's roughness coefficient = 0.03 for earthen ditches

R = Hydraulic Radius of ditch flow = $\left(\frac{cross\ sectional\ area}{wetted\ perimeter}\right)$

S = ditch slope

Mass Balance:

$V = Q/A$
where

Q = ditch flow rate
A = ditch flow cross-sectional area

These two equations were set equal while solving for flow depth at each point. This process, used with the Moritz equation, yielded a seepage loss value (cfs/mi ditch) for each ditch cross-sectional measurement point.

For each study field, average seepage loss volume (in acre feet) was calculated by averaging Moritz S values for each point that irrigation water traveled through to reach the field and multiplying by the length of earthen ditch. Earthen ditch lengths for headland ditches were assumed to equal half of total headland ditch length since irrigation water sets typically start at one end (where L = total headland L) and finish at the opposite end (where $L = 0 *$ total headland L).

Total ditch seepage loss for each farm (in acre feet) was calculated by averaging seepage loss values for each field within a farm and adding average off-farm lateral loss for each farm. This method assumes equal distribution of irrigation water amongst all fields within a farm during the year and yields a single average volumetric seepage loss value for each farm per year.

Table 11: Average Ditch Seepage Loss by Farm

Total Avg Ditch Seepage Losses per Farm During Typical Run (48 hr) (ac ft)										
Year	**McClave Lateral Farms**				**Sunflower Lateral Farms**			**Las Animas Farms**		
	M1	**M2**	**M3B**	**M4**	**S1**	**S2**	**S3**	**LA1**	**LA2**	**LA3**
2017	0.180	0.203	0.477	0.875	0.356	0.354	0.318			
2018	0.184	0.207	0.496	0.859	0.358	0.356	0.306	0.097	0.136	0.000
2019								0.097	0.136	0.000

III.d. Precipitation Amounts and Timing

The effect of precipitation on runoff through tailwater measurement stations during irrigation events was accounted for using the runoff equation developed by the NRCS, incorporating the runoff curve number (CN). The curve number affects runoff by accounting for hydrologic conditions as well as soil types and surface conditions.

$$Q = \frac{(P - 0.05S_{0.05})^2}{P + 0.95S_{0.05}} \; for\ P > 0.05S\ or\ Q = 0\ for\ P \leq 0.05S$$

where
Q = runoff in inches
P = rainfall in inches
S = the potential maximum soil moisture once runoff begins in inches. S incorporates CN as:

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

Measured precipitation amounts were collected from rain gauges in the study areas after each rain event throughout the 2017, 2018 and 2019 irrigation seasons. Additionally, data from a nearby CoAgMet station was utilized as necessary. These measurements yielded *P* for each irrigation run at each field.

To determine *S*, *CN* values were selected from Table 12 based upon cover type, treatment and hydrologic condition for each farm. Cover type and treatment of the study fields were determined by observed crop types and residue coverage in each field each year. Hydrologic conditions were identified as "Good." Soil types in the study area were determined at each identification point (Point ID) using the NRCS Web Soil Survey. The majority of Point ID soil types had resulting saturated hydraulic conductivity values (K_{SAT}) of 0.2 in/hr, corresponding with the NRCS Hydrologic Soil Group B.

Table 12: NRCS Runoff Curve Number (CN) Values for Cultivated Agricultural Lands

Cover description			Curve Numbers for Hydrologic Soil			
Cover type	**Treatment[A]**	**Hydrologic condition**	**A**	**B**	**C**	**D**
Fallow	**Bare soil**	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	**Straight row (SR)**	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T + R	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	**SR**	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + R	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	**SR**	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

Source: https://en.wikipedia.org/wiki/Runoff_curve_number

Resulting *CN*s utilized in the study runoff calculation are listed in Table 13. When crop rotation created two different crop types in a field within a year, the *CN*s of the crop types were averaged for the field. A *CN* value for each farm was calculated using a weighted average of field *CN*s within the farm by acres per field. This weighted average *CN* was then used to calculate *S* in the runoff equation.

Table 13: Curve Number (CN) Values for Study Area

Cover Type	Curve Number (CN)
Alfalfa	72
Fallow	83
Grain Corn	75
Oats	72
Sorghum	72
Wheat	72

Finally, *Q* was calculated for each field and correlated to corresponding irrigation runs by date of precipitation event to determine if the tailwater amount of the run was affected. If an effect of the precipitation was determined, the amount was subtracted from the total runoff measured through the tailwater flume during the run.

Table 14: Precipitation Contribution to Tailwater Amount

Total Precipitation Contribution to TW Flume Amounts per Farm (ac ft)								
Year	**McClave Lateral Farms**				**Sunflower Lateral Farms**			**Las Animas Farms**
	M1	**M2**	**M3B**	**M4**	**S1**	**S2**	**S3**	**All Farms**
2017	0.30	5.52	0.79	9.87	9.68	8.58	1.29	
2018	2.39	1.11	0.94	0.05	2.89	3.86	0.53	16.72
2019								30.08

III.e. Irrigation Monitoring

Irrigation monitoring continued after Phase One in March 2017 and continued through mid-November 2019. Diversion and tailwater measurement stations were generally visited one to four times per irrigation event and once afterward. Monitoring activities during the course of irrigation included equipment inspection, SDR calibration (if necessary), observation of flow conditions and farm diversion verification. Post-irrigation monitoring activities included equipment inspection, SDR data retrieval and inspection of channel conditions (including sediment removal if necessary). All irrigation events were monitored in 2017, 2018, and 2019 with 1079, 846, and 779 measurement station checks performed respectively.

III.f. Verification of Flume Accuracy

In order to confirm the accuracy of flow measurement in flumes, each structure was checked using a USGS Pygmy Current Meter in combination with AquaCalc Pro Plus Stream Flow Computer (JBS Instruments). The flume verification procedure that was utilized for this study was identical to the procedure used by Colorado Division of Water Resources, Division 2 hydrographers during a training trip to the study area in June 2015. Consistent with DWR practice, any flume showing less than ± 5% error (as compared to current meter analysis) was assumed to be measuring accurately and no shift was applied to SDR stage data.

III.g. SDR Data Analysis

Sutron® Stage Discharge Recorders were used to measure and record upstream (at staff gauge) flow depth (stage) values in flumes. SDRs recorded stage values every five minutes. In-field calibration of SDRs took place when staff gauge reading and SDR value differed by 0.01 feet or more and was subsequently applied to 2017, 2018, and 2019 data during processing. SDRs were typically downloaded following each irrigation event and converted to Microsoft Excel files for further processing.

III.h. TWF Calculations

Net application amount on each farm was calculated in acre/feet as follows:

$$\begin{aligned} &Net\ Farm\ Application\ Amount \\ &\quad = (Lateral\ Diversion\ Measured\ Amount * Box\ Split\ Fraction) \\ &\quad - Off\ Farm\ Lateral\ Seepage\ Loss - On\ Farm\ Ditch\ Seepage\ Loss \end{aligned}$$

Net tailwater amount from each farm was calculated in acre/feet as follows:

$$Net\ Tailwater\ Amount = Tailwater\ Flume\ Measured\ Amount - Precipitation\ Runoff$$

TWF values were calculated as follows on a farm basis as well as for the entire study area:

$$Farm\ Tailwater\ Fraction = \frac{(Net\ Farm\ Tailwater\ Amount)}{(Net\ Farm\ Application\ Amount)}$$

$$Study\ Area\ Tailwater\ Fraction = \frac{(Net\ Study\ Area\ Tailwater\ Amount)}{(Net\ Study\ Area\ Application\ Amount)}$$

III.i. Tailwater Results

Results of diversion amounts, tailwater amounts and tailwater fractions are provided in Tables 15 through 20.

Table 15: Tailwater Fractions by Farm

Tailwater Fractions by Farm (ac ft)								
Year	McClave Lateral Farms				Sunflower Lateral Farms			Las Animas Farms
	M1	M2	M3B	M4	S1	S2	S3	All LA
2017	1.74%	2.10%	4.23%	3.43%	14.35%	3.32%	6.13%	
2018	6.07%	0.28%	0.61%	0.23%	7.03%	2.98%	2.94%	15.66%
2019								9.67%

Table 16: Net Diversion Amount by Farm per Irrigation Run

Net Diversion Amount by Farm Per Run (ac ft)										
Year	McClave Lateral Farms				Sunflower Lateral Farms			Las Animas Farms		
	M1	M2	M3B	M4	S1	S2	S3	LA1	LA2	LA3
2017	827.42	1083.10	436.47	798.85	934.84	1129.66	161.08			
2018	492.96	645.02	262.72	483.45	528.25	637.82	93.43	502.00	215.06	96.24
2019								2102.60	433.54	186.35

Table 17: Net Tailwater Amount by Farm per Irrigation Run

Net Tailwater Amount by Farm per Run (ac ft)								
Year	McClave Lateral Farms				Sunflower Lateral Farms			Las Animas Farms
	M1	M2	M3B	M4	S1	S2	S3	Total All LA Farms
2017	14.41	22.74	18.47	27.38	134.11	37.46	9.88	
2018	29.94	1.81	1.61	1.11	37.13	19.01	2.74	127.36
2019								263.26

Tables 18-20: Tailwater Statistics by Year

2017 Study Area Tailwater Statistics	
Total Net Diversion Amount (ac ft)	5773.47
Total Net Tailwater Amount (ac ft)	264.44
Average Tailwater Fraction (TWF) (%)	**4.58%**
Highest Annual Average TWF (%)	14.35%
Lowest Annual Average TWF (%)	1.74%

2018 Tailwater Statistics				
	McClave Lateral Farms	Sunflower Lateral Farms	Las Animas Farms	**All Study Area**
Total Net Diversions (Study Farms Only) (ac ft)	1884.14	1259.50	813.30	3956.93
Total Net Tailwater Volume (ac ft)	34.47	58.88	127.36	220.72
Average Tailwater Fraction (TWF) (%)	1.83%	4.68%	15.66%	**5.58%**
Highest Annual Average TWF (%)	6.07%	7.03%		15.66%
Lowest Annual Average TWF (%)	0.23%	2.94%		0.23%

2019 Study Area Tailwater Statistics	
Total Net Diversion Amount (ac ft)	2722.49
Total Net Tailwater Amount (ac ft)	263.26
Average Tailwater Fraction (TWF) (%)	**9.67%**

III.j. Tailwater Conclusions

Diversions by the FLCC during 2017, 2018, and 2019 were 250,682 ac ft; 191,594 ac ft; and 219,417 ac ft respectively compared to the 20-year average of 205,997 ac ft.

The average measured yearly TWFs for the McClave study area during 2017 and 2018 were 4.58% and 5.58% respectively. Average measured yearly TWFs for the Las Animas study area during 2018 and 2019 were 15.66% and 9.67% respectively. The average yearly TWF for all study areas combined during 2018 was 5.58%. These values combined with McClave study area TWFs measured during 2015 (5.3%) and 2016 (4.07%) suggest that actual TWF amounts are consistently lower for single share (per acre) farms than the TWF value assumed in the HI and ISAM models (9.65%). Measured TWF for the Las Animas area was consistent with the models during 2019 but higher during 2018. The relatively high variation between the two years suggests that additional tailwater data might be needed in the Las Animas study area to make a definite conclusion regarding actual TWF in areas with higher share to acre ratios.

IV. Maximum Farm Efficiency (MFE) Methods and Results

The Maximum Farm Efficiency (MFE) factor is used in the soil-water budgeting procedure to account for the non-uniform distribution of irrigation water associated with flood irrigation practices and acts as an upper limit on the percentage of irrigation water applied to a crop that can be consumed by the crop. Field data for parameters used in the calculation of MFE were collected during 2019 on seven fields within a single farm in the McClave Drain study area.

IV.a. Farm Characteristics

Figures 10 and 11 provide images of Farm EFF used for MFE data collection during 2019. EFF contains 8 fields (seven which were irrigated during 2019) that are irrigated using flood irrigation methods under the Fort Lyon Canal via the Sunflower Lateral. The farm is approximately 144 acres in area with all fields except EFF2 planted to alfalfa during 2019. The predominant soil type is Rocky Ford clay loam which covers approximately 94% of the farm area with the other 6% classified as Numa clay loam. Land slopes within Farm EFF are generally to the south, southeast with an average farm slope of 1.18%, maximum slope of 1.43% and minimum of 0.91%. Average field lengths from headland to field bottom are 780 ft with a minimum of 425 ft and a maximum of 1070 ft. Approximately 65 ac (45%) of the farms area has the potential for tailwater reuse from up-gradient fields. Earthen ditches comprise about 84% of the total irrigation conveyance structure length while concrete ditches make up approximately 16%.

Figure 10: Farm EFF

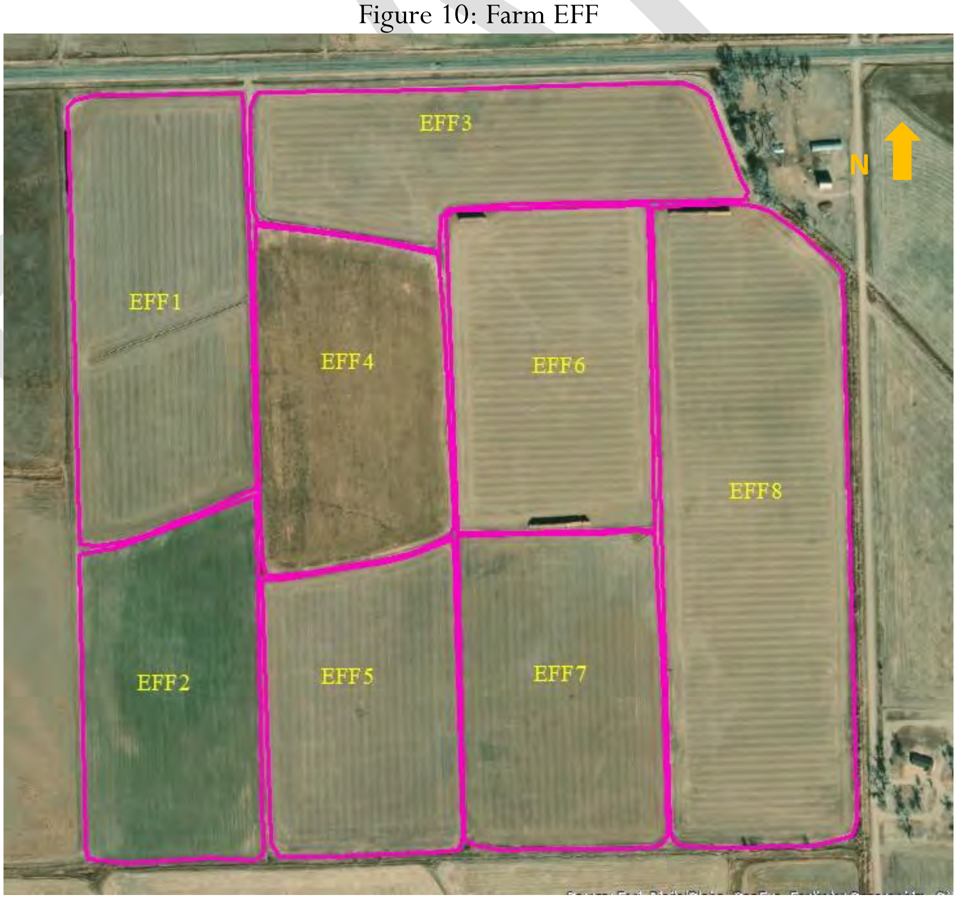


Figure 11: Water Flow Map for Farm EFF

IV.b. Diversion (Application) and Tailwater Flow Measurement

Irrigation application amounts were derived from a flow measurement station (3 ft Parshall) in the Sunflower Lateral located upstream of the Farm EFF diversion point. Tailwater amounts were measured from a tailwater flow measurement station (18-inch Parshall Flume) located downstream of the southwest corner of Farm EFF. Both measurement stations were equipped with a stilling well, equipment box, and Sutron® Stage Discharge Recorder (SDR) with solar panel and battery.

Flume installation and accuracy verification were conducted as described in Sections III.a and III.f earlier in the report. On-farm ditch seepage losses were calculated according to the Moritz equation as described in section III.c of the report

IV.c. Irrigated Acreage

Following the conclusion of an irrigation event, irrigated acreage was determined through visual inspection of each field area and boundaries were recorded using UTM GeoMap. These boundary maps were used to record irrigation timing and irrigated areas on fields throughout the irrigation season.

IV.d. Initial Soil Moisture Content

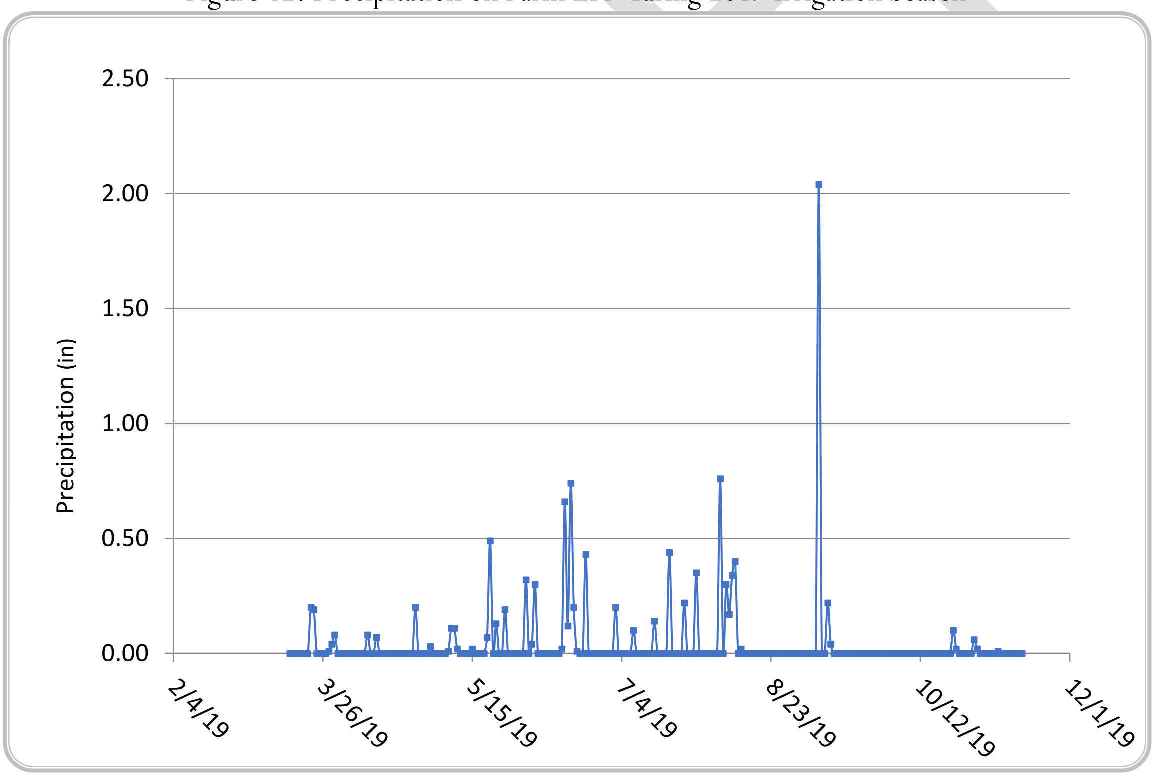
Average soil moisture content within the crop root zone was determined for each field through the gravimetric method (ASTM D 2216). Soil samples were collected in each field in early March to a depth of approximately 4 ft using a Giddings probe mounted in a Ford F250 pickup. Soil moisture values for each field were averaged to obtain a single volumetric water content starting value for each field.

IV.e. Effective Precipitation

Precipitation data was collected using a Dynamax SapIP-MICRO system with tipping bucket rain gauge (accuracy ± 4%). Rainfall data prior to weather station installation was obtained from the CoAgMet McClave weather station located 2.5 miles north of Farm EFF.

Total precipitation was converted to effective precipitation using the NRCS Curve Number method described in Section III.d of the report.

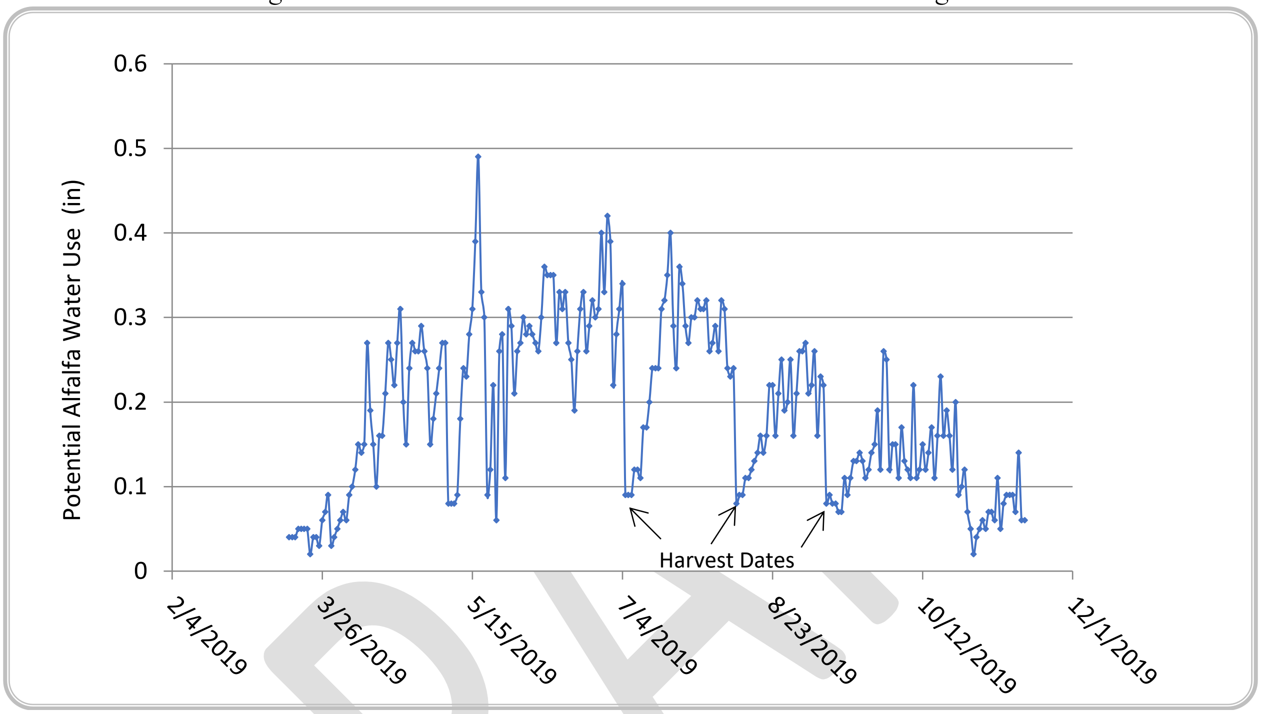
Figure 12: Precipitation on Farm EFF during 2019 Irrigation Season



IV.f. Crop Evapotranspiration

Potential crop water use was determined using the Penman-Kimberly Method (and corresponding alfalfa crop coefficients) for weather data at the CoAgMet McClave station. March 15 was used as the alfalfa green-up date for all fields. Crop harvest dates were also used as subsequent green-up dates throughout the season for each field.

Figure 13: Potential Alfalfa Water Use for Field EFF8 during 2019



IV.g. Crop Root Zone Depth, Soil Available Water Capacity

As used in the HI and ISAM models for the Fort Lyon Canal, a uniform crop rooting depth of 4.07 ft, and available water holding capacity of 0.17 was assumed for all fields in the study.

IV.h. Irrigation Infiltration, Distribution

Infiltration rates were measured on each field by conducting double-ring infiltration tests (ASTM D3385) using ditch water over an 8-hour period which generally provided convergence to a steady-state infiltration rate. Average set cutoff time, advance time, and recession time were determined at different distances from the headland ditch to field bottom for each field.

To account for the non-uniformity of irrigation water distribution from the headland to the field bottom, the following procedure was employed:

1. Calculate infiltration rate for each hour of double ring infiltration test data.

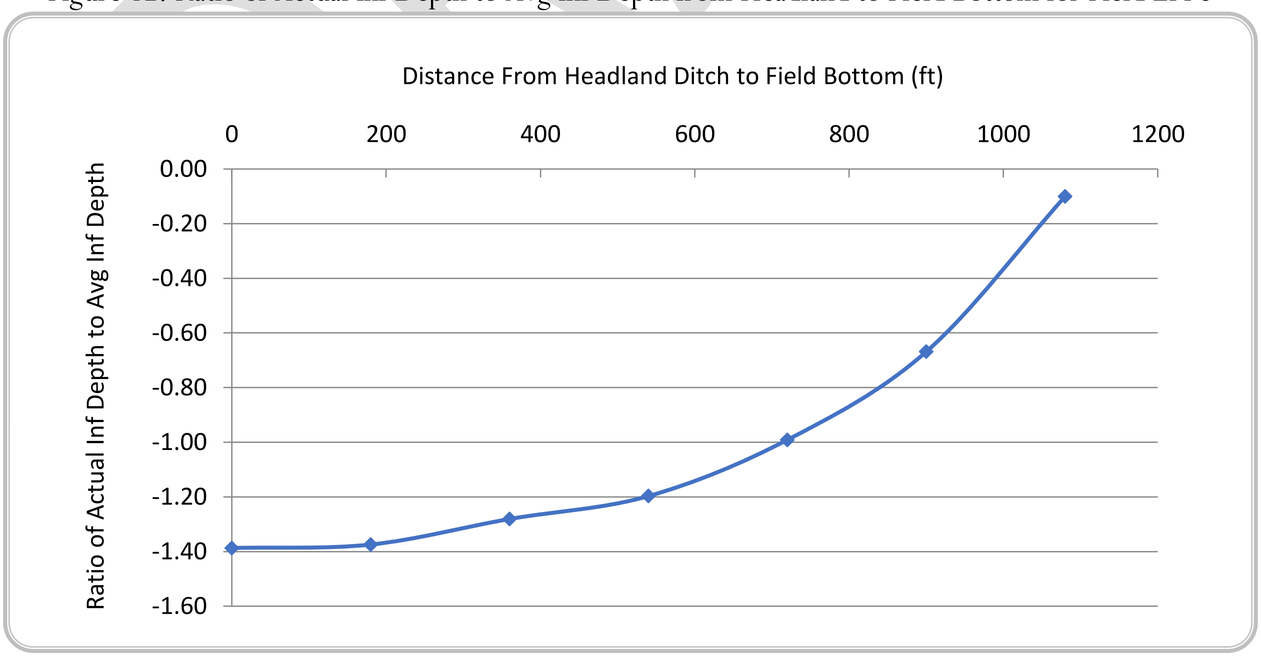
2. Calculate actual infiltrated depth (using double ring infiltration data) for different distances from headland to field bottom. These values represent the different infiltrated depth that would occur at each location during double ring infiltration test based on different infiltration opportunity times.
3. Calculate average infiltrated depth from double ring infiltration test. This value represents the infiltrated depth that would occur if opportunity time for each location were the same (equal distribution across all locations).
4. Calculate ratio of actual infiltrated depth to average infiltrated depth for each location from headland to field bottom. These ratios are applied to average infiltrated depths from each irrigation event for different locations from headland to field bottom in order to calculate actual infiltrated depth at each location.

These calculations yield an Infiltration Ratio curve unique to each field that decreases in (absolute) value with distance from the headland ditch.

Table 21: Infiltration Ratio Data for Field EFF6

	From Double Ring Infiltration Data		
Distance from Headland Ditch (ft)	Actual Infiltrated Depth (in)	Average Infiltrated Depth where DU =1 (in)	Ratio of Actual Infiltrated Depth to Avg Infiltrated Depth
0	6.30	4.54	1.39
180	6.24	4.54	1.37
360	5.82	4.54	1.28
540	5.44	4.54	1.20
720	4.50	4.54	0.99
900	3.04	4.54	0.67
1080	0.46	4.54	0.10

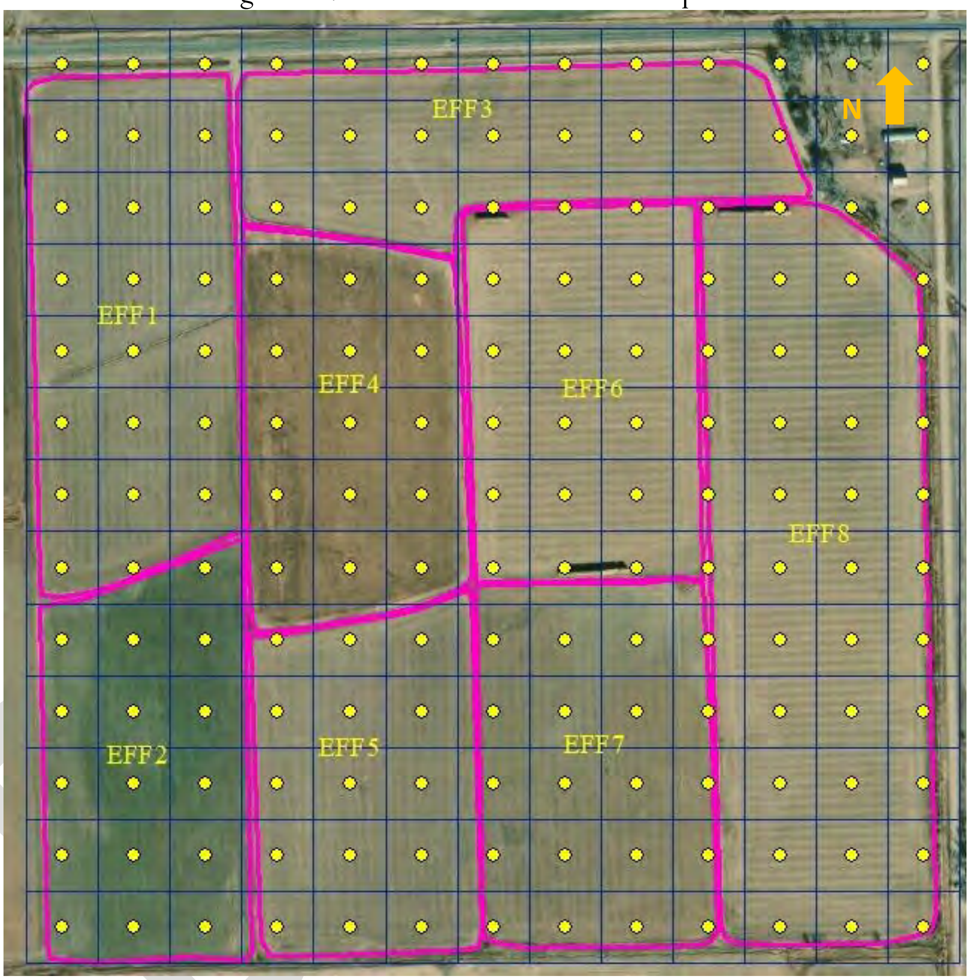
Figure 12: Ratio of Actual Inf Depth to Avg Inf Depth from Headland to Field Bottom for Field EFF6



IV.i. Subfield Analysis

In order to account for non-uniform irrigation infiltration, tailwater reuse, and irrigation timing, study fields were further divided into 1-acre (or smaller if located on field boundary) subfields for modeling purposes. All subfields within a particular field were assumed to have the same soil moisture budget parameters except for actual irrigation infiltrated depth and irrigation timing.

Figure 13: Farm EFF Subfields with Midpoints



IV.j. MFE Calculations

MFE estimates were calculated independently for each subfield using a daily time step soil-water budget with initial soil moisture values derived as described in Section IV.d. Starting and ending dates corresponded to the irrigation season on the Fort Lyon Canal. Daily ET amount acted as a reduction to soil moisture content while effective precipitation and actual irrigation infiltration acted as accretions to soil moisture. Soil moisture extraction followed the same methodology used in ISAM where extraction is not restricted until soil moisture content reaches 64% of field capacity. At this point extraction follows the (linear) slope of the "Dogleg" extraction function until reaching wilting point.

Net irrigation diversion, tailwater, and irrigated acreage were measured for each run. Average infiltrated depth across the irrigated area was calculated as follows:

$$Avg\ Infiltration = \frac{(Net\ Diversion - Tailwater)}{Irrigated\ Area}$$

Actual infiltration was calculated for each subfield based on its distance from the headland ditch as follows:

$$Actual\ Infiltration = Avg\ Infiltration * Infiltration\ Ratio$$

Tailwater Fraction was calculated on an irrigation event basis as follows:

$$Tailwater\ Fraction = \frac{(Net\ Farm\ Tailwater\ Amount)}{(Net\ Farm\ Application\ Amount)}$$

Deep percolation amount was defined as the amount of actual infiltration that exceeded soil moisture space (AWC minus water content prior to irrigation) within the crop root zone. Deep Percolation Fraction was calculated for each subfield on an irrigation event basis as follows:

$$Deep\ Percolation\ Fraction = \frac{(Deep\ Percolation\ Amount)}{(Net\ Application\ Amount)}$$

Efficiency was calculated for each subfield on a seasonal basis as follows:

$$Efficiency = 1 - Deep\ Percolation\ Fraction - Tailwater\ Fraction$$

IV.k. MFE Results

Seasonal efficiency values for subfields were (acreage-weight) averaged for each study field to establish an average seasonal efficiency value for each field. These values were then (acreage-weight) averaged to determine an average seasonal efficiency value for the farm.

Table 22: 2019 Average Field and Farm Efficiency Values for Farm EFF

Field EFF1	Field EFF3	Field EFF4	Field EFF5	Field EFF6	Field EFF7	Field EFF8	Farm Avg
47.7%	79.9%	75.8%	57.7%	72.7%	57.8%	67.4%	**65.4%**

Fort Lyon diversions during 2019 were slightly higher than the preceding 20-year average as well as the median. In order to gain a better understanding of MFE during low irrigation diversion years, MFE was modeled using data from 2012 when diversions were approximately one-third of average. The following parameters were adjusted in the efficiency modeling workbook for 2012:

- Irrigation timing – determined through canal records.
- Irrigation diversions –based on the number of shares diverted to Farm EFF during 2012.
- Tailwater – average tailwater amount per run from 2019 was applied to each run during 2012.
- Irrigated acreage – average area irrigated per run during 2019 was applied to 2012 data.
- Initial soil moisture content – obtained from ISAM version 17 SM sheet for 2012 SW.
- Potential crop water use – obtained from CoAgMet McClave station for 2012 for alfalfa.
- Precipitation – obtained from CoAgMet McClave station for 2012.

With all other input parameters left unchanged and calculations consistent with 2019, the following results were found for 2012 seasonal farm efficiency:

Table 23: 2012 Average Field and Farm Efficiency Values for Farm EFF

Field EFF1	Field EFF3	Field EFF4	Field EFF5	Field EFF6	Field EFF7	Field EFF8	Wt Farm Avg
81.2%	71.5%	Not Irrigated	74.9%	73.1%	67.5%	76.8%	**74.6%**

IV.l. MFE Conclusions

MFE data collected on a farm-scale during 2019 (considered a relatively average irrigation diversion year) show an average MFE value consistent with the value used in the HI and ISAM models. However, further modeling of MFE using 2019 irrigation set characteristics along with 2012 (a low diversion year) diversion, rainfall and ET data, shows an MFE value nearly 10% higher than that used in the HI and ISAM models. The higher efficiency value during a dry year is believed to be caused by less frequent irrigation application and therefore a larger soil moisture deficit within the crop root zone at the start of irrigation. Adjustment to other irrigation factors such as shorter irrigation set cutoff times were not considered when modeling 2012 data but could prove to increase MFE values even more during low diversion years.

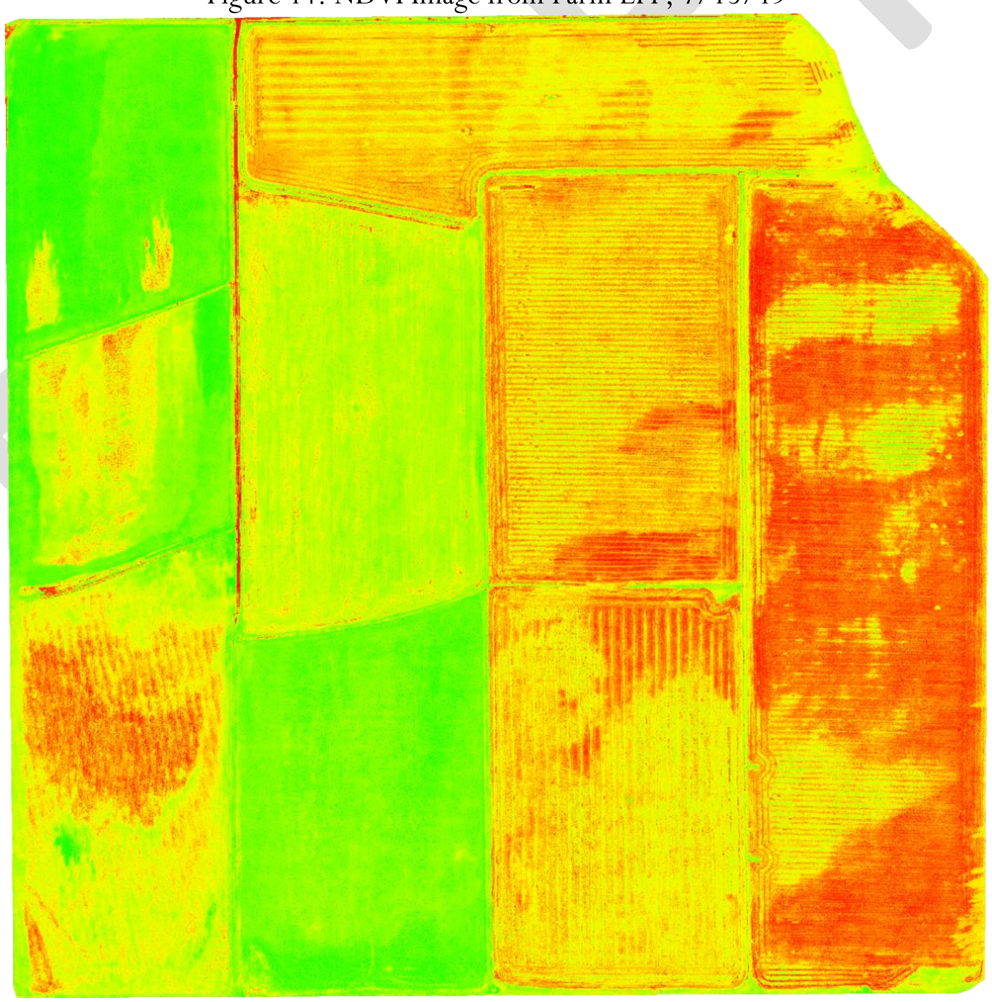
V. Evaluation of MFE with Aerial Imaging

Because of the cost-prohibitive nature of measuring MFE parameters on a large scale, the use of aerial imaging to gain an understanding of MFE, namely soil moisture content and crop water use, was explored during the summer of 2019 as a more efficient means of MFE parameter collection.

V.a. Multispectral Crop Imaging

Crop imaging data was collected using a DJI Matrice 100 unmanned aerial vehicle (UAV) with mounted MicaSense® Red Edge multispectral camera capable of capturing simultaneous images in the Near-Infrared (NIR), Blue, Green, Red, and Red Edge reflectance bands. Micasense Atlas Flight and DJI GO apps were used to plan flight missions for automated reflectance captures. Image stitching, processing and reflectance index calculations were performed using Pix4D Fields® software.

Figure 14: NDVI Image from Farm EFF, 7/13/19



V.b. Soil Moisture Stations

Soil moisture data was collected using Dynamax® ML3 Theta Soil Moisture Sensors buried at 1 ft, 2ft, 3ft, and 4ft depths at 10 locations across Farm EFF (one location was within a fallowed field that wasn't irrigated during the season). Each soil moisture station was equipped with a Dynamax® SapIP wireless data logging system.

Figure 15: Farm EFF Soil Moisture Station Locations

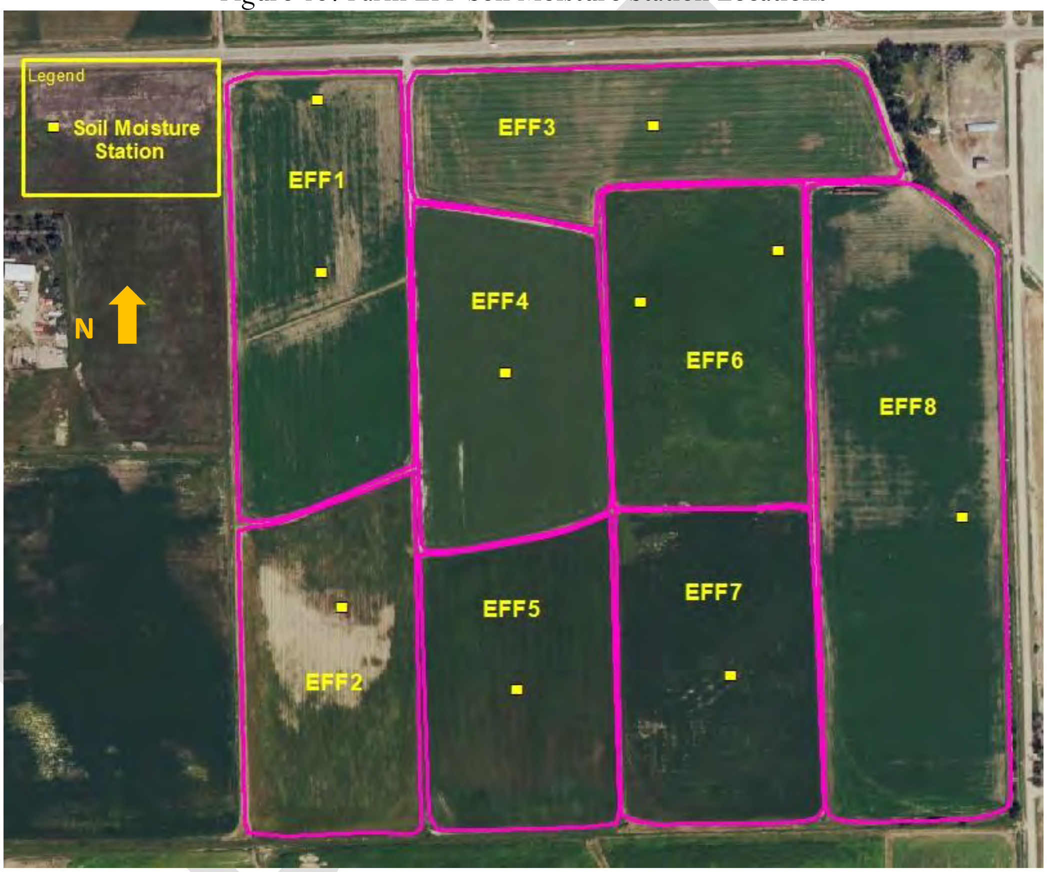
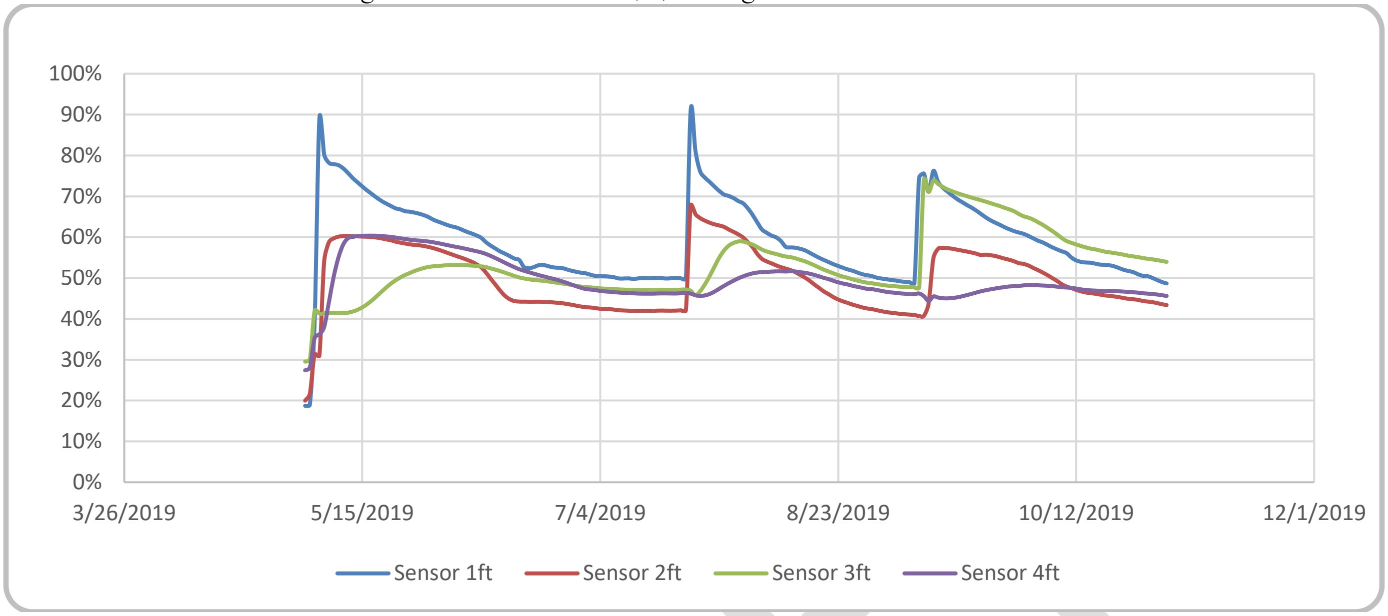


Figure 16: Soil Moisture (%) during 2019 at Station 92125



V.c. Methods and Results

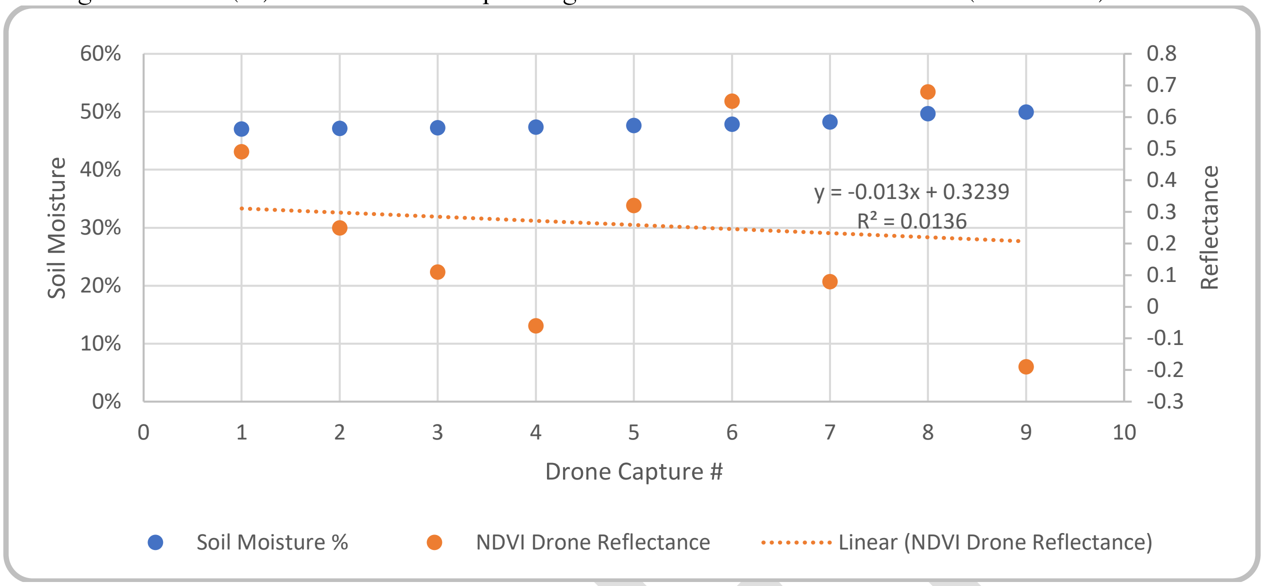
Multispectral crop imaging was conducted during 11 different flight missions during the summer of 2019 on Farm EFF with the following goal:

> To determine whether a numerical correlation exists between soil moisture content (and ultimately crop consumptive use) and any spectral reflectance index.

V.c.i Soil Moisture vs. Reflectance

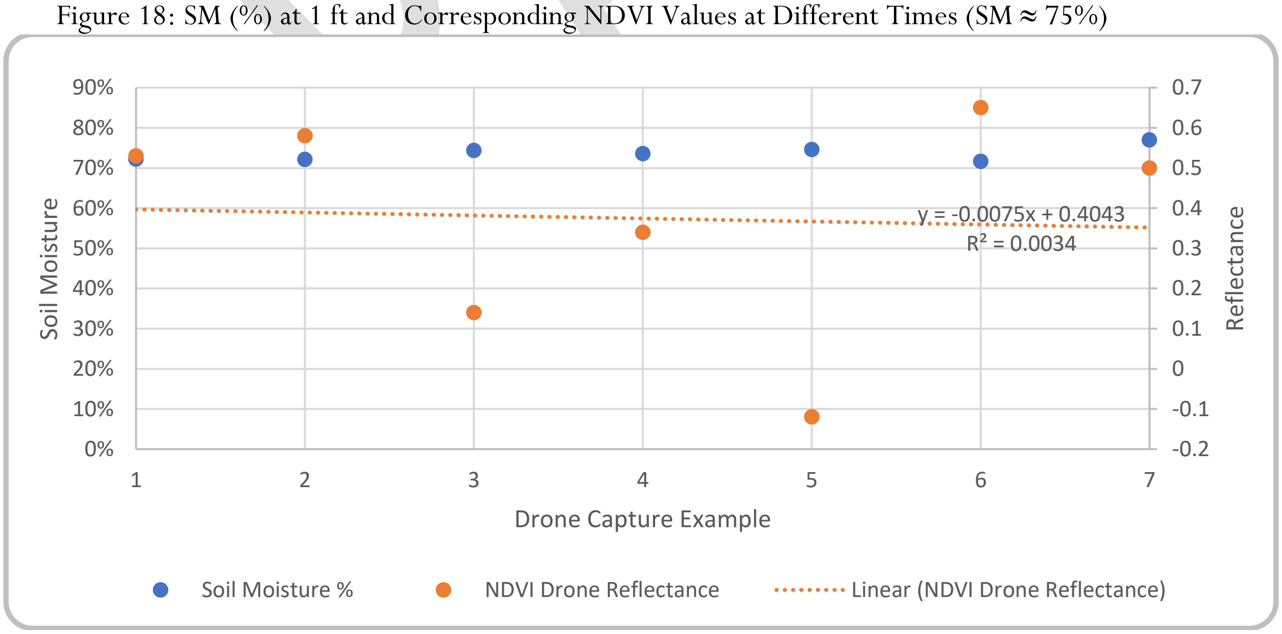
Following data collection with UAV and RedEdge camera, raw reflectance images were stitched and processed into NDVI, NDRE, VARI, TGI, SIPI2, and LCI indices using Pix4D software. These reflectance indices were individually analyzed to estimate a single reflectance value for each index at each soil moisture station location for each flight date. Through this process it was determined that NDVI provided the most consistent numerical reflectance values compared to the other indices and was chosen as the spectral baseline for comparison with soil moisture.

Figure 17: SM (%) at 1 ft and Corresponding NDVI Values at Different Times (SM ≈ 50%)



Analysis of the relationship between soil moisture and NDVI was conducted by first finding similar values of soil moisture across different stations at different times. The corresponding NDVI values were then plotted versus these similar soil moisture values. Figure 17 reveals that the relationship between these two variables is very poor with NDVI values ranging from -0.19 to 0.68 for soil moisture values between 47% and 50%.

Figure 18: SM (%) at 1 ft and Corresponding NDVI Values at Different Times (SM ≈ 75%)



Similar findings were found in Figure 18 with NDVI values ranging from -0.12 to 0.65 for soil moisture values between 72% and 77%.

Daily soil moisture values for individual stations were then plotted with NDVI values taken throughout the growing season as shown in Figures 19-20.

Figure 19: Average SM (Over 4 ft Depth) and NDVI for Station 92123 with Alfalfa Cut Date

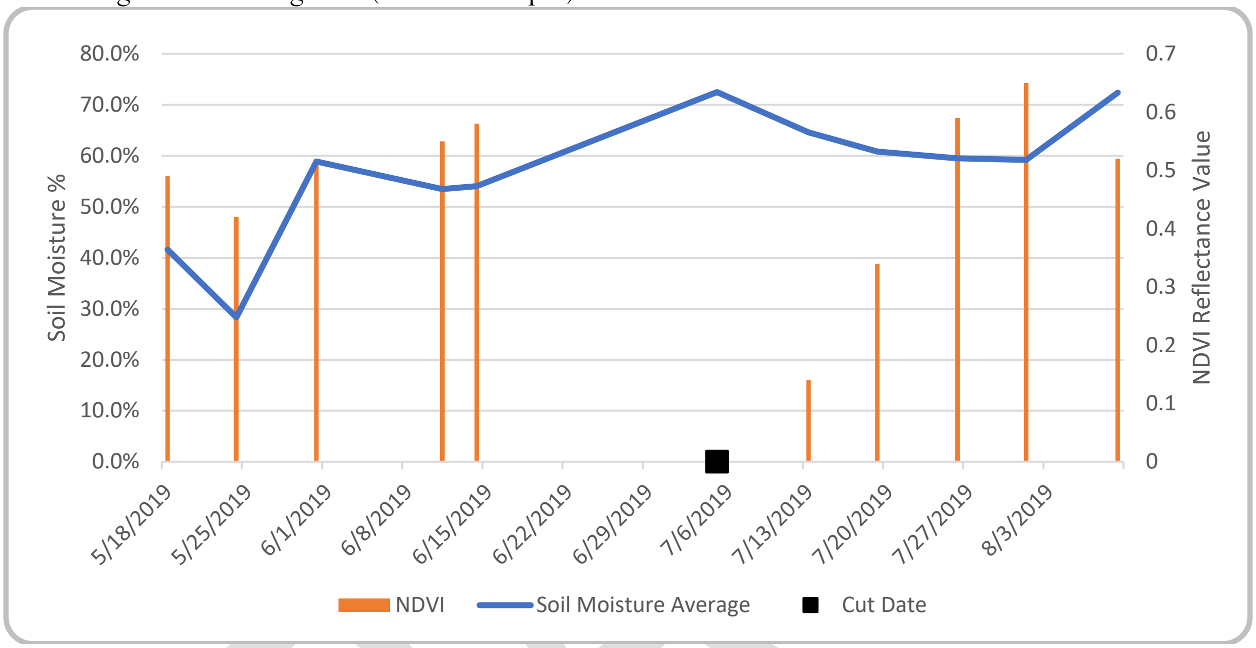


Figure 20: Average SM (Over 4 ft Depth) and NDVI for Station 92125 with Alfalfa Cut Date

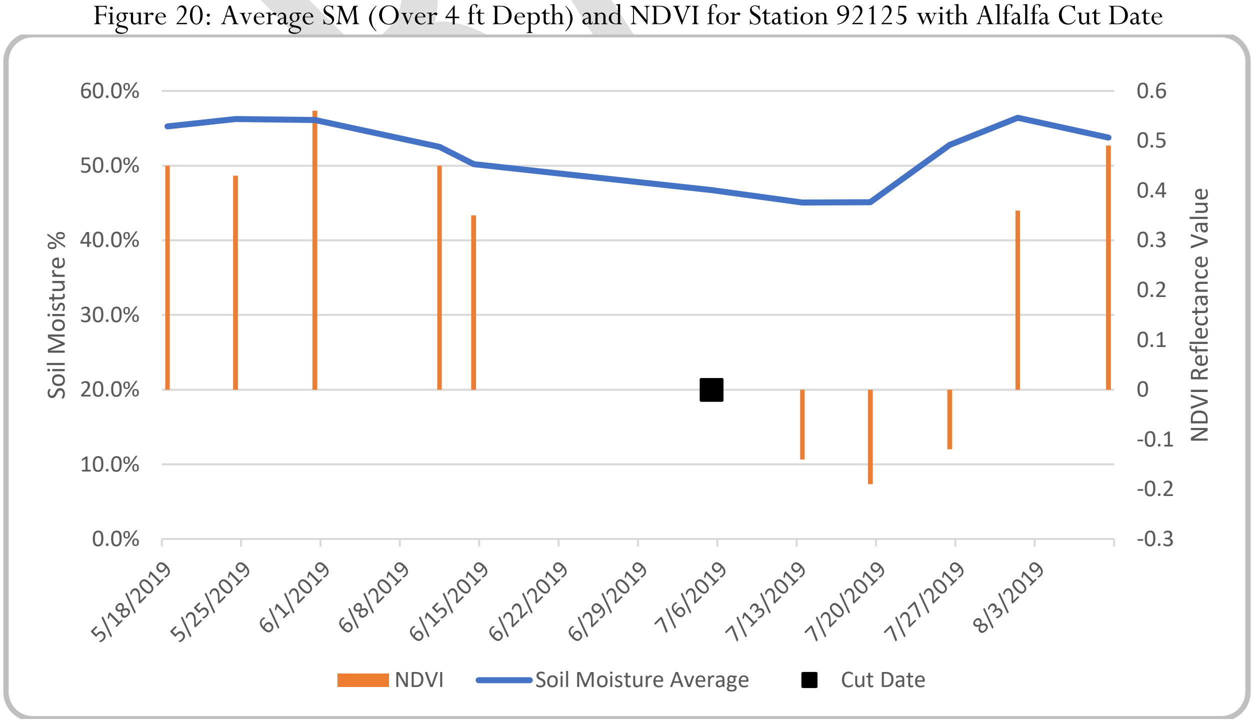


Figure 19 indicates that for a two-week period after harvest, NDVI values remain relatively low even though soil moisture levels within the crop root zone are adequate for full crop water use. This is believed to be caused by low levels of foliage present during the initial re-growth stage of the crop. NDVI values during high-foliage stages of crop growth are more consistent than low-foliage periods but still show up to 5% variation for similar soil moisture contents.

Figure 20 indicates that for a two-week period following harvest, soil moisture remains constant (possibly signifying reduced water uptake from sub-dog-leg soil moisture conditions) until irrigation occurs around day 14. NDVI is negative for the first two weeks following harvest as well as one week following irrigation signifying delayed plant re-growth response after irrigation. NDVI values during high-foliage stages of crop growth are more consistent than low-foliage periods but still show up to 25% variation for similar soil moisture contents.

V.d. Aerial Imaging Conclusions

While multispectral crop imaging using UAVs can prove useful in determining the overall health of a particular crop, reflectance values obtained in this study failed to distinguish between low foliage growth and low soil moisture for approximately 2 weeks following harvest. In addition, NDVI values during high foliage periods showed up to 25% variation for similar soil moisture conditions. Because of the degree of accuracy to which MFE affects ISAM and HI model output, aerial imaging using current reflectance technology may not be appropriate in estimating soil moisture and ultimately MFE.

It is important to note that soil moisture determination using NDVI reflectance values may be more achievable for annual crops such as corn or sorghum since in-season harvest intervals do not occur.

VI. Evaluation of Potential Phase III of Project

The average measured yearly TWFs for the McClave study area during 2017 and 2018 were 4.58% and 5.58% respectively. Average measured yearly TWFs for the Las Animas study area during 2018 and 2019 were 15.66% and 9.67% respectively. The average yearly TWF for all study areas combined during 2018 was 5.58%. These values combined with McClave study area TWFs measured during 2015 (5.3%) and 2016 (4.07%) suggest that actual TWF amounts are consistently lower for single share (per acre) farms than the TWF value used in the HI and ISAM models (9.65%). Measured TWF for the Las Animas study area was consistent with the models during 2019 but higher during 2018. The relatively high variation between the two years suggests that additional tailwater data might be needed in the Las Animas study area to make a definite conclusion regarding actual TWF in areas with higher share to acre ratios.

While measurement of MFE during 2019 (average water diversion year) yielded a value similar to that used in the HI and ISAM models, further modeling of MFE using (2019) measured irrigation set characteristics in combination with irrigation diversion, precipitation, and potential ET data from 2012 (a low water diversion year) yielded an MFE value of nearly 75% (10% higher than HI and ISAM models).

A Phase 3 study could prove beneficial in establishing trends of decreasing water supplies yielding higher farm efficiencies and should be further explored with the possibility of creating an adjustable MFE value in the HI and ISAM models based on water supply and/or soil moisture values.

A third phase of study would most likely focus on irrigation set characteristics (set advance, recession, and cutoff times) and infiltration data over a much larger study area. It may also include additional tailwater data collection on farms with higher share to acre ratios.