DISSERTATION

OPTIMAL WATER ALLOCATION FOR JOINT SUSTAINABILITY OF IRRIGATED AGRICULTURE AND URBAN GROWTH

Submitted by

Manijeh Mahmoudzadeh Varzi

Department of Civil and Environmental Engineering

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Doctoral Committee:

Advisor: Ramchand Oad

Kendall DeJonge
Neil Grigg
Melinda Laituri

ABSTRACT

OPTIMAL WATER ALLOCATION FOR JOINT SUSTAINABILITY OF IRRIGATED AGRICULTURE AND URBAN GROWTH

Historically, agriculture was the main water consumer in Colorado. But the state's demand for water has increased because of rapid urban growth and development of oil and gas industry. Urban communities started buying agricultural water rights to satisfy their growing demands. However, alternative land uses for farms without water right are limited and often they are left fallow. Colorado's newly finalized water plan recognizes agriculture dry-up as one of the primary water challenges of the state and supports projects that explore alternatives to the permanent transfer of agricultural water rights to municipal and industrial users.

This research has investigated deficit irrigation and limited irrigation strategies as methods of reducing farm water consumption as well as methods of temporary transfer of water, viable under Colorado's Water Law. These two sets of information formed a conceptual framework for defining an effective transfer method. An economic model was developed to determine optimal water partitioning between on-farm water uses and off-farm water renting. The model proves partitioning water is only optimal when crop water production function is concave; for linear functions the optimal option is to allocate all farm water to the most profitable.

Field experimentation has determined the effect of water scarcity on agricultural production and revenue. In particular, crop yield response to water stress was quantified in experimental farms for three common crops in Colorado: corn, sunflower, and sorghum-sudangrass. The filed

observations support a linear crop water production function for sorghum-sudangrass and a concave function for corn and sunflower with corn function being more concave than sunflower function.

The economic model was used for South Platte River Basin to determine the minimum renting price of water for water partitioning to be optimal. The results show current renting prices of water in South Platte River Basin are too low and need to increase to more than six times before partitioning of water becomes a worthwhile practice. It was also concluded that two set of engineering tools are required for implementation of deficit irrigation; 1) tools to accurately apply desired amount of water, and 2) tools to measure farm consumptive use on a daily basis. At institutional level, Colorado Water Law's no-injury and anti-speculation rules need to be simplified for deficit irrigation to be a worthwhile alternative method to buy-and-dry.

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As a water engineer I always appreciated our old saying that goes: water is brightness; those ancient people who valued water so dearly were not trying to be poetic, they were realistic.

DEDICATION

دانی عرق نقطه به روی سخن از چیست

بسیار به دنبال سخن‌فهم دویده است

کلیم کاشانی

TABLE OF CONTENTS

ABSTRACT ii

ACKNOWLEDGMENT iv

DEDICATION vi

LIST OF TABLES xi

LIST OF FIGURES xii

NOTATIONS xiv

CHAPTER 1 INTRODUCTION 1

1.1 Problem Definition: Declining Water Availability for Irrigation 1

1.2 Background: Water Right Transfers and Their Impact 2

1.3 Context: Colorado Water Law 5

1.4 Possible Solutions: Alternative Transfer Methods 8

1.5 Research Objective and Questions 9

CHAPTER 2 CONCEPTUAL FRAMEWORK 11

2.1 Components of Water Transfer Plans 11

2.2 Reducing Consumptive Water Use 12

2.2.1 Deficit irrigation 13

2.2.2 Limited irrigation strategies 14

2.2.3 Rotational fallowing 15

2.2.4 Efficiency improvements in irrigation sector 16

2.2.5 Water Conservation Plans 19

2.3 Institutional Frameworks for Water Transfer 19
2.3.1 Water banking 20
2.3.2 Interruptible supply agreements 22
2.3.3 Water cooperatives 23
2.4 Recharge Structures 24
2.4.1 Recharge ponds 25
2.4.2 Augmentation stations 27
2.5 Water Transfer Example: Super Ditch 27
2.6 On Regulating Deficit Irrigation 29
2.6.1 Crop water production functions and their evolution 30
2.6.2 Optimal water allocation at farm level 37
2.6.3 Farm income improvement due to deficit irrigation 43
CHAPTER 3 STUDY AREA 46
3.1 Study Area: Weld County, Colorado 46
3.2 Experimental farms 49
3.2.1 Subsurface Drip Irrigation Efficiency Project 50
3.2.2 Limited Irrigation Research Farm 55
CHAPTER 4 MATERIALS AND METHODS 57
4.1 Choice of Crops 57
4.2 Irrigation Treatments 58
4.3 Measurements and Instrumentation 61

4.3.1 Soil water content measurements ... 62
4.3.2 Crop canopy cover ... 62
4.3.3 Yield ... 63
4.4 Calculations and Procedures ... 64
4.4.1 Evapotranspiration ... 64
4.4.2 Crop productivity indices ... 66
4.5 Statistical analysis ... 67
CHAPTER 5 RESULTS ... 69
5.1 Sorghum-sudangrass ... 69
5.1.1 Sorghum-sudangrass crop water production function ... 71
5.1.2 Optimal water allocation for sorghum-sudangrass ... 72
5.1.3 Sorghum-sudangrass hay quality ... 72
5.2 Corn ... 73
5.2.1 Corn crop water production function ... 75
5.2.2 Optimal water allocation for corn ... 76
5.2.3 Corn farm income improvement due to deficit irrigation ... 79
5.3 Sunflower ... 84
5.3.1 Sunflower crop water production function ... 85
5.3.2 Optimal water allocation for sunflower ... 86
5.3.3 Sunflower farm income improvement due to deficit irrigation ... 89
5.4 Discussion ... 93

5.4.1 Implication of research results for Colorado 93

5.4.2 Deficit irrigation 99

CHAPTER 6 CONCLUSIONS 102

REFERENCES 109

LIST OF TABLES

Table 1 Main independent variable influence farm income increase due to deficit irrigation 45

Table 2 Common crops of Weld County in 2016 47

Table 3 SIEP farm target water regimes as percent of non-stressed crop evapotranspiration 59

Table 4 Irrigation treatments in LIRF in vegetative and maturation stages 60

Table 5 LIRF crop blocks 60

Table 6 Components of soil water balance and yield for sorghum-sudangrass 2015-2016 69

Table 7 Components of soil water balance and yield for corn, obtained in Greeley, 2008-2011. 74

Table 8 Corn farm optimal water allocation for Northeastern Colorado 77

Table 9 Components of soil water balance and yield for sunflower, in Greeley 2008-2011 84

Table 10 Sunflower farm optimal water allocation for Northeastern Colorado 87

LIST OF FIGURES

Figure 1 Colorado Big Thompson Project command area and changes in its shares ownership ... 3

Figure 2 Schematic presentation of function of a recharge pond 25

Figure 3 Recharge ponds on Subsurface Irrigation Efficiency Project, in Kersey, CO................ 26

Figure 4 Augmentation station.. 27

Figure 5 Generalized relationship between yield and water amount... 36

Figure 6 Schematic presentation of optimal water allocation.. 41

Figure 7 Optimal water allocation for linear crop water production function............................. 42

Figure 8 Colorado Division of Water Resources divides the state into seven water divisions ... 47

Figure 9 Study area, Location of Weld County in South Platte Basin 48

Figure 10 Location of LIRF and SIEP around Kersey, Weld County, CO 49

Figure 11 Subsurface Drip Irrigation Project (SIEP) research farm, on U.S highway 34............ 50

Figure 12 SIEP farm soil texture classification 51

Figure 13 Layout of irrigation system in SIEP farm.. 52

Figure 14 SIEP filter house.. 53

Figure 15 KSY02 weather station of Colorado Agricultural Meteorological Network................ 54

Figure 16 Limited Irrigation Research Farm plot layout... 56

Figure 17 Crop growing seasons and approximate ground cover during each growth stage 58

Figure 18 Treatments applied to SIEP farm zones; colors delineate a block 60

Figure 19 sorghum-sudangrass canopy picture and classification on July 7th 2015, 7% vegetation cover.. 63

Figure 20 Components of soil root zone water balance... 66

Figure 21 Sorghum-sudangrass crop water production function 71

Figure 22 Nitrate content in sorghum-sudangrass dry hay versus actual crop evapotranspiratio 73

Figure 23 Corn crop water production function 75

Figure 24 Corn minimum required renting price of water as a function of farm achievable ET . 79

Figure 25 Corn farm income increase due to deficit irrigation (*inc*) versus θ 80

Figure 26 Corn farm income increase due to deficit irrigation (*inc*) versus σ 81

Figure 27 Corn farm income increase (*inc*) due to deficit irrigation versus effective rainfall 82

Figure 28 Corn farm income increase due to deficit irrigation versus price of crop 83

Figure 29 Sunflower crop water production function 85

Figure 30 Sunflower minimum required renting price of water as function of achievable ET 88

Figure 31 Sunflower farm income increase due to deficit irrigation (*inc*) versus θ 89

Figure 32 Sunflower farm income increase due to deficit irrigation (*inc*) versus σ 90

Figure 33 Sunflower farm income increase due to deficit irrigation (*inc*) versus *ER* 91

Figure 34 Sunflower farm income increase due to deficit irrigation versus price of crop P_y 92

Figure 35 Farmer's decision space when considering deficit irrigation 98

NOTATIONS

˚C	Degree Celsius
a	Parameter of quadratic crop water production function
adj_R^2	Adjusted R^2
ac	Acre
AF	Acre-foot
ARDEC	Agricultural Research, Development and Education Center
ARS	Agricultural Research Service
ASCE	American Society of Civil Engineers
ATM	Alternative Transfer Methods
aw	Available water
AWYR	Relationship between yield and available water
b	Parameter of quadratic crop water production function
bu	Bushel
c	Parameter of quadratic crop water production function
$C(ET_a)$	Cost of agricultural production as a function of actual evapotranspiration
$c(w_y)$	Cost of agricultural production as a function of irrigation water used
C-BT	Colorado-Big Thompson
CDWR	Colorado Division of Water Resources
CU	Consumptive use
CWP	Crop water productivity
CWPF	Crop Water Production Function

cwt	hundredweight
D	Total dry matter
DP	Deep percolation
e	Irrigation application efficiency
E_o	Average free water surface evaporation
ER	Effective rainfall
ET	Evapotranspiration
ET_a	Actual crop evapotranspiration
ET_m	Maximum crop evapotranspiration when soil water in not limiting
FAO	Food and Agricultural Organization
FAO 56	Food and Agricultural Organization Irrigation and Drainage Paper 56
FAO 33	Food and Agricultural Organization Irrigation and Drainage Paper 33
f_c	Percent of ground covered by green canopy
g	Parameter of linear crop Water Production Function
h	Parameter of linear crop Water Production Function
ha	Hectare
i	Crop growing stage
I	amount of applied irrigation
inc	Farm income increase due to deficit irrigation
$IWUE$	Irrigation water use efficiency
K_{cb}	Basal crop coefficient
K_e	Evaporation component of crop coefficient
K_s	Water stress factor

Ky	Yield response factor
LFT	Lease Fallow Tool
LIRF	Limited Irrigation Research Farm
m	meter
m	Crop factor in de Wit's model
M&I	Municipal and Industrial
m^3	Cubic meter
$maxP_{off}$	Maximum allowable net leasing price of water
MCM	Million Cubic Meter
$minP_{off}$	Minimum required net leasing price of water
mm	millimeter
mv	Marginal Value
n	Crop factor for humid condition in de Wit's model
N	Number of growing stages in Jensen's model
np	number of predictors
NPSHr	Required Net Positive Suction Head
P	Precipitation
P_{off}	Net off-farm price of water
P_s	Net selling price of unit of water right
P_y	Price of unit of yield
R^2	Coefficient of determination
RAW	Relative available water
RO	Surface runoff

SIEP	Subsurface Irrigation Efficiency Project
ss	sample size
SWSI	Statewide Water Supply Initiative
t	Water travel time as groundwater
T	Transpiration
USDA	United States Department of Agriculture
UF	Upflux of water from groundwater
$V(ET_a)$	Value of water in farming
W	Farm's total available water
WBWG	Water Bank Work Group
w_{off}	Amount of water allocated to off-farm activities
WUE	Water use efficiency
w_y	Amount of water allocated to crop production
x	Crop parameter in de Wit's model
y	General crop factor in de Wit's model
Y	Obtained marketable yield
$Y(ET_a)$	Obtained marketable yield as a function of amount of ET
$y(w_y)$	Obtained marketable yield as a function of amount of water
Y_a	Actual crop yield
Y_m	Maximum crop yield
ΔS	Change in soil water content in the root zone
α	Marginal variable costs of production
β	Fixed costs of production

θ	Marginal variable cost of increasing a unit of ET_a
λ	Crop relative sensitivity to water stress
σ	Constant of cost function

CHAPTER 1 INTRODUCTION

1.1 Problem Definition: Declining Water Availability for Irrigation

In Colorado, demand for water has increased at a very fast pace due to rapid urban growth and newly developing oil and gas industry (Colorado Water Conservation Board, 2015). Currently, available fresh water supplies are very limited and fully appropriated among existing water users. Therefore, urban communities started buying agricultural water rights to satisfy their growing demands. This tactic may leave the land without water right fallow; a practice so common that has received a title: “buy and dry”.

Urban communities need water and can afford its high price while farmers are often willing to sell their water rights and retire. So in pure monetary terms, this transfer is simply flow of a commodity (water) from low value use (agriculture) to a high value use (municipal and industrial a.k.a. M&I) and may seem to be a win-win situation (Howe et al., 1990). However, as agricultural economy disappears from the region, concerns have been raised about negative social and economic effects of “buy and dry” on rural communities and the state’s food security, as well as its negative environmental impacts (Ag Water NetWORK, 2016). Therefore, some middle ground is sought so that agriculture and urban users can both benefit from water resources.

Colorado’s Water Plan (Colorado Water Conservation Board, 2015) puts forward methods that can be adopted by agricultural sector to free up water for M&I sector. The plan was released by Governor of Colorado in 19, November 2015 and provides guidelines for new laws, regulations and projects related to the State’s water resources. This chapter provides a background to understand the impact of “buy and dry” and state’s interest to avoid it; which are also the motivation for the current research.

1.2 Background: Water Right Transfers and Their Impact

By the 1970s Colorado’s water supplies have been almost fully appropriated by different uses (Pritchett and Thorvaldson, 2008). However, population growth has continued, forcing municipalities to seek water in agriculture sector. The first major water right transfer from agriculture to the city of Pueblo occurred in 1965 from Otero Canal in Arkansas River Basin (Sutherland and Knapp, 1988) in southern Colorado. By 1988, water has been removed from 59% of prime agricultural lands in Arkansas River basin (*ibid*) leaving previously productive lands fallow. Purchase of water rights from agriculture for urban areas has ever since become the common water appropriation strategy for cities, an “inevitable” process as described by Pritchett and Thorvaldson (2008).

More recent data on South Platte River Basin shows a constant transfer of water right from agriculture to cities. According to Statewide Water Supply Initiative (SWSI) report (Colorado Water Conservation Board, 2010) total municipal and industrial water use in the South Platte River Basin was 254 million cubic meters (MCM) (206,000 acre-feet (AF)) in 2008. The report predicts that this will reach an amount between 428 MCM (347,000 AF) and 495 MCM (401,000 AF) in 2050.

The same source estimated agricultural water demand for irrigation 1,845 MCM (1,496,000 AF) during 2008 of which only 1,378 MCM (1,117,000 AF) was supplied in South Platte Basin. Agricultural demand is expected to reduce because of the reduction of irrigated land, due to urbanization and water transfers. Moreover, in 2006 a shortage of augmentation water led to large scale well shut down in the central South Platte Basin. Consequently, a significant part of irrigated land has been gradually taken out of production. The 2010 SWSI report predicts this trend will continue since the cost of acquiring augmentation water in the central South Platte Basin is prohibitive for the agricultural community. So, by 2050, irrigated land is estimated to reduce to 246 thousand hectare (ha) (607,000 acres (ac)) and irrigation requirement to 1,349 MCM (1,094,000 AF).

An example of water reallocation trend in Colorado is the change in owned shares of Colorado-Big Thompson (C-BT) Project. This Project transports water from the upper Colorado River Basin, west of the continental divide, to Colorado's eastern slope via a tunnel system. Northern Colorado Water Conservancy District provides the project's water resources management, project operations, and conservation services. Figure 1 illustrates the gradual change in owned shares of C-BT from agriculture to M&I. Still, in 2016, the actual amount of water used in agriculture was 50% of C-BT water delivery (personal communication[1]) because, during wet years, M&I water right holders sell their excess water back to agriculture. The C-BT's command area is also given in Figure 1.

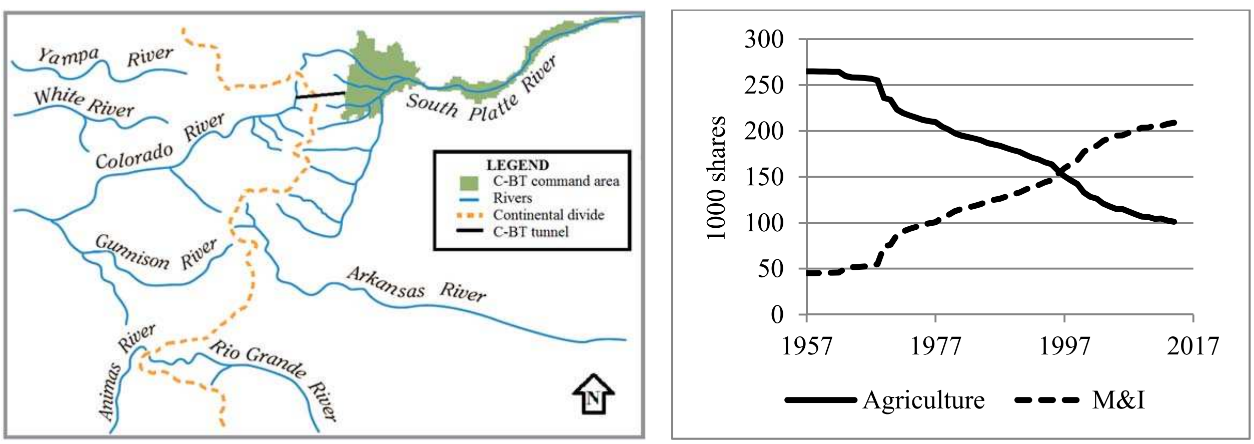


Figure 1 Colorado Big Thompson (C-BT) Project command area and changes in its shares ownership[2]

[1] Email communication with Roger Burns of Northern Water district

[2] Map adapted from Northern Water website and graph courtesy of Zach Allen of Northern Water District

Pritchett and Thorvaldson (2008) believe rural economies are at risk because of the large scale and fast pace of this reallocation trend. In a preliminary study of water right transfer in Yuma County, Colorado, Pritchett and Thorvaldson (2008) predicted that 7,700 ha (19,000 ac) of land would have gone fallow due to the transfer. They predefine three kinds of effects from this transfer on the rural economy; 1) direct effects due to decreased revenue flow from the sale of irrigated crops, 2) indirect effect on businesses depending on agriculture due to reduced demand for agricultural inputs, and 3) induced impact due to change of demand for agricultural labor and decrease of employment. Schaffer and Schaffer (1984) expect the decline of farm income to reallocate wealth, resources and population; they explain that migration out of rural areas has adverse impact on local governmental and private services, eroding the rural infrastructure and social institutions.

There are also environmental concerns about agricultural lands that are left unirrigated. For example, after water right transfers of the 1980s in the Arkansas River Basin, where natural precipitation is inadequate for dryland farming, wind erosion increased drastically (Sutherland and Knapp, 1988). In areas with more precipitation non-native plants take over the fallow lands and serious dust storms create public safety issues (Devine, 2015). Now Colorado water court's water transfer decrees require the revegetation of irrigated land to rangeland (*ibid*). Revegetation is not required when water is rented out of farm and the water right is not sold (DiNatale Water Consultants, 2013).

Howe et al. (1990) analyzed the economic impacts of agricultural to urban water transfers on Arkansas River Basin and concluded that effects were not dramatic on the basin's overall economy. There were, however, third parties who were not directly involved in the transaction, but have suffered from water transfers. A recent study (Devine, 2015) found that transitional assistance to these third parties was opposed by municipal planners and rural leaders “on philosophical grounds or grounds of efficacy”.

Literature on impacts of buy-and-dry is either outdated, or based on preliminary studies before the actual implementation of water transfer. There is a lack of new studies on social and economic impact of more recent water transfers. Nevertheless, as apparent in Colorado’s Water Plan, State of Colorado is now interested in finding alternative transfer methods (ATM) so that both urban and agricultural water users benefit from the State’s limited water resources.

1.3 Context: Colorado Water Law

All water transfers occur under provisions of the Colorado Water Law and must be adjudicated by the Colorado Water Court. Colorado water law follows a strict prior appropriation system of water allocation (Jones and Cech, 2009). Prior appropriation system is described as “first in time, first in right” (Hobbs, 2004). Senior water right holders can take their full allocated right before junior right holders can divert any water. This means in times of scarcity junior right holders may not receive their water allocation because the senior right holders have already diverted all the available water.

Colorado’s water law is rooted in the mid-19th century Gold Rush era (Smith, 2009). Mining depended on water for washing dirt and extracting gold. But goldfields were not necessarily close to water sources so water was conveyed from far distances with sluices. Miners put claim on mineral deposits with the theory of “first in time first in right” which they also applied to water rights (Smith, 2009, p.39) even though a riparian doctrine was legally in place in the United States. In 1855, California Supreme Court recognized prior appropriation system for water which was then adapted by Colorado miners during Colorado gold and silver rush (Jones and Cech, 2009). Under the irrigation act of 1879 and 1881 “anyone with a legitimate interest can petition the district court for the adjudication of rights on a stream" (Maass and Anderson, 1978).

For a share of surface water, users apply for water right in court showing proof of beneficial water use. Beneficial use was commonly delineated for household, agricultural and industrial purposes. But it has evolved to include environmental and ecological uses also (Hobbs, 2004). The court will adjudicate a water right decree specifying the priority date, its source of supply, amount, point of diversion, type and place of use, and includes conditions to protect against injury to other water rights. The concept of "beneficial use" has a central role in Colorado's water law. A water right holder must in fact use water for the specified beneficial use without being wasteful; otherwise the court can curtail the right.

Groundwater follows the same regulations when it belongs to the category of tributary water. Tributary waters are defined as stream waters and the groundwater aquifers that are hydrologically linked to them. For example, extracting groundwater depletes stream flows. For this reason, the water rights associated with these aquifers are similar to that of stream flows, i.e. a well has a decree with a priority date (Jones and Cech, 2009).

Currently water supplies of Colorado are fully appropriated (Pritchett and Thorvaldson, 2008). A new user can apply and acquire a water right but in a normal year, no water is left for such user after senior right holders divert their shares. Therefore, Colorado water law recognizes augmentation plans since 1969. "Augmentation plans allow for out-of-priority diversions by replacing the water that junior water users consume" (Hobbs, 2004). The replaced water, however, should resemble the senior water right in time, quantity, quality and place of diversion. For example, a junior right holder can build groundwater recharge ponds and store stream water during non-growing season. The recharge pond is designed so that it feeds the stream flow from which senior right holders take their share of water (also see section 2.4.1 on page 25). Augmentation plans must be approved by regional water courts.

In Colorado, water rights are tradable and separable from the land they are used on (Goemans and Pritchett, 2014); therefore, a new water user can buy a senior water right and enjoy the priority in water diversion. However, water right holders do not own the water; they can only use the appropriated water for the specific beneficial use stated in their adjudication (Article 16 § 5 Constitution of the State of Colorado); this means, for example, they cannot reuse their return flows. In agricultural lands where surface irrigation methods (*e.g.* furrow, flood, and basin) are used, much of water use is due to losses to the ground water and run-off at the tail end of farms. These losses rejoin the basin's hydrologic cycle and are reused in the downstream several times. Thus, a reduction in use, an increase in irrigation efficiency, or change in location of use may injure the water users who benefit from return flows.

This brings up another central concept of Colorado Water Law when decreeing change of use which is the "no injury" rule. Per this rule a change in water right use cannot injure other water users and hence the return flow must be maintained as before the change. This means return flows must resemble to that of before the change in volume, location and time. Colorado Revised Statute § 37-92-305(3) expresses this rule as follows: "A change of water right, implementation of a rotational crop management contract, or plan for augmentation, including water exchange project, shall be approved if such change, contract, or plan will not injuriously affect the owner of or persons entitled to use water under a vested water right or a decreed conditional water right." It is upon the applicant of water right transfer (the seller and the buyer), and not the opponents, to prove the transfer do not cause any such injuries. In water court proceedings, the historic rates of consumptive use and return flows are determined before a change in water use is decreed. This is done for a substantial period of time to account for the consumption variability over the years (MacDonnell, 2015).

Efficient irrigation systems (center pivot or drip irrigation as compared to furrow or flood irrigation) can considerably decrease irrigation losses and hence decrease the return flow. But per Colorado Water law, water saved using a more efficient irrigation system, cannot be sold (Smith and Smith, 2013) or reused: in agricultural lands, only the consumptive use can be sold or rented to other uses. Moreover, a court can interpret the ability to conserve water as evidence that past uses were wasteful and reduce the consumptive use associated with the water right (MacDonnell, 2015). In this way, Colorado water law discourages on-farm water savings through efficiency improvement.

Additionally, if water right holders fail to put their allocated water into beneficial use for more than ten years, they could have their rights curtailed. Although in practice water court have provisions to reserve farmers' water right when they reduce water losses (Senate Bill 05-133 and Senate Bill 13-019), farmers are still reluctant to save water in the fear of losing their water right (Waskom et al., 2016).

Water transfer in Colorado has a long complicated process due to no injury rule. Macdonnell et al. (1990) describe it as a highly legalistic approach. They found the procedure is markedly slower than the other states they studied. Kenney (2015) has compiled all the challenging legislations that must be fulfilled before a water transfer is decreed by Colorado's Water Court.

1.4 Possible Solutions: Alternative Transfer Methods

Colorado's Water Plan (2015) is interested in keeping the State's agriculture sector productive. The overall objective of the plan for the sector is "that agricultural economic productivity will keep pace with growing state, national, and global needs, even if some acres go out of production." It also expects the agricultural community to release at least another 62 MCM (50,000 AF) of water by 2030 to be used in urban areas. The plan does not set measurable objectives in supporting agriculture and fails to define specific measures for achieving the overall objective, instead suggests possible alternative transfer methods (ATM).

In the context of Colorado's agricultural water transfer, ATMs are methods of water transfer that avoid the practice of "buy and dry" (CDM Smith, 2011). These are lease-fallowing agreements, deficit irrigation, water banking, interruptible supply agreements, rotational fallowing, water conservation programs, and water cooperatives. The alternative methods are different from "buy-and-dry" in that the ownership of water right stays in agricultural sector, land is not permanently taken out of production, and water transfers are temporary (Kenney, 2015). Alternative methods of water transfer will be discussed in the next chapter.

1.5 Research Objective and Questions

Alternative transfer methods have inspired several research projects with the aim of examining their practicality and possibilities of adapting them to Colorado's conditions. This dissertation, in line with other efforts, investigated the alternative ways to the current practice of buy-and-dry so that negative impacts of water scarcity at farm level are minimized and water preserved on-farm can be transferred to urban areas. As such the main objective of this research is: **Investigating different strategies for water conservation in irrigated agriculture sector to free up water for urban users**

The specific research questions are:

- What is the effect of reducing consumptive water use on crop productivity?
- What is the effect of reducing consumptive water use on farm income?
- What is optimal water allocation between farm and urban areas?

The alternative transfer methods, listed in Colorado's Water Plan and other related literature, are studied here. The research has an interdisciplinary approach linking agricultural engineering and economy and focuses on modeling optimal water allocation between agricultural and M&I uses.

CHAPTER 2 CONCEPTUAL FRAMEWORK

Literature review and study of current situation of water transfers in Colorado has provided the research framework, which is presented in this chapter.

2.1 Components of Water Transfer Plans

Colorado's Water Plan (2015) and Statewide Water Supply Initiative (2010) define several methods of water reallocation with the objective of avoiding complete fallowing of agricultural lands. The scopes of these alternative transfer methods are different and it is helpful to divide them into three categories. These are: (i) on-farm methods to reduce agricultural consumptive water use, (ii) institutional frameworks to facilitate the transfer of water, and (iii) engineering techniques or structures to ensure proper and accurate replacement of water rights without injuring third party water right holders. This last category is not mentioned in Colorado's official documents as they mainly focus on decision making level rather than engineering level.

Any water reallocation plan has to contain one method from each category in order to successfully conduct the transfer under Colorado's water law. First, water consumption needs to be reduced at farm level using methods such as deficit irrigation, rotational fallowing, or other limited irrigation strategies. Transfer of water saved on individual farms is not practical or beneficial for urban water users. Therefore, larger entities such as ditch companies or irrigation districts use mechanisms such as water banks and interruptible supply contracts to reallocate water. Finally, the water transfer might injure senior water right holders whose water sources are hydraulically interlinked with the transferred water. Specific structures are required to compensate the injured rights if any. These structures are called recharge structures in this document. Examples are augmentation stations and recharge ponds.

A water transfer plan is not complete without including one method from each category described above. Therefore, rather than categories, describing them as the three “components” of water transfer is more explanatory and relevant. Neither Colorado’s Water Plan nor the Statewide Water Supply Initiative (2010) distinguishes the functional differences of their suggested methods. In recent years, several transfer agreements in Colorado have adapted the alternative methods, such as Catlin Canal’s lease-fallowing agreement (see Page 27) or Northeast Colorado Water Cooperative (see Page 23). Study of these agreements shows that they include all the three required components of water transfer. Recognizing these components will help policy makers to have more holistic view of water transfer.

2.2 Reducing Consumptive Water Use

Consumptive use in agriculture is the amount of water that is used by crop for growth. As it will be shown later, this is equal to crop evapotranspiration (see page 29). This water is evaporated from soil surface or transpired through plant tissues and does not return to water sources. Water that is applied to crop but leaves the farm as surface run-off or deep percolation is called return flow because it joins water sources and can be used downstream. Sometimes crop production needs additional water for salt leaching or land preparation, or subsurface drip irrigation systems are injected with an anti-rodent agent at the end of growing season. These types of water uses are also considered consumptive use although water is not consumed by crop and often returns to the water sources.

Colorado’s Water Plan only mentions deficit irrigation as a method to reduce consumptive use. The water plan does not provide a definition of this term and therefore deficit irrigation and limited irrigation are used interchangeably in many research and policy documents. Here the two terms are used for two different practices as will be discussed presently. Rotational fallowing is another method of reducing consumptive use at farm level. Conservation plans are designed to reduce household water use. These methods are discussed in this section together with efficiency improvement in irrigation sector for thoroughness.

2.2.1 Deficit irrigation

Irrigation is a way to supplement the water needs of crops and produce higher yields. Deficit irrigation is defined as "the deliberate under-irrigation of the crop" (English, 1990) that reduces crop yield but saves some water at the farm level. The saved water can be sold or rented for off-farm uses including municipal and industrial (M&I) needs.

This type of water saving is different than reducing water losses due to irrigation and farm management inefficiencies. It is giving up a part of crop water requirement, which will then reduce the crop yield. Advocates of deficit irrigation argue that with optimal water allocation to on- and off-farm activities farmers can increase their net return from their water right. They reason that the combination of the return from crop production plus the return from water market may be larger than either one alone (English and Raja, 1996; Fereres and Soriano, 2007). In other words, when water is a limiting factor, farmers can aim to stabilize crop yield and reach maximum economic income per volume of used water rather than maximum yields (Geerts and Raes, 2009). Zhang (2003) argues that the risk of deficit irrigation is low because crop production function has a wide plateau therefore a considerable percentage of irrigation water can be saved without significant yield reduction.

The main objective of deficit irrigation is to maximize farm income by taking advantage of opportunity cost of water. In this practice the farm available water is not necessarily lower than farm required water but there are other opportunities for use of water. In other words, there is a market for water and therefore farm income can be improved by renting a part of its water.

2.2.2 Limited irrigation strategies

Literature review shows the terms “limited irrigation” and “deficit irrigation” are used interchangeably referring to application of irrigation water with amounts lower than crop water requirement. However, here deficit irrigation is defined as practice of retaining crop water requirement with purpose of leasing the retained water and maximizing farm income. Limited irrigation, on the other hand, is a condition imposed on agricultural lands due to limited available water. Reasons could be declining well capacity (Kisekka et al., 2017), government restrictions on groundwater or surface water withdrawal (Rudnick et al., 2017), or untimeliness of water supply. Experimental research in central plains of United States have tried to define the best time and amount of water application under limited irrigation conditions. The purpose of these research efforts is to help farmers to maximize their yield when crop full water requirement cannot be satisfied (Schneekloth, 2015).

Three main strategies are adopted to cope with limited water supplies (Rudnick et al., 2017): (i) plant crops with less water requirement (Farré and Faci, 2006); (ii) reduce land under a conventional crop with high water requirement so that available water is sufficient for full irrigation of crop, plant the rest of the land under rain-fed agriculture or leave it fallow; (iii) time water stress so that yield reduction is minimized. Combining two or all above strategies, farmers can often cope better with water shortage.

Past research shows that crop responses differently to water shortage in different stages of growth (Doorenbos and Kassam, 1979; Gerik et al., 1998; Payero et al., 2006; Shaner, 2012; Tolk and Howell, 2003; Zhang, 2003). Most crops have the highest sensitivity to water stress during the reproductive stage. Also, water stress during the initial growth stage needs to be avoided to ensure good crop stand and later sufficient crop cover. Therefore, extension specialists recommend providing full crop water requirement during reproductive stage and apply partial irrigation during vegetative and maturation stages (Irmak and Rudnick, 2014; Klocke et al., 2006; Lamm et al., 2014). This last strategy is often combined with practices such as reduced tillage and crop residue management in order to retain soil profile water for the next season. It has also been shown that crop rotation can increase yield, versus planting the same crop every year (Schneekloth et al., 1991).

Colorado Water Conservation Board (CWCB) has been supporting these kinds of programs through Alternative Agricultural Water Transfer Methods Grants since 2009 (CDM Smith, 2012). Colorado State University Extension has also developed research projects to test different cropping rotations (Schneekloth, 2015). Likewise, USDA's Agricultural Research Services supports projects with the aim of coping with limited irrigation (Hansen et al., 2011).

2.2.3 Rotational fallowing

Land fallowing is practiced by farmers as a strategy to cope with limited water. When farm's available water is not enough to irrigate the entire farm, a part of farm is left fallow. When water is continuously limited each year the fallowed land is rotated within the farm (Colorado Water Conservation Board, 2015). Land fallowing has also been used to reestablish depleted soil minerals (Clark, 2007). While the objective of deficit and limited irrigation is to spread the insufficient amount of water over the entire farm, in rotational fallowing farmers fully irrigate parts of their land. This method is suggested to provide additional water to meet new demands or to replace the existing yield of nonrenewable groundwater supplies (CDM Smith, 2011).

On one hand, farm economic return will reduce due to fallowing, directly, because of less agricultural production and indirectly due to costs of land, equipment and management (Hansen et al., 2010). Moreover, as Colorado’s Water Plan (2015) describes, revegetation protection, erosion control, and weed control become important considerations during fallowing.

On the other hand, the consumptive use is reduced to zero in this practice. While in deficit irrigation the consumptive use is decreased and the reduction has to be measured and the return flow associated with that reduction has to be estimated. Therefore, implementation of rotational fallowing under Colorado water law is more practical. MacDonnell (2015) suggests focusing on rotational fallowing as a process to implement alternative transfer methods.

2.2.4 Efficiency improvements in irrigation sector

Although thermoelectric is the largest water use category in the United States, irrigation remains the largest *consumptive* water user with 128,000 million gallons per day (The USGS Water Science School, 2010). In irrigation systems, the amount of water diverted from natural water sources (streams, lakes, groundwater, etc.) is always significantly larger than crop water requirement due to system losses. Because of inefficiencies in water conveyance infrastructure or irrigation systems, losses occur along the conveyance path or on-farm after water is applied to the crop. At the farm level a part of applied irrigation water is lost to deep percolation, surface run-off.

In the study area, efficiency measurement in Central Water Conservancy District shows that irrigation efficiency of surface systems ranges between 7% and 70%, with an average of 33% (Emond et al., 1993). Modern pressurized systems, however, can increase the efficiency to 90% or more with proper water management practices (Coleman, 2016). This increase is achieved mainly due to shortening the distance between water application point and soil root zone where water is consumed by crop. For example, in furrow irrigation water is applied at the head of a field and has to travel to the end of the field; a considerable amount of water is lost in this process to runoff and deep percolation, without being used by the crop. But in a pressurized irrigation system like center pivot or drip irrigation, water is applied with sprinklers or emitters at the location of each plant; therefore, losses due to deep percolation or surface run off can be minimized. Subsurface drip irrigation system localizes water application even further to the root zone where it is at the crop root's disposal.

Although pressurized irrigation systems need high initial investment, they allow farmers to benefit more from their available water. They are interesting conservation tools because by lowering farm water requirement, less water needs to be diverted for agricultural uses; the saved water can benefit other users or stream habitats(Oad and Kullman, 2006). However, in fully developed basins such as many basins in eastern Colorado, water distribution system has already been established. All the losses in one farm return to the basin's hydrological cycle through surface streams or groundwater; hence, called return flow. Therefore, the lost water on one farm will be available for another user at some point downstream (Smith et al., 1996). In fact, in overly developed basins water is used several times before it exits the basin's hydrological cycle.

Although use of modern irrigation systems allows farmers to reduce their farm water consumption, the saved water is often used to expand land under irrigation, especially in arid Colorado where farmers have more land than they can irrigate (Ward and Pulido-Velazquez, 2008). These systems also allow frequent irrigation application as needed, and therefore, increase water use (Green and Hamilton, 2000). There is evidence that increasing irrigation efficiency have increased water consumption because of improved irrigation uniformity and increased crop evapotranspiration (Clemmens and Allen, 2005). In this way, farm return flow becomes unavailable for the downstream users who previously could receive it through stream flows or groundwater (Pereira et al., 2012). Perhaps, for this reason in Colorado, farmers are not permitted to rent or sell such savings to off-farm users. Water right holders only own the beneficial or consumptive portion of their water right. Per Colorado Water Law, farm and system losses are not part of beneficial use.

At basin level, the development of irrigation networks and ditches establishes a new hydrologic cycle. For old systems, this human-influenced cycle has already altered the availability of water in different parts of the basin and water extraction patterns are adapted to the altered hydrologic cycle (Perry, 1999). While delivery system modernization can be beneficial (Oad and Kullman, 2006) it will not create new water at basin level (Allen et al., 2003). Increasing the conveyance efficiency of existing irrigation canals will take the saved water out of the reach of downstream users (Samani and Skaggs, 2008). Thus, planners need to consider the effect of the conservation programs on the downstream water users and basin-wide (Allen et al., 2003).

Likewise, modern water delivery systems are employed mainly to control water levels and flows in the canals so that water can be distributed on farmers' demand and not by water availability or convenience of irrigation district. They also enable ditch riders to accurately measure water delivered at every outlet, which is required for water accounting (Stringam et al., 2016).

The popularity of modern irrigation systems are mainly due to their adaptability to automation, being less labor intensive, and in case of drip irrigation being adaptable to diverse topography (Kooij et al., 2013). In Colorado, use of subsurface drip irrigation systems (SDI) is increasing among farmers (Bartolo, 2005) and researchers (Mahmoudzadeh Varzi and Oad, 2016). In research farms this has been mainly due to flexibility of irrigation control and ease of farming practices. Also in Lower Arkansas River Basin, SDI system improved melon yield quality (Bartolo, 2005).

Colorado water law does not encourage irrigation efficiency improvement at farm level and Colorado's Water Plan does not include such programs as an alternative transfer methods. Instead, "Water Conservation Plans" are encouraged for households (see below).

2.2.5 Water Conservation Plans

Although most statewide efforts are focused on reducing agricultural water consumption, there are conservation programs that try to reduce household water use. In this way, less water will be required for urban areas. Colorado Water Conservation Board supports these plans through "Water Efficiency Grant" (Colorado Water Conservation Board, 2005). In their website water conservation is defined as "any beneficial reduction in water loss, waste, or use … by implementation of water conservation or water efficiency measures. It is improved water management practices that reduce or enhance the beneficial use of water." Although this broad definition can include agricultural water conservation plans, the grant only covers entities that provide water to domestic, commercial, industrial, or public facility customers (*ibid*). For example cities of Ouray and Westminster and Security Water District in Colorado Springs have used this grant to fund or develop a water conservation plan.

2.3 Institutional Frameworks for Water Transfer

An institutional framework is generally understood as the system of formal regulations and informal norms that form and restrain socioeconomic activity (Donnellan et al., 2012). In the context of Colorado's water transfer, institutional frameworks are mechanisms required to ensure legal and efficient transfer of water. Farmers can conserve water on their farms but individual farmers do not, necessarily, have access to transfer structures. Besides, the amount of water saved on one farm is usually not sufficient for municipal uses and therefore, leasing water collaboratively among multiple farms is more efficient. The institutional frameworks suggested by Colorado's Water Plan are water banks, interruptible supply agreements, and water cooperatives.

2.3.1 Water banking

A water bank is a mechanism for temporary water reallocation (Goemans and Pritchett, 2014). In this form of transfer, volunteer water right holders sell their water to interested water users. The ownership of water right, however, will remain with the original right holders. Here a volume of water is sold, but not the water right itself. This transaction is possible through a bank that stores water either physically or as a freed-up portion of a canal's water right (Singletary, 1998).

Colorado General Assembly authorized the first pilot water bank in 2001. The next year, the State Engineer established rules for Arkansas Basin water bank upon request by Southeastern Colorado Water Conservancy District. A few storage rights were deposited in the bank but none were leased (Castle and Macdonnell, 2016), due to high prices ($800-$1000 per AF per year) and the absence of storage facility (*ibid*). Currently a Water Bank Work Group (WBWG) was formed in western Colorado (Cabot, 2016) in 2014 as a pilot project for a future operational water bank in Colorado, Gunnison and Southwest basins (Godbout, 2014). A study conducted for Colorado River Water Conservation District, perceives the form of future water banks as follows (MWH Americas, 2012). Willing senior water users from the agricultural sector will fallow or partially irrigate their lands and will be compensated for the water they are not consuming in agriculture. The water saved in this way will be available to users subscribed to the bank. The fallowing is anticipated to be rotational among the irrigated lands of the three participating basins. Although the water bank could also store any extra water for subsequent years, the work group has excluded such practice from its agenda (MWH Americas, 2012).

An example of relatively functional water bank (see page 27) in Colorado is Arkansas River Super Ditch discussed in more depth later. The Super Ditch and WBWG are both supported by state grants and research on their progress is ongoing. The literatures cited here are published by a wide range of organizations from state authorities to academic and non-governmental organization, which reflects the interest of various entities on success of water banks in Colorado.

By extending the scope of water reallocation to recharging natural resources, another institution formed in Colorado will fit to the definition of water bank and worth mentioning here. In San Luis Valley (southwestern Colorado), the Rio Grande Water Conservation District has initiated a plan to recharge groundwater aquifers (Carswell, 2013). The district is in process of forming six sub-districts composed of agricultural lands within the command area of ditches already managed together. In each sub-district well-owners are given two options; foregoing irrigation and receive a monetary compensation per acre of fallowed land, or irrigate and pay a fee per acre-foot of water used plus a fee per acre of land cultivated (Rio Grande Water Conservation District and Davis Engineering Service Inc., 2017). The objective is to encourage farmers to reduce groundwater consumption and recover falling groundwater levels. The fist sub-district (sub-district No. 1) was formed in 2006 and sub-district No.2 is still in process of initiation. This project, however, is not self-sufficient and relies on USDA's Conservation Reserve Enhancement Program fund for approximately 80% of its costs (Davis et al., 2013).

The concept of water bank has been famously used in Murray-Darling Basin in Australia and was very successful, but the legal framework there is highly fungible (MacDonnell, 2015); for example, the prior appropriation doctrine is not the base of water law and all right holders are treated equally. The proper solution for Colorado, therefore, will be different because the water banks need to fine-tune to the water law's no-injury and anti-speculation rules. Even each basin in Colorado may need to adopt a different approach depending on their hydrology, infrastructure, or available institutional capacity (Devine, 2015).

2.3.2 Interruptible supply agreements

Under interruptible supply agreements, the lessee pays a baseline fee, either a lump-sum at the beginning or an annual fee over the course of the contract (Goemans and Pritchett, 2014). The lessor guarantees to provide a maximum amount of water per year whenever the lessee requests. The lessees are normally municipal water users with water rights that are not sufficient during drought years. The lessors are the agricultural water right holders who are willing to interrupt their irrigation practices during drought years. The lessor charges the lessee for the actual volume of water requested whenever water is transferred to the lessee. House Bill 13-1130 (enacted on June 5th, 2013 by governor of Colorado) allows 3 years of transfer in a single 10-year period, and the state engineer can reapprove an agreement up to two additional times. City of Aurora and the Rocky Ford Highline Canal entered such an agreement in 2004 and again in 2005. Two sets of contracts were implemented, one with the ditch company for facilitating water transfer and the other with individual farmers who interrupted their irrigation practices to provide the water (CDM Smith, 2011). In 2008, city of Aurora and Highline Canal started a 10-year renewable interruptible supply agreement (*ibid*).

2.3.3 Water cooperatives

Although the Colorado Water Plan refers to water cooperatives as a separate method of water transfer, it is not different from water banks. Perhaps the term has entered the water plan because a new organization, called Northeast Colorado Water Cooperative, has started working along Lower South Platte River from Kersey, CO to the Colorado-Nebraska state border (The Fence Post, 2013). The members are entities or individuals with agricultural water rights. They own decreed or pending water decrees for augmentation plans (*ibid*). On a given day, any member of water cooperative may have more water credits than the member can use. Unused recharge credits primarily occur from proper use of augmentation plans. In 2008, for example, in the cooperative's prospective command area the unused recharge credits summed up to 30,000 AF. This was 80,000 AF for both 2009 and 2010 (Brown and Caldwell et al., 2015). Meanwhile, other members may have less credit than they need. Members with extra water can supply water to members with unsatisfied water demand. The cooperative facilitates water sharing and transferring water credits among its members (Barker, 2014). Legal consultants determined that cooperative will best suit such water sharing purposes. The cooperative considers leasing unused credits as another service it will provide to its members (Brown and Caldwell et al., 2015); however, they do not discuss more details on the subject.

Although the Water Cooperative has not facilitated any water exchange yet but it was able to produce a computer tool that evaluates the exchange capacity between various points of diversion on the South Platte River (Brown and Caldwell et al., 2015). When exchanges are conducted, this tool will be used together with data on location and priority of supplying and demanding members. As such the function of this cooperative is similar to a water bank and classifying it as a different method of water transfer will only create confusion.

Since all members of Northeast Colorado Water Cooperative are agricultural right holders the water will stay in agricultural sector and the transfer is not considered out-of-sector. Moreover, the cooperative will only be involved in reallocating augmentation credits, which requires no reduction of farm consumptive use. As such this project is hardly an example of ATM. This may be why the water cooperative has not attracted much attention among scholars and policy makers. Although, the cooperative received two grants through CWCB's alternative agricultural water transfer grants, systematic literature on its framework and function are scarce. The existing documents are ordered by the water cooperative (mainly to obtain ATM grants) and the rest are news articles in local newspapers. Still, research on progress of this organization can produce valuable lessons for other water banks. This organization is especially an interesting case because the stakeholders felt it was required and formed it according to their needs. Moreover, this cooperation is considering rotational fallowing as a future plan to expand its water supplies (Brown and Caldwell et al., 2015).

2.4 Recharge Structures

Implementation of water transfer plans changes the hydrological cycle in a basin. On farm water losses that used to reach groundwater or surface streams may not occur anymore or transfer to new locations. And so, the water users who were benefitting from these return flows will have less available water. When such water users are senior water right holders, Colorado's water law requires replacement of the return flows. Two main water structures are used for this purpose, recharge ponds and augmentation stations. These are referred to as recharge structures in this manuscript. Normally transfer plans utilize both recharge ponds and augmentation stations to replace their return flows.

2.4.1 Recharge ponds

Recharge ponds are built near irrigation ditches and filled with water from the ditch. Water can percolate through the bottom of the pond to recharge the groundwater table. The location of recharge pond is selected so that water eventually returns to the original river where it was diverted from. Currently recharge ponds are mainly used in Colorado for augmentation plans. These plans are the right to divert water out of priority but they need to replace the diverted water at the exact location with the exact time and amount. Figure 2 shows how an augmentation plan works.

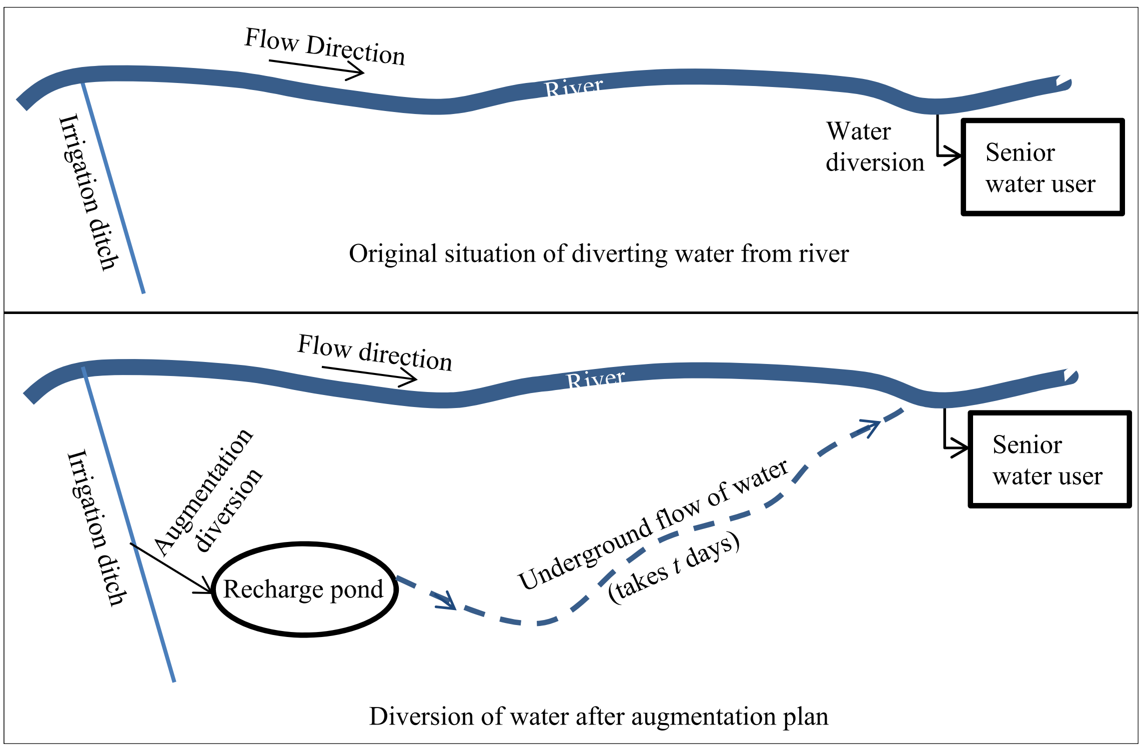


Figure 2 Schematic presentation of function of a recharge pond

Augmentation plans divert water during non-growing seasons or use storage water. The diverted water is stored in a pond so it can seep into the ground. Water then returns into the river through groundwater but later (*t* in the diagram of Figure 2) and a downstream location (e.g.

location of senior water user in the diagram). The period needed for water to travel back to river is known. Therefore, the pond location can be chosen so that it transfers water to a desired downstream location, at a desired time. The owner of augmentation plan is credited to use water at his diversion structure (augmentation diversion in the diagram) after water travel time (*t*) is elapsed. By choosing correct location the owner of augmentation plan can take water credit during high demand period without injuring downstream senior water right holders.

Although mainly augmentation plans use recharge ponds, the same structure can be adapted to release the return flow as well. The three interconnected recharge ponds on Subsurface Irrigation Efficiency (SIEP) Project in Kersey CO shown in Figure 3 is an example. These ponds are currently not used as recharge structures but they are designed to receive water from the adjacent irrigation ditch and return it to South Platte River about a mile to their north.

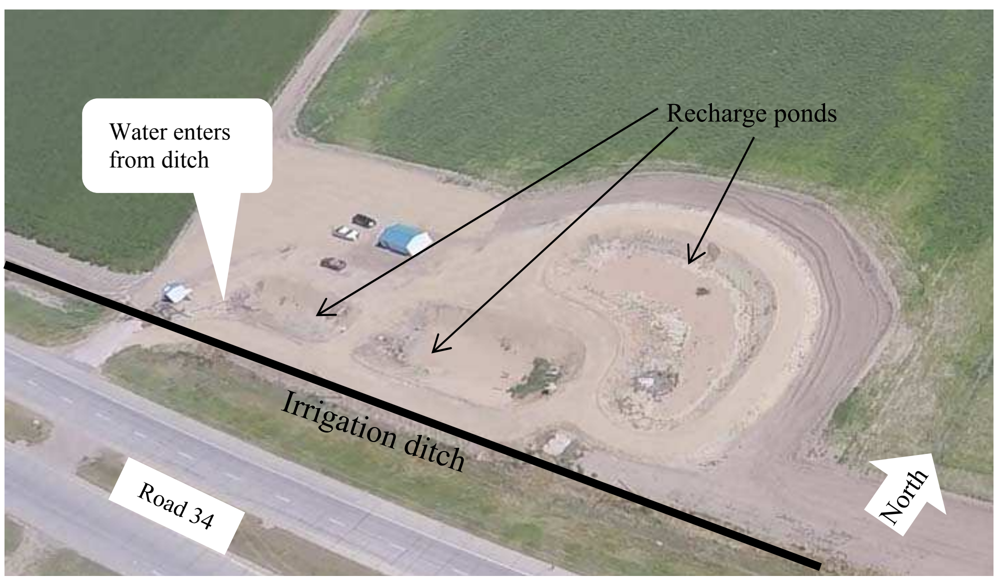


Figure 3 Recharge ponds on Subsurface Irrigation Efficiency Project, in Kersey, CO

2.4.2 Augmentation stations

Augmentation structures are any structure used to maintain return flows after a change in location of water use. When a water right change of use and location is decreed, only the consumptive portion is transferred to the new user and the return flow is diverted to the original stream. Similar to recharge ponds, augmentation stations are also commonly used for augmentation plans. Their function is also very similar except they use a surface canal to return water to a stream. An example of an augmentation station is shown in Figure 4. In this setting, a gate diverts the return flow of the irrigation ditch into a small conveyance canal behind it. Flow is measured at the gate before it travels to the river a half mile downstream.

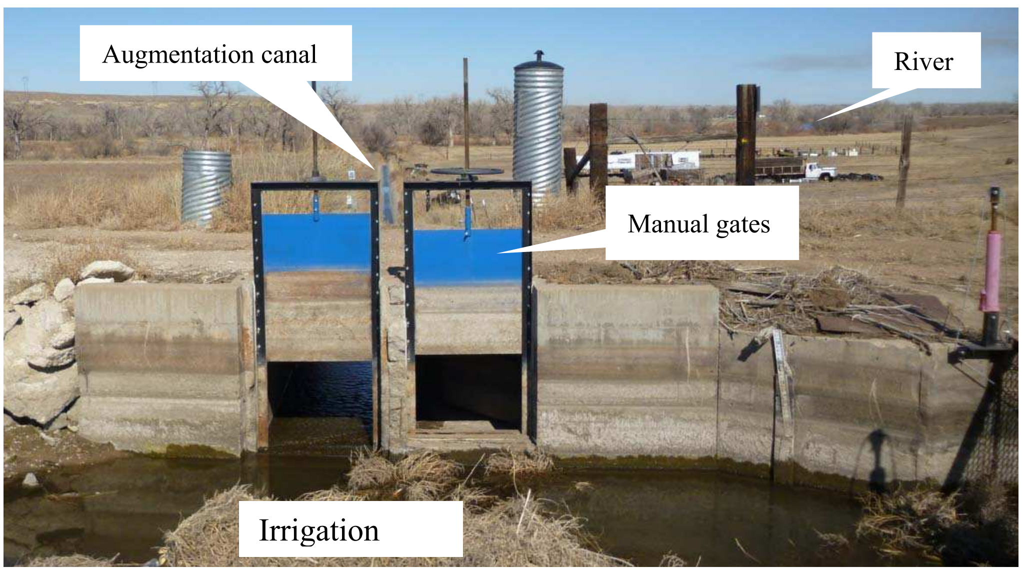


Figure 4 Augmentation station

2.5 Water Transfer Example: Super Ditch

Catlin Canal in Lower Arkansas Valley is used as an example to clarify components of a new water transfer plan. In a pilot project in 2015, Catlin Canal provided 0.6 MCM (500 AF) of water to few neighboring cities and communities (Zaffos, 2015). This is part of an initiative among seven ditch companies in the region, called Arkansas Valley Super Ditch (HDR Engineering, 2007). Under the terms of agreement, the water-receiving communities can use water for 3 years in a 10-year period to supply homes and recharge their wells. No more than 30% of individual farm grounds can be fallowed in any year (Colorado House Bill 13-1248, enacted June 13, 2013). During those years, the irrigators earn money from the leased water (Zaffos, 2015) and rain-fed agriculture, in case they choose to practice it. In 2015, the company charged $500 for every acre foot of water transferred (Campbell, 2015). The main purpose here is to keep rural communities viable, unlike practice of "buy and dry" that forces farmers to leave their lands. One augmentation station and two recharge ponds were used in this agreement (*ibid*).

The Super Ditch uses rotational fallowing to decrease on-farm water use. Then using the model of water bank, transfers the saved water to the urban areas and uses both augmentation stations and recharge ponds to replace the return flows. Local News articles refer to this combination of methods as lease-fallowing agreement. Perhaps for this reason, lease-fallowing agreements are mentioned in Colorado's Water Plan as an alternative transfer method. Colorado Division of Water Resources has created a lease fallow tool (LFT), a computer tool that estimates historic depletions (consumptive use) and return flows from irrigation (Colorado Division of Water Resources website). Colorado's House Bill 13-1248 refers to this combination as Fallowing-leasing. Although fallowing-leasing has entered Colorado's legal terminology, there is no legal or practical obligation to combine these two specific methods in a transfer plan and hence use of such terms is redundant.

The challenge remains for schemes like the Super Ditch to prove that their water supply is reliable for municipal users. Cities prefer not to rely on a new source of water every year, when a more permanent buy-and-dry tactic is accessible (Devine, 2015), especially because the legal and administrative costs of leasing water can be as high as buying water rights (MacDonnell, 2015).

2.6 On Regulating Deficit Irrigation

To systematically regulate deficit irrigation, the relationship between crop yield and water stress must be known (Hoyt, 1984). The total crop water requirement is the maximum amount of water that a crop can use productively when the soil water content is not limiting (Brouwer and Heibloem, 1986). Crops mainly need water for cooling purposes; most of the root's water uptake is released back to the atmosphere through transpiration, and only a negligible fraction is retained for crop growth. In field experiments, for example with lysimeter, partitioning transpiration from soil water evaporation is difficult (Kool et al., 2014). Therefore, in practice, evapotranspiration (ET) is measured or calculated. Evapotranspiration is the combination of two separate processes whereby water is lost from the soil surface by evaporation and from the crop by transpiration (Allen et al., 1998).

The United Nation's Food and Agricultural Organization (FAO) has published Irrigation and Drainage Paper 56 (FAO 56) for ET calculation. The reference ET procedure given in FAO 56 is standardized by American Society of Civil Engineers (ASCE) (Allen et al., 2005) which is widely used for ET calculations.

Crop yield can be related to different parameters that describe amount of water used by crop. These are crop transpiration, crop evapotranspiration, amount of available water for crop in the root zone, or amount of applied irrigation water. Several mathematical functions are developed based on experiments that relate crop yield to one of the above-mentioned parameters (Doorenbos and Kassam, 1979; Jensen, 1968; Wit de, 1958). However, any amount of available water beyond ET is not consumed by the crop. Research shows that ET and yield are well correlated and ET is the main input to yield production (Tanner and Sinclair, 1983). Therefore, the useful practice when developing yield-water relationships is to relate yield to ET. This relationship is called crop water production function (CWPF) which must be used in optimizing water allocation.

2.6.1 Crop water production functions and their evolution

In the first half of the twentieth century, scientists tried to find the relationship between yield and water use by growing plants in containers. According to Vaux and Pruitt (1983) the containers were covered to prevent evaporation from the soil surface and were weighed to define the transpiration. Analyzing these early studies, de Wit (1953) found a linear relationship between transpiration and total dry matter production as:

$$\boldsymbol{D = m\frac{T}{E_o}}$$

Equation 2.1

where

D is total dry matter production in kg/ha

T is total transpiration during crop growing season in cm

E_o is average free water surface evaporation rate during growing season in cm/day

m is a crop factor having dimensions of kg/ha/day

He also found that Equation 2.1 can be simplified for humid conditions because the ratio of T/E_o does not change appreciably when water is not limited. Therefore, under humid conditions:

$$D = nT$$

Equation 2.2

where $n = m/E_o$.

Then, the crop factor n has dimensions of kilograms per hectare. So, he presented the general equation as:

$$D = y\, TE_o^{\ -x}$$

Equation 2.3

where x = 1 and y = m for locations with a large percentage of bright sunshine, and x = 0 and y = n in locations with small percentage of bright sunshine. He speculated that x can fall between zero and one for some climates but did not have enough data to prove it. Factors m and n depend only on the type of crop, if the soil nutrient level and/or soil excess water content are not hampering crop growth. Therefore, de Wit concludes that the same equations can be used for crops grown in the field.

Although de Wit's method was used for modeling plant yield as influenced by water (for example Hanks, 1974; Todorovic et al., 2009), it has two main limitations. First the equation calculates total biomass production while only the marketable yield is interesting in an economic analysis. Besides, as mentioned earlier, separating crop transpiration from soil evaporation is not straightforward. Later research showed that y is not just crop dependent; experiments with corn gave different values of y for the same experimental treatments (Tanner and Sinclair, 1983). Moreover, some growing stages are more sensitive to shortage of water, but this method does not account for the effect of water stress timing. Nevertheless, de Wit's method is a valuable first step in quantifying yield-water relationship. Wageningen University has developed the WOFOST (World Food Studies) model based on his method (Wit de, 2014); however, not many scientific works were found to use this model.

In another approach Jensen (1968) related water stress to yield as follows:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{N} \left(\frac{ET_a}{ET_m}\right)_i^{\lambda_i}$$

Equation 2.4

where

Y_a is the actual crop yield

Y_m is the maximum crop yield when soil water is not limiting

ET_a is the actual crop evapotranspiration

ET_m is the crop evapotranspiration when soil water is not limiting

i is the crop growing stage

λ_i is the relative sensitivity of the crop to water stress during the stage of growth i (unitless)

N is the number of growth stages

Inclusion of maximum yield and maximum ET, accounts for climate and soil variability so the sensitivity factor, λ, only depends on the type of crop. A greater λ represents more sensitivity to drought. The equation accounts for sensitivity of the crop to different growing stages. Jensen considered three stages (emergence to boot, boot to milk, and milk to harvest) for sorghum, but in an experiment, the growing season can be divided into any number of stages to define desired λ values. He also derived λ for different stages of grain sorghum growth as 1) emergence to boot stage λ = 0.5, 2) boot to milk stage λ =1.5, and 3) milk to harvest stage λ =0.5. Zhang et al. (2008) determined λ values for corn as 1) sowing-jointing λ=0.1, 2) Jointing-tasseling λ=0.2, tasseling-grouting λ=0.4, and 4) grouting-ripening λ=0.2.

Because of the multiplicative structure of the equation, when ET_a is zero in any one stage, the overall yield will be zero. Zero ET_a means the crop is not transpiring and is dead, hence not producing yield. In his paper, Jensen used the term “water use” instead of ET. This may be why some researchers, have used available water in Jensen's equation rather than ET while calculating λ for different crops (such as Nairizi and Rydzewenski, 1977). However using available water rather than ET_a in this equation is not correct.

Crop relative sensitivity, λ, has been defined by experimentation for sorghum (Jensen, 1968), wheat (Zhang and Oweis, 1999), corn (Zhang et al., 2008), cotton, peanut, and soybean (Woli et al., 2014). According to these studies, although, λ value for a certain crop varies in different stages, for the entire growing season, it has a value close or equal to one, suggesting that yield has a linear relationship with ET.

Later, Doorenbos and Kassam (1979) analyzed results of several studies on the ET-yield relationship and introduced a yield response factor (*Ky*) in FAO Irrigation and Drainage Paper 33 (FAO33) and suggested the following linear function:

$$1 - \frac{Y_a}{Y_m} = Ky\left(1 - \frac{ET_a}{ET_m}\right),$$

Equation 2.5

where $1 - \frac{Y_a}{Y_m}$ is the relative crop yield decrease and $1 - \frac{ET_a}{ET_m}$ is the relative evapotranspiration deficit. Crops with higher *Ky* are more sensitive to water deficit. The FAO equation is very similar to an equation derived by Stewart and Hagan (1973), for corn, grain sorghum, and pinto beans.

To account for different growing stages, Dooernbos and Kassam rewrote their equation as:

$$1 - \frac{Y_a}{Y_m} = \sum_{i=1}^{N} Ky_i(1 - \frac{(ET_a)_i}{(ET_m)_i}).$$

Equation 2.6

The same paper provides *Ky* for entire growing season as well as Ky_i for 26 crops. Literature review shows this equation has been used extensively in planning deficit irrigation. An openaccess software, AquaCrop, has been developed based on this method (Raes et al., 2009; Steduto et al., 2009).

The FAO equation predicts some yield when ET_a, at least in one stage, is non-zero. However, $ET_a = 0$ at any stage means no transpiration at which point the crop dies. Therefore, this equation overestimates yield production. Conversely, Zwart and Bastiaanssen (2004) review of 84 publications shows that the amount of Y_m/ET_m for wheat, rice, cotton and corn exceeds those reported by Doorenbos and Kassam in all experiments. That is, Equation 2.6 underestimates yield production. Possibly the underestimating factors cancel out the effect of overestimating factor because about 80% to 85% of observations in different locations confirm that crop yield reduction can be described with the FAO method and K_y values given in FAO33 (Raes et al., 2006).

Crop water production function is one way of describing yield-water relationship. Another way of modeling yield production against the amount of water is using the “available water”. Available water is the amount of water made available to crop through precipitation, irrigation, residual soil moisture, and groundwater capillary rise. The crop typically cannot use all the water that is available to it because of surface runoff and drainage (loss terms). Therefore, total water consumed by crop (ET) is less than the total available water to crop. In fact, when available water exceeds a certain amount, depending on crop type, the yield is reduced due to water logging, absence of air in the root zone and plant diseases.

Several studies defined the relationship between available water and yield. For example, Soybean yield (Klocke et al., 1989; Yaron, 1967) was described by a quadratic function as:

$$Y = \alpha + \beta\,(aw) + \gamma\,(aw)^2, \qquad \textbf{Equation 2.7}$$

where aw is the available water and α, β, and γ are regression coefficients depending on crop type. This function, however, is symmetric around maximum yield, a shape that is not supported by field observations. Solomon (1985) suggested a quartic equation based on the results of several field experiments for the 37 crops that he found in the literature as follows:

$$Y = a_0 + a_1 (RAW) + a_2 (RAW)^2 + a_3 (RAW)^3 + a_4 (RAW)^4,$$

Equation 2.8

In Equation 2.8, RAW is the relative available water or "the ratio of available water to that value of available water that corresponds to the maximum yield" (Solomon, 1985). Solomon determined a_0 to a_4 (regression coefficients) for each of the 37 crops for low, medium, and high yield sensitivity to excess water. The function sometimes returns negative yields for RAW below 0.1, and sometimes, it predicts yields bigger than maximum yield.

Hexem and Heady (1978) gave an extensive report of a collaborative experimentation on the effect of agricultural inputs and soil characteristics on crop yield. The study was conducted on corn (grain and silage), cotton, wheat, sugar, and beets in Colorado, Texas, Kansas, Arizona, California, and Oregon from 1968 to 1971. Study variables were plant population, depth of available water, amount of nitrogen applied per unit of area, soil pH, soil electrical conductivity, soil available water holding capacity (in upper 1.2m of soil) and depth of pan evaporation over the silking period (defined as critical period). They defined a generalized equation relating the independent variables to the yield for each of the five crops. Since, in this study, the amount of available water (as opposed to the amount of consumed water or ET) was measured, the results are not transferable to other locations. Even in one location the correlation coefficient were not acceptable and they had to define an extra equation per crop improve this coefficient.

Non-transferability of "Available water – yield" function is inevitable. As described above the difference between amount of available water and consumed water or evapotranspiration comes from loss terms. The losses depend on soil type, farm topography, type of irrigation system, and farm management practices. Therefore, this function is farm specific and varies from year to year. Yield production is a physiological response to the amount of ET that does not include any losses or inefficiencies of irrigation system. Therefore, "Available water – yield" or "applied water- yield" functions must not be used for yield prediction. A better practice would be defining yield based on ET and then accounting for system losses.

Experimental equations in this section show that CWPF normally fit into a linear function and the relationship between yield and available water (AWYR) into a curvilinear concave function (Vaux and Pruitt, 1983). In scientific literature (English, 1990; Rogers et al., 2015) the two forms of water – yield relationship are generalized as Figure 5.

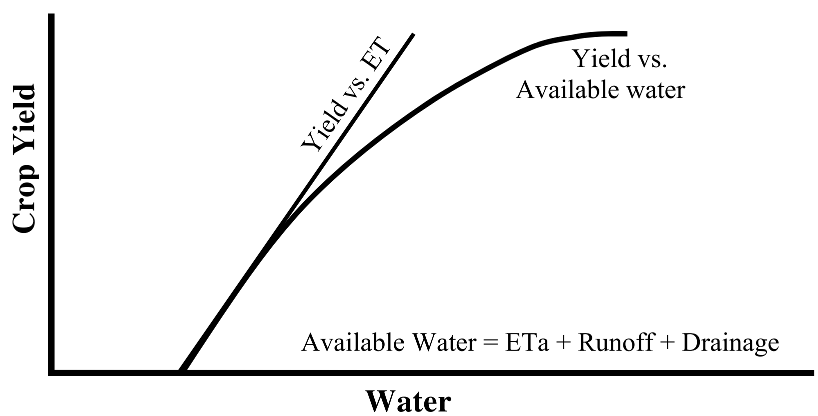


Figure 5 Generalized relationship between yield and water amount[3]

When the amount of available water is low, most of it can stay in the soil root zone and the crop can eventually use it. As water availability increases, soil root zone fills and water will have less chance to stay in this zone; therefore, water losses increase and AWYR curve separates from CWPF. Reducing losses (for example by improving irrigation efficiency) will reduce the gap

[3] Adapted from Rogers et al. (2015) and English (1990)

between the two functions. The gap also decreases by moving down on AWYR function (moving towards smaller amounts of available water in soil root zone).

2.6.2 Optimal water allocation at farm level

To achieve the maximum revenue water needs to be allocated optimally to on farm and off farm activities. Optimal allocation must be defined based on an objective. Then certain metric should be employed to compare the value of different options and choose the optimal one. At the farm level value of water can be determined by the income that it generates for the farmer. A farm can be considered as an entrepreneurial agent who strives for profit maximizing decisions (Griffin, 2006). At the farm level, water can be allocated to different crops or leased to off-farm users. We set the objective to allocate water to maximize farmer's profit with limited available water. Then for a certain crop the question is how much of the water should be used for on-farm yield production and how much should be rented for off-farm uses. Therefore, the following maximization problem can be written for the farm:

$$\begin{aligned}&\textit{Maximize } [y(w_y)P_y - c(w_y) + w_{off}P_{off}]\\&\textit{By changing: } w_y, w_{off}\\&\textit{Subject to}\quad 0 \le w_y \le W,\ 0 \le w_{off} \le W\ ,\ \textit{and } w_y + w_{off} = W\end{aligned}$$

Equation 2.9

where:

w_y is the irrigation water applied to crop (yield) production, or the on-farm water use,

$y(w_y)$ is the obtained marketable yield as a function of irrigation water,

P_y is selling price of unit of yield,

$c(w_y)$ is cost of production as a function of irrigation water applied,

w_{off} is the amount of water allocated to off-farm activities,

P_{off} is the net off-farm price of water (price of water after any withdrawal costs),

W is farm's total available water for diversion.

In other words, the goal here is to partition the limited amount of farm's available water W to w_y and w_{off} in a way that maximum profit is obtained from W. By using w_y unit of water an amount of yield equal to $y(w_y)$ is produced. The product of $y(w_y)$ units of yield and the price per unit of yield, P_y, is the gross profit obtained from allocating w_y unit of water to farming (the first term in the maximization problem). Subtracting costs of production, $c(w_y)$ (the second term in maximization problem), from gross profit, gives the net profit (English, 1990). Leasing w_{off} unit of water obtains a profit equal to $w_{off}P_{off}$ (the third term in the maximization problem). Off-farm price of water (P_{off}) is the net price after any withdrawal or transfer costs. The goal is to maximize the summation of profit from farming and profit from leasing.

The two conditions in Equation 2.9 ensure that the amount of water allocated to each use (each of w_y and w_{off}) and the total water allocated to different uses ($w_y + w_{off}$) does not exceed farm's available water (W). Other off-farm uses of water, if any, can be added to the above maximization problem. Similarly, if total available water is used to grow more than one crop the other crops can be added to the problem. Here the assumption is that all farm available water can be productively used for yield production. In other words, the farm does not own excess water.

To solve Equation 2.9 the relationship between crop yield and amount of irrigation applied to the crop (w_y) must be known (Wang and Nair, 2013). However, the relationship between yield and irrigation water is farm specific and depends on soil type, farm topography, type of irrigation system, and farm management practices. It also varies from year to year depending on precipitation that satisfies part of crop water requirement. Therefore, in solving Equation 2.9, crop water production function must be used. Then the relationship between w_y and ETa is defined as below:

$$w_y = (ET_a - ER)/e$$

Equation 2.10

where *ER* is the effective rainfall and *e* is the irrigation system's application efficiency. Effective rainfall is the amount of precipitation stored in soil root zone and used by crop, and application efficiency is the ratio of the depth of irrigation water stored in the soil root zone to the depth of irrigation water applied to the farm (this includes the residual soil moisture due to out of season precipitation) . Both effective rainfall and application efficiency can fluctuate with ET_a.

However, in Colorado water right holders only own the farm crop consumptive use (*CU*) or crop ET. For this reason, the available water, *W*, in Equation 2.9 must be replaced by farm consumptive use and the growers must demonstrate that they are reducing ET. As a result, the relationship between yield and ET must be used in formulating optimization problems. To conform to Colorado water law, Equation 2.9 changes to:

$$\begin{aligned}&\textit{Maximize } [Y(ET_a)P_y - C(ET_a) + w_{off}P_{off}]\\&\textit{By changing: } ET_a \textit{ and } w_{off}\\&\textit{Subject to} \quad 0 \le ET_a \le CU,\ 0 \le w_{off} \le CU\ ,\ \textit{and } ET_a + w_{off} = CU\end{aligned}$$

Equation 2.11

where:

ET_a is crop actual evapotranspiration

Y(ET_a) is crop water production function or crop yield as a function of ET_a

$C(ET_a)$ is farm costs of achieving ET_a

CU is farm historical consumptive use

Cortignani and Severini (2009) and English (1990) write the cost as a linear function:

$$c(w_y) = \alpha\, w_y + \beta$$

Equation 2.12

Where β is the fixed costs of production (capital costs associated with land and farm equipment, taxes, insurance, and fixed costs of farming) and α is the marginal variable costs of production (such as pumping, labor, and other costs associated with irrigation). Using Equation 2.10 cost can be expressed as a function of ET_a:

$$C(ET_a) = \alpha \left(\frac{ET_a - ER}{e}\right) + \beta$$

Or:

$$C(ET_a) = \theta\, (ET_a - ER) + \beta$$

where: $\theta = \alpha / e$

So in $C(ET_a) = \theta\, (ET_a - ER) + \beta$

θ is the marginal variable cost of increasing a unit of ET_a (electricity, labor and water cost of irrigation). Since effective rainfall (ER) for a given year are constant $C(ET_a)$ can be written as:

$$C(ET_a) = \theta\, ET_a + \sigma$$

Equation 2.13

where: $\sigma = \theta\, ER$

Fort the purpose of this dissertation values of θ and σ are directly calculated from crop enterprice budget.

In Equation 2.11, the derivative of $(Y(ET_a)P_y)$ with respect to ET_a and the derivative of $(w_{off}\, P_{off})$ with respect to w_{off} describe each term's extremum. The derivative functions or the marginal values (mv) of water for each use with respect to the amount of ET are as below:

Marginal value of water in yield production:

$$mv_y = \frac{d[Y(ET_a)P_y - C(ET_a)]}{dET_a} = P_y \frac{d[Y(ET_a)]}{dET_a} - \frac{d[C(ET_a)]}{dET_a}$$

Equation 2.14

Marginal value of water allocated to leasing:

$$mv_{off} = \frac{d[w_{off}\, P_{off}]}{dw_{off}} = P_{off} = \text{Constant}$$

Equation 2.15

Optimum allocation happens when the two marginal values are equal (Wang and Nair, 2013), as illustrated in Figure 6. Since $ET_a + w_{off} = CU$ both ET_a and w_{off} are shown on the horizontal axis by using two axes with opposite directions, then the marginal values can be shown on two vertical axes.

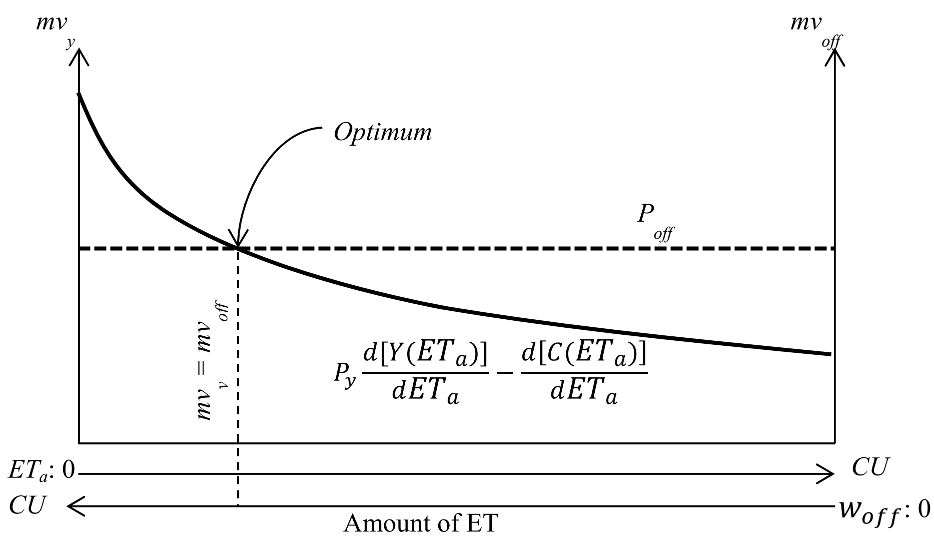


Figure 6 Schematic presentation of optimal water allocation

Commonly used models, discussed in section 2.6.1, describe yield as a linear function of ET_a like:

$$Y(ET_a) = g\, ET_a + h$$

Equation 2.16

where g and h are function parameters. Considering this function and the cost function in

$C(ET_a) = \theta\,(ET_a - ER) + \beta$

the marginal value of water in yield production in Equation 2.14, is:

$mv_y = g\,P_y - \theta$ = constant

Equation 2.17

Suppose $(gP_y - \theta) > P_{off}$ as graphed in Figure 7. Then allocating all the available water to yield production (keeping water on farm) always generates more income because the marginal value of water in farming always exceeds that of leasing. Similarly, when $(g\,\mathrm{P_y} - \theta) < \mathrm{P_{off}}$, it is optimal to allocate all the available water to off farm uses; that is, to lease all the water. In other words, for a linear crop water production function, the optimal solution for Equation 2.11 does not justify partitioning of water between on- and off-farm uses but the optimal solution is to allocate all the available water to the use with higher economic value.

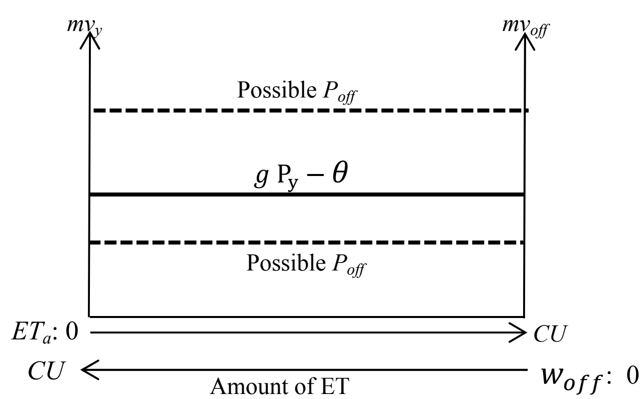


Figure 7 Optimal water allocation for linear crop water production function

This research will reevaluate the assumption of linearity of crop water production functions. However, Figure 6 suggests, even for a non-linear function, $\mathrm{mv_{off}}$ can be much lower than $\mathrm{mv_y}$ so that P_{off} always falls below $\mathrm{mv_y}$. Or $\mathrm{mv_y}$ can be much lower than mv_{off}. In both cases optimal allocation will not justify partitioning of water. In case of a quadratic crop water production function as:

$$Y(ET_a) = a\, ET_a^{2} + b\, ET_a + c$$

Equation 2.18

The mv_y will be:

$$mv_y = P_y\, (2\, a\, ET_a + b) - \theta$$

Equation 2.19

The amount of P_{off} has to be equal to mv_y in Equation 2.19 to justify the partitioning of water. If the intersection happens at the far right end of the graph in Figure 6, the result is the minimum P_{off} for deficit irrigation to improve farm income ($minP_{off}$), below which allocating all CU to farming is profit maximizing. Therefore, the required minimum net price of leasing is:

$$P_y(2\, a\, CU + b) - \theta = minP_{off}$$

Equation 2.20

And the maximum P_{off} happens when the two marginal values intersect at the left end of the graph of Figure 6. At this point ET_a=0 and $maxP_{off}$ is:

$$P_y b - \theta = maxP_{off}$$

Equation 2.21

These values are determined for research crops in CHAPTER 5.

2.6.3 Farm income improvement due to deficit irrigation

As long as renting price of water falls between the minimum and maximum renting prices defined in the previous section, farm income will improve by renting the optimal amount of water. Farm income increase due to deficit irrigation (*inc*) is:

$$inc = \frac{farm\ income\ with\ deficit\ irrigation - farm\ income\ from\ full\ irrigation}{farm\ income\ from\ full\ irrigation}$$

$$inc = \frac{P_y\, Y(ET_a) - C(ET_a) + P_{off}\, w_{off} - (P_y\, Y(ET_a) - C(ET_a))}{P_y\, Y(ET_a) - C(ET_a)} \rightarrow$$

$$inc = \frac{P_{off}\, w_{off}}{P_y\, Y(ET_a) - C(ET_a)}$$

Equation 2.22

However, when renting price is just above minimum, farm income is mainly due to yield production and renting part of water may not appreciably increase the income. Similarly, at prices just below maximum renting price of water, farm is mainly relying on renting water for generating income and yield production may not have a considerable contribution to income. When renting price of water is close to its limits, farmers may not find the income increase worthwhile of the effort to manage and arrange for both activities. They may choose to forego the minimal income increase and allocate their water only to one use, either yield production or renting. Therefore, this research will define the effect of different factors on farm income increase to identify the favorable conditions for deficit irritation to be a viable strategy against buy-and-dry.

Equation 2.22 indicates that income increase depends on cost and yield functions. Several independent variables determine these two functions. On one hand, the yield function is defined as a dependent variable of ET_a therefore it varies with effective rainfall, *ER*, (see Equation 2.10) and indirectly by farm available water, *W* (through the condition of optimality in Equation 2.9). On the other hand, the cost function reflects fixed costs such as rent or mortgage and equipment and depreciation, as well as variable costs of agricultural products and insurance. Equation 2.13 depicts the fixed costs as σ and the marginal change in variable costs as θ. Finally, Equation 2.22 suggests amount of *inc* is also a function of selling price of yield (P_y) and renting price of water

(P_{off}). Changing these variables within their limits of variation defines "farm income increase". These independent variables (also listed in Table 1) will be analyzed in the results chapter (page 69).

Table 1 Main independent variable that influence farm income increase due to deficit irrigation

Effective rainfall, ER
Farm available water, W
Selling price of yield, P_y
Renting price of water, P_{off}
Variable cost of increasing a unit of actual evapotranspiration, θ
Constant of cost function, σ

CHAPTER 3 STUDY AREA

This research was sponsored by the Platte River Water Development Authority headquartered in Denver, Colorado. The sponsor is interested in evaluating alternate strategies for conserving water in South Platte Basin. Hence the development authority dedicated a tract of land to research in Colorado's Weld County and started Subsurface Irrigation Efficiency Project (SIEP). Research is focused on deficit irrigation and subsurface drip irrigation. Weld County is especially interesting with regard to Colorado water transfers because it has witnessed a booming oil and gas industry (Malin, 2015) following by transfer of agricultural water rights (WestWater Research LLC, 2016).

3.1 Study Area: Weld County, Colorado

Weld County located in the eastern plains of Colorado, an arid region "almost always in or on the verge of drought" (Doesken et al., 2003). The average annual rainfall in Greeley, the seat of the county, is 36 cm (14.2 inches) (Western Regional Climate Center, 2016); although most of it occurs during crop growing season (Doesken et al., 2003) it provides just half of most crops' water requirement; hence irrigation is necessary for crop production.

Weld County is historically known as an important agricultural region (Mehls and Mehls, 2006). According to the USDA census of Agriculture (2012) it is the leading agricultural producer in Colorado and the ninth in the nation, when market value of products sold is considered. In 2015, the county's market value of products sold was more than $1.5 billion, of which more than 70% is from livestock industries (Colorado Department of Agriculture, 2017) and about 50% of farms are pasturelands (*ibid*). Weld County's five top crop items are wheat, corn, alfalfa, sugar beets and dry beans (Table 2).

Table 2 Common crops of Weld County in 2016

Crop	Harvested area (ha)	Production (Mg)	Value ($1,000)
Winter wheat	48,562	7,581,694	19,965
Corn	24,564	16,263,330	39,483
Alfalfa	29,542	22,098,986	72,674
Sugar Beets	4,452	21,772,400	18,680
Dry beans	1,963	285,763	3,171

From: National Agricultural Statistics Service (2016)

The County falls entirely in South Platte River Basin. South Platte River Basin is approximately 22,000 square miles (about 56,980 square kilometers) (NOAA, 2014) with a population of 3.5 million and 830,000 ac (about 335,890 ha) irrigated land (Colorado Water Conservation Board, 2010) making 24% of Colorado's irrigated land. It contained about 20% of Colorado's population in 2008 (*ibid*). At the state level, the basin water rights are administered under Colorado Division of Water Resources and falls in Division 1 (see map of divisions in Figure 8). South Platte River Basin and its main tributaries are shown in Figure 9.

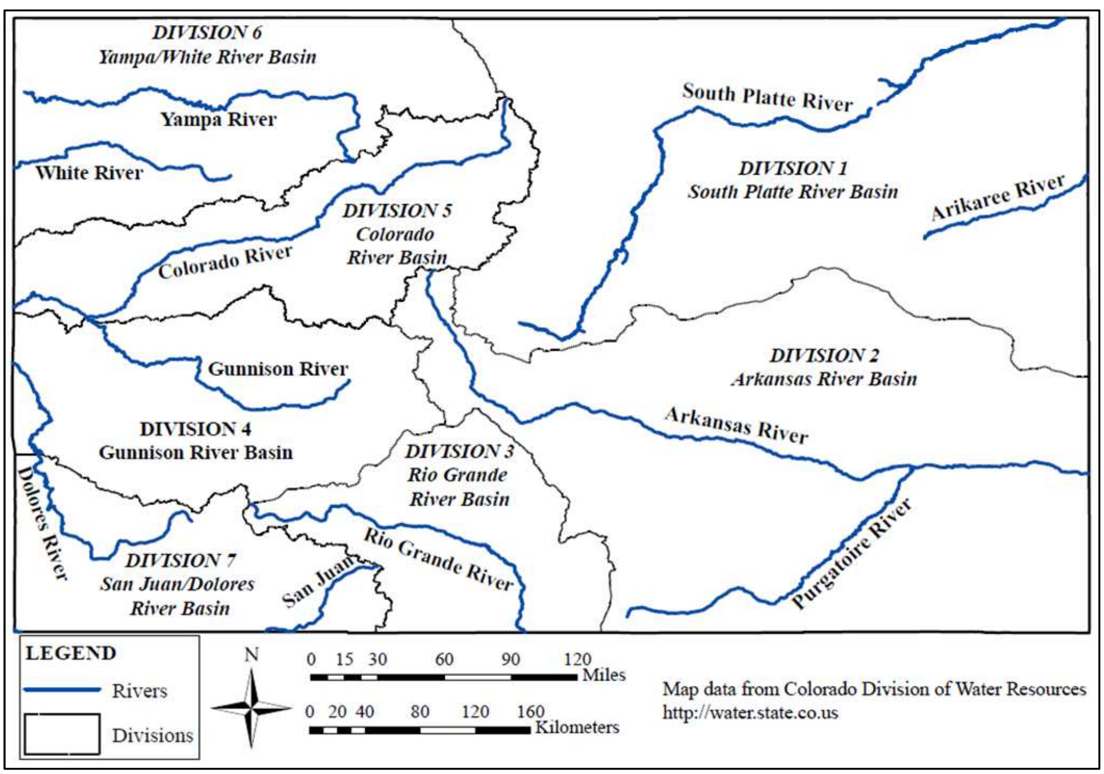


Figure 8 Colorado Division of Water Resources divides the state into seven water divisions

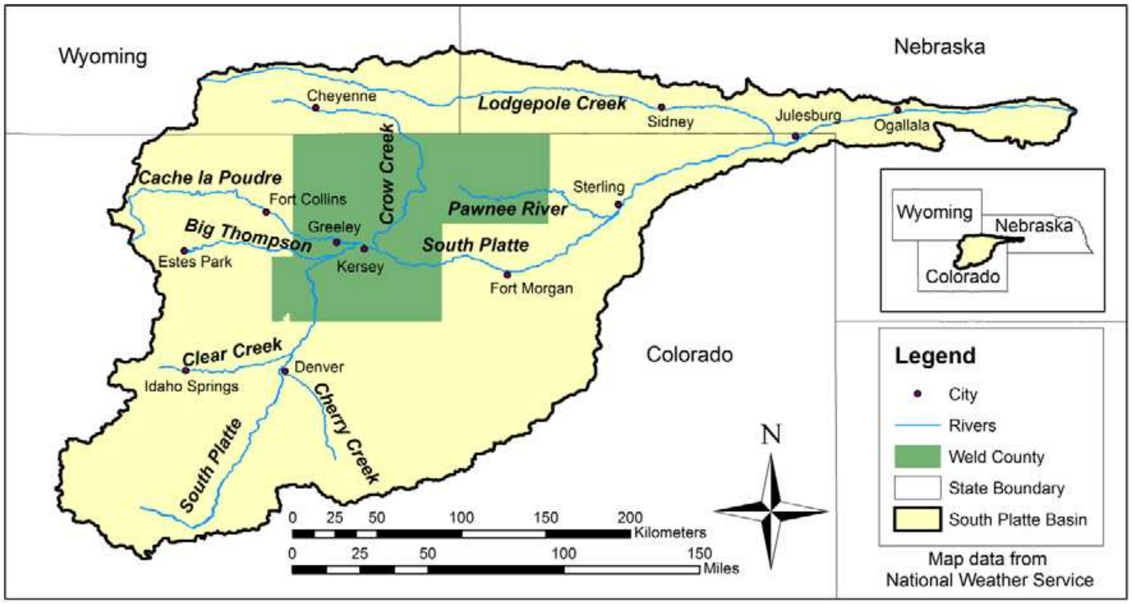


Figure 9 Study area, Location of Weld County in South Platte River Basin

An example of buy-and-dry in Weld County occurred in 1986 when city of Thornton bought more than 7,000 ha (17,750 ac) of land spread across 104 farms in Weld and Larimer Counties (Young, 2015). The purchased land is mainly located around Ault and Pierce, two small towns in Weld County. Strong opposition formed against this purchase, especially in Ault, when it was revealed the buyer is a municipality, exempt from land taxes (Baker, 2016). The deal stayed in the Water Court until 1998, when a court ruling required Thornton to minimize its impact on water rights. Thornton started to pay a voluntary payment to Ault in lieu of property taxes, convert dry farms to native grassland, and lease land and water to the farmers for agricultural purposes (BizWest, 2005). But recently the city has started constructing a pipeline to convey the acquired water to its citizens in mid 2020s; the plan is to transfer all the water to Thornton by 2060 (Young, 2015).

Since no other large scale water right purchase has happened in Weld County, the rural communities have not felt the full effect of buy-and-dry yet. No example of ATM was found in

South Platte Basin, except Northeast Colorado Water Cooperative, the purpose of which is to provide more water to agricultural sector (see page 23), thus, does not fall in the category of ATMs. As the surrounding urban areas grow, M&I users must turn to agricultural sector for their water requirement (Pritchett and Thorvaldson, 2008). In the absence of ATM institutions, Weld County can expect more buy-and-dry cases to follow. As Thornton withdraws her purchased water out of Weld County's rural communities, it is time to study the results and examine effectiveness of Water Plan's provisions in this basin.

3.2 Experimental farms

Other than data collected in SIEP experimental farm another set of data was available for this research from Limited Irrigation Research Farm (LIRF) funded by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Water Management Research Unit, based in Fort Collins, CO. The LIRF experimental farm is also located in Weld County and is about 12 miles away from SIEP farm (Figure 10).

Figure 10 Location of LIRF and SIEP around Kersey, Weld County, CO

3.2.1 Subsurface Drip Irrigation Efficiency Project

Subsurface Drip Irrigation Efficiency Project (SIEP) farm is a 67-ha (165 ac) tract of land near Kersey, CO and is a part of South Platte River Basin and Colorado's eastern planes. The farm is located at the intersection of U.S highway 34 and County Road 63; about 7 miles to the east of town of Kersey and 15 miles to the east of Greeley (Figure 9). The farm has been used for research since 2015 and is equipped with a newly installed subsurface drip irrigation system. Three ditches pass through the farm and divide it to three parts as shown in Figure 11.

Figure 11 Subsurface Drip Irrigation Project (SIEP) research farm, on U.S highway 34

The western section of the farm, with an area of 33 ha (82 ac), is equipped with subsurface drip irrigation system. A well, pumping house and filtration house are the other components of the irrigation system installed in this section of the farm. Research experimentation is conducted in the western section. A weather station is installed in the northern section (see under Figure 15 for details). The eastern section is dedicated to future expansion of the research project. It also contains a newly constructed office, a soil laboratory, and a workshop for storing machinery.

The three ditches are used for both irrigation and drainage purposes and they eventually drain in South Platte River. Since SIEP farm is only about one mile away from the South Platte River, this part of the ditches mainly functions as drainage system. The farm is irrigated with pumped groundwater, and not water from the ditch. The result of textural analysis of soils in the farm is shown in Figure 12. It is seen that on average the soils are mostly of clay loam texture. The farm has a slight slope from south to North (see Figure 13) towards South Platte River.

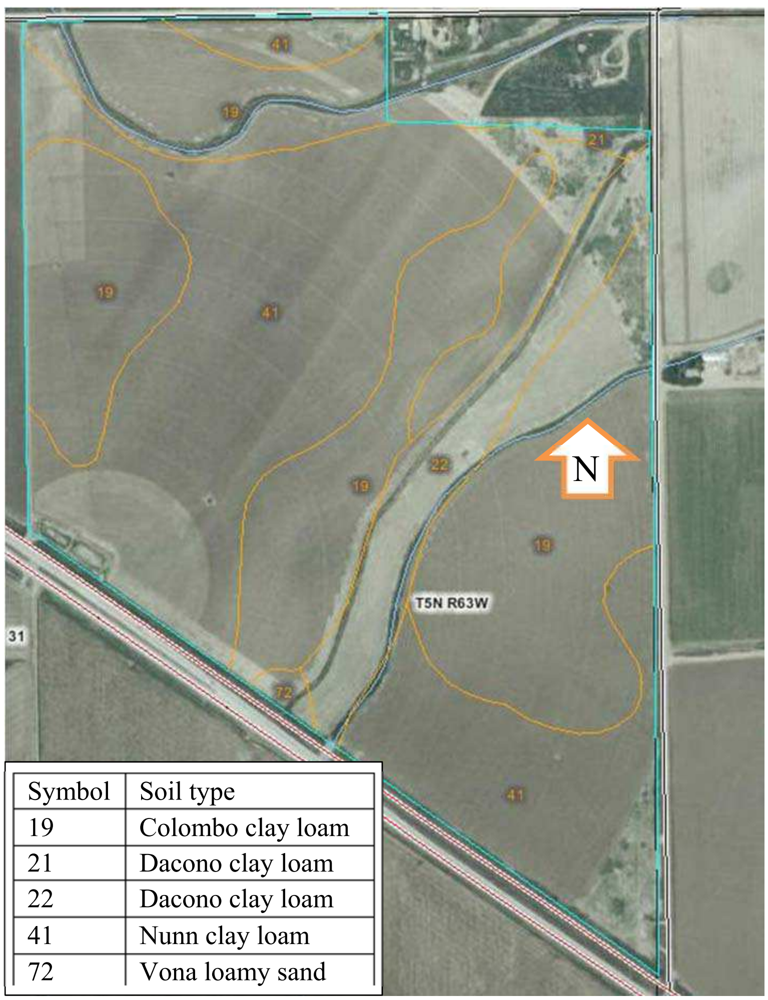


Figure 12 SIEP farm soil texture classification

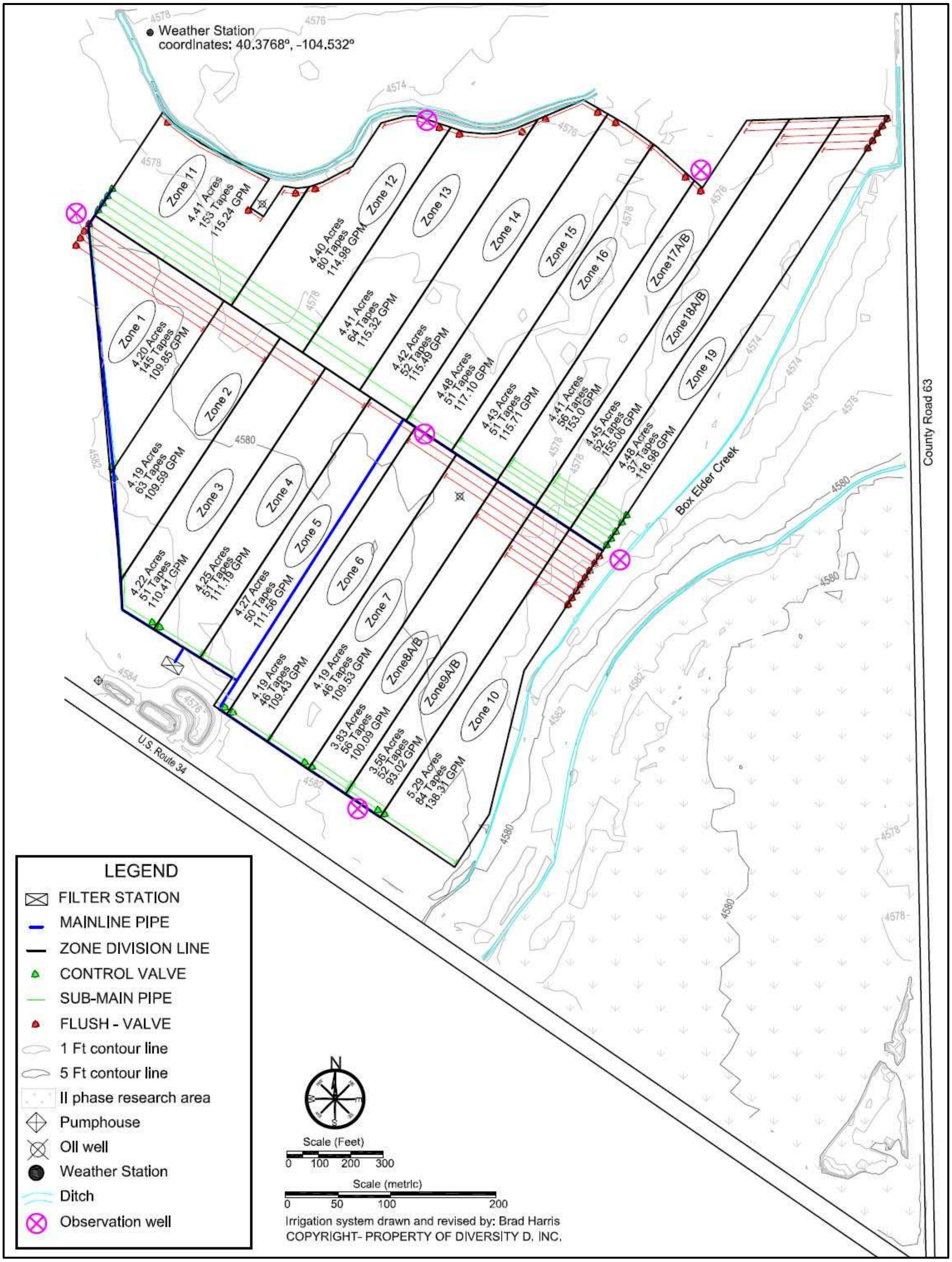


Figure 13 Layout of irrigation system in SIEP farm

The western section is divided into 19 zones as illustrated in Figure 13. Each zone's area is between 1.6 and 1.8 ha (4 to 4.5 ac). A valve at the head of each zone controls water application and flow; therefore, zones can be irrigated separately. A flow meter is installed after each valve to measure flow rates. Zone size is larger than conventional research plots and is closer to farming plot size in the area (normally farmers irrigate every 10 ac under one valve).

The valves are hard-wired to a controller and can be operated automatically or manually through the controller. The underground driplines are 101.6 cm (40 in) apart and are buried at a depth of 25.4 cm (10 in). On the driplines, the emitters are about 61 cm (24 in) apart. The running pressure of the system is 135 to 150 KPa (20 to 22 psi).

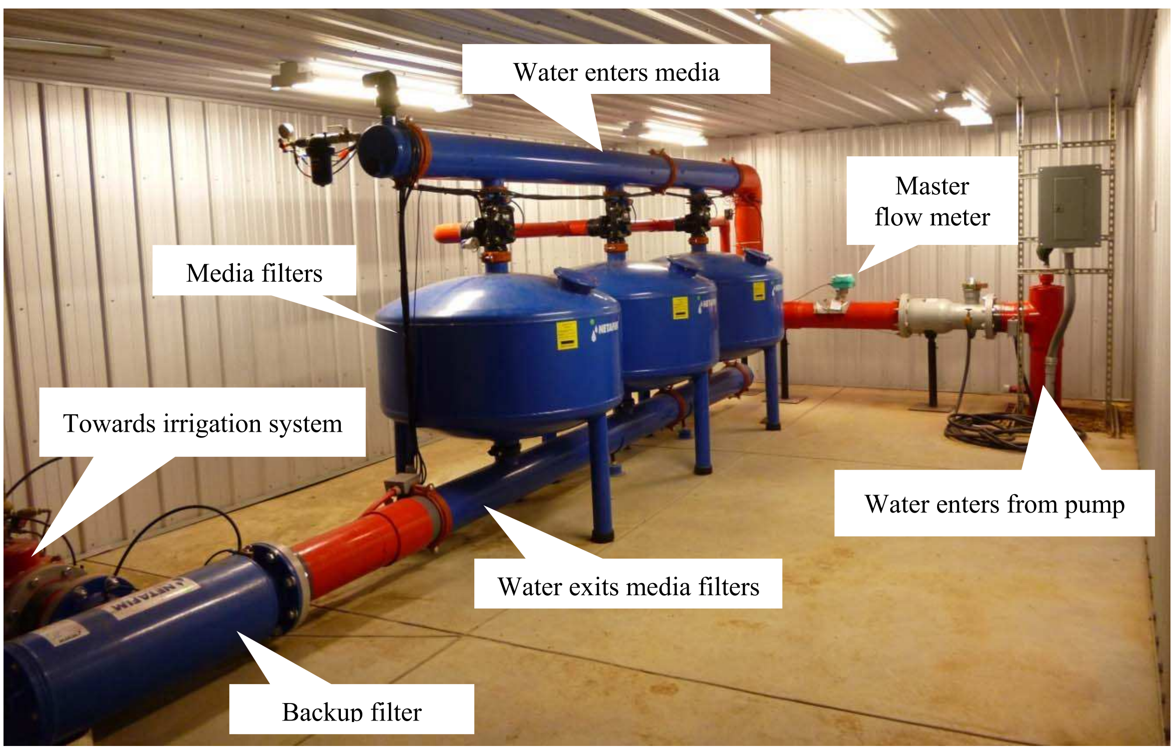


Figure 14 SIEP filter house

Water for the research field is pumped from a well and water quotas are granted by the Lower Latham Ditch and Reservoir Companies. Well water electric conductivity (EC) is 2.69 mmhos/cm (2.69 dS/m) and the amount of total dissolved solids (TDS) is 2130 ppm. Both values show moderate salinity problem (Ayers and Westcot, 1994) and can result in yield reduction. Well pump is designed for flow of 3.785 m^3/s (1000 gpm) and head of 46 m (152 ft). At this performance point pump has an efficiency of 82% and needs 34.9 KW (46.8 hp) power. Required net positive suction head (NPSHr) is 4.5 m (14.9 ft).

Well water is filtered with three media filters. At any given time, only two of the sand filters work and the third one is a backup. Another filter is installed at the downstream of sand filters to capture any left debris. Figure 14 shows the setting of SIEP filter house.

Colorado Agricultural Meteorological Network (COAGMET) has installed a weather station in the northern section of farm (see Figure 13). This station is sponsored by SIEP sponsors. Station coordinates are 40.38˚ N and -104.53˚ E. The weather station is pictured in Figure 15.

Figure 15 KSY02 weather station of Colorado Agricultural Meteorological Network

The weather station has instruments to record mean temperature (˚C), relative humidity (%), vapor pressure (kPa), solar radiation (kJ/m^2 /min), mean wind speed (m/s), vector average wind direction (in degrees, 0 and 360 being north), precipitation (mm), mean soil temperature at 5 cm (˚C), mean soil temperature at 15 cm (˚C), wind gust (m/s), and wind gust direction (degrees). The recorded data are available online on coagmet.com on an hourly basis from January 1, 2015. The station name on the online data library is Kersey2 (ID: KSY02). Elevation of weather station is 1395 m (4577 ft) from sea level which is a good representation of farm average elevation.

3.2.2 Limited Irrigation Research Farm

In 2008, USDA-ARS Water Management Research Unit in Fort Collins began a field study of the water productivity of corn, sunflower, wheat and dry bean under different amounts of irrigation, under supervision of Dr. Thomas Trout, agricultural engineer in ARS. The research is now ongoing under the supervision of Dr. Kendall DeJonge. This farm is located 6 miles to the north-east side of Greeley (40°26’50” N, 104°38’10” W, with an elevation of 1425 meters above sea level). The average rainfall during summer growing season (May 1 to Sept 30) is 215 mm for this region (PRISM, 2015). Farm soils predominately classify as sandy loams with some areas and layers of sandy clay loams and loamy sands. Soil water content at field capacity averaged 0.24 m^3 m^{-3} from 0–45 cm depth, 0.21 m^3 m^{-3} from 45–75 cm depth, and 0.19 m^3 m^{-3} from 75–105 cm depth. A CoAgMet weather station identical to SIEP farm’s weather station is installed on the farm, called Greeley4 (ID: GLY04).

A 5-ha piece of land in LIRF is dedicated to experimentation on yield response to water shortage. This part was divided into four blocks each comprising of 24 plots as shown in Figure 16. The plots were 9 m by 44 m. Twelve rows with 0.76m (30 inches) spacing were planted in each plot. The blocks were separated with a buffer zone of 4.5 m wide.

The plots were equipped with surface drip irrigation system with thick-walled drip tubing. One tube was placed along each crop row. The emitters were spaced 30 cm on the tubing and had a flow rate of 1.1 L/hr. Every year, the crop planted in a block was rotated.

Trout and Bausch (2016) provided a detailed description of water balance measurements and calculations and comprehensive corn experimental data in USDA-ARS Colorado Corn Water Productivity Dataset 2008-2011. Trout and DeJonge (2017) presented an analysis of the water productivity of corn experiment.

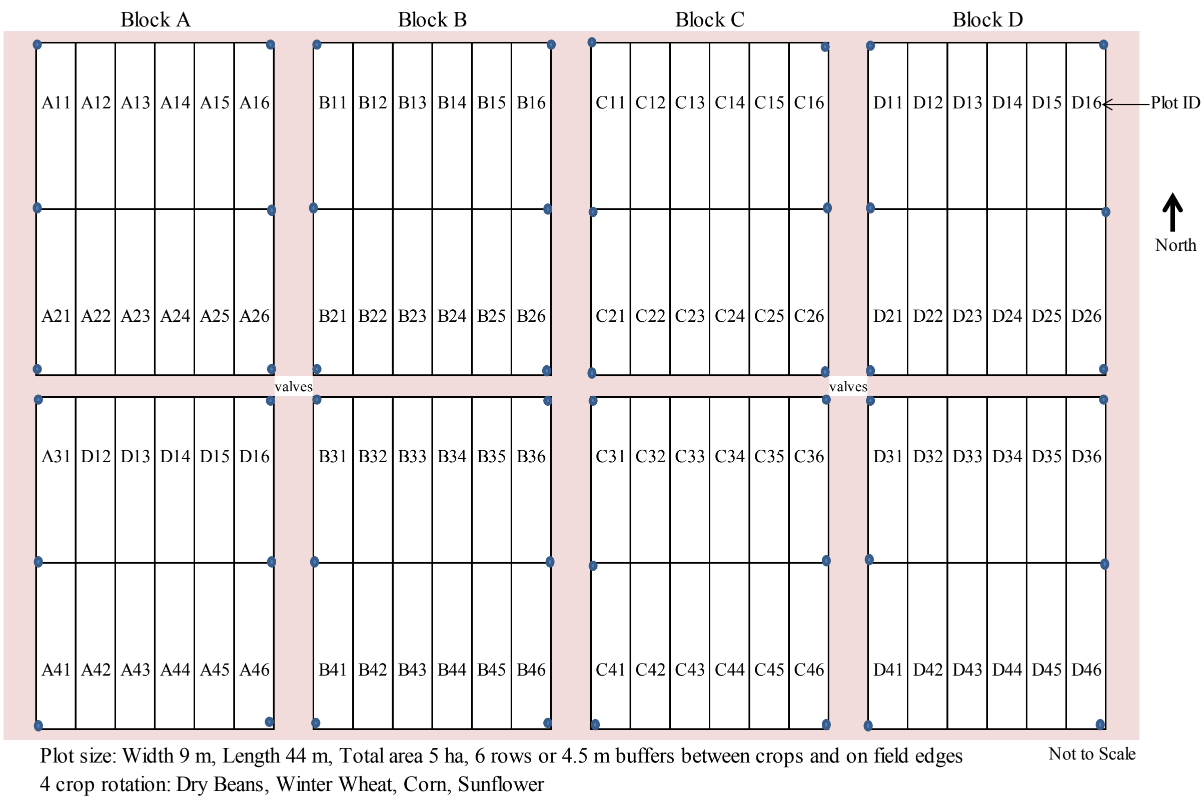


Figure 16 Limited Irrigation Research Farm plot layout

CHAPTER 4 MATERIALS AND METHODS

The response of sorghum-sudangrass to water deficit was examined in SIEP farm. Also the ARS team examined several crops in LIRF facility; their results on corn and sunflower are analyzed for this research. The experimental farm settings, treatment description, measurements and calculations are discussed in this chapter.

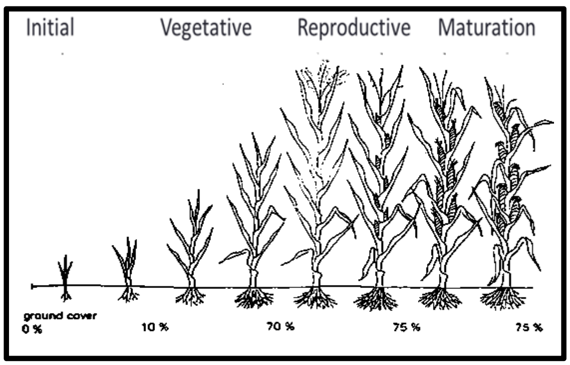
4.1 Choice of Crops

Commonly grown crops in the study region are alfalfa, wheat, sorghum, corn, dry bean, and sugar beet (Table 2). Between the two research farms, most of these common crops were tested. In the SIEP farm, sorghum-sudangrass (cross hybrid between sorghum and sudangrass) was examined during the 2015 and 2016 growing seasons. This is a heat and drought tolerant crop (Clark, 2007; Gerik et al., 1998; Grubinger, 2008) and can have several cuttings during the cropping season. Soil fertility tests in both years showed that soil nitrate and sulfate level was sufficient for sorghum-sudangrass growth and no fertilizer was applied. Sorghum-Sudangrass must be cut before the reproductive stage because its quality as hay will reduce with the start of tasseling (Clark, 2007). After that, irrigation can be continued to obtain a second cut. Therefore, this crop can have more than one vegetative stages. In this research, only one harvest was obtained every year.

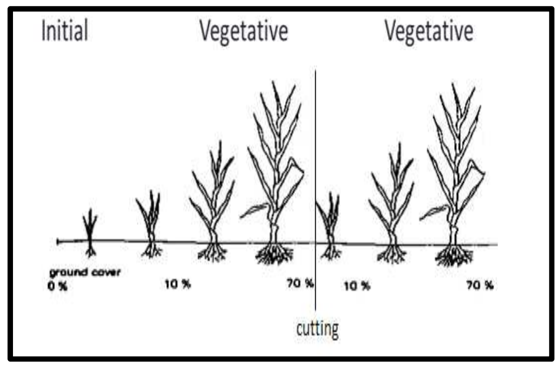
In LIRF facility, the ARS team examined with four crops over a four year period from 2008 to 2011. Corn (Zea mays L.), sunflower (Helianthus annuus), dry bean (Phaseolus vulgaris), and winter wheat (Triticum aestivum) were planted in a rotation. The author obtained the data for corn and sunflower crops from ARS and analyzed it along with data collected at the SIEP farm. Corn data was available for all four years of ARS experimentation. In 2009, an over application of herbicide destroyed the sunflower crop, therefore 2009 sunflower data are excluded from analysis.

4.2 Irrigation Treatments

Crop sensitivity to water stress often varies by growth stage. In accordance to FAO Irrigation and Drainage Paper 56 (FAO 56) main crop growth stages considered in this research are initial (until crop covers 10% of ground), vegetative, reproductive (flowering and beginning of yield formation), and maturation (ripening) stages, schematically graphed in Figure 17.



Grain crop



Hay crop

Figure 17 Crop growing seasons and approximate ground cover during each growth stage

Past research shows water stress during the reproduction stage of crop development reduces yield regardless of the water stress during either the vegetative or the maturation stages (Doorenbos and Kassam, 1979; Gerik et al., 1998; Payero et al., 2005; Shaner, 2012; Tolk and Howell, 2003; Zhang, 2003). Therefore, water deficit was avoided during this stage. Furthermore, no water stress was imposed at the initial stage of plant growth to ensure homogenous initial crop cover and plant establishment. With these two considerations in mind SIEP treatments were planned as listed in Table 3. It is important to note these are the target levels and achieving them, especially the lower levels depend on the amount of rainfall that the research does not control. For example, in a wet year rainfall may equal to 50% of crop water requirement in which case it will not be possible to reach water a 30% water stress level.

To ensure the target levels are achieved, irrigation amount was calculated for Treatment 1. Then a fraction of irrigation time for Treatment 1 was applied to the stressed treatments depending on the water regimes in Table 3. Adjustments to irrigation duration were required after the few rainfall events or system cut-off due to maintenance. Irrigation application was controlled at the head of the system by a controller. Application rates were set on the controller. Flow meters at the head of zones record total volume of water passed through head valves. These meters are calibrated to ensure errors under 5%.

Table 3 SIEP farm target water regimes as percent of maximum or non-stressed crop evapotranspiration

Treatment	Initial stage	Vegetative stage
1	100	30
2	100	50
3	100	70
4	100	100

In 2015, the 19 zones in the SIEP farm were planted with sorghum-sudangrass, but only eight zones were monitored as research plots. Each treatment in Table 3 was applied to two zones therefore there were two replications of each treatment (and two blocks). In 2016, one more block was added to the experimentation and therefore three replicas of each treatment were randomly applied to different zones. The rest of the zones were left fallow. Treatments and blocks are shown in Figure 18. Border effects between plots were eliminated by taking yield samples from the middle 15 m strip of each zone.

In LIRF the six irrigation treatments were randomly assigned among the field, for each crop and each year. The treatments were designed to meet a desired fractions of full crop water requirement during vegetative and maturation stages as listed in Table 4. The blocks of land that were planted by each crop in LIRF are listed in Table 5 for every year of experimentation.

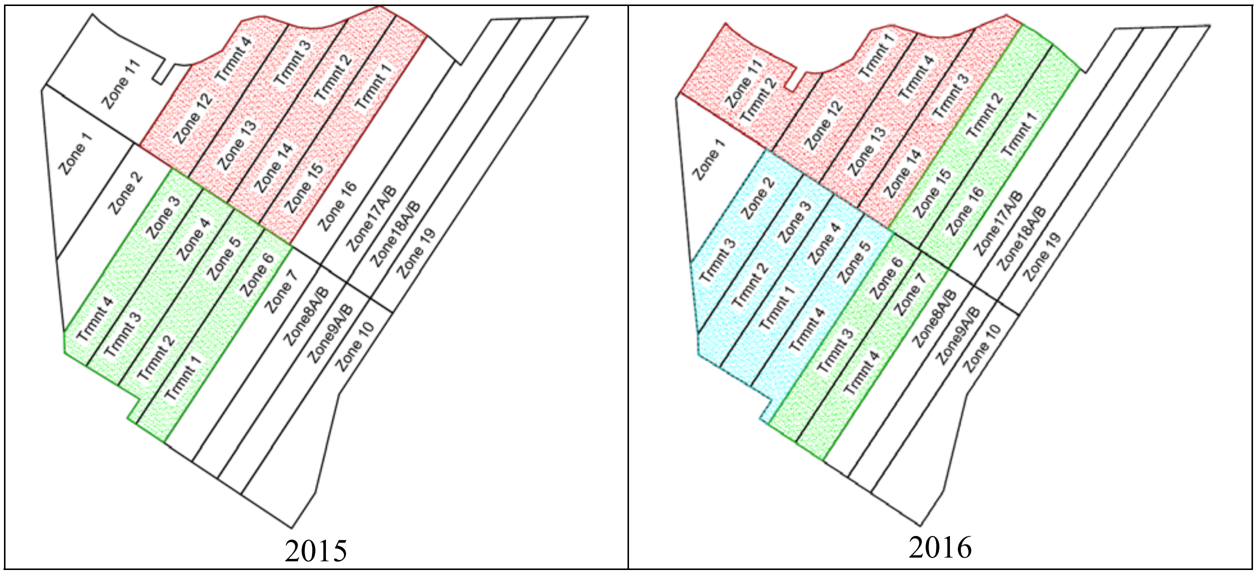


Figure 18 Treatments applied to SIEP farm zones; colors delineate a block

Table 4 Irrigation treatments in LIRF in vegetative and maturation stages

Treatment	
T1	100% of crop water requirements (no stress)
T2	85% of T1
T3	75% of T1
T4	70% of T1
T5	55% of T1
T6	40% of T1

ET at the reproductive stage was 100% of crop water requirement for all treatments.

Table 5 LIRF crop blocks

Year	Corn block	Sunflower block
2008	D	C
2009	B	D
2010	A	B
2011	C	A

Refer to Figure 16 for a layout of blocks.

No water stress was applied during initial and reproductive stages of crop growth. The 100% treatment, T1, was irrigated so that crop water requirement as calculated per FAO 56 was met with combination of water from irrigation, precipitation, and water stored in the soil profile. The crop was managed consistently other than water; that is, all treatments had the same plant population at sowing and same amount of applied fertilizer. Therefore, the only variable among treatments was water application.

4.3 Measurements and Instrumentation

Parameters measured in both research fields are:

1. Hourly weather parameters (solar radiation, relative humidity, wind speed, air temperature)
2. Applied irrigation
3. Soil water content
4. Crop canopy cover
5. Phenology (planting date, emergence, growth stages, canopy ground cover, crop height)
6. Final above ground biomass
7. Marketable yield
8. Crop management activities, including tillage, seeding, fertility, and pest control

Additionally, the following parameters were recorded only at the LIRF facility:

1. Soil texture and water retention vs. water potential
2. Biomass total carbon and nitrogen (only 2008 and 2009)

The following data were only measured for SIEP:

1. Soil fertility parameters
2. Well water quality parameters

3. Hay quality parameters
4. Ground water level (Since LIRF groundwater level was low it was not monitored)

4.3.1 Soil water content measurements

At LIRF soil water content was measured at least 2 times a week, typically before and after irrigation. A neutron probe (CPN-503 Hydroprobe, InstroTek, San Francisco, CA) was used for measurements at 30, 45, 75, and 105 cm. At SIEP same measurements were performed on a weekly basis for depths of 30, 60, 90, 120, 150, 180 cm using a similar neutron probe. This instrument emits neutron ions that hit Hydrogen (*e.g.* H_2O) molecules in soil and are reflected back. By counting the number of reflected neutrons and comparing them with number of reflected neutrons in dry environment (standard counts) soil water content is obtained. Neutron probe readings are not accurate for top soil; therefore, at LIRF a portable time domain reflectometer (TDR, Minitrase, Soilmoisture Equipment Corp, Santa Barbara, CA) was used for surface soil (shallower than 15 cm). At SIEP a reflectometer (HydroSense II, Campbell Scientific, Logan, UT) was used to measure soil water content at the depth of 20 cm. This device measures soil electric resistivity between two electrodes installed in the soil. The resistivity of soil is then related to soil water content.

4.3.2 Crop canopy cover

Another necessary measurement is percent of ground covered by crop canopy, f_c. This value is required when calculating crop evapotranspiration and water requirement. Nadir pictures of crop canopy are classified to vegetation cover and background (soil, surface residue, and senesced leaves) and the percent of picture's surface covered by vegetation is determined.

In SIEP farm a digital RGB camera was used to take pictures of canopy cover every week from 2.5 m above ground. Then ENVI (a software platform for image processing) was used to classify pictures and determine f_c. A picture and the results of its classification are shown in Figure 19.

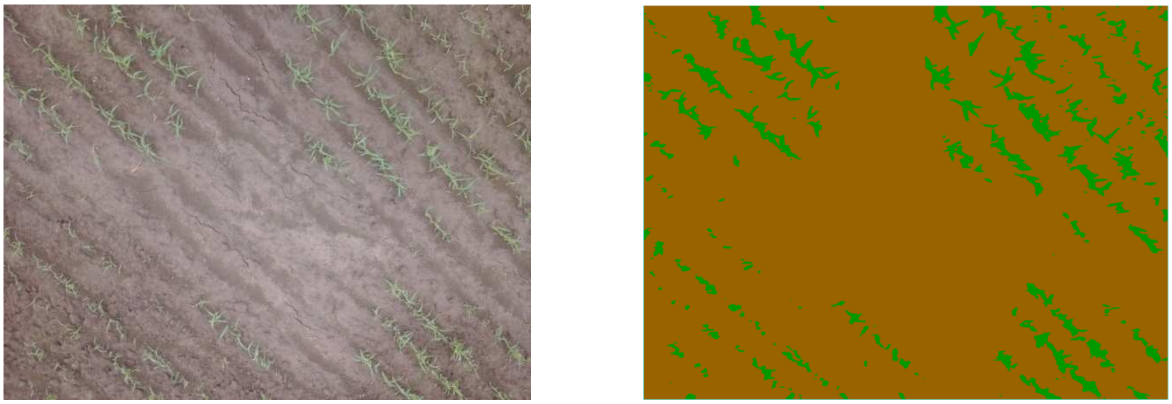


Figure 19 sorghum-sudangrass crop canopy picture and classification on July 7th 2015, 7% vegetation cover

Canopy ground cover measurements were collected in LIRF on a weekly basis near solar noon. The pictures were taken with a digital camera from a nadir view 6 m above ground surface (Trout and Bausch, 2017) and processed using a code in ArcGIS. Training polygons were manually defined for pictures collected in both farms.

4.3.3 Yield

Sorghum-sudangrass growers cut the crop it before tasseling occurs and let the crop dry in the field until hay moisture content is 14%. Then the hay is baled. In SIEP research farm several yield samples were collected and weighed from plots of 1x1 m chosen randomly from the middle section of each research zone. Crop fresh yield at a zone is calculated as the average of yield in four the 1x1 m plots. To obtain the marketable yield the crop was dried in ovens at 37˚C until its moisture content reached 14%, at which point it was weighed again. The rest of the crop was harvested and baled in the farm. The produced hay was tested for hay quality as required for cattle feed.

Harvest in LIRF was done manually, from center 15 m of the center four rows of each plot. The grains were completely dried and weighed. Corn marketable yield is grain with 15.5% moisture content, so the dry weight was normalized for 15.5% moisture content.

4.4 Calculations and Procedures

Crop water requirement or crop actual evapotranspiration is an important parameter that was required for planning irrigation water application in this research. The procedure given in FAO 56 and its soil water balance approach was used for all three data sets (sorghum-sudangrass, corn, and sunflower) to calculate the crop water requirement. The reader is referred to FAO 56, chapters 7 and 8 for more details and comprehensive explanation.

4.4.1 Evapotranspiration

Calculation of crop actual evapotranspiration starts with calculating reference evapotranspiration (ET_o). Reference evapotranspiration depends on weather conditions and is defined for a reference crop. For this research a computer program called Ref-ET (Allen, 1999) was used for calculation of ET_o (short reference) following the procedure given in ASCE standardized reference evapotranspiration (Allen et al., 2005).

The maximum crop evapotranspiration can be calculated for ideal situation when crop is not under any stress such as water and salinity stress, crop density, pets and diseases, weed infestation or low fertility (FAO 56). This value of crop evapotranspiration is commonly known as ET_c and is defined by the following simple equation:

$$ET_c = (K_{cb} + K_e)\, ET_o$$

Equation 4.1

In Equation 4.1 K_{cb} is the basal crop coefficient for estimating transpiration component of crop coefficient and K_e is soil evaporation component of crop coefficient. This procedure, known as dual crop coefficient, is explained in chapter 7 of FAO 56. To account for effect of water shortage a water stress factor (K_s) is added to Equation 4.1:

$$ET_a = (K_s\, K_{cb} + K_e)\, ET_o$$

Equation 4.2

The result is the actual crop evapotranspiration (ET_a) as opposed to maximum crop evapotranspiration. There is no soil water stress at K_s=1; as K_s decreases and approaches zero soil water becomes more and more limited. Values of K_s, K_{cb}, and K_e are defined on a daily basis. Soil water balance and FAO 56 dual crop coefficient procedure were used for calculating daily crop evapotranspiration. The water balance is:

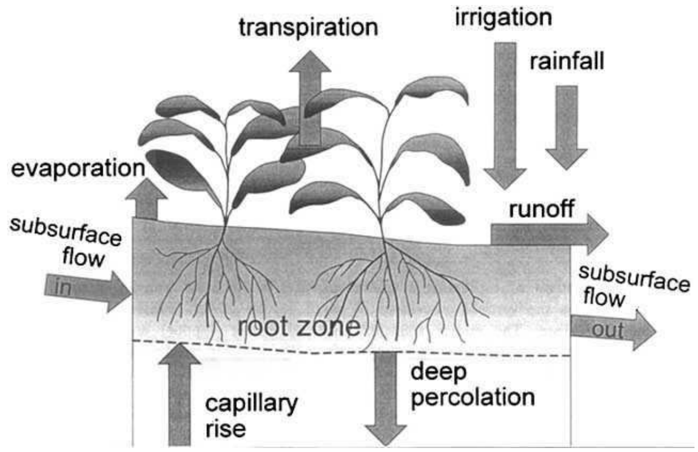
$$\Delta S = I + P + UF - DP - RO - ET_a$$

Equation 4.3

where ΔS is change in soil water content in the root zone; I is the amount of applied irrigation; P is precipitation; *UF* is the upflux of water from groundwater (assumed 0 because the groundwater table was more than 5 m deep in both research farms); *DP* is deep percolation away from the root zone; *RO* is surface runoff of precipitation or irrigation; the surface runoff (*RO*) was assumed to be zero due to relatively flat field; adequate soil infiltration, and drip irrigation; and, ET_a is crop evapotranspiration (see also Figure 20). Hence, ET_a was estimated as:

$$ET_a = I + P - \Delta S - DP$$

Equation 4.4



Reference: FAO 56

Figure 20 Components of soil root zone water balance

4.4.2 Crop productivity indices

In irrigation science several indices are used to evaluate performance of crop with respect to its water use. Before defining productivity indices, it is necessary to clarify a common misnomer. Irrigation literatures often refer to water productivity indices as "water efficiency". However, efficiency is the ratio of output to input or the slope of the functional relationship, Δoutput/Δinput (Sadras et al., 2012). The result is normally a unit-less value because input and output have the same units. One example is the amount of water that is converted to an irrigation system (input) and the amount of water that reaches an irrigated farm (output) in calculation of conveyance efficiency.

The indices that are used here, however, have different units for outputs and inputs; therefore, titling them "efficiency" is incorrect. For this reason, FAO has suggested using "water productivity" instead of "water efficiency" (Sadras et al., 2012). For example, crop water use efficiency (WUE) is defined as the ratio of marketable yield (Y) to evapotranspiration (Tolk and Howell, 2003). Instead, we will use the term crop water productivity (CWP) for the same ratio:

$$CWP = \frac{Yield}{ET_a}$$

Equation 4.5

Another common index is "irrigation water use efficiency" (IWUE), defined as the ratio of marketable yield to the amount of irrigation water applied (Irmak et al., 2011). However, irrigation water is not the only source of available water for crop. Precipitation and soil residual water at the beginning of growing season also contribute to crop yield. The aim of this research is to define crop performance regardless of variabilities in available water. Therefore, use of IWUE is rather misleading in the context of this research.

4.5 Statistical analysis

As previously discussed, the shape of crop water production function is a defining factor in usefulness of deficit irrigation and limited irrigation practices. Both linear and quadratic regressions were produced for the experimental data (the observed values). The superior regression or model must have a better goodness of fit to the observed data. The goodness of regression is analyzed using statistical indicators such as *p-value* and R^2. The two statistical indicators used in this research are defined here.

In hypothesis test, *p-value* determines the statistical significance. This is the probability of obtaining a value of the test statistic that is as likely or more likely to reject the null hypothesis as the actual observed value of the test statistic. This probability is computed assuming the null hypothesis is true. Here the null hypothesis is that the quadratic regression is not superior to the linear regression. Considering a confidence interval of 95%, the *p-value* associated with the quadratic term ($ET_a{}^2$) must be smaller than 0.05 (or 5%) to show a significant improvement in the model. In other words, when p-value of the quadratic term is greater than 0.05, the quadratic term is not significantly improving the model fit and there is not enough evidence to reject the linear regression as a proper model. Then the linear model must be accepted as the superior model for estimating the relationship between the two observed parameters (here yield and ET_a). On the contrary, when the *p-value* is smaller than 0.05 the quadratic model is superior.

A parameter often used to determine the goodness of fit is the coefficient of determination or R^2. The higher this coefficient, the better the regressed model fits to the observed data. The dependable variable in this research is the yield; therefore, the R^2 for this research is calculated as:

$$R^2 = 1 - \frac{\text{Sum of squared distances between the actual and predicted values of dependent variable}}{\text{Sum of squared distances between the actual values of dependent variable and their mean}}$$

Equation 4.6

However, this coefficient always increases by adding terms to model; that is, a quadratic model's R^2 is always greater than that of a linear model. To account for this problem, an adjusted version of R^2 is used which, only increases if the new term improves the model more than would be expected by chance. The adjusted R^2, abbreviated to *adj-*R^2, is:

$$adj\_R^2 = 1 - \frac{(1-R^2)(ss-1)}{ss-np-1}$$

Equation 4.7

where

np is number of predictors

ss is the total sample size or number of observations

The only predictor used in this research is actual evapotranspiration (ET_a) so *np*=1.

The p-value and *adj-* R^2 are the two statistical parameters that are used later in the results chapter to determine model's goodness of fit.

CHAPTER 5 RESULTS

To investigate the feasibility of different methods of reducing farm water consumption, the first step was to develop the relationship between the amount of water consumed by crop (crop ET) and the related yield. The current research investigated these relationships for three crops – sorghum sudan-grass, corn and sunflower. These results are used to develop crop water production function, calculate crop water productivity indices and determine farm optimal water allocation strategy for each crop.

5.1 Sorghum-sudangrass

Sorghum-sudangrass was cultivated in the Subsurface Irrigation Efficiency Project (SIEP) farm during 2015 and 2016 growing seasons. In plots of 1.6 ha to 1.8 ha; four levels of water stress were applied; 30%, 50%, 70%, and no stress (corresponding to treatment 1, 2, 3, and 4 respectively). The results are given in Table 6.

Table 6 Components of soil water balance and yield for sorghum-sudangrass in Kersey 2015-2016

Year	Treatment	Precipitation (mm)	Irrigation (mm)	Deep Percolation (mm)	ETa (mm)	Yield (Mg ha^{-1})	CWP=Y/ETa (Mg ha^{-1} mm^{-1})
2015	1	72	144	47	181	9.57	0.0530
	2		161	48	195	11.08	0.0569
	3		174	42	205	9.80	0.0478
	4		211	45	236	12.85	0.0545
2016	1	49	98	8	129	7.29	0.0567
	2		108	7	137	8.71	0.0637
	3		187	9	198	10.77	0.0544
	4		257	9	234	12.13	0.0519

Each water stress treatment had 2 replications in 2015 and 3 replications in 2016; in this table values reported for each treatment are the averages over the respective replications. Calculated values of water productivity indices are also presented in Table 6. All the deep percolation in both years occurred due to rainfall events. For this reason, deep percolation has decreased in 2016 which had lower precipitation during growing season. With the data collected in SIEP research farm it was possible to calculate crop water productivity (CWP) using actual evapotranspiration and yield values; this parameter is also listed in Table 6 for ease of comparison.

A maximum yield of 12.85 Mg ha^{-1} was achieved in SIEP farm. Yields are similar to those obtained in Agricultural Research, Development and Education Center (ARDEC) in Fort Collins, a local research facility of Colorado State University, where fully irrigated (wheel move irrigation system) sorghum-sudangrass produced a maximum yield of 13.58 Mg ha^{-1} in ARDEC. The same farm harvested a minimum of 7.02 Mg ha^{-1} of hay in dryland plots (Larson et al., 2013). Vendramini et al. (2015) observed a maximum of 26 Mg ha^{-1} for humid areas of southeastern United States (Florida and Georgia) without irrigation and a minimum yield of 5.4 Mg ha^{-1}. Little information is available on sorghum-sudangrass rate of evapotranspiration; most studies report irrigation requirement. Pan et al. (2011) recorded a maximum of 382 mm of ET_a in northern China, a humid area where growing sorghum-sudangrass requires minimum irrigation only in very dry years. This is 60% more than the maximum ET_a obtained in SIEP farm. However, they have achieved an average yield of 10.5 Mg ha^{-1} which is comparable to SIEP yields.

5.1.1 Sorghum-sudangrass crop water production function

Crop water production function (CWPF) or the relationship between marketable yield and crop evapotranspiration for sorghum-sudangrass is given in Figure 21. A linear function and a quadratic function were fitted to the observed data. The quadratic regression does not offer a significant improvement in the model fit; since the p-value calculated for the quadratic term is 0.638. Also, the adjusted R^2 for the linear regression (0.865) is slightly higher than that of quadratic regression (0.846) indicating that the linear regression provides a better fit in the model. Therefore, the linear model is accepted as crop water production function for sorghum-sudangrass which is:

$$Y = 0.043\ ET_a + 2.14$$

Equation 5.1

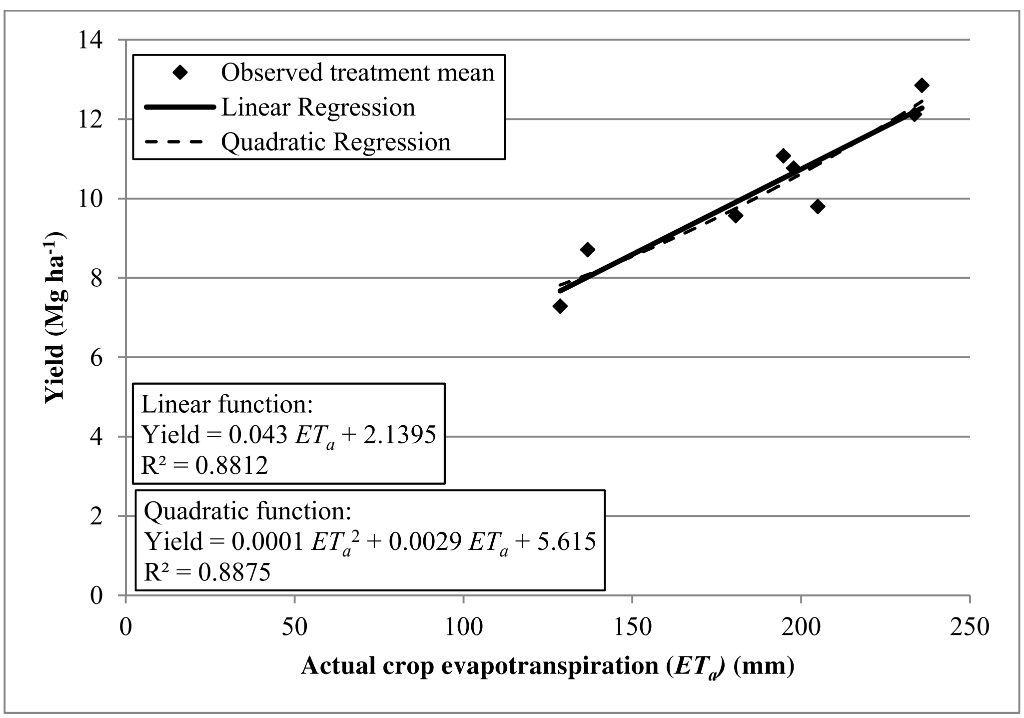


Figure 21 Sorghum-sudangrass crop water production function

In this equation yield is in Mg ha^{-1} and ET_a is in mm. The minimum amount of obtained ET_a for sorghum sudangrass was slightly less than 130 mm for these two years. The maximum amount of achieved ET_a was below 234 mm for the first cut. Extrapolation of Equation 5.1 to ET_a values beyond these two limits will be associated with some uncertainties. No report of CWPF for sorghum-sudangrass was found in other research works.

5.1.2 Optimal water allocation for sorghum-sudangrass

Research results support a linear CWPF for sorghum-sudangrass. As discussed in the conceptual framework (solution to Equation 2.11), when CWPF is linear partitioning water between crop production and renting does not maximize farm income. Instead, allocating all available water to the use with higher value will achieve the maximum income. Therefore, it can be concluded that deficit irrigation does not benefit a sorghum-sudangrass farm.

5.1.3 Sorghum-sudangrass hay quality

Hay Nitrate (NO_3) concentration below 2500 ppm is considered non-toxic and is safe for animal consumption (Bolan and Kemp, 2003). However, water stress can cause excessive concentration of nitrate in sorghum species (Cash et al., 2006). In 2015, hay samples from SIEP were tested for feed quality after baling. All samples had high nitrate (NO_3) levels making them unsuitable as cattle feed (average nitrate level in the five random samples was about 8500 ppm). Of note, irrigation zones or treatments were not baled separately and it was not possible to associate the samples to a zone/treatment. Therefore, nitrate contents could not be related to the amount of evapotranspiration in each zone.

In 2016, baling was done more systematically and hay samples were taken from bales within a zone. The nitrate contents were related to evapotranspiration in each zone and illustrated in

Figure 22. This figure does not indicate any obvious relationship between nitrate and crop actual evapotranspiration. No fertilizer was applied during the growing season and soil average nitrate content was 33.6 kg ha^{-1} (30 lb ac^{-1}) at the beginning of 2016 growing season. In addition, the well water's nitrate content is 12.74 ppm which is well below the threshold of 75 ppm for irrigation purposes. Therefore, a combination of factors is causing this problem and further research is required to determine them.

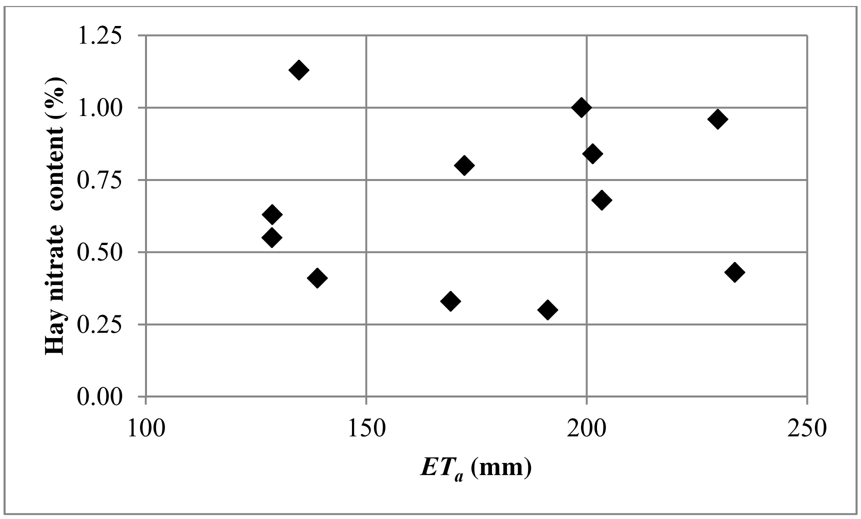


Figure 22 Nitrate content in sorghum-sudangrass dry hay versus actual crop evapotranspiration (ET_a)

Due to this problem, in 2015 the yield was sold for land reclamation in oil fields and in 2016 the hay was used for cattle feed but the buyer mixed it with high quality hay. For this reason, the hay was sold with prices under maximum price of sorghum-sudangrass.

5.2 Corn

Corn data were gathered in LIRF from 2008 to 2011 by the USDA-ARS water management team. Components of soil water balance, water productivity indices and amount of effective rainfall are given in Table 7. Each treatment had 4 replications and values reported in the table are the averages over the respective replications. A maximum yield of 13.6 Mg ha^{-1} was achieved in 2011 in the fully irrigated corn treatments. In 2011, the amount of actual evapotranspiration for this treatment was 650 mm.

Table 7 Components of soil water balance and yield for corn, obtained in Greeley, 2008-2011

Treatment	Year	Precipitation (mm)	Irrigation (mm)	Deep Percolation (mm)	ET_a (mm)	Yield (kg ha^{-1})	CWP= Yield/ET_a (kg ha^{-1}mm^{-1})
1	2008	251	438	80	633	13,228	21
2			338	38	557	12,935	23
3			282	16	536	12,601	24
4			271	30	514	11,345	22
5			180	22	445	9,009	20
6			137	0	430	8,824	21
1	2009	225	418	0	628	12,101	19
2			346	0	573	11,588	20
3			299	0	537	11,166	21
4			244	0	488	10,317	21
5			168	0	424	8,043	19
6			110	0	374	5,940	16
1	2010	212	366	0	616	11,168	18
2			303	0	560	11,441	20
3			252	0	506	10,465	21
4			219	0	461	9,315	20
5			153	0	393	7,151	18
6			100	0	354	5,505	16
1	2011	201	485	0	650	13,640	21
2			388	0	570	12,498	22
3			328	0	528	10,369	20
4			306	0	511	10,294	20
5			222	0	425	7,232	17
6			157	0	370	3,966	11

Data courtesy of Dr. Thomas Trout of USDA-ARS Water Management Research Unit

Corn crop water production function has been extensively studied in experimental farms all over the world. Trout and DeJonge (2017) provide a list of literature on corn; the maximum amount of ET_a reported among these studies was 840 mm with a yield of 12 Mg ha^{-1} (Howell et al., 1989) and highest yield in the list is 15 Mg ha^{-1} which is achieved by evapotranspiration rates similar to LIRF (630 mm, 640 mm, 660 mm, and 670 mm).

5.2.1 Corn crop water production function

To model corn crop water production function both linear and quadratic regressions were considered (Figure 23). The quadratic regression offered a significant improvement in the model fit (p-value = 0.0010 corresponding to quadratic term in the model with 95% confidence).

In addition, adjusted R^2 was higher for the quadratic model ($adj\text{-}R^2$ = 0.9151) as compared to the linear model ($adj\text{-}R^2$ = 0.8651). Therefore, the quadratic model is accepted as crop water production function for corn which is (also derived by Trout and DeJonge, 2017):

$$Y = -0.00008\, ET_a^{2} + 0.11\, ET_a - 24$$

Equation 5.2

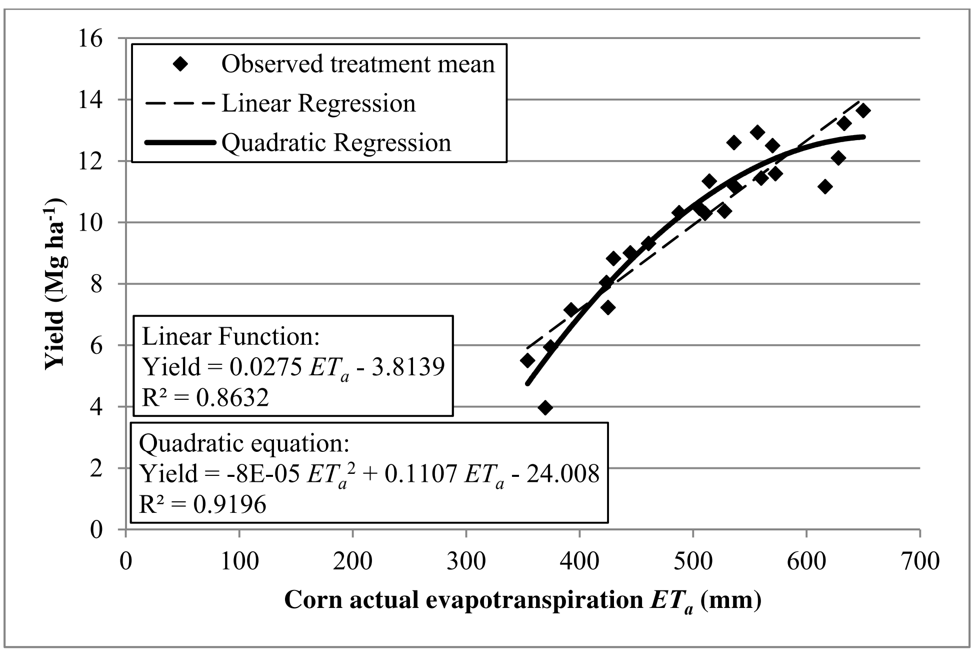


Figure 23 Corn crop water production function

Unfortunately many research papers relate available water to yield; hence, their results are not comparable with this study. Literatures that found CWPF mostly report a linear function, either to conform to FAO 33 and Jensen approaches (Djaman et al., 2013; Igbadun et al., 2007) or because the linear function provides an acceptable correlation coefficient (Schneekloth et al., 1991). The correlation function of linear regression in Figure 23 is also high (R^2= 0.86). As the linear model is reliable enough some scientists see no need to opt for a more sophisticated alternative.

5.2.2 Optimal water allocation for corn

Since corn crop water production function is non-linear, in this case, deficit irrigation can potentially be useful for corn farms. To evaluate the possibility, the cost function has to be defined. To do so, costs of dryland farming and irrigated farming are required together with yield prices. Colorado State University Extension Crop Enterprise Budget website[4] provides this information. In this website the most recent data set belongs to 2015 with costs of irrigated farming equal to 347.24 \$ ha^{-1} and cost of dryland farming equal to 119.48 \$ ha^{-1}. It is assumed full irrigation requires ET_a equal to the averages maximum ET_a observed over the four years of experimentation (633 mm, 628 mm, 616 mm, and 650 mm). Schneekloth et al. (1991) found the amount of ET_a for dryland farming is 295 mm. With these data the cost function for 2015 is:

$$C(ET_a) = 0.68\ ET_a + 119.48$$

Equation 5.3

In 2016, market price of corn was 3.75 \$ bu^{-1} while farming costs associated with irrigated corn was 5.42 \$ bu^{-1}. As such, the net returns to management and risk of irrigated agriculture was negative for a corn farm. In the same year costs of dryland farming were 3.38 \$ bu^{-1} so farmers would be better off to lease out all their available water. Therefore, 2016's data, although available, is not analyzed in Table 8.

[4] http://wr.colostate.edu/ABM/cropbudgets.shtml

Table 8 Corn farm optimal water allocation for Northeastern Colorado

Year		2010	2011	2012	2013	2014	2015
Rainfall[1]	(mm)	222	215	131	226	360	239
Cost of irrigated farming[2]	($ ac^{-1})	707.80	800.69	890.52	821.54	778.90	858.04
	($ ha^{-1})	286.44	324.03	360.38	332.47	315.21	347.24
Cost of dryland farming[2]	($ ac^{-1})	202.31	228.88	303.59	288.31	285.09	295.23
	($ ha^{-1})	81.87	92.62	122.86	116.68	115.37	119.48
CU (ET_a for full irrigation)[3]	(mm)	632	632	632	632	632	632
ET_a of dryland farming[4]	(mm)	295	295	295	295	295	295
θ (variable cost of increasing a unit of ET_a)	($ $ha^{-1}mm^{-1}$)	0.61	0.69	0.71	0.64	0.59	0.68
σ (constant of cost function)	($ ha^{-1})	81.9	92.6	122.9	116.7	115.4	119.5
P_y (selling price of corn)	($ bu^{-1})	5.25	6.20	6.80	4.54	3.70	3.70
	($ Mg^{-1})	207	244	268	179	146	146
P_{off} (leasing price of water)	($ AF^{-1})	24	24	24	34*	80**	44
	($ $ha^{-1}mm^{-1}$)	0.19	0.19	0.19	0.28	0.65	0.36
Optimum ET_a	(mm)	632	632	632	632	614	623
Saved ET_a = $(CU-ET_a)/CU$	(%)	0.0%	0.0%	0.0%	0.0%	2.8%	1.5%
Optimum w_{off}	(mm)	0	0	0	0	18	9
Yield with full irrigation	(Mg ha^{-1})	12.71	12.71	12.71	12.71	12.71	12.71
Cost with full irrigation	($ ha-1)	465.55	526.65	568.36	521.41	490.19	546.67
Value of full irrigation	($ ha^{-1})	2161	2576	2834	1750	1361	1305
Yield with deficit irrigation	(Mg ha^{-1})	12.71	12.71	12.71	12.71	12.58	12.65
Cost of farming with deficit irrigation	($ ha-1)	465.55	526.65	568.36	521.41	479.60	540.43
Value of renting water	($ ha^{-1})	0	0	0	0	12	3
Value of farming with deficit irrigation	($ ha^{-1})	2161	2576	2834	1750	1365	1306
inc (increased value due to deficit irrigation)	(%)	0.00%	0.00%	0.00%	0.00%	0.28%	0.08%
$minP_{off}$ (min required renting price of water)	($ $ha^{-1}mm^{-1}$)	0.54	0.67	0.78	0.35	0.22	0.13
	($ AF^{-1})	67	83	96	43	27	16
$maxP_{off}$ (max allowable renting price of water)	($ $ha^{-1}mm^{-1}$)	22.26	26.32	28.92	19.14	15.53	15.44
	($ AF^{-1})	2746	3247	3567	2361	1915	1905

[1] Rainfall during growing season is for coagmet.com Greeley 4 station.
[2] Colorado State University Crop Budget Enterprise
[3] Average over the four years of field experiments (2008-2011)
[4] Schneekloth et al. (1991)
* Average of 2012 and 2015
** Personal communication with Scott Williams of Water Colorado LLC.

The leasing prices of water (P_{off}) listed in Table 8 are the prices when water is transferred within the same ditch system. Therefore, there is hardly any cost associated with the physical transfer of water or legal procedures; and it is safe to assume these are the net prices of renting water. Agricultural water users must have a decree from water court to rent their water to other users (M&I users). The same procedure as selling water right must be followed to determine farm consumptive use and to prove no injurie to other right holders.

In practice, very often farm available water and effective rainfall do not satisfy maximum crop evapotranspiration (ET_m). In other words, farm available ET_a is decreased. As farm available water decreases, higher amounts of $minP_{off}$ are required to justify water partitioning (the inverse relationship is due to the negative value of $a = -8E-5$ in Equation 2.20). For example, considering 2015 values of θ and σ, the change in $minP_{off}$ for different prices of corn will be as Figure 24 shows. So for this year (P_y= 3.7 \$ bu^{-1}), as farm's achievable evapotranspiration drops to 80% of ET_m, the value of $minP_{off}$ increases to 250 \$ AF^{-1} (2.03 \$ ha^{-1} mm^{-1}). As selling price of corn increases, the increase in $minP_{off}$ takes a steeper slope. However, price of corn has dropped further since 2015 (2.79 \$ bu^{-1} or about 110 \$ Mg^{-1} in 2017) and if this trend continues, smaller water prices will justify renting part of farm available water.

In 2015, on the average renting price of water (P_{off}) in the South Platte River Basin was 44 \$AF^{-1} (0.36 \$ ha^{-1} mm^{-1}) (WestWater Research LLC, 2016). Therefore, a corn farm in this year could allocate 1.5% of its consumptive use to leasing with the average price and improve farm income by 0.08%. The maximum price of renting water is 1,905 \$AF^{-1} (15.44 \$ ha^{-1} mm^{-1}), above which deficit irrigation will not improve farm income and all the water should be allocated to leasing. Given yield and water prices in 2015, only a small amount of irrigation water could be saved for renting purposes. Under such minimal improvements it is improbable farmers would consider renting water as a worthwhile practice and municipalities may not be interested in renting such small amounts of water. Renting price of water in 2015 was higher than previous years, therefore, farm income increase and saved water for those years were lower than 2015 (see Table 8).

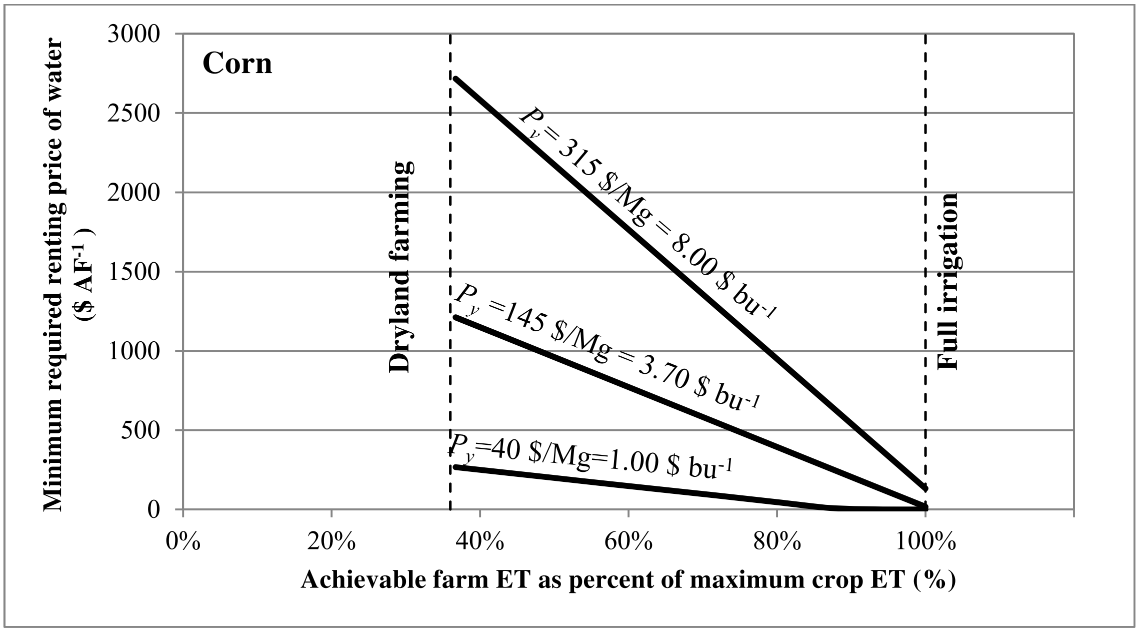


Figure 24 Corn minimum required renting price of water as a function of farm achievable ET

5.2.3 Corn farm income improvement due to deficit irrigation

In a deficit-irrigation scenario, renting price of water and selling price of yield are not the only factors determining farm income increase (see section 2.6.3). The relevant independent variables are listed in Table 1 (page 45) and their limits are provided in Table 8. Farm available water can vary between zero and the amount required for full irrigation. Full irrigation is when full crop consumptive use is satisfied and evapotranspiration is equal to maximum evapotranspiration (ET_m).

Cost of agricultural production is reflected in the value of θ and σ. As these two factors increase, deficit irrigation can provide more income increase (*inc*) for farm. This trend is graphed in Figure 25 and Figure 26 for when price of corn is 3.70 \$ bu^{-1} (146 \$ Mg^{-1}) as it was in 2015. The effect is more pronounced when renting price of water is low. For example, when renting price of water is 100 \$ AF^{-1} (0.81 \$ ha^{-1} mm^{-1}), farm income increase at $\theta = 0.55$ \$ ha^{-1} mm^{-1} is 0.45% and at $\theta = 0.75$ \$ ha^{-1} mm^{-1} is 0.93%. So an increase of one unit in value of θ could double *inc* about in 2015. At renting price of 500 \$ bu^{-1} (4.05 \$ ha^{-1} mm^{-1}), *inc* improvement is 1.2 times (21.5% at $\theta = 0.55$ \$ ha^{-1} mm^{-1} and 29% at $\theta = 0.75$ \$ ha^{-1} mm^{-1}). This still may be considered an acceptable improvement but if the price of crop increases as well the improvement deteriorates; for example, when corn can be sold for 6.80 \$ bu^{-1} (268 \$ Mg^{-1}) and water rented for 500 \$ AF^{-1} farm income increase does not change appreciably with change of θ. Therefore, cost of production becomes less influential in farm income increase when renting price of water is high. The fixed cost of production does not have an appreciable effect on farm income increase (Figure 26).

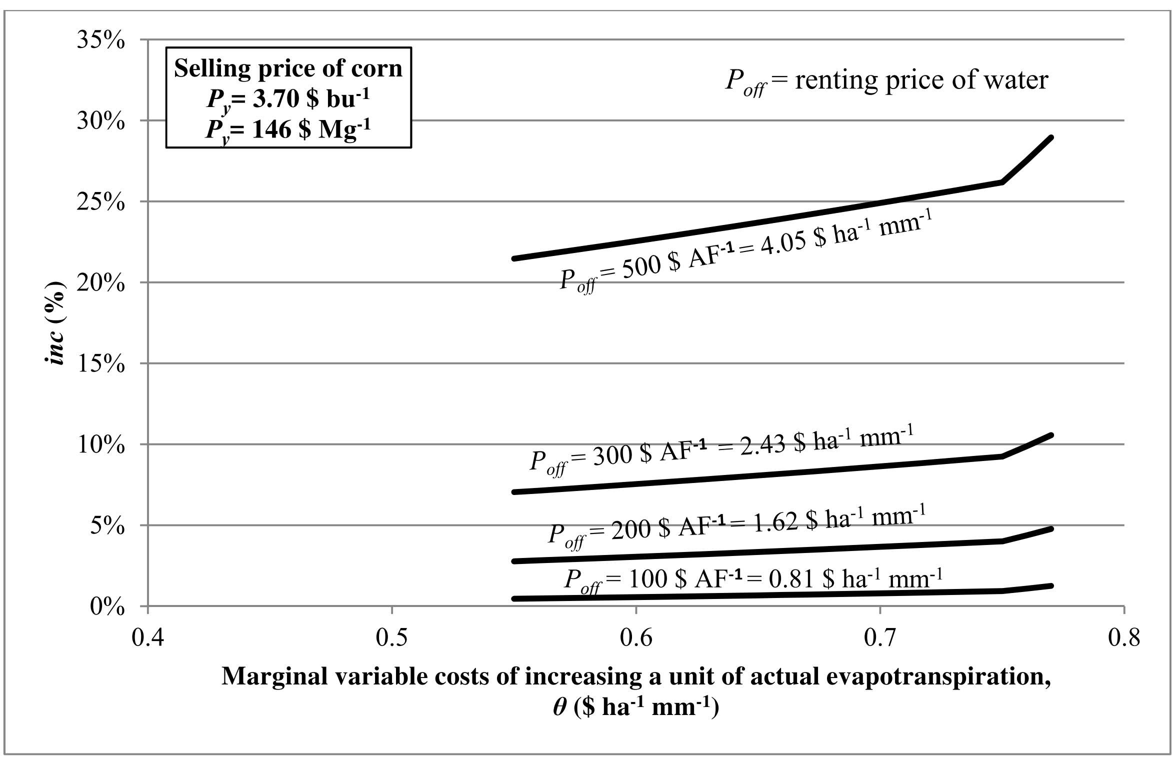


Figure 25 Corn farm income increase due to deficit irrigation (*inc*) versus θ

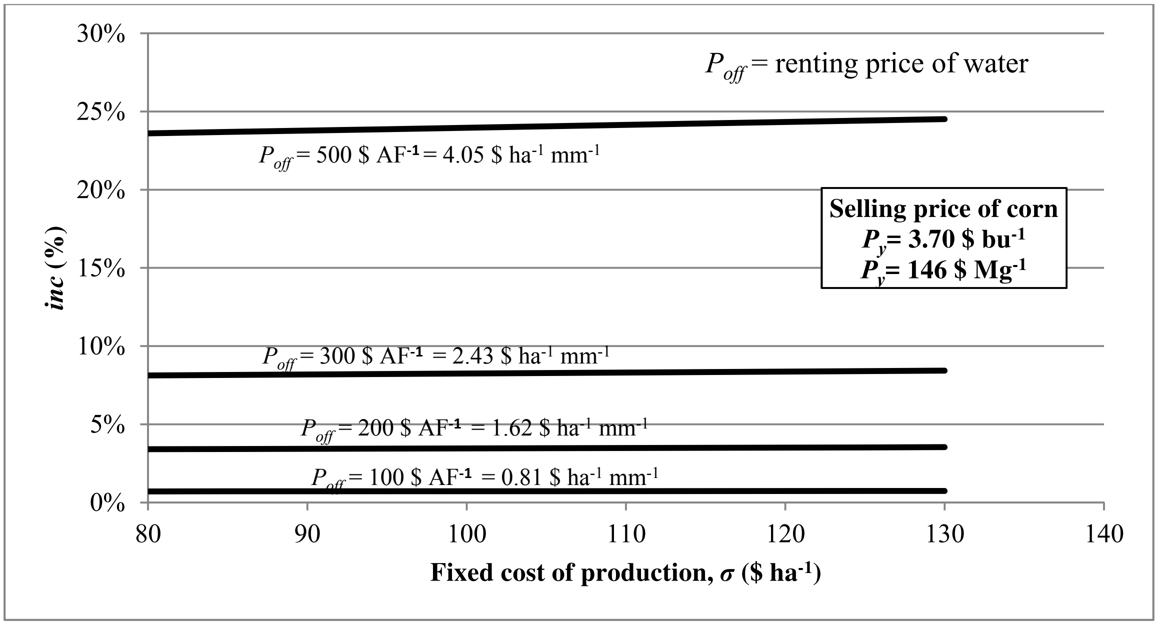


Figure 26 Corn farm income increase due to deficit irrigation (*inc*) versus σ

Next parameter discussed here is the effect of effective rainfall (*ER*) (Figure 27). The amount of *ER* considered for this analysis is between zero and 240 mm over the growing season. In a year with more than 240 mm of effective rainfall, a corn farm will have excess water (above corn irrigation requirement) and therefore larger amounts of *ER* are not shown in Figure 27. Overall, increase in effective rainfall improves corn farm income increase, especially for high renting prices of water (about 500 $ AF^{-1}or 4 $ ha^{-1} mm^{-1}). However, this effect is less pronounced when selling price of corn is higher than 4 $ bu^{-1} (158 $ Mg^{-1}).

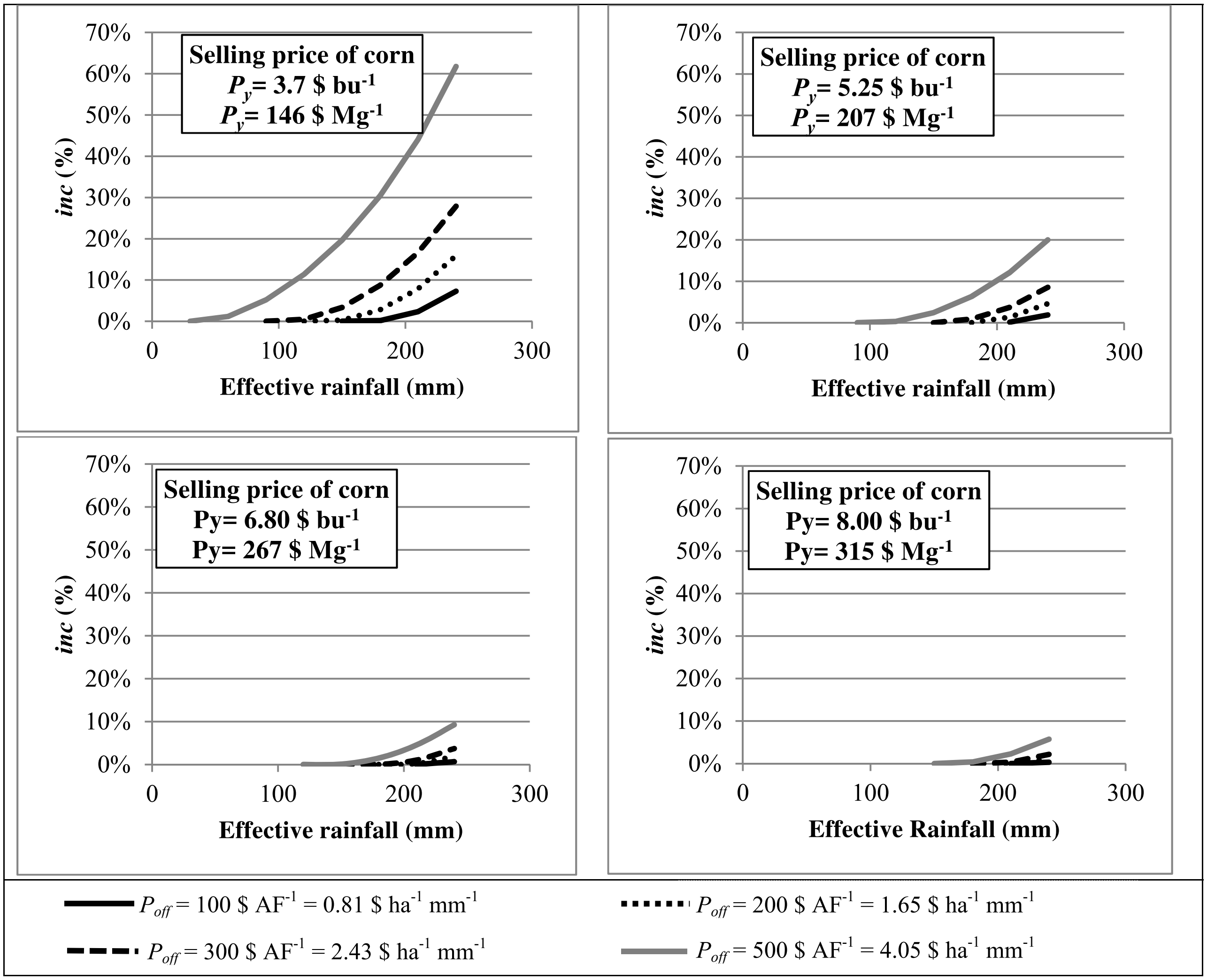


Figure 27 Corn farm income increase (*inc*) due to deficit irrigation versus effective rainfall

The effect of price of yield on farm income increase is determined for θ and σ values similar to that of 2015 and assuming farm achievable evapotranspiration is at ET_m. Under these conditions, as expected, deficit irrigation considerably improves farm income only when the price of yield is low (Figure 28). For yield prices lower than 78.80 \$ Mg^{-1} (2.00 \$ bu^{-1}) condition of optimality allocated all water to renting. Therefore, the P_y-*inc* lines in Figure 28 stop at this value. As the renting price of water increases, the farm income increase due to deficit irrigation increases as well (see how *inc* increases from P_{off}= 200 \$ AF^{-1} to P_{off}= 750 \$ AF^{-1}in Figure 28).

This trend continues until renting price of water becomes high enough to make deficit irrigation not optimal again at lower prices of yield (see the difference in lower limit of *inc* curves for P_{off}= 750 \$ AF^{-1} to P_{off}= 1000 \$ AF^{-1} in Figure 28). Therefore, with the crop prices of 2015 there is a potential to almost double farm income when the renting price of water is around 750 \$ AF^{-1}. For income improvement more than 20%, in 2015, the renting price of water had to be above 200 \$ AF^{-1}.

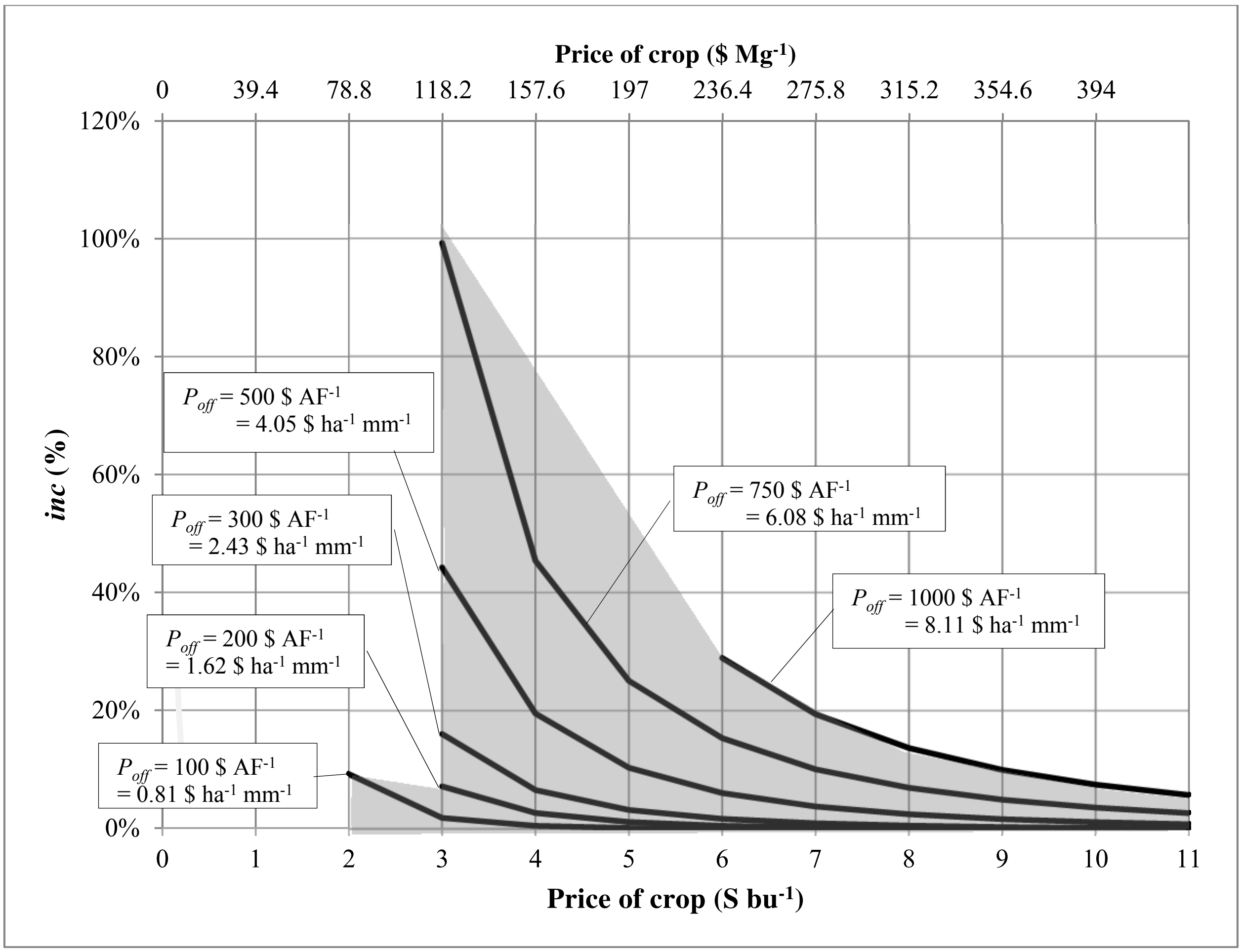


Figure 28 Corn farm income increase due to deficit irrigation versus price of crop

The gray area in Figure 28 is where the requirements of deficit irrigation are satisfied; *i.e.* for a P_{off} deficit irrigation can improve farm income when the price of crop falls within the gray area. Full irrigation is optimal choice at right side of gray area and leasing all the water is the optimal decision at its left side.

5.3 Sunflower

Sunflower soil water balance parameters are given in Table 9. Values reported in the table are the averages over the four replications. In 2009, researchers mistakenly applied excessive amount of herbicides with the result that most crop was lost. Therefore, 2009 data is excluded from analysis.

Table 9 Components of soil water balance and yield for sunflower, in Greeley 2008-2011

Treatment	year	Precipitation (mm)	Irrigation (mm)	Deep Percolation (mm)	ET_a (mm)	Yield (Kg ha^{-1})	CWP (kg ha^{-1} mm^{-1})
1	2008	230	299	63	479	3,305	6.91
2			224	35	466	3,459	7.42
3			189	29	450	3,238	7.19
4			188	35	447	3,264	7.30
5			105	4	416	2,957	7.11
6			79	13	405	3,070	7.58
1	2009	211	240	54	404	2,646	-
2			18	0	327	1,913	-
3			16	0	331	0	-
4			0	0	307	0	-
5			17	0	333	0	-
6			0	0	334	0	-
1	2010	153	269	0	455	3,566	7.84
2			220	0	425	3,459	8.13
3			175	0	376	3,099	8.23
4			137	0	345	2,679	7.77
5			99	0	318	2,491	7.84
6			20	0	240	1,798	7.48
1	2011	105	436	78	427	3,291	7.70
2			355	0	419	3,330	7.95
3			297	0	408	3,163	7.75
4			277	0	378	3,164	8.37
5			215	0	360	2,737	7.60
6			141	0	286	1,956	6.85

Data courtesy of Dr. Kendall DeJonge of USDA-ARS Water Management Research Unit

Generally literature report higher yields as LIRF's yield with higher ET_a achieved in farm. Tarjuelo et al. (1996) achieved a yield of 5 Mg ha^{-1} in Spain with 700 mm of crop actual evapotranspiration. Karam et al. (2007) conducted a two-year experiment on sunflower in Lebanon and were able to produce a maximum yield of 5.59 Mg ha^{-1}. This amount of yield was produced with 629 mm of ET_a. Their lowest yield was 3.95 Mg ha^{-1} with 535 mm of total ET_a during the growing season. Therefore, the higher yields are due to higher ET_a *CWP* for these two experiments is similar to those calculated for LIRF.

5.3.1 Sunflower crop water production function

Both linear and quadratic regressions were considered for modeling sunflower crop water production function (Figure 29). Here also the quadratic regression offered a significant improvement in the model fit (*p-value* = 0.0223 with 95% confidence). In addition, adjusted R^2 was slightly higher for the quadratic model ($adj\_R^2 = 0.9079$) as compared to the linear model ($adj\_R^2 = 0.8763$).

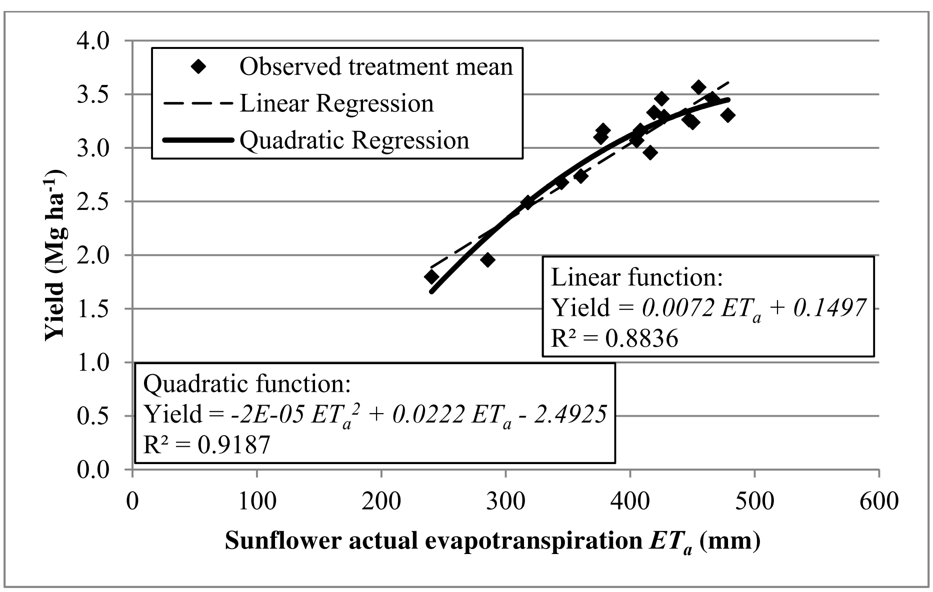


Figure 29 Sunflower crop water production function

Therefore, the quadratic model is accepted as crop water production function for sunflower which is:

$$Y = -0.00002\ ET_a^{2} + 0.02\ ET_a - 2.5$$

Equation 5.4

Notice that with a confidence interval of 99% we would reject the significance of quadratic function and accept the linear function for sunflower. This is also apparent in the smaller value of quadratic term's coefficient (*a*); the absolute value of "*a*" for sunflower is smaller than that of corn ($a_{corn} = -8E{-}5$ and $a_{sunflower} = -2E{-}5$). In other words, sunflower's crop water production function is less concave and closer to a linear shape. Again similar to corn, most literature report a linear CWPF for sunflower (Aiken et al., 2011; Moroke et al., 2011).

5.3.2 Optimal water allocation for sunflower

Although sunflower's crop water production function is only marginally non-linear, analysis of farm income improvement was performed for this crop to investigate the effect of deficit irrigation practice. The cost function and the farm consumptive use determine the minimum leasing price of water that makes deficit irrigation a feasible strategy. Cost function for sunflower is determined using similar data as corn (listed in Table 10). The cost function in 2015 is then determined as:

$$C(ET_a) = 0.59\ ET_a + 110.47$$

Equation 5.5

Selling price of sunflower in 2016 was 16.80 \$ cwt^{-1} while the costs of growing sunflower was 21.22 \$ cwt^{-1}; therefore, sunflower growers' return was negative and this year's data is not analyzed or presented in Table 10.

Table 10 Sunflower farm optimal water allocation for Northeastern Colorado

Year		2010	2011	2012	2013	2014	2015
Rainfall[1]	(mm)	222	215	131	226	360	239
Cost of irrigated farming[2]	(\$ ac^{-1})	447.67	503.62	587.21	564.49	488.10	596.9
	(\$ ha^{-1})	181.17	203.81	237.64	228.44	197.53	241.56
Cost of dryland farming[2]	(\$ ac^{-1})	219.86	246.92	285.01	272.82	217.26	272.98
	(\$ ha^{-1})	88.97	99.93	115.34	110.41	87.92	110.47
CU (ET_a for full irrigation) [3]	(mm)	454	454	454	454	454	454
ET_a of dryland farming[4]	(mm)	233	233	233	233	233	233
θ (variable cost of increasing a unit of ET_a)	(\$ ha^{-1}mm^{-1})	0.42	0.47	0.55	0.54	0.50	0.59
σ (constant of cost function)	(\$ ha^{-1})	88.97	99.93	115.34	110.41	87.92	110.47
P_y (selling price of corn)	(\$ cwt^{-1})	18.60	31.70	25.70	19.57	20.00	20.20
	(\$ Mg^{-1})	410	699	567	431	441	445
P_{off} (leasing price of water)	(\$ AF^{-1})	24	24	24	34*	80**	44
	(\$ ha^{-1}mm^{-1})	0.19	0.19	0.19	0.28	0.65	0.36
Optimum ET_a	(mm)	454	454	454	454	454	454
Saved $ET_a = (CU-ET_a)/CU$	(%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Optimum w_{off}	(mm)	0	0	0	0	0	0
Yield with full irrigation	(Mg ha^{-1})	3.37	3.37	3.37	3.37	3.37	3.37
Value of full irrigation	(\$ ha^{-1})	824	1727	1172	744	841	724
Yield with deficit irrigation	(Mg ha^{-1})	3.37	3.37	3.37	3.37	3.37	3.37
Value of renting water	(\$ ha^{-1})	0	0	0	0	0	0
inc (increased value due to deficit irrigation)	(%)	0	0	0	0	0	0
$minP_{off}$ (min required renting price of water)	(\$ ha^{-1}mm^{-1})	1.09	2.09	1.52	1.05	1.12	1.04
	(\$ AF^{-1})	134	258	188	129	138	128
$maxP_{off}$ (max allowable renting price of water)	(\$ ha^{-1}mm^{-1})	8.68	15.03	12.01	9.03	9.28	9.28
	(\$ AF^{-1})	1070	1854	1482	1114	1145	1145

[1] Rainfall during growing season is for coagmet.com Greeley 4 station.
[2] Colorado State University Crop Budget Enterprise
[3] Average over the four years of field experiments (2008-2011)
[4] Moroke et al. (2011)
* Average of 2012 and 2015
** Personal communication with Scott Williams of Water Colorado LLC.

Again it is assumed, the combination of farm available water and effective rainfall provides enough water to compensate full crop water requirement (maximum $ET_a = ET_m$). The amount of $minP_{off}$ for sunflower in 2015 is 128 \$ AF^{-1} (1.04 \$ ha^{-1} mm^{-1}). Since this is bigger than leasing price of water in this year, deficit irrigation will not improve farm income and the optimal decision is to allocate all the available water to leasing. This result was true for all years analyzed (2010-2015).

As farm available water decreases $minP_{off}$ increases (also see section 5.2.2 on page 76) with the trends illustrated in Figure 30. For example, with θ, σ, and P_y values of 2015, a farm that can achieve 80% of ET_m will only start to benefit from deficit irrigation if renting price of water is above 550 \$ AF^{-1} (4.46 \$ ha^{-1} mm^{-1}).

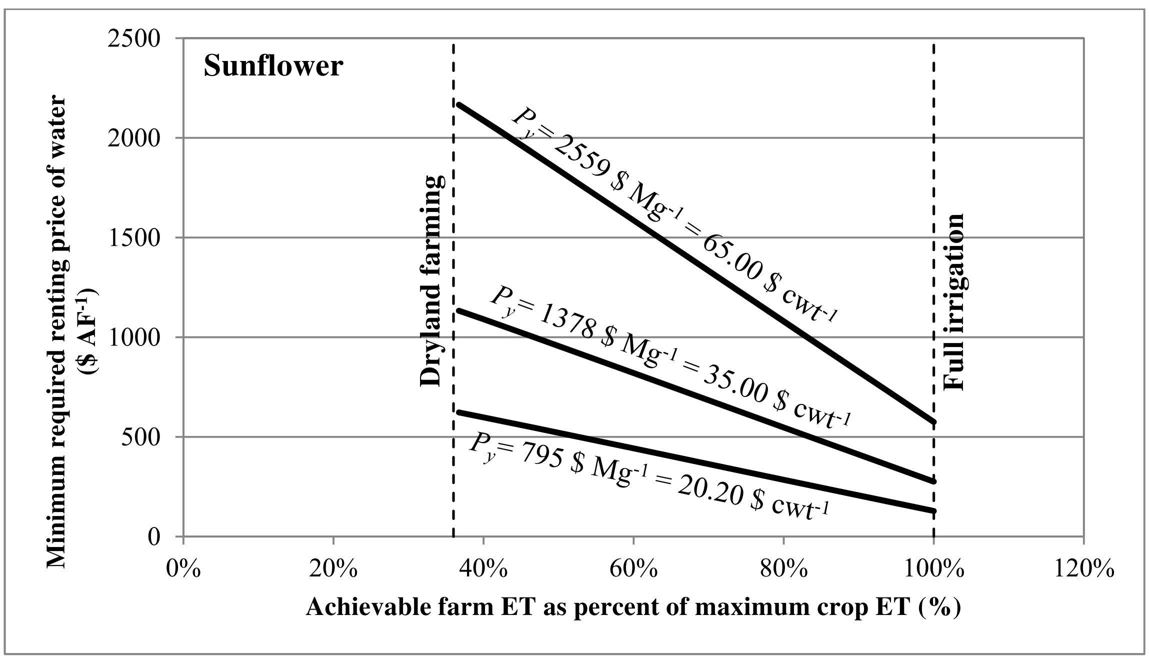


Figure 30 Sunflower minimum required renting price of water as a function of farm achievable ET

The renting price of water that improves farm income under deficit irrigation (for example between 128 and 1,145 \$ AF^{-1} in 2015) falls in a smaller interval as compared to corn (16 to

1,905 \$ AF^{-1} in 2015). The reason is that sunflower's CWPF is only marginally concave behaving similar to linear functions.

5.3.3 Sunflower farm income improvement due to deficit irrigation

Similar to corn limits of the independent variables that define farm income increase (Table 1 on page 45) are listed in Table 10 (see section 5.2.3 for references and detailed explanation). As expected, a sunflower farm's income increase improves when cost of production is larger. Both θ and σ have a direct influence in income increase (Figure 31 and Figure 32), while the improvement of *inc* increases as the renting price of water increases. However, the impact of σ does not impact farm income increase appreciably, especially when renting price of water is low (around 100 \$ AF^{-1}).

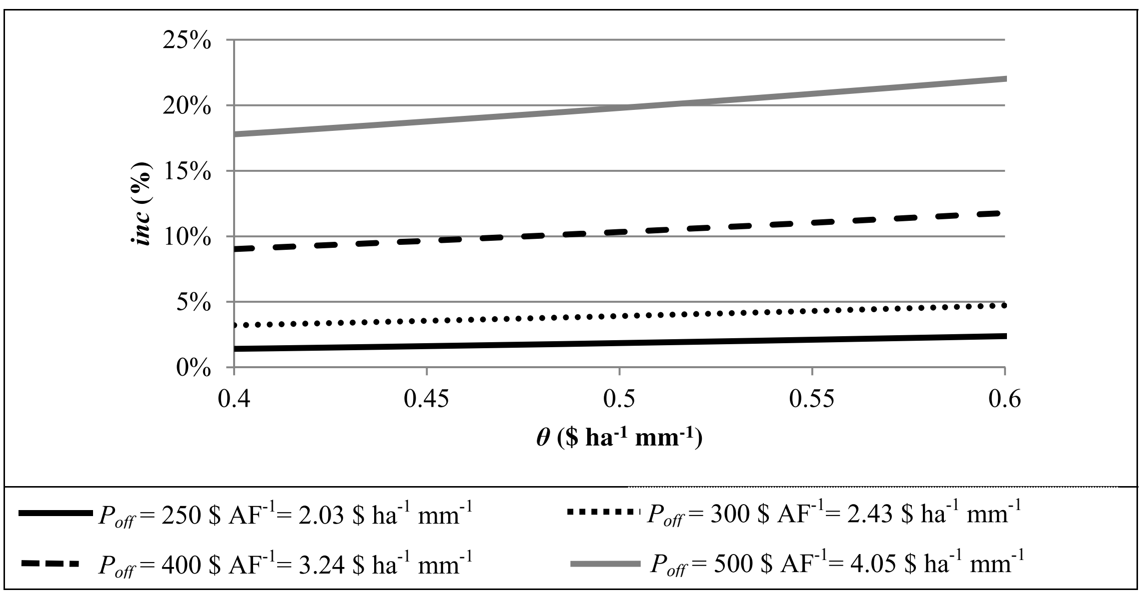


Figure 31 Sunflower farm income increase due to deficit irrigation (*inc*) versus θ

The impact of θ, conversely, decreases for higher renting prices of water. This is in line with results of corn data; i.e. costs of production become a less determining factor in farm income increase as the renting price of water increases. Figure 32 is especially interesting because it shows σ barely has an effect on farm income increase. The reason is that with the increase of σ the amount of water allocated to leasing does not increase appreciably and therefore the percent change in income improvement stays more or less constant. Again the main reason for this behavior is small value of a, which leads to results expected from a linear function.

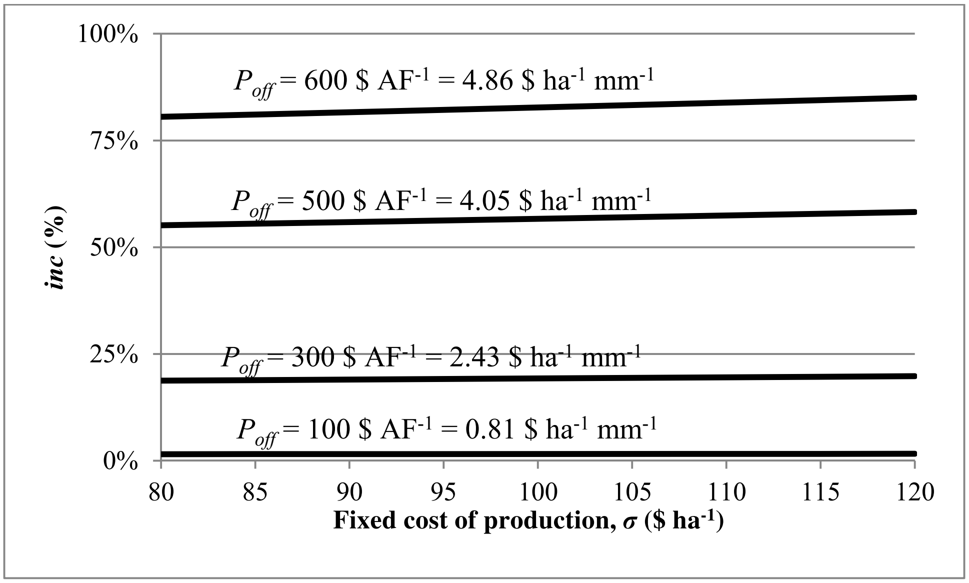


Figure 32 Sunflower farm income increase due to deficit irrigation (*inc*) versus σ

The impact of changes of effective rainfall (*ER*) on sunflower farm is similar to that of corn; as the amount of effective rainfall increases farm income increase improves (Figure 33). Again similar to the results of corn, the improvement of farm income due to larger *ER* is less substantial when price of crop is larger. For sunflower, a maximum effective rainfall of 210 mm over growing season is analyzed because larger amounts of rainfall mean the farm has excess irrigation water. The model developed in this dissertation analyzes water allocation only when water farm does not own excess water.

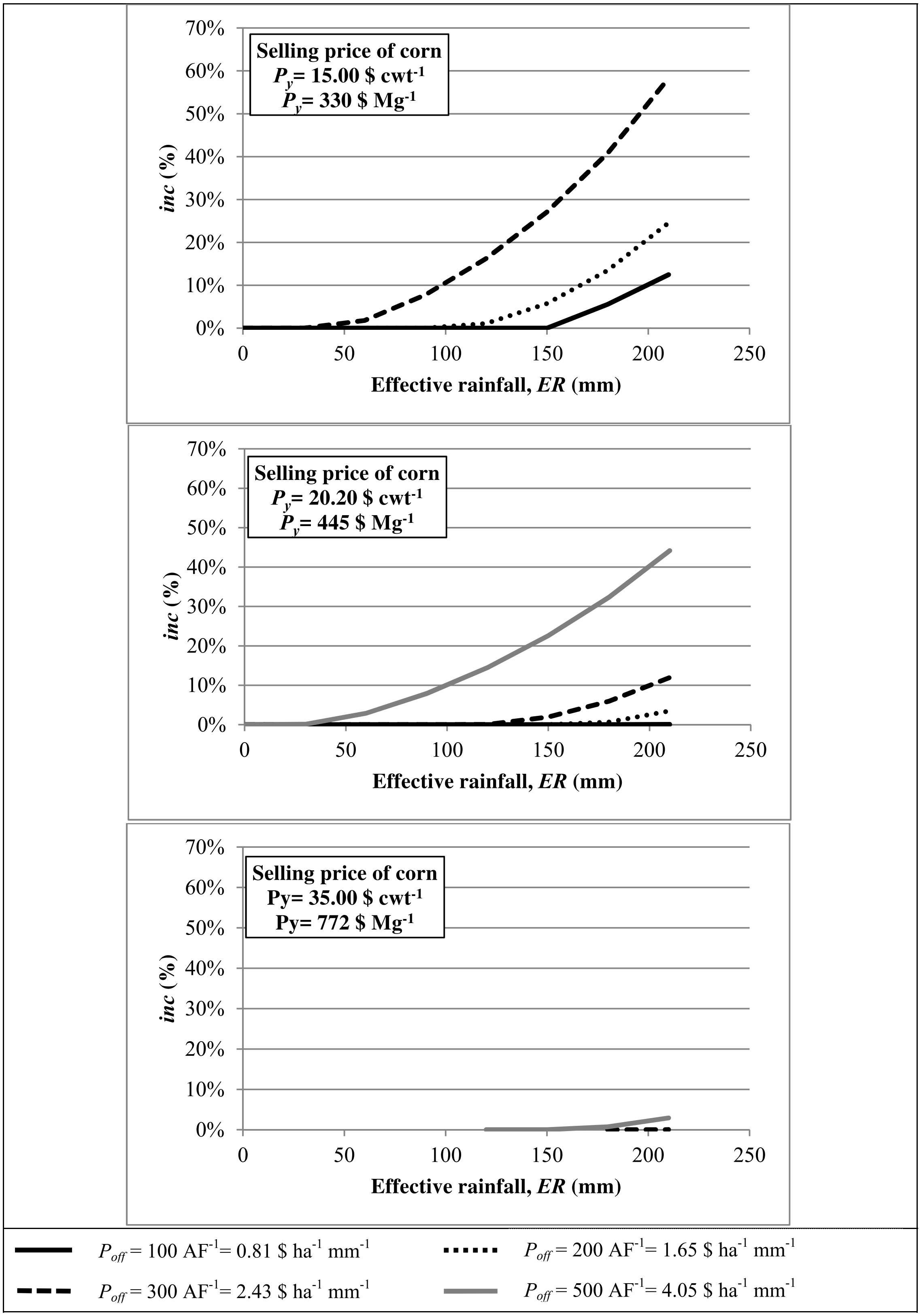


Figure 33 Sunflower farm income increase due to deficit irrigation (*inc*) versus *ER*

The effect of price of yield on farm income increase is determined using the economic model developed in the conceptual framework, θ and σ values similar to that of 2010 and assuming farm achievable evapotranspiration is at ET_m (Figure 34). At lower crop price farm income increase due to deficit irrigation is larger; this effect is more pronounced when leasing price of water increases. Therefore, a sunflower farm under deficit irrigation does not harm from low prices of crop as long as renting price of water is high (according to Figure 34 a minimum renting price of 200 \$ AF^{-1} is required).

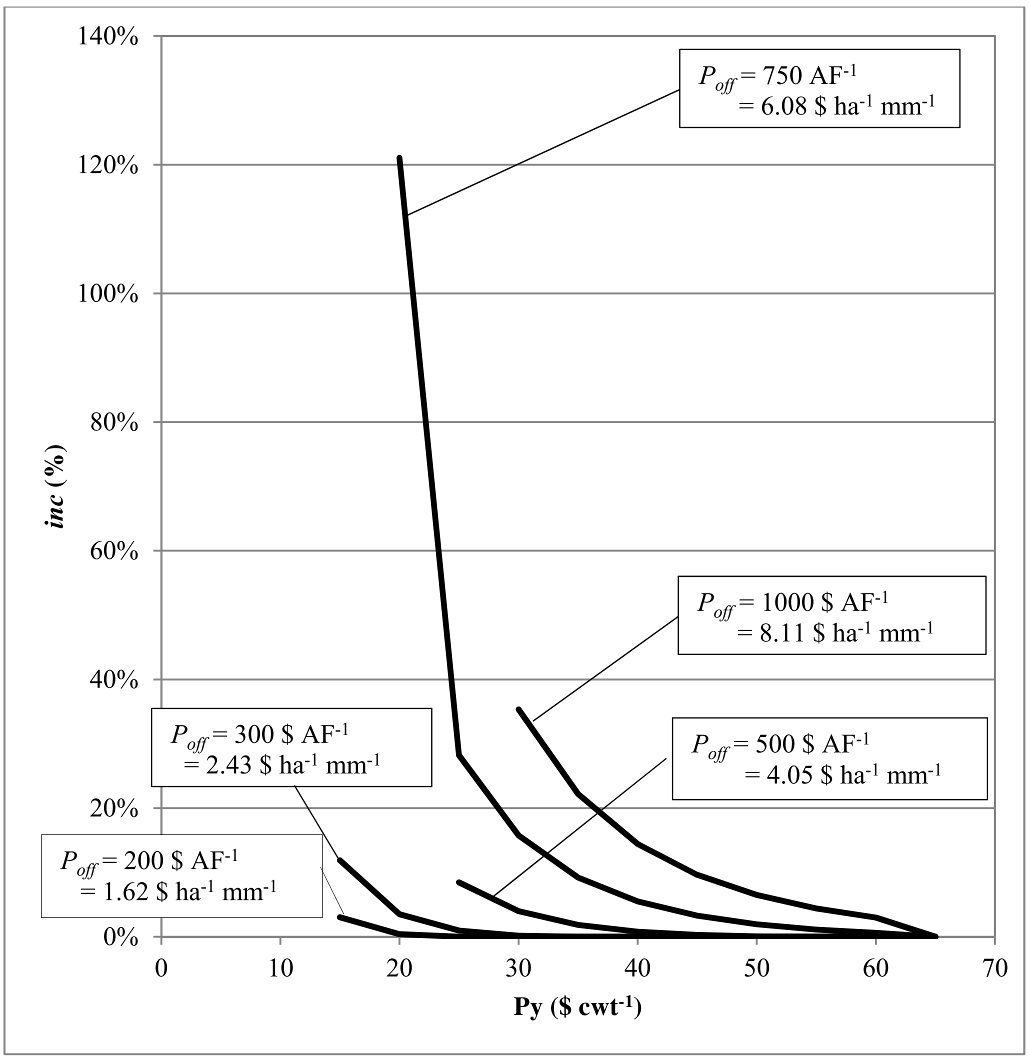


Figure 34 Sunflower farm income increase due to deficit irrigation (*inc*) versus price of crop P_y

5.4 Discussion

5.4.1 Implication of research results for Colorado

In this chapter the results of farm experiments were applied to the optimization model developed in CHAPTER 2. Colorado's prior appropriation of system water allocation requires using crop consumptive use or ET in optimization models. Therefore, crop water production functions or the relation between yield and crop ET enters the optimization model. Model analysis proves crop water production functions must be concave for deficit irrigation to improve farm income. Concave functions have decreasing marginal production thus production per unit of ET is improved by reducing the amount of ET. But linear functions have a constant marginal yield and changes in production per unit of ET does not alter by changes in ET. According to the results of field experiments, sorghum-sudangrass has a linear crop water production function and hence does not benefit from deficit irrigation.

Corn can potentially benefit from deficit irrigation due to its concave crop water production function; this is true when leasing prices of water are within the required limits determined in section 2.6.2. These required prices were defined for the study area, South Platte River Basin, for seven years (2010-2016). According to the analysis, corn farm highest water savings and income improvements could happen in 2015, when deficit irrigation could increase farm profitability by 1.5% by leasing 0.08% of its consumptive use. It is improbable such improvements provide enough incentive for water right holders to enter a leasing contract. Moreover, it is unlikely the small water savings can satisfy M&I users' water requirement.

Now the question is what are the criteria that will make deficit irrigation a worthwhile strategy for both M&I and agricultural water users? To answer this question the effect of different variables involved in farm income increase are analyzed. These are effective rainfall

(ER), farm available water (W), cost of production, selling price of yield (P_y), and leasing price of water (P_{off}). It was shown that although an increase in ER improves farm income increase, the effect deteriorates as the price of yield or renting price of water increases. Besides, the value of ER is not controllable. Therefore, achieving the conditions under which deficit irrigation can be worthwhile is not possible by altering effective rainfall.

In Colorado, farm available water for transfer, W, is equal to farm consumptive use (CU). This amount has a direct effect on the minimum renting price of water under which partitioning water into on-farm and renting uses is economically optimal. Parts of research analysis in this document assume that farm CU is sufficient for full irrigation of chosen crop. However, this is not the always the case; therefore, the effect of a reduction in available water was determined on minimum renting price of water. In normal years, as the amount of W decreases the farm cannot compensate full crop evapotranspiration. Then higher renting prices of water are required to make deficit irrigation a viable strategy and justify partitioning of water. Therefore, deficit irrigation is a less attractive option for farms already experiencing water shortage during normal years.

Two factors describe the cost of production; a variable cost (θ) and a constant parameter (σ) ($C(ET_a) = \theta\, ET_a + \sigma$). Higher values of both factors better improve farm income increase. However, the income increase due to increasing θ takes a slower pace as renting price of water increases. Value of σ, in general, has a smaller effect in the increase of income. The effect of σ is smaller at lower renting prices of water. Furthermore, it was shown that farm income increase under deficit irrigation is higher when price of yield, P_y, is low. As price of yield increases and farm production is more income generating, income increase due to deficit irrigation decreases.

Although statistical tests show that sunflower's CWPF only has a slight deviation from linear function, similar analysis (for 2010-2016) was performed for this crop. The results further support linearity of sunflower's CWPF, reflected in smaller feasible range for water leasing prices (P_{off}), lower farm income improvement, and minor on-farm water savings. Overall, sunflower's CWPF behaves very similar to a linear function and as such, practice of deficit irrigation is not a worthwhile strategy to prevent selling water rights.

Generally, analysis of factors influencing farm income increase suggests, leasing price of water has to be high enough for deficit irrigation to become a worthwhile strategy. The leasing price of water has to be higher for sunflower due to its less concave production function. Leasing prices of water reported for South Platte River Basin, are the prices within a ditch system, when one farm rents to another farm and water remains in agricultural sector. Leasing prices to M&I users is expected to be higher. For example, Arkansas Valley Super Ditch Company (see section 2.5), has leased water for 500 \$ AF^{-1} (WestWater Research LLC, 2016). In Colorado, out of sector leasing transactions must be decreed by Water Court through a legal procedure similar to selling transactions. Hence non-agricultural users normally prefer to secure their water by buying water right rather than renting water (MacDonnell, 2015). The Super Ditch Company had to use state's special provisions to materialize its plan for leasing water. The legal procedures were simplified for this company through Colorado House Bill 13-1248 to perform a pilot project on alternative methods of water transfer (Colorado Water Conservation Board, 2016).

Fortunately, there is no restriction for other basins in Colorado to use the same provisions and start an out-of-sector leasing market. This research has only found one water transfer institution in Weld County, the Northeast Colorado Water Cooperative (see section 2.3.3). However, the aim of this nonprofit organization is to reallocated shares of water among the members who are all agricultural water right holders. As such Northeast Colorado Water Cooperative does not facilitate out-of-sector water transfers. Perhaps in Weld County, the start of a water market is not as urgent as in southern part of Colorado where large areas of agricultural land has gone fallow (see section 1.2). New research needs to define the reason for the low prices of water in South Platte River Basin and the requirements to develop a water market.

The Super Ditch Company does not use deficit irrigation as the method of reducing farm consumptive use. Instead the company has chosen to practice rotational fallowing. This brings up the other concern about deficit and limited irrigation. To conform to Colorado Water Law, after a water transfer, the return flows, have to be similar to those before the transfer in location, time and quantity (Hobbs, 2004). Therefore, farm return flows need to be monitored on a daily basis together with claimed reduction of farm consumptive use. The technical and administrative requirements of such practices are concerning (Schneekloth, personal communication; Kenney, 2015). Kullberg (2015) has developed a procedure to calculate the reduction of evapotranspiration (as a measure of consumptive use) using crop canopy temperature. Another way of measuring evapotranspiration reduction is using soil water sensors and soil root zone water balance. Both methods rely on point measurements of canopy temperature or soil water content. However, evapotranspiration can vary widely over a farm due to soil and microclimate variabilities; point measurement methods need to be robust enough to detect these variabilities. Another way of measuring actual evapotranspiration is using remote sensing. Remotely sensed imagery can offer a more realistic estimation of evapotranspiration; however, these images are not available on a daily basis. For a given location the frequency of images can vary between 26 to 8 days (Lillesand et al., 2008) depending on the satellite's revisit period. Besides, pictures showing large cloud covered areas are not usable. Image resolution is another issue; images with low resolution (100 m or 30 m) are only beneficial when estimating ET for large areas such as watersheds. At farm level smaller areas are of interest and higher resolution is required (Vashisht, 2016).

Although literature on daily measurement of ET is available, still, the results need to be presented in user friendly formats for water court and institutions implementing water leasing. In other words, an easy-to-use tool has to be available for performing the required calculations.

Another technical requirement of deficit irrigation is to be able to accurately apply the amount of water that is allocated to irrigation. It will be easy for producers to use the optimization model developed in this research and determine the level of ET that maximizes farm income. However, that level of ET has to be achieved by irrigation. In farms that use irrigation systems with low application efficiency, it is very difficult to control water losses and guarantee reaching the target ET, unless all water losses (surface runoff and deep percolation) can be accurately measured. The data for this research were obtained from farms equipped with drip irrigation systems, where controlling crop evapotranspiration is easier due to high application efficiency and adaptability to automation. The drip system, especially the subsurface system can minimize most of loss terms to negligible amounts if managed properly. However, drip irrigation is not very common in the study area (Mahmoudzadeh Varzi and Oad, 2016).

Even when calculation and monitoring of consumptive use is routinized, the legal procedures can make the implementation of deficit irrigation a challenge. Because in Colorado it is on the parties involved in the water leasing to prove the transfer is not injuring other right holders (Kenney, 2015). Third parties can always claim a new transfer is injurious to their water right, and will do so because the cost of proving the claim is not on them. MacDonnell (2015) has suggested placing the burden of proving unreasonable injury on opposing parties. In fact none of

Colorado's ongoing pilot projects on alternative transfer methods have chosen to practice deficit irrigation (these projects are explained in sections 2.3.1, 2.3.2, and 2.5). Many water right specialists consider the complicated legal requirements the main impediment to leasing water in Colorado (Castle and Macdonnell, 2016; Kenney, 2015; MacDonnell, 2015).

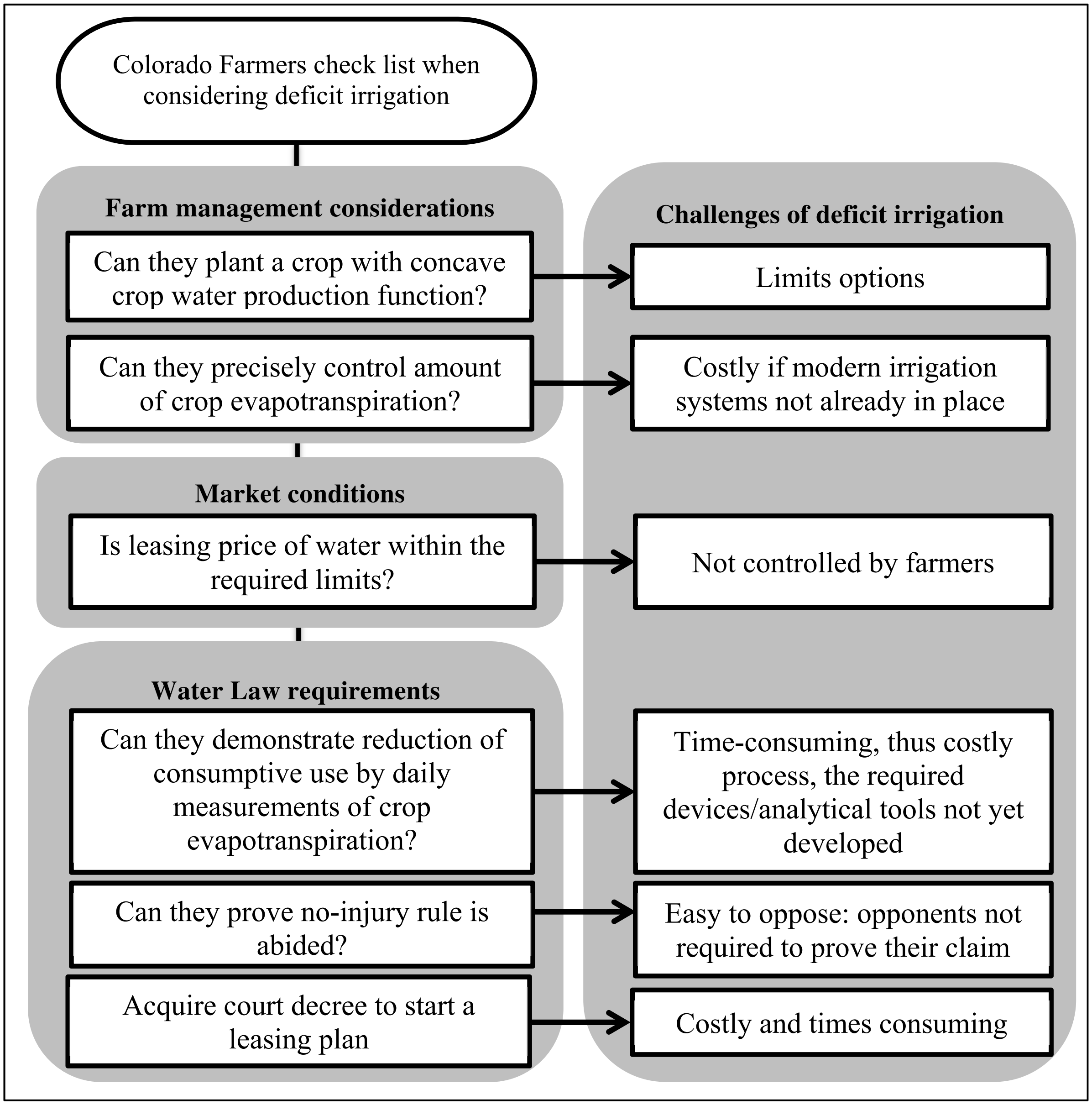


Figure 35 Farmer's decision space when considering deficit irrigation

In summary, practice of deficit irrigation in Colorado requires several conditions to be satisfied on three different levels: 1) farm management level, 2) water market level, and 3) institutional level (Figure 35).

First, farmers need to make sure their choice of crop has a concave CWPF. They also need to have reasonable control on application of irrigation water to guarantee that ET is kept at desired levels (derived from optimization model). At the market level, the leasing price of water has to be above the required minimum price and less than the allowable maximum price (as defined in Equation 2.20 and Equation 2.21 and calculated in Table 8 and Table 10). Finally, the leasing plan has to abide the requirements of Colorado Water Law; *i.e.* it has to demonstrate reduction of consumptive use. Moreover, it is the duty of parties involved in a leasing plan to prove the plan is not injurious to senior water right holders. Figure 35 also summarizes the challenges associated with satisfying these requirements.

5.4.2 Deficit irrigation

As discussed in CHAPTER 2 Colorado's water law can be considered as a special case because of its strict prior appropriation doctrine. Main implication of prior appropriation doctrine on leasing market is that water right holders only own their consumptive use rather than the amount of water they extract from a water source. However, in many parts of the world, such as eastern United States, water users have the right to the amount of water they divert (Perry, 1999). In such cases, as presented in Equation 2.9, optimization needs to be modeled for the amount of irrigation water instead of ET water. Most literature on deficit irrigation focuses on this type of setting where farm can make use of all diverted water (*e.g.* English, 1990; Kipkorir et al., 2002; Wang and Nair, 2013). All the above-mentioned literature used an optimization model similar to Equation 2.9 and solved it for a case study. Interestingly, in none of the case studies leasing water was a possible option and farm income improvement was expected to be achieved by increasing land under cultivation.

Here, it is worthwhile to reemphasize that crop yield only has a physiological relationship with evapotranspiration but not with amount of irrigation water. The amount of irrigation water allocated to farming has to be determined by using Equation 2.10 ($w_y = (ET_a - ER)/e$). Therefore, two more sets of data are required when modeling optimal allocation of irrigation water: 1) effective rainfall over the growing season and 2) a good estimate of farm irrigation application efficiency. Hence, optimization models accounting for the amount of irrigation water are more data demanding. Perhaps for this reason, several research efforts have focused on determining the relationship between “irrigation water” and yield. As discussed in section 2.6.1, these relationships are farm and year specific and may not be generalized for modeling purposes.

The other challenge of accounting for ER and e is that they increase for lower amounts of ET_a and when soil root zone has less available water. Because soil root zone can store a larger portion of precipitation (which increases ER) or irrigation water (which increases e). One way of accounting for variability of ER and e is to define them for two or more levels of soil water content.

In some western states of the U.S., where prior appropriation doctrine is implemented less strictly, agricultural sector is allowed to take advantage of reducing losses. For example, in New Mexico ditch companies obtain credit by reducing their water diversion, the objective is to preserve river flows for aquatic habitat (Oad and Kullman, 2006). Middle Rio Grande Conservancy District was able to obtain storage credits by modernizing its conveyance systems and reducing conveyance losses (Kinzli, 2010). When reducing losses is legal, improving irrigation efficiencies is the obvious solution. However, the planners need to be aware of the side effects of modern irrigation systems with higher efficiencies. As discussed in section 2.2.4 modern irrigation systems may improve irrigation application efficiency but they also make frequent irrigations easier and improve crop health by localizing irrigation application; both changes can result an unintentional increase in crop ET. Policy makers need to make sure irrigators do not increase the amount of farm ET after improving irrigation application efficiency.

Overall, the optimization model presented in Equation 2.9 provides the base of analysis for deficit irrigation, and has to be modified for specific situations as was done for the case of Colorado Water Law. It also can be expanded to include several crops and water uses.

CHAPTER 6 CONCLUSIONS

This research has analyzed how to use crop production functions and farm economics to demonstrate decision trade-offs for Colorado farmers. It has also investigated the different strategies to conserve water on Colorado's agricultural sector with the purpose of providing water for the state's growing urban and industrial sectors. The common practice in the state is to buy agricultural water right and transfer it for municipal uses. But the negative impacts of drying agricultural lands and its recent fast pace have concerned the rural communities. The concerns on the buy-and-dry trend are reflected in Colorado's Water Plan. As a response to these concerns this research has examined different methods of reducing farm consumptive water use while remaining economically viable. The study area is Weld County in South Platte Basin, a county with strong agricultural economy facing oil industry growth.

Methods identified for this purpose were improving irrigation efficiency, deficit irrigation, and rotational fallowing. Efficiency improvement was rejected as a possible method because water saving is only at farm level. At basin level the water lost on one farm is used further downstream by other users. This is especially true for highly developed basins of Colorado were water is used several times before it exits the basin's hydrological cycle. More importantly, such savings are not tradable or transferable under Colorado's Water Law. In Colorado, water right holders do not own their farm return flow. Return flows are a property of the state, therefore, not tradable or transferable. Only the amount of water consumed on farm for crop growth (farm consumptive use) belongs to the water right holder. Therefore, this research has concentrated on the methods of reducing farm consumptive use; deficit or limited irrigation.

First the effect of water stress and subsequent ET_a reduction on crop productivity (and hence farm income) was determined by developing crop water production functions. Crop water production function describes the relationship between crop yield and crop consumptive water use or evapotranspiration. The aim of deficit irrigation is to partition farm consumptive use into two parts; one that will be used for crop production and the other that will be free for leasing to off-farm activities. The objective is to maximize farm income by the combination of revenue from farming and revenue from leasing water. An economic model was developed to determine the optimal allocation plan for this objective. Model analysis shows that crop water production function must be concave for deficit irrigation to improve farm income. When crop water production function is linear, partitioning water is not justifiable as long as farm income improvement is concerned. With linear function, all water must be allocated to the use with higher marginal value (*i.e.* crop production versus water leasing).

Past research has modeled crop water production as a linear function. Therefore, the shape of this function was reevaluated through field experimentation for three crops; sorghum-sudangrass, corn and sunflower. The results suggest that sorghum-sudangrass has a linear function, corn has a concave water production function, and sunflower's crop water production function slightly deviates from a linear function towards a concave function. Therefore, a corn farms may potentially benefit from deficit irrigation. Solving the economic model for corn suggests a marginal improvement in farm income by practice of deficit irrigation. The sunflower crop production function, when used in the economic model, behaves similar to a linear function due to its marginal concavity.

Overall it was concluded leasing price of water in the study area is too low to incentivize practice of deficit irrigation. Higher leasing prices of water are reported for other basins in

Colorado. Higher price is believed to be mainly due to government interventions in supporting pilot projects on alternative transfer methods. Alternative transfer methods are methods that prevent buy-and-dry. In basins with higher leasing price of water an institution is present to facilitate transfer of conserved water to urban areas. Different forms of such institutional frameworks are water banks and interruptible supply agreements. In the study area only one such institution was found using the format of water bank to reallocate water among members, who are all agricultural water right holders. Transfer of water to urban areas is expected to justify higher leasing prices.

Currently deficit irrigation, as defined in this research, is not used in Colorado. Pilot projects such as Water Bank Working Group and Super Ditch Company practice rotational fallowing to reduce farm consumptive use. In this method, parts of lands in one irrigation district or under a ditch company are fallowed, the owners of fallowed lands are compensated for their loss, and the reduction of consumptive use is determined for the growing season. Deficit irrigation, on the other hand, requires daily evaluation of consumptive use. Although engineering methods for determining reduction of consumptive use on a daily basis are available, they are in preliminary stages of development, therefore, lack a user-friendly format such as a computer tool or software package. Deficit irrigation also requires precise application of water to ensure the desired / optimal crop evapotranspiration is achieved. Modern irrigation systems need to be in place for precise water application, which may need initial investment. Moreover, Colorado's long and costly legal procedures give little incentive to employ these methods or improve their format. Especially because buy-and-dry tactics require the same procedure but provide more secure water rights. Water law specialists have proposed simplifying the legal procedures to encourage alternative transfer methods.

Overall, in South Platte River Basin, leasing prices of water are too low to compensate farm lost revenue due to reduction of consumptive use. However, as apparent in Colorado Water Plan, the state's policy makers expect agricultural sector to release more water for urban areas. Therefore, farm lands need to be properly compensated for their loss. The goal of alternative transfer methods is to keep farm water rights in the agricultural sector and prevent economic and social undermining of rural communities. The water that was previously used for farming, however, will leave the rural areas to support increasing urban water demand. In a way, urban growth is favored over agricultural development, which can encourage yet more urban growth. This trend cannot be free of consequences for Colorado.

The basin optimization model presented in this dissertation can be used for locations other than Colorado with other types of water law. Only model components (like how the available water and water right are determined) need to be modified for specific cases.

Finally this research has raised more research questions. Subjects that need further investigation are:

1. Irrigation and agricultural engineering issues:
    - Shape of crop water production function: this research concluded that some crops such as sorghum-sudangrass have linear CWPF. Other crops have concave CWPF, for example, data on corn suggests a concave shape for CWPF. However, most experimental research use linear regression to describe their yield-ET observations, perhaps to follow the already well established models like FAO 33 and Jensen (1968). These functions are accurate enough for irrigation scheduling or farm management purposes because the concavity of most CWPF is rather small as it was found for sunflower. However, in the context of deficit irrigation and optimal allocation of farm water, shape of crop water

production function is determinative and needs to be determined with greater accuracy. Moreover, with the progress of precision agriculture, more accurate information can be effectively used to improve farm production.

- Measuring ET reduction on a daily basis: the FAO 56 dual procedure calculates actual crop evapotranspiration employing k_s or the stress coefficient. This coefficient depends on soil water holding capacity and soil water content. Even in research plots measuring soil water content for the entire root zone is time consuming and labor intensive. Therefore, the water content is measured on weekly or bi-weekly basis. Recently, reflectometers are available in the market for soil water measurements. Reflectometers determine soil water content indirectly by measuring soil resistance to electric current. They can stay in the soil and take continuous records of soil water content however the sensors available in market are not very accurate and dependable. Research can focus on adapting these sensors to soil water balance approach and measure ET reduction on a daily basis.
- Effect of rotational fallowing on land: few pilot projects in Colorado have employed rotational fallowing to produce leasing water for cities (lease-fallow contracts). Past research has provided recommendations on good fallowing practices. These projects are a good opportunity to determine the effect of fallowing practices in a real world situation. Besides, the fallow farms need to cope with weed infestation and erosion. Research can determine best practices in controlling erosion and weed.
- Effect of salinity on yield: SIEP farm uses saline groundwater for irrigation. Saline water reduces yield due to reduced capacity of crop to extract water from soil solution. It is worthwhile to design an experiment to determine the effect of saline water

on amount and quality of yield. Also to develop a plan to alleviate the effect of saline water and schedule regular leaching events. This topic is especially relevant because as more water is transferred from South Platte River Basin, more farmers will need to rely on saline groundwater sources of this area. When planning for the entire basin, finding the source of salinity in the area will help to find possible solutions.

2. Institutional and economic aspects:

- Farmer's tendency to practice deficit irrigation: this research has concluded that with current leasing prices of water, deficit irrigation can only marginally increase farm income and farmers may not be willing to participate in deficit irrigation practices. Past research have used interviewing methods to determine farmer's willingness to practice rotational fallowing in South Platte River Basin and what would be their minimum expected price for fallowing an acre of land (Pritchett, 2008). Similar research in the basin can determine farmers' minimum expected income improvement by deficit irrigation. This data can make a base for the next research question below.

- Requirements of leasing market: South Platte River Basin has not felt the pressure of buy-and-dry as southern Colorado. No ATM institution has evolved in the basin and the renting price of water is lower than other places in the State. In the meantime, small scale water transfers continue to happen to Front Range region. So what are the reasons for low renting price of water in South Platte River Basin? Are the rural communities interested in ATMs? Do the agricultural water right holders have mechanisms other than ATM to cope with water transfer? If so what are these mechanisms? If not, do ATMs provide suitable adaptive strategies for the basin? These research questions are especially timely as city of Thornton withdraws her water rights out of the basin.

- Progress of ATM pilot projects: Monitoring the progress, challenges and achievements of current working ATMs will be valuable; these are Northeastern Colorado Water Cooperative, The Super Ditch, and sub-districts of Rio Grande Water Conservation District. Fortunately the Water Bank Work Group has a good support from local NGOs and governmental entities.

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