5-2016

Analyzing Irrigation District Water Productivity by Benchmarking Current Operations Using Remote Sensing and Simulation of Alternative Water Delivery Scenarios

Jonna D. van Opstal

Recommended Citation

van Opstal, Jonna D., "Analyzing Irrigation District Water Productivity by Benchmarking Current Operations Using Remote Sensing and Simulation of Alternative Water Delivery Scenarios" (2016). *All Graduate Theses and Dissertations*. 4920.
https://digitalcommons.usu.edu/etd/4920

ANALYZING IRRIGATION DISTRICT WATER PRODUCTIVITY BY BENCHMARKING CURRENT OPERATIONS USING REMOTE SENSING AND SIMULATION OF ALTERNATIVE WATER DELIVERY SCENARIOS

by

Jonna D. van Opstal

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Irrigation Engineering

Approved:

Dr. Christopher M.U. Neale Major Professor	Dr. Lawrence E. Hipps Committee Member
Dr. Bethany T. Neilson Committee Member	Dr. Bruce Bugbee Committee Member
Dr. Mac McKee Committee Member	Dr. Mark McLellan Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2016

ABSTRACT

Analyzing Irrigation District Water Productivity by Benchmarking Current Operations Using Remote Sensing and Simulation of Alternative Water Delivery Scenarios

by

Jonna D. van Opstal, Doctor of Philosophy

Utah State University, 2016

Major Professor: Dr. Christopher M.U. Neale
Department: Civil and Environmental Engineering
Division: Irrigation Engineering

Irrigation systems are designed to deliver water to crops, but their efficacy varies widely due to operational decisions, weather variability, and water availability. The operation of an irrigation system is studied in this dissertation to determine irrigation performance and potential for improvement.

Satellite remote-sensing was used to determine inter-annual variability in crop evapotranspiration and link it with weather patterns and operational decisions. A decade was studied to include several dry, wet and average years of snowfall. It was found that the irrigation district has the capacity to buffer a dry year, but crop evapotranspiration patterns indicated that the buffer capacity of the irrigation district is limited in a second dry year.

Studying the current operations of an irrigation system also requires an analysis of the spatial variability within the system to identify potential areas for improvement. Achieving such information is challenging due to the spatial heterogeneity between farm fields. The Ador irrigation system simulation model is used in this study with satellite remote sensing data, which were combined in the calibration and validation process to ease the re-adjustment of management parameters. This approach provides a cost-effective and innovative method for model simulation when field observations are limited.

Alternative water delivery scenarios were simulated with the Ador irrigation system simulation model to quantify changes in the water balance, irrigation performance, and water productivity. Results for implementing a minimal irrigation time indicated that irrigation events occurred with a higher frequency and reduced crop water stress. Water productivity for the irrigation district increased substantially in this scenario, whilst district water savings were achieved by diverting less irrigation water. Advantages are only achieved if farmers collectively make the decision to change.

A water accounting analysis is required to examine if water savings are achieved at basin scale. There is a potential for the rebound effect to occur, which suggests that an increase of water efficiency causes the increase of water consumption. Simulation results indicated that if the efficiency is increased through improvements of the water delivery, the water consumption increased. Water savings achieved by reducing irrigation diversions did not compensate for the decrease in drainage that downstream users depend on.

(182 pages)

PUBLIC ABSTRACT

Analyzing Irrigation District Water Productivity by Benchmarking Current Operations Using Remote Sensing and Simulation of Alternative Water Delivery Scenarios

Jonna D. van Opstal

The competition for fresh water is vastly increasing particularly in semi-arid areas. Agricultural irrigation areas are urged to decrease their water use, being the largest consumer of fresh water in these areas. Improvements in irrigation management aim at increasing crop production whilst maintaining or decreasing water use. The analysis of water productivity at the irrigation district scale is challenging due to spatial heterogeneity between fields and temporal variability between growing seasons.

This dissertation makes use of satellite-based remote sensing imagery and an irrigation system simulation model to determine the water management at different spatial scales from field scale to the irrigation scheme to the basin scale. Integrated analysis at the various spatial scales determines the potential for improvements in water management and is a comprehensive approach for studying water productivity of irrigation districts.

Findings from a decade of satellite remote sensing imagery indicated that water consumption greatly varies annually, therefore management strategies should be flexible to cope with this variability. Assimilation of satellite-based remote sensing data in an irrigation system simulation model enabled benchmarking a spatially diverse system with various farm management strategies. The calibrated simulation model was thereafter applied for the simulation of alternative water delivery scenarios to determine potential for improvement of water productivity. Finally, the impact on downstream water users from changes in irrigation diversions are evaluated using a water accounting approach of the water flows.

This study provides quantifiable insight on the consequences and profits of alternative water delivery scenarios and aids regional water managers in their decisions. Additionally, it proposes an approach of benchmarking and improving the management of irrigation districts to cope with future water scarcity.

ACKNOWLEDGMENTS

Even though one name and six others are on the title page of this doctoral work, there are numerous people to thank for bringing this work into existence. I will like to share a few words of thanks to the following people and organizations.

Many thanks to the Utah Water Research Laboratory for funding this project and research assistantship. Thanks also for the opportunities given to travel to conferences and gain experience with presenting research, whilst being inspired by other researchers. Thanks also to the Utah Agricultural Experimental Station for providing funding for the fieldwork equipment.

My greatest thanks to my major advisor, Christopher Neale, for his supervision, mentoring and guidance throughout the PhD process. I am grateful for his time, effort and availability to continually support me also from a distance and help me with bringing this work into the final end phase.

A special thanks to my committee members: Bethany Neilson, Mac McKee, Bruce Bugbee, and Lawrence Hipps for their time and valuable input in this doctoral research. I especially appreciate Lawrence Hipps for his many conversations on being a good researcher, fieldworker and thinker. I am also thankful to Gary Merkley for helping me apply for this doctoral program at Utah State University.

My deepest gratitude to Sergio Lecina for giving an abundance of his time with the Ador simulations and providing training during my visit to Zaragoza, Spain. Also my thanks to him and his colleagues at the Cita de Aragon (EEAD-CSIC) for being wonderful hosts during my stay there.

My great appreciation to the Bear River Canal Company and local farmers for the several meetings, and great interest in this work. Thank you to the canal managers Dan Davidson and Darin McFarland for providing information on the canal company and arranging meetings with the local irrigators. A special thanks to the farmers Charles Holmgren, Curtis Marble and Newell Norman for making fields available for conducting experiments and having interesting conversations on farming.

Thanks to my current and former colleagues of the Remote Sensing Services Lab in the Department of Civil and Environmental Engineering for their assistance both in the lab and out in the field.

My thanks to Rose for assisting with fieldwork throughout early morning hours and scorching hot days. You made doing fieldwork double the fun.

Thanks to my parents, brother and sister for continually supporting me throughout this process with prayers and encouraging words. You have inspired and challenged me on so many levels, which made me the person I am today.

Thanks to my several friends in Logan who gave me plenty of joy and kept my life in balance. Thanks for introducing me to American and multi-national cultural experiences. I will treasure the many memories we made on our adventures exploring Logan, Utah and other states.

Thanks to my friends back in the Netherlands and elsewhere, for their continuous encouragement and patience. Thanks for staying in touch and keeping our friendships, which I value so much.

First and foremost my gratitude goes to the Lord Almighty, whom gave me strength and perseverance throughout the doctoral program and lets us live life to the fullest.

CONTENTS

CHAPTER

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

1.1 General introduction

When assessing the performance of irrigation management in agricultural areas, two questions need to be asked: “Are we doing things right; and are we doing the right thing?” (Bos, 1997 p.120) This quote expresses the key point of this research, which provides an approach of assessing current irrigation system operations and analyzes the benefits of potential modifications to irrigation systems to optimize productivity and water savings. Irrigation systems are designed to achieve a certain level of performance. However, the performance of an operating irrigation system might vary greatly from the designed level due to several factors such as changes in water availability or crop choices. It is evident that we have left the era of constructing numerous new irrigation schemes and need to focus investments on improving existing irrigation systems (Turral et al., 2010).

Irrigation areas are continuously challenged to decrease their water use, whilst maintaining or increasing productivity. Water scarcity is a global issue with a large portion of the world population likely being affected by it in the coming decades (Rijsberman, 2006). Several regions anticipate physical water scarcity, meaning that water demands cannot be fulfilled, in contrast to economic water scarcity where investments in improving infrastructure can fulfill water demands (Rijsberman, 2006). Additionally, climate scenarios predict that an increase of temperature will result in a shift of the hydrograph making the peak flow of major rivers earlier (Barnett et al., 2005). Major changes in runoff patterns are expected to be widespread with every continent, particularly populous regions, being affected (Turral et al., 2010). The agricultural sector is the largest user of fresh water with approximately 70% globally (IWMI, 2007) and is therefore constantly examined to determine the potential for water savings. In addition, food demands from the agricultural sector are increasing due to the growing world population (IWMI, 2007). Increasing the crop production per volume of water, i.e., water productivity, is often seen to be the answer for ensuring global food security in the future whilst coping with water scarcity issues (Molden et al., 2010).

The quantification of crop production and water use at different spatial scales in an irrigation system is a considerable challenge. Not one field is similar to another due to the several factors determining the irrigation and crop management at the field scale (Clemmens, 2006). These can be biophysical factors such as crop type and variety, soil characteristics, slope and geometry; or social factors regarding decisions made by the farmer on irrigation duration, cropping pattern, fertilizer and pesticide application. Studying the combination of both the social and physical aspects of irrigation management is challenging (Lenton, 2014). Aside from the spatial heterogeneity within the irrigation system, there is also a temporal diversity caused by changes in management between different growing seasons. An analysis of water productivity in an irrigation system requires a vast amount of data to cover the extensive variability existing in a large-scale agricultural area. Fortunately, remote sensing tools have been introduced in the past decades and are a welcome asset in the study of irrigation systems due to their capability of covering large areas and potential for distinguishing spatial and temporal diversity.

Remote sensing tools for irrigated agriculture have rapidly developed providing useful insight at different spatial scales. The practical applications of these tools, specifically at the irrigation system scale, are currently trailing these developments and need to be elaborated. In particular examples and approaches of incorporating remote sensing data for the analysis of the current management practices of large-scale irrigation systems are limited. The connection between water productivity at field scale and the water delivery network needs to be identified before modifications in the irrigation system can be made (Clemmens, 2006). This insight is required to determine if management changes at the field or irrigation system scales might be less efficient at a basin scale (van Halsema and Vincent, 2012).

This dissertation research provides an innovative approach using satellite-based remote sensing tools for analyzing the management of an irrigation system. Research conducted in data-limited regions or requiring costly fieldwork, can implement this approach for improving model simulations. The comprehensiveness of this research will be demonstrated in the interconnectivity between the different spatial scales from field to water delivery network to basin scales. Insights gained throughout this research show the need of incorporating the spatial and temporal diversity of an irrigation area for improving water management and crop productivity. These findings will aid agricultural water managers worldwide in increasing crop water productivity through management modifications.

1.2 Problem statement

The major challenge for agricultural areas is to increase water productivity, which in this study is considered to be the crop production achieved for the volume of irrigation water applied. At field scales several technologies are available to farmers to increase crop production. However, there are few studies for improving water delivery systems to increase the water productivity. A major constraint for several farmers in achieving higher water productivity is the restrictions implemented by the water delivery schedule. The scheduling is frequently not adapted to the crop water requirements at field scale (Jensen, 2007). This can potentially cause crop water stress and reduces the crop yield. Both timing and duration of water delivery is not fully regulated by the farmers in the majority of agricultural areas (Clemmens and Molden, 2007). Therefore, there is a potential for improving the performance of irrigation systems by focusing on the water delivery (Clemmens and Molden, 2007; Clemmens, 2006).

This potential for improvement is particularly relevant for irrigation systems with a rigid water delivery schedule, such as pre-determined rotations independent of crop water demands. However, even some irrigation systems incorporating an on-demand schedule are not capable of fulfilling crop water requirements. This was indicated by a study on several irrigation districts in the Western US with 75% of evaluated districts experiencing problems with the timing of water delivery (Burt and Styles, 2000).

Finding ways to improve the water delivery system and introduce more flexibility for the farmers in receiving irrigation water is not straightforward. Performance indicators have been developed in earlier research (Bos, 1997; Bos et al., 2005; Burt et al., 1997) to characterize the operation of the irrigation system. These mainly focus on efficiency and uniformity at field scale; whilst equity and reliability are more important for evaluating water delivery. It is time consuming to collect sufficient data to calculate the performance for a large irrigation district. Additionally, some indicators are not representative of the benefits because what seems to be inefficient at a field scale might be beneficial at a larger scale (van Halsema and

Vincent, 2012). Furthermore, indicators are usually static measures and do not show the dynamics between growing seasons.

There is a need for greater and quantifiable insight on the link between the water delivery and the water productivity of an irrigation system. This requires an effective approach of characterizing the current performance of the irrigation system including spatial and temporal variability. The benefit of modifications to the water delivery on crop production at farm scales need to be identified to inform irrigation districts on the potential that can be achieved. In addition, the consequences of changes to the operations of a large agricultural area need to be evaluated to prevent negative impacts on the environment.

1.3 Significance of research

This research will provide an approach for assessing the management of an irrigation system using satellite remote sensing data. This approach allows for the consideration of the spatial and temporal variability within the system due to the spatial resolution and decadal archive provided by satellite imagery (Ambast et al., 2002). This makes it possible to compare inter-annual differences and determine the source of variations in seasonal water use of the irrigation district. Additionally, remote sensing provides data for a large agricultural area and enables the calculation of a water balance when field results are limited (Taghvaeian and Neale, 2011). Furthermore, the assimilation of remote sensing data into a simulation model makes it possible to quantify the water management at field scale, without needing an extensive amount of field data (Bastiaanssen et al., 2007). This data assimilation method has rarely been implemented for evaluating an irrigation system, but has proven to be successful for farm and hydrology studies (Bastiaanssen et al., 2007).

A thorough understanding of the current operation of an irrigation system is required before potential improvements can be identified. This research provides suggestions for modifications to the water delivery scheme of an irrigation system. Outcomes resulting from potential operational modifications are analyzed to determine changes to water productivity and also the impact on the environment. At present, information on the connection between water delivery and water productivity is limited but is crucial for achieving improvements in the water productivity of irrigation systems (Clemmens, 2006).

Irrigation districts need to meet the future challenges of higher food demands and water scarcity by increasing water productivity. This research provides an essential approach for increasing water productivity in a cost-effective way that will benefit large agricultural areas. Insights gained from this research will aid irrigation districts worldwide in understanding the connection between water delivery and water productivity and the importance of flexibility of the water delivery. Additionally, institutions governing the regional water management will be informed on the benefits and consequences of modifications in the irrigation system water delivery.

1.4 Research questions

The main objective of this dissertation is two-fold:

a) Evaluate the capability of an irrigation system to adapt to inter-annual variations in weather.
b) Quantify the potential for increasing water productivity of an irrigation system by modifying water delivery schemes.

The overarching research question for this dissertation is:

How do the different spatial levels, from field to water delivery network to basin scales, interact when making modifications in the irrigation management to increase water productivity?

This question is answered through the following working questions, which are discussed in each chapter:

1) Are the inter-annual variations of water consumption in an irrigation district i.e. crop evapotranspiration, explained by weather patterns, cropping patterns or both?
    a. Are inter-annual variations of water consumption solely related to the variability of reference evapotranspiration?
    b. Do changes in cropping patterns explain the inter-annual variability of water consumption?
    c. Does seasonal water availability from snowpack and summer precipitation explain the inter-annual variability of water consumption?

   d. Does the seasonal water availability from a previous year influence the water consumption of the current year?
   e. Does the irrigation district (in this study) have the capacity to buffer one, two or more years of low water availability?

2) Is the spatial variability of irrigation performance identified using an irrigation system simulation model and assimilating remote sensing data?
   a. Does data assimilation with remote sensing aid model simulations by determining areas of disagreement thus avoiding the necessity of extensive fieldwork?
   b. Can a re-adjustment process with remote sensing data improve model simulations at different spatial scales?
   c. Do model results indicate the spatial variability between fields regarding the application efficiency, distribution uniformity and water productivity?
   d. Do model simulations identify headgate areas with potential for over-allocations during the peak irrigation period?
3) Are improvements in water productivity of an irrigation system possible with modifications of the water delivery schedule?
   a. Does the water productivity of the irrigation district (in this study) increase if changes are made in the water delivery timing or duration?
   b. Does the water productivity of the irrigation district (in this study) increase if changes are made in flow rates from selected ditches?
   c. Is there a potential to save water and decrease irrigation diversions by making modifications in the water delivery?
4) Is there a potential for the rebound effect to occur with improvements of the water delivery in the irrigation system (in this study)?
   a. Do model simulations indicate an increase in the water consumption under a different water delivery schedule, thereby demonstrating the potential of the rebound effect?

b. Is there a change in the runoff from the irrigated area to downstream water users predicted according to model simulations?

c. Can this change in runoff be compensated with the decrease in irrigation diversions?

1.5 Conceptual framework

The placement of each research question in the overall study is depicted in Figure 1-1, which presents a schematic of the conceptual framework. Firstly, the different concepts that are used in this research are defined. Following is a description of the connections between the different research questions and the limitations of this study.

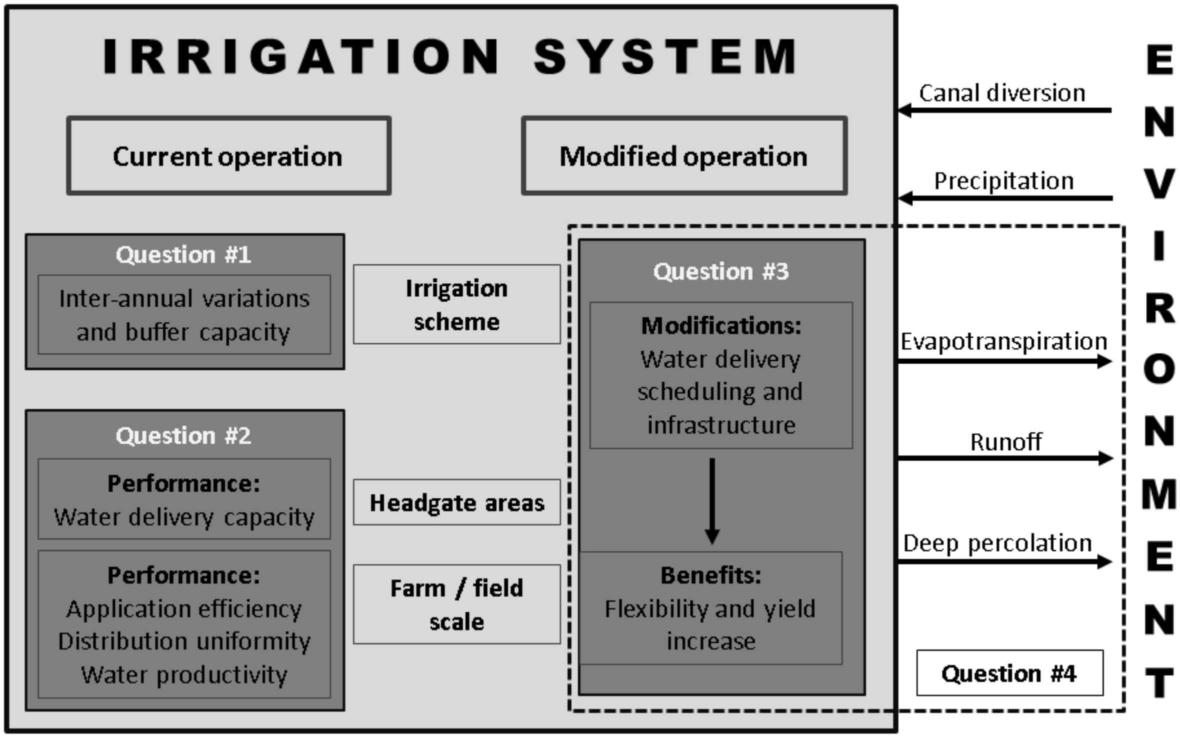


Figure 1-1. Conceptual framework.

The irrigation system is the main focus of this research, which is defined as both the physical and social attributes in an irrigation area. The function of the irrigation system is to convey water from a source to agricultural fields and apply to the root zone to benefit crop growth (Small and Svendsen, 1992). There are three spatial scales defined in the irrigation system: irrigation scheme, headgate area and farm or field scale. The irrigation scheme is the main canal system, which conveys irrigation water from the source to the headgate areas. It is composed of main canals, secondary or lateral canals, and control structures (Skogerboe and Merkley, 1996). The headgate areas are also considered the tertiary part of the irrigation scheme. It is defined as the conveyance element after the last control structure, and transports the irrigation water from the canal system to the fields (Skogerboe and Merkley, 1996). Headgate areas are usually a collection of numerous fields and are the responsibility of the farmers. The field scale is considered in this research to be the smallest unit of the irrigation system. The operation of the irrigation scheme is defined as all activities that convey, store or deliver water (ASCE, 1991). The irrigation district is the agency responsible for the operation of the irrigation scheme and delivers the water to the tertiary or headgate units (ASCE, 1991). In this schematic, performance is evaluated at two different scales, namely headgate areas and at field scales. Definitions of the performance indicators will be elaborated on in the next chapter. Operational modification or modernization is defined as any major change in the operation of the irrigation system or improvements in the infrastructure to enhance the water delivery service (Burt and Styles, 2000; Playán and Mateos, 2006).

The first two research questions, as indicated in Figure 1-1, develop an evaluation of the current operational performance of the irrigation system. The first research question determines the inter-annual variability of seasonal water use in the irrigation system and identifies the capacity of the irrigation system to buffer variations in seasonal precipitation. The second research question identifies the spatial variability in irrigation performance and detects areas of limited performance. These areas have potential for improvement, as will be pointed out in suggested operational modifications in the water delivery analyzed in the third research question. The fourth research question studies the impact of the modifications on the surrounding water-users. In this research, hydrological interactions at basin level are limited to quantifying the in- and outflows, as depicted in Figure 1-1. Sources from the environment are determined to be the precipitation and diversion from the river. Sinks to the basin are percolation, drainage or runoff at certain collection points and evapotranspiration from the agricultural fields.

1.6 Study area

The study area used for this research project is called the Bear River Canal Company (BRCC) and is located in Northern Utah. It is at the downstream end of the Bear River Basin, which is a 796 km (= 495 mile) river originating in the Uintah Mountains (Utah) and flowing through the states Wyoming, Idaho and back into Utah where it terminates in the Great Salt Lake (see Appendix A). The irrigated area (referred to as command area) serviced by the BRCC encompasses 29,764 ha (= 73,549 acres). The main crops grown in this area are alfalfa (37.4 %) and corn (16.7 %) for fodder; wheat and other grains (29.4 %); and onions (1.5 %). The main soil types in the area are clay to clayey loam soils, with a few areas of sandy loam soils. Maps of the spatial distribution of crop and soil types can be found in Appendix B and C. The BRCC diverts irrigation water at Cutler Dam and has four major canals: Hammond Canal, West Canal, East Canal and Central Canal (see Appendix D). Four ditchriders are each responsible for a main canal and a canal manager is head of the company. The water delivery follows a fixed rotation schedule, which remains unchanged each year. The rotation schedule is designed to irrigate one third of the BRCC command area at 1cfs per 80 acres (28 L/s per 32 ha.) per week (information from meetings with BRCC ditchriders and managers). The main irrigation method in the area is border irrigation, with a few instances of sprinkler or basin irrigation.

The BRCC is a good example of the several issues relevant to irrigation districts worldwide. The region is experiencing a rapid growth in population, with the population growth of Utah being one of the fastest of the US. The BRCC is also solely dependent on winter snowpack for irrigation water and is therefore impacted by predicted changes in runoff according to climate scenario modeling. Additionally, it is a large agricultural area operated by an agency with constraints in the existing water delivery schedule. This allows for a greater potential in introducing more flexibility in the water delivery. For practical purposes this location was also ideal due to the overlapping path lines in Landsat satellite overpasses resulting in double the amount of remote sensing imagery available for analysis. These reasons provide a good basis for using the BRCC as study area and enable the connection to global issues existing in other agricultural areas.

References

Ambast, S.K., Keshari, A.K., Gosain, A.K., 2002. Satellite remote sensing to support management of irrigation systems: concepts and approaches. Irrig. Drain. 51, 25–39.

ASCE, 1991. Management, operation and maintenance of irrigation and drainage systems, 2nd Edition. ed. ASCE, New York, NY.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–9. doi:10.1038/nature04141

Bastiaanssen, W.G.M., Allen, R.G., Droogers, P., D'Urso, G., Steduto, P., 2007. Twenty-five years modeling irrigated and drained soils: State of the art. Agric. Water Manag. 92, 111–125. doi:10.1016/j.agwat.2007.05.013

Bos, M., 1997. Performance indicators for irrigation and drainage. Irrig. Drain. Syst. 11, 119–137.

Bos, M.G., Burton, M.A., Molden, D.J., 2005. Irrigation and drainage performance assessment - Practical guidelines. CABI Publishing.

Burt, C., Clemmens, A., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Eng. 123, 423–442.

Burt, C.M., Styles, S.W., 2000. Irrigation district service in the Western United States. J. Irrig. Drain. Eng. 126, 279–282.

Clemmens, A.J., 2006. Improving irrigated agriculture performance through an understanding of the water delivery process. Irrig. Drain. 55, 223–234. doi:10.1002/ird.236

Clemmens, A.J., Molden, D.J., 2007. Water uses and productivity of irrigation systems. Irrig. Sci. 25, 247–261. doi:10.1007/s00271-007-0067-y

IWMI, 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan, International Water Management Institute, London, Colombo.

Jensen, M.E., 2007. Beyond irrigation efficiency. Irrig. Sci. 25, 233–245. doi:10.1007/s00271-007-0060-5

Lenton, R., 2014. Irrigation in the Twenty-First Century: Reflections on Science, Policy and Society. Irrig. Drain. 63, 154–157. doi:10.1002/ird.1844

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agric. Water Manag. 97, 528–535. doi:10.1016/j.agwat.2009.03.023

Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manag. 80, 100–116. doi:10.1016/j.agwat.2005.07.007

Rijsberman, F.R., 2006. Water scarcity: Fact or fiction? Agric. Water Manag. 80, 5–22. doi:10.1016/j.agwat.2005.07.001

Skogerboe, G.V., Merkley, G.P., 1996. Irrigation maintenance and operations learning process. Water Resources Publications, LLC, Highlands Ranch, CO.

Small, L.E., Svendsen, M., 1992. A framework for assessing irrigation performance (No. 1), IFPRI Working Papers on Irrigation Performance. Washington D.C.

Taghvaeian, S., Neale, C.M.U., 2011. Water balance of irrigated areas: a remote sensing approach. Hydrol. Process. 25, 4132–4141. doi:10.1002/hyp.8371

Turral, H., Svendsen, M., Faures, J.M., 2010. Investing in irrigation: Reviewing the past and looking to the future. Agric. Water Manag. 97, 551–560. doi:10.1016/j.agwat.2009.07.012

van Halsema, G.E., Vincent, L., 2012. Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. Agric. Water Manag. 108, 9–15. doi:10.1016/j.agwat.2011.05.016

CHAPTER II

LITERATURE REVIEW

This chapter is devoted to explaining a few key topics relevant to this research and presenting the accomplishments reported in literature. There remains an amount of obscurity in defining efficiency of irrigation systems and other water-related nomenclature. Irrigation professionals, hydrologists and plant scientists use several terms for evaluating the performance of agriculture and definitions remain unclear (Perry, 2007). Therefore, the first three sections are used to elaborate on explaining the terms and how they relate at different spatial scales. The last section provides a review of the various remote sensing approaches for estimating evapotranspiration (ET) in agricultural areas.

2.1 Water accounting

Before discussing irrigation management and performance of agricultural areas, it is necessary to first define the several concepts involved in determining water flows of irrigated agricultural areas.

For agriculture, the different destinations of irrigation water flows can be divided in consumptive and non-consumptive use. The consumptive use includes the water that is either lost to the atmosphere or incorporated in the plant and is therefore not recoverable and is omitted for further use (Burt et al., 1997). Non-consumptive use is considered the remainder and is divided into reusable and non-reusable fractions. The non-reusable fraction indicates a degradation of water quality, which makes it unsuitable for further use (Pereira et al., 2012).

Furthermore, both the consumptive and non-consumptive uses can be sub-divided in beneficial and non-beneficial use. These terms were introduced and defined by Burt et al. (1997), and later elaborated on by Pereira et al. (2012, 2002). Water for the purpose of increasing yield and production is considered to be beneficial use in the agricultural sector (Pereira et al., 2012). Non-beneficial use is considered to be water that is applied but is futile for agricultural production either due to soil evaporation, deep percolation or runoff. Burt et al. (1997) also defines reasonable use as another sub-category. It considers that some water uses are perceived to be non-beneficial but are accepted in certain situations because it is necessary for the practice. Examples are the evaporation from reservoirs and sprinkler irrigation.

Categorization of irrigation water flows depends on the boundary of the scale. Some water flows might be categorized as non-beneficial but might be beneficial at a larger scale for downstream users (van Halsema and Vincent, 2012). The definitions of beneficial, reasonable and non-beneficial uses are therefore subjective and depend on the stakeholders and their perspectives (Burt et al., 1997).

Water accounting is a method that uses the water balance of an agricultural area and determines all the water flows in and out of the irrigation system. It is an approach used by irrigation engineers and hydrologists and gives a common perspective for discussing water resources management (Karimi et al., 2013; Perry et al., 2009). It is relevant to include the basin perspective in evaluating different irrigation management strategies. Different strategies will influence the outflow (i.e. runoff and drainage) from the irrigation system and will therefore have an impact on the basin. Setting up a water balance of the basin, will indicate if certain strategies can provide ‘real’ water savings or if the water is displaced to other water balance components (Molden et al., 2010; Seckler, 1996; van Halsema and Vincent, 2012). ‘Real’ water savings signifies either a decrease in consumptive use, or a decrease in water losses (i.e. non-reusable water flow). Some consumptive uses are beneficial because it contributes to the production of the area. Non-beneficial consumptive uses such as evaporative losses from weeds or bare soil need to be reduced (Gleick et al., 2011). Currently, water management gives insufficient consideration to future water demands and the need of storage (Frederiksen and Allen, 2011). It is therefore relevant to study basin management in quantitative terms, such as a water accounting approach. Additionally, it is essential to evaluate the impact of agricultural outflows on the environment and downstream users. This is especially of concern when the local stream is impaired and water quality needs to be strictly monitored (Thayalakumaran et al., 2007). Ultimately, each basin is different and has its own set of issues, therefore there is not a single solution for all basins but each should be studied separately and needs an ‘integrated basin-specific approach’ (Gleick et al., 2011).

2.2 Performance indicators

Field scale performance

There are several performance indicators used at field scale to determine the productivity and efficiency of irrigation practices. These can evaluate current and alternative practices to determine good performance. The farmers are especially interested in saving water and reducing labor, whilst maintaining the same or improved yields. In a case study, Khan and Abbas (2007) demonstrate that through irrigation modernization at farm level, water use and labor was reduced whilst yield and crop quality increased. Changes in irrigation method can potentially increase performance at farm level. Bos et al. (2005) indicated that surface and sprinkler irrigation vary between 60 to 90% application efficiency, whilst drip irrigation has an efficiency of up to 95%. At present, there is also a trend of increasing water productivity at field scale (Pereira et al., 2012), which can be achieved through different irrigation and agronomic practices (Clemmens and Molden, 2007).

Some commonly used performance indicators at the field level are defined according to its use in this research. It is relevant to understand how these indicators are calculated and what is represented in the nominator and denominator. However, there is some diversity in reported literature in defining these indicators (Jensen, 2007).

Application efficiency

The application efficiency (AE) is the indicator that is most relevant to the farmers. It considers the efficiency of fulfilling crop water requirements. The AE is also defined by Heermann and Solomon (2007) as:

$$\mathrm{AE} = \frac{\text{Volume of water stored in the root zone for crop use}}{\text{Volume of water delivered to the field}} \text{ x } 100\%$$

However, it is important to note that sometimes it is better to express AE as a ratio instead of efficiency, because it indicates a ratio between actual and intended or total value (Bos, 1997; Bos et al., 2005).

Additionally, farmers might be interested in achieving a high AE for irrigation events, but sometimes at a larger scale this is less beneficial. Therefore, water resource managers might use different terms than ‘efficiency’ because it can be misleading (Jensen, 2007).

Distribution uniformity

The distribution uniformity (DU) is another indicator of interest to the farmer, because it indicates if the applied irrigation water is evenly distributed over the field. If certain areas are constantly under-irrigated it can lead to yield loss in those sections. The DU for surface irrigated fields is defined by Heermann and Solomon (2007) as:

$$\mathrm{DU} = \frac{\text{Average infiltrated depth of the lower quarter of the field}}{\text{Average infiltrated depth of entire field}}$$

The lower quarter of the field is the quarter of the field receiving the least amount of water, usually at the end of the field.

Water productivity

The term water productivity (WP) is expressed in different ways but the concept is to find the ratio between crop productivity and the volume of water consumed. For crop physiologists this is the amount of carbon assimilated in the plant per unit of water transpired (Molden et al., 2010). However, at field scale there are numerous definitions for WP used by irrigation engineers varying between biomass and yield or transpiration (T), evapotranspiration (ET) or irrigation depth (Perry et al., 2009). The definition for WP used in this research was defined by Pereira et al. (2012):

$$\mathrm{WP} = \frac{\text{Actual crop yield achieved [kg]}}{\text{Irrigation water applied to the field } [\mathrm{m}^3]}$$

The difference between using water consumed (ET or T) in comparison with irrigation water use, is that the latter includes the non-consumed fraction during an irrigation event. The relationship between yield and ET (or practically T) is generally linear over a certain range, however the relationship between irrigation depth and yield is curvilinear as studied by Contor and Taylor (2013). Contor and Taylor indicated that with an increase in water applied the yield increases up to an optimum after which waterlogging causes a decrease in crop growth. The linear relationship between yield and T indicates that maximizing T will achieve higher crop yields (Perry et al., 2009).

In practice WP varies due to physical aspects such as crop variety and climate. It is also influenced by management practices such as the application of fertilizers and pest control (Clemmens and Molden, 2007; Molden et al., 2010). Additionally, the timing of irrigation events is in practice more important than the quantity of irrigation water to prevent water stress and thus yield reductions to occur (van Halsema and Vincent, 2012).

Irrigation system performance

The performance of an irrigation system is usually determined by the efficiency and quality of the water delivery (van Halsema and Vincent, 2012). Several performance indicators are used to evaluate and monitor the irrigation system. These can consider volumetric water balance methods, which match the supply and demand in the system. Additionally, the reliability, equity and flexibility of the service needs to be evaluated, however these terms are more subjective (Bos, 1997). Flexibility is determined by the level of restrictions on flow rate, duration and timing (Clemmens and Molden, 2007).

Evaluating and monitoring the performance of irrigation systems is necessary to determine the adequacy of the water delivery. However, in practice the water delivery is seldom monitored by the managers. It has been reported that a vast number of irrigation systems are unreliable and do not adapt with the fluctuations between wet and dry years (Jensen, 2007). Usually the delivery schedule does not match up with the crop water requirements at field scale, which causes deficits or excess of irrigation water (Jensen, 2007; Zaccaria et al., 2010). Irrigation systems are generally not capable of delivering the full supply to every user at any time. In addition, several large scale irrigated areas require long travel times due to the length of the canal system (Clemmens and Molden, 2007). The discharge and timing by the irrigation system to the agricultural system (i.e., the farmers) is essential. If the service is not delivered in a timely fashion, yield reductions can be the consequence (Pereira et al., 2012).

The performance of the irrigation system is evaluated in this research using depleted fraction and water delivery capacity of head gate areas.

Depleted fraction

The depleted fraction (DF) considers the inputs and consumed fraction of the water balance for the area under the irrigation system. Bos et al. (2005) defines the depleted fraction as:

$$\mathrm{DF} = \frac{\text{Actual crop evapotranspiration } ET_a}{\text{Precipitation} + \text{ Irrigation canal diversion}}$$

If precipitation is not significant during the growing season, it can be neglected in the equation; such is the case in arid areas (Clemmens and Molden, 2007). The irrigation canal diversion is the volume of water diverted from a surface water body (i.e., river or reservoir) flowing into the main canal system. It is recommended to study the DF of an irrigated area during a season. DF can be used by water managers as a monitoring instrument during the growing season. The volume of water diverted can be selected, which consequently influences the ET_a due to the water availability for the crops (Bos, 2004). The critical value for DF found from different case studies is approximately 0.6, which can fluctuate between 0.55 and 0.7 depending on the drainage properties of the soil (Bos, 2004). For DF values below the threshold value ($DF<0.6$) it indicates that water goes to the groundwater storage and the water table increases. For values above the threshold ($DF>0.6$) it indicates that storage decreases and additional water is required from diversions (Bos et al., 2005). It is best to divert less water during months that DF is less than 0.6 to store the water in reservoirs for the dry season.

Water delivery capacity

The water delivery capacity (WDC) is estimated for each headgate area by taking the peak month of crop ET and comparing it with the conveyance capacity. This indicates if the conveyance capacity or water delivery schedule is a limiting factor to the crop water demands. The WDC was expressed by Molden et al. (1998) as:

$$\mathrm{WDC} = \frac{\text{Canal capacity of headgate } [\mathrm{m}^3\mathrm{s}^{-1}]}{\text{Monthly average crop ET during peak month } [\mathrm{m}^3\mathrm{s}^{-1}]}$$

2.3 Field vs irrigation system vs basin scale

The different concepts, issues and performance assessments at the field and irrigation system scale have been elaborated in the previous sections, in addition to a description of the water accounting approach at the basin scale. The interactions between the different scales are essential to examine. Seckler (1996) argues for a holistic approach in irrigation management and conceptualizes the phenomena called scale effects. This concept proposes that “what is true of all the parts is not necessarily true of the whole” (Seckler, 1996 p.9). This is evident in the accounting of water consumption and losses of agricultural areas. It is argued that ‘losses’ at a local scale can contribute to the efficiency of the system or basin at a holistic scale (van Halsema and Vincent, 2012). In recent publications on irrigation management there is a trend for emphasizing that the term efficiency is misleading because it indicates an increase in water availability however, this is most often not the case (Jensen, 2007; Pereira et al., 2012; Perry et al., 2009).

This phenomena is also referred to as the rebound effect, which implies that “the increase in efficiency also increases the consumption of the resource” (Berbel et al., 2014 p.2). The possibility of this effect occurring in water resources management has been described by Contor and Taylor (2013), where improvements in irrigation technology, increased irrigation efficiency but also caused an increase in water consumption. This can occur when the irrigated area expands or crop yield increases. Therefore, if a higher yield is achieved, the transpiration and thus water demand needed to achieve this yield is also higher. Nevertheless, improvements in irrigation technology and precision agriculture are important and positive emerging trends. Frequently these improvements are beneficial, yet it is advisable to study the water balance at both farm and basin scale first to determine the potential consequences of a change in irrigation practices (Berbel et al., 2014; Contor and Taylor, 2013). Khan and Abbas (2007) demonstrate in a case study the importance of up-scaling water savings from a field scale to a system scale and the impact it can potentially have to support decision-making. Another case study showed that changes in frequency of water delivery resulted in a decrease of drainage from the fields, despite the fact that volume of applied water was the same (Tromboni et al., 2014).

Improvements should be implemented as a total package considering both the infrastructure and the operation and include all levels from farm to basin. Playán and Mateos (2006) emphasize the need for changes in management and stress that improving uniformity between fields has the most potential for increasing productivity of the irrigation system. This is echoed by Clemmens (2006) stating that the productivity of an irrigation system is a collective result and cannot be attributed to a single level. A case study described by Pereira et al. (2012) shows that improvements were achieved at the system level. However, farmers were less involved and therefore not the same water productivity increases were achieved at farm level. This point is accentuated by Clemmens and Molden (2007) suggesting that improvements in uniformity should be made both at field and water delivery scale. This can achieve a more reliable and adequate irrigation management and reduce yield losses. Ultimately, increasing efficiency is not the only objective for irrigation management, but reliability and flexibility of irrigation water are equally important to consider (Pereira et al., 2002). Performance of an irrigation system can either be described in terms of external or internal performance. External performance is considered the results or production achieved with irrigation, whilst internal performance is considered the quality of water delivery service (Clemmens and Molden, 2007).

Any modifications at the irrigation system level should be in conjunction with the farmers, who are the end-users of the irrigation water (Lenton, 2014). It is necessary to incorporate their perspectives and priorities. It is found by Knox et al. (2012) that financial benefits are most important for farmers and that they have less interest in basin efficiency or the holistic view of the irrigation system. It is therefore important to share some insight on the issues at a larger scale and the links existing between the different entities. Additionally, modifications to irrigation techniques are frequently implemented incorrectly and therefore do not achieve full potential (Levidow et al., 2014). It is therefore crucial to instruct irrigators and make technologies user-friendly. Ultimately, it is essential to realize that irrigation is a practice that involves both social and physical aspects (Lenton, 2014). Therefore, interventions should include both social and technical attributes and be able to adapt to the diversity of irrigation systems (IWMI, 2007).

2.4 Remote sensing algorithms for ET estimation

Remote sensing is “the art and science of obtaining information about an object without being in direct physical contact with the object. It is a scientific technology that can be used to measure and monitor important biophysical characteristics and human activities on Earth” (Jensen, 2000 p.xiii). There are several satellites producing images for different uses (Bastiaanssen et al., 2000). In addition, airborne imagery and UAV’s (unmanned aerial vehicle) are used to achieve high spatial resolution imagery of fields or areas. These different platforms provide imagery that can be used for different applications in water resources management. One of those applications is the estimation of evapotranspiration (ET) from agricultural fields. Traditionally, ET of an agricultural region was estimated using a water balance and measurements at different gages in the region. However, there remained a certain level of uncertainty in the measurements, which caused inaccuracies in the estimation of ET (Senay et al., 2011). The advantage of remote sensing is that it provides information of a large area at regular intervals (Bastiaanssen et al., 2000; Bastiaanssen and Bos, 1999). Additionally, remote sensing is capable of capturing the actual field conditions of the crop and incorporate the influence of water stress (Pereira et al., 2015). However, remote sensing for ET estimation should be used with caution because it is not a direct measurement of ET but approximated using published algorithms on atmospheric and surface processes (Allen et al., 2011b).

Several surface energy balance algorithms have been developed to estimate instantaneous ET. These can be distinguished between one source and two source models (Kalma et al., 2008). These models typically calculate ET as a residual of the energy balance and differ in the approximation of the sensible heat flux (H) (Gowda et al., 2008). Numerous one source models make use of an internal calibration method utilizing extremes within the (satellite) image to estimate H. The triangle method is an example of using the extremes from the image, by plotting all pixels and determining a ‘warm’ and ‘cold’ edge of the plot to achieve maximum and minimum temperature of the image (Carlson, 2007). It has proven to be a simple approach for estimating ET and does not require atmospheric corrections of the thermal band (Carlson, 2013). The Surface Energy Balance Algorithm for Land (SEBAL) uses a similar approach but selects single pixels to be representative of the extreme condition in the image. The algorithm is presented by Bastiaanssen et al. (1998) and suggests selecting a pixel from a water body and bare soil to represent 'cold' and 'hot' conditions of the image. Instantaneous ET estimations from SEBAL have found to be at 15% accuracy and 1 to 5% for seasonal estimations. It has been applied successfully in different climates with multiple settings and thus is a robust method for ET estimation (Bastiaanssen et al., 2005). The Mapping ET with Internalized Calibration (METRIC) algorithm builds on the SEBAL algorithm but differs in the selection of extreme pixels. METRIC suggests choosing pixels solely from agricultural areas (Allen et al., 2011a, 2007b). METRIC has also been successfully validated with field experiments in different settings. Daily ET estimates were found to follow the patterns measured by lysimeter observations (Allen et al., 2007a). Another experiment compares METRIC data with Bowen ratio estimates and found 11% agreement when comparing the latent heat flux (i.e. ET) (Cuenca et al., 2013). Both SEBAL and METRIC are widely adopted for water resource studies especially in irrigated agricultural settings in arid and semi-arid regions (Allen et al., 2011a, 2007a). However, the disadvantage is that the selection of hot and cold pixels is subjective according to the user. It is therefore crucial that the user is trained and knowledgeable in the atmospheric sciences and environmental physics (Allen et al., 2011a, 2007a). A comparison of the triangle, SEBAL and METRIC method showed that METRIC performed slightly better, but the impact of pixel selection was crucial for achieving accurate results (Long and Singh, 2013). An automated approach has been developed recently to avoid the subjectivity involved with selecting the pixels. Results show promise, however, differences between the user and automated approach were minor (Morton et al., 2013). Another disadvantage of the use of internalized calibration is the assumption that extreme conditions are present in the satellite image (Anderson et al., 2012). In irrigation districts this is usually a correct assumption due to well-irrigated and fully growing fields. However, problems might occur in the early or late season, when fields are not fully covered by vegetation.

The second category of surface energy balance algorithms are two source models. These models distinguish between the surface and the vegetation energy balance, combining the sensible heat flux (H) estimated at both heights using mechanistic forms of processes (Norman et al., 1995). The two source model approach has shown to be a better approach for estimating ET especially for studies in riparian areas including bare soil (Timmermans et al., 2007). However, the need for atmospheric corrections and the initial setting up of the model can be challenging and time-consuming (Anderson et al., 2012). Another study indicated minor differences between a two source approach and METRIC, but slightly better performance by the two source approach (Gonzalez-Dugo et al., 2009).

The calculation of daily or seasonal ET from the instantaneous ET estimations achieved from a surface energy balance algorithm needs to be achieved through interpolation, when using satellite imagery. Satellite overpasses occur commonly at 16 day intervals. In addition, cloud cover can cause images to be unusable for analysis. Interpolation is necessary to approximate daily ET for the days without a satellite image. Interpolation can either make use of the evaporative fraction (Λ), representing the fraction of available energy used for evaporation, or the crop coefficient (ET_rF or k_c), referring to the ratio between actual and reference ET (Kalma et al., 2008). There are three interpolation methods for estimating seasonal ET: curvilinear, linear or fixed using ET_rF. The curvilinear method has found to perform slightly better, but not significantly, than the other methods due to the similarities with the crop growing curves (Singh et al., 2012). However, the time gap between some satellite images can be several weeks, which causes inaccuracies in the estimation of seasonal ET. This issue is particularly profound if a precipitation event occurred on the day of image acquisition. A number of corrections are suggested by Kjaersgaard et al. (2011) to adjust for errors caused by the precipitation event. Additionally, it is suggested to combine different satellite platforms using a coupling of shortwave, thermal and passive microwave image.

Recent developments have focused on improving seasonal ET by fusing data from moderate spatial resolution imagery with low resolution imagery but high temporal frequency (Anderson et al., 2012; Cammalleri et al., 2013; Gowda et al., 2008). This data fusion approach is based on the two source model algorithm and is named disALEXI. Results from a comparison of disALEXI results and a field experiment showed that estimations from disALEXI coincided with trends observed by the experiment throughout the season (Cammalleri et al., 2014). Another approach for improving ET estimations is by using a thermal sharpening technique on moderate or low spatial resolution imagery (Gao et al., 2012). This sharpening tool relates the land surface temperature to NDVI (normalized difference vegetation index). This can improve the use of low resolution imagery, which is usually available with smaller time intervals. Additionally, thermal sharpening can aid the estimation of ET for smallholder agricultural areas.

Another approach for estimating ET that does not require an energy balance is the reflectance-based crop coefficient method. This approach makes use of vegetation indices such as NDVI or SAVI (soil adjusted vegetation index) to adjust the crop coefficient during the growing season (Gowda et al., 2008). This method is simple but requires empirical relationships between crop coefficients and vegetation indices, which are specific for each crop. A hybrid approach is suggested, which combines the reflectance-based crop coefficient approach and two source energy balance approach (Neale et al., 2012). This approach improves results for seasonal estimations due to using a reflectance-based crop coefficient for interpolation.

These approaches for estimating ET have been incorporated in several water management studies. Improvements are consistently made to increase the accuracy of seasonal ET estimates. Adding satellite platforms can provide a higher temporal and spatial frequency of ET estimations (Anderson et al., 2012). Numerous studies validate the outcomes of these various approaches. However, the current focus should be on the practical application of these models in agricultural areas and making models and results user friendly (Bastiaanssen et al., 2000; Gowda et al., 2008).

References

Allen, R.G., Irmak, A., Trezza, R., Hendrickx, J.M.H., Bastiaanssen, W., Kjaersgaard, J., 2011a. Satellite-based ET estimation in agriculture using SEBAL and METRIC. Hydrol. Process. 25, 4011–4027. doi:10.1002/hyp.8408

Allen, R.G., Pereira, L.S., Howell, T. a., Jensen, M.E., 2011b. Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agric. Water Manag. 98, 899–920. doi:10.1016/j.agwat.2010.12.015

Allen, R.G., Tasumi, M., Morse, A., Trezza, R., Wright, J.L., Bastiaanssen, W., Kramber, W., Lorite, I., Robison, C.W., 2007a. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications. J. Irrig. Drain. Eng. 133, 395–406. doi:10.1061/(ASCE)0733-9437(2007)133:4(395)

Allen, R.G., Tasumi, M., Trezza, R., 2007b. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Model. J. Irrig. Drain. Eng. 133, 380–394. doi:10.1061/(ASCE)0733-9437(2007)133:4(395)

Anderson, M.C., Allen, R.G., Morse, A., Kustas, W.P., 2012. Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources. Remote Sens. Environ. 122, 50–65. doi:10.1016/j.rse.2011.08.025

Bastiaanssen, W.G., Molden, D.J., Makin, I.W., 2000. Remote sensing for irrigated agriculture: examples from research and possible applications. Agric. Water Manag. 46, 137–155. doi:10.1016/S0378-3774(00)00080-9

Bastiaanssen, W.G.M., Bos, M.G., 1999. Irrigation performance indicators based on remotely sensed data: a review of literature. Irrig. Drain. Syst. 13, 291–311.

Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A., Holtslag, A.A.M., 1998. A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation. J. Hydrol. 212-213, 198–212. doi:10.1016/S0022-1694(98)00253-4

Bastiaanssen, W.G.M., Noordman, E.J.M., Pelgrum, H., Davids, G., Thoreson, B.P., Allen, R.G., 2005. SEBAL Model with Remotely Sensed Data to Improve Water-Resources Management under Actual Field Conditions. J. Irrig. Drain. Eng. 131, 85–93. doi:10.1061/(ASCE)0733-9437(2005)131:1(85)

Berbel, J., Gutiérrez-Martín, C., Rodríguez-Díaz, J. a., Camacho, E., Montesinos, P., 2014. Literature Review on Rebound Effect of Water Saving Measures and Analysis of a Spanish Case Study. Water Resour. Manag. doi:10.1007/s11269-014-0839-0

Bos, M., 1997. Performance indicators for irrigation and drainage. Irrig. Drain. Syst. 11, 119–137.

Bos, M.G., 2004. Using the depleted fraction to manage the groundwater table in irrigated areas. Irrig. Drain. Syst. 18, 201–209.

Bos, M.G., Burton, M.A., Molden, D.J., 2005. Irrigation and drainage performance assessment - Practical guidelines. CABI Publishing.

Burt, C., Clemmens, A., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Eng. 123, 423–442.

Cammalleri, C., Anderson, M.C., Gao, F., Hain, C.R., Kustas, W.P., 2013. A data fusion approach for mapping daily evapotranspiration at field scale. Water Resour. Res. 49, 4672–4686. doi:10.1002/wrcr.20349

Cammalleri, C., Anderson, M.C., Gao, F., Hain, C.R., Kustas, W.P., 2014. Mapping daily evapotranspiration at field scales over rainfed and irrigated agricultural areas using remote sensing data fusion. Agric. For. Meteorol. 186, 1–11. doi:10.1016/j.agrformet.2013.11.001

Carlson, T., 2007. An Overview of the “Triangle Method” for Estimating Surface Evapotranspiration and Soil Moisture from Satellite Imagery. Sensors 7, 1612–1629. doi:10.3390/s7081612

Carlson, T.N., 2013. Triangle Models and Misconceptions. Int. J. Remote Sens. Appl. 3, 155–158.

Clemmens, A.J., 2006. Improving irrigated agriculture performance through an understanding of the water delivery process. Irrig. Drain. 55, 223–234. doi:10.1002/ird.236

Clemmens, A.J., Molden, D.J., 2007. Water uses and productivity of irrigation systems. Irrig. Sci. 25, 247–261. doi:10.1007/s00271-007-0067-y

Contor, B. a., Taylor, R.G., 2013. Why Improving Irrigation Efficiency Increases Total Volume of Consumptive Use. Irrig. Drain. 62, 273–280. doi:10.1002/ird.1717

Cuenca, R., Ciotti, S., Hagimoto, Y., 2013. Application of Landsat to Evaluate Effects of Irrigation Forbearance. Remote Sens. 5, 3776–3802. doi:10.3390/rs5083776

Frederiksen, H.D., Allen, R.G., 2011. A common basis for analysis, evaluation and comparison of offstream water uses. Water Int. 36, 266–282. doi:10.1080/02508060.2011.580449

Gao, F., Kustas, W.P., Anderson, M.C., 2012. A data mining approach for sharpening thermal satellite imagery over land. Remote Sens. 4, 3287–3319. doi:10.3390/rs4113287

Gleick, P.H., Christian-Smith, J., Cooley, H., 2011. Water-use efficiency and productivity: rethinking the basin approach. Water Int. 36, 784–798. doi:10.1080/02508060.2011.631873

Gonzalez-Dugo, M.P., Neale, C.M.U., Mateos, L., Kustas, W.P., Prueger, J.H., Anderson, M.C., Li, F., 2009. A comparison of operational remote sensing-based models for estimating crop evapotranspiration. Agric. For. Meteorol. 149, 1843–1853. doi:10.1016/j.agrformet.2009.06.012

Gowda, P.H., Chavez, J.L., Colaizzi, P.D., Evett, S.R., Howell, T. a., Tolk, J. a., 2008. ET mapping for agricultural water management: present status and challenges. Irrig. Sci. 26, 223–237. doi:10.1007/s00271-007-0088-6

Heermann, D.F., Solomon, K.H., 2007. Efficiency and uniformity, in: Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L. (Eds.), Design and Operation of Farm Irrigation Systems. ASABE, pp. 108–119.

Jensen, J.R., 2000. Remote sensing of the environment, 1st ed. Prentice-Hall, Inc., Upper Saddle River, NJ.

Jensen, M.E., 2007. Beyond irrigation efficiency. Irrig. Sci. 25, 233–245. doi:10.1007/s00271-007-0060-5

Kalma, J.D., McVicar, T.R., McCabe, M.F., 2008. Estimating Land Surface Evaporation: A Review of Methods Using Remotely Sensed Surface Temperature Data. Surv. Geophys. 29, 421–469. doi:10.1007/s10712-008-9037-z

Karimi, P., Bastiaanssen, W.G.M., Molden, D., 2013. Water Accounting Plus (WA+) - a water accounting procedure for complex river basins based on satellite measurements. Hydrol. Earth Syst. Sci. 17, 2459–2472. doi:10.5194/hess-17-2459-2013

Khan, S., Abbas, A., 2007. Upscaling water savings from farm to irrigation system level using GIS-based agro-hydrological modelling. Irrig. Drain. 56, 29–42. doi:10.1002/ird

Kjaersgaard, J., Allen, R., Irmak, A., 2011. Improved methods for estimating monthly and growing season ET using METRIC applied to moderate resolution satellite imagery. Hydrol. Process. 25, 4028–4036. doi:10.1002/hyp.8394

Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A., 2014. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. Agric. Water Manag. 146, 84–94. doi:10.1016/j.agwat.2014.07.012

Long, D., Singh, V.P., 2013. Assessing the impact of end-member selection on the accuracy of satellite-based spatial variability models for actual evapotranspiration estimation. Water Resour. Res. 49, 2601–2618. doi:10.1002/wrcr.20208

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agric. Water Manag. 97, 528–535. doi:10.1016/j.agwat.2009.03.023

Molden, D., Sakthivadivel, R., Perry, C., de Fraiture, C., Kloezen, W.H., 1998. Indicators for comparing performance of irrigated agricultural systems - Research report no.20.

Morton, C.G., Huntington, J.L., Pohll, G.M., Allen, R.G., Mcgwire, K.C., Bassett, S.D., 2013. Assessing Calibration Uncertainty and Automation for Estimating Evapotranspiration from Agricultural Areas Using METRIC. J. Am. Water Resour. Assoc. 49, 549–562. doi:10.1111/jawr.12054

Neale, C.M.U., Geli, H.M.E., Kustas, W.P., Alfieri, J.G., Gowda, P.H., Evett, S.R., Prueger, J.H., Hipps, L.E., Dulaney, W.P., Chávez, J.L., French, A.N., Howell, T. a., 2012. Soil water content estimation using a remote sensing based hybrid evapotranspiration modeling approach. Adv. Water Resour. 50, 152–161. doi:10.1016/j.advwatres.2012.10.008

Norman, J.M., Kustas, W.P., Humes, K.S., 1995. Source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature. Agric. For. Meteorol. 77, 263–293. doi:10.1016/0168-1923(95)02265-Y

Pereira, L.S., Allen, R.G., Smith, M., Raes, D., 2015. Crop evapotranspiration estimation with FAO56: Past and future. Agric. Water Manag. 147, 4–20. doi:10.1016/j.agwat.2014.07.031

Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manag. 108, 39–51. doi:10.1016/j.agwat.2011.08.022

Pereira, L.S., Oweis, T., Zairi, A., 2002. Irrigation management under water scarcity. Agric. Water Manag. 57, 175–206. doi:10.1016/S0378-3774(02)00075-6

Perry, C., 2007. Efficient irrigation; inefficient communication; flawed recommendations. Irrig. Drain. 56, 367–378. doi:10.1002/ird

Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. Agric. Water Manag. 96, 1517–1524. doi:10.1016/j.agwat.2009.05.005

Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manag. 80, 100–116. doi:10.1016/j.agwat.2005.07.007

Seckler, D., 1996. The new era of water resources management: From “dry” to "wet’ water savings (No. 1), Research Report. Colombo, Sri Lanka.

Senay, G.B., Leake, S., Nagler, P.L., Artan, G., Dickinson, J., Cordova, J.T., Glenn, E.P., 2011. Estimating basin scale evapotranspiration (ET) by water balance and remote sensing methods. Hydrol. Process. 25, 4037–4049. doi:10.1002/hyp.8379

Singh, R.K., Liu, S., Tieszen, L.L., Suyker, A.E., Verma, S.B., 2012. Estimating seasonal evapotranspiration from temporal satellite images. Irrig. Sci. 30, 303–313. doi:10.1007/s00271-011-0287-z

Thayalakumaran, T., Bethune, M.G., McMahon, T.A., 2007. Achieving a salt balance—Should it be a management objective? Agric. Water Manag. 92, 1–12. doi:10.1016/j.agwat.2007.05.004

Timmermans, W.J., Kustas, W.P., Anderson, M.C., French, A.N., 2007. An intercomparison of the Surface Energy Balance Algorithm for Land (SEBAL) and the Two-Source Energy Balance (TSEB) modeling schemes. Remote Sens. Environ. 108, 369–384. doi:10.1016/j.rse.2006.11.028

Tromboni, F., Bortolini, L., Martello, M., 2014. The use of water in the agricultural sector: a procedure for the assessment of large-scale irrigation efficiency with GIS. Irrig. Drain. 63, 440–450. doi:10.1002/ird.1833

van Halsema, G.E., Vincent, L., 2012. Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. Agric. Water Manag. 108, 9–15. doi:10.1016/j.agwat.2011.05.016

Zaccaria, D., Oueslati, I., Neale, C.M.U., Lamaddalena, N., Vurro, M., Pereira, L.S., 2010. Flexible delivery schedules to improve farm irrigation and reduce pressure on groundwater: a case study in southern Italy. Irrig. Sci. 28, 257–270. doi:10.1007/s00271-009-0186-8

CHAPTER III

THE ADAPTABILITY OF AN IRRIGATION DISTRICT TO SEASONAL WATER AVAILABILITY USING A DECADE OF REMOTELY-SENSED EVAPOTRANSPIRATION ESTIMATES[1]

Abstract

Water competition is increasing in highly populated areas especially those regions located in arid and semi-arid climates. Different water uses are examined to determine the potential for water savings. In particular, the agricultural sector is studied because it is the largest consumer of water. However, information is limited on the year-to-year variability of agricultural irrigation management, specifically the variability related to seasonal water availability. Remote sensing is a useful input into models to estimate actual evapotranspiration (ET) for large irrigation districts and provides an archive of historical data. A decade of remote sensing data is used applying the METRIC surface energy balance algorithm and a linear interpolation method to achieve seasonal ET estimates. Inter-annual variations in seasonal ET are related to snowpack, weather, irrigation diversions and crop data to understand the factors having an impact. It is found that consecutive (2nd) years of dry or wet events impacted the seasonal ET, indicating limitations in the buffer capacity of the irrigation district. Additionally, the other years showed better correlation between actual ET and snowpack data than with reference ET. Decisions made by farmers in the early growing season according to snowpack, might have a larger impact on actual ET than reference ET for most years. This study shows that the irrigation district is capable of adapting to extreme dry or wet events during the first year, but changes occur in seasonal ET during a consecutive year of extreme dry or wet weather. Additionally, cropping patterns indicate that the crop choices in the irrigation district do not change during extreme events.

---

[1] Co-authored with Dr. Christopher M.U. Neale and Dr. Lawrence E. Hipps

3.1 Introduction

Water scarcity and unreliability is a growing issue in several areas worldwide. Demands for water are increasing, driven by rapid population growth, high food demands, and climate variability. The agricultural sector is the largest consumer of fresh water supplies and is consequently affected by changes in water availability. In periods of extreme drought, regional water managers discuss water allocations and evaluate water use in irrigation areas (Rijsberman, 2006). However, there is a lack of insight in the irrigator decision-making during prolonged drought events. These individual irrigators are the end-users of the agricultural irrigation water and have an essential impact on the water use in agricultural areas (Lenton, 2014). Analysis of the spatial and temporal variability of water management is required to evaluate the operational and management decisions of the irrigation district. This is made possible with remote sensing, which is capable of distinguishing spatial diversity and offers an archive of historical data (Bastiaanssen et al., 2000). Crop evapotranspiration (ET) is a major component of the water balance therefore spatial estimates of ET gives crucial insight on the agricultural water management (Jensen, 2007). Remote sensing provides spatial information of large areas, which makes crop ET estimations at basin scale possible. Distinguishing inter-annual variations in seasonal crop ET increases our understanding of irrigators' responses to seasonal water availability.

One way crop ET is traditionally calculated is to use a reference ET value from a weather station multiplied with empirical crop coefficients reported in FAO 56 (Allen et al., 1998). This is a simple method for approximating crop ET and is useful for water managers and scientists alike (Pereira et al., 2015). Estimations of crop ET at the basin scale are commonly calculated using a traditional water balance approach. However, the accuracy of the results is determined by, among other things, the accuracy of the flow and rainfall measurements (Senay et al., 2011). Fortunately, recent decades have seen great improvements in estimating crop ET for large areas accurately by making use of satellite remote sensing data (Anderson et al., 2012). The great advantage of remote sensing methods compared to traditional methods is the incorporation of spatial variability in large areas, and the capability of representing actual ET conditions such as the influence of water stress on crops (Gonzalez-Dugo et al., 2009; Senay et al., 2011).

Traditionally the water stress is represented in the crop coefficient method with a stress factor k_s as presented by Allen et al. (1998). However, this requires information on the soil water balance for each field, whereas remote sensing indirectly incorporates this factor in the estimation of actual crop ET without needing a soil water balance.

Several methods exist incorporating multispectral and thermal bands from satellite imagery to estimate actual crop ET (Gowda et al., 2008; Kalma et al., 2008). One of these methods is the Mapping ET at high Resolution with Internal Calibration (METRIC) algorithm as published by Allen et al. (2011a, 2007b). The algorithm estimates three of the four surface energy balance terms, and calculates latent heat flux (i.e., ET) as a residual. METRIC applies an internal calibration using extreme pixels of well-irrigated and dry soil agricultural fields, to calculate the instantaneous ET (Allen et al., 2007b). This calibration approach requires less additional atmospheric data for running the model and is therefore widely used for estimating large scale crop ET in agricultural areas. For that reason it is well-suited for this study to estimate seasonal actual crop ET for a large agricultural irrigation district. However, it should be noted that remote sensing is not a measurement of ET, but makes approximations from observed radiation at different wavelengths to describe the atmospheric and surface interactions (Allen et al., 2011b). These estimations need to be validated with field measurements of ET such as eddy covariance data, which is a direct measurement of ET. There remains some uncertainty in the estimation of ET with remote sensing at a larger scale, which cannot be validated with point measurements.

Even though remote sensing methods for estimating ET in large areas have rapidly and vastly improved during the past decades, practical applications of remotely-sensed ET estimates are deficient. The studies making use of remotely-sensed ET to evaluate regional water balances and irrigation performance are limited (Taghvaeian and Neale, 2011). However, there is a considerable demand for applying the spatially distributed ET estimations into practical information, which can assist regional water managers. The 30 year database of remote sensing imagery can be used to aid in decisions regarding water allocations especially where competition for water increases due to limited water supplies (Anderson et al., 2012). Studies on multi-decadal vegetation indices derived from remote sensing have been reported. For example one study uses multiple decades of NDVI data to analyze the expanse of irrigated area for a region (Jordan and Barroll, 2013). Another study uses multiple years of remote sensing data to evaluate the irrigation performance of an agricultural area (Al Zayed et al., 2015), but have not related this information to weather or water variability.

Cycles of dry and wet years are evident in many regions including the Intermountain West. These cycles will be intensified or altered according to future climate scenarios. Regions, such as the Western US can expect earlier snowmelt and less accumulation of snow with an increase of temperature in the future. This will lead to less water available during the growing season and will impact mountainous areas (Barnett et al., 2005). The shift in water availability can be buffered by using reservoirs. Additionally, an irrigation system can have the capacity of buffering the impact of a change in water availability. Water can be stored as soil water storage, or water users can adapt by changing on-farm irrigation, cropping pattern, or water delivery scheduling. A study by Nam et al. (2015) analyzed the vulnerability of irrigation systems to future climate scenarios according to the capacity of reservoirs for irrigation in Korea. The results show that under future climate scenarios, irrigation districts will be more vulnerable and can be negatively impacted if measures are not undertaken. Another study in New Mexico analyzes certain operational changes made by farmers to cope with a decrease in water availability (Ward, 2014). Findings showed that irrigators typically apply less irrigation water and decrease irrigated area. Additionally, crop choices change to salt tolerant or low water use crops. Irrigation systems are designed with a certain capacity, but the operation of the system can vary greatly. These operational decisions can provide a buffer capacity to withstand a drought event up to a critical value. It is essential that agricultural areas improve irrigation performance and anticipate a change in water availability (Turral et al., 2010). Therefore, insight is needed on current adaptability to seasonal water availability areas to be able to make well-informed decisions for future scenarios.

This paper aims at identifying inter-annual variations of seasonal crop evapotranspiration (ET) in an irrigation district and relating these variations to weather conditions or management changes. Weather patterns affect ET through available water from snowpack stored soil water, atmospheric properties promoting and/or constraining the ET process, and local precipitation. Meanwhile, operational decision-making is characterized in this study as irrigation canal diversions and cropping patterns. Actual ET from an agricultural area in this study is computed from three components, reference ET (ET_r), crop coefficient (k_c) and a water stress factor (k_s) (Allen et al., 1998). The ET_r component is influenced by weather conditions. However the latter two components are influenced by a combination of weather conditions and management decisions. These three factors are evaluated at the irrigation system scale and therefore lumped to this spatial scale.

This paper is set-up in a threefold of objectives. Firstly, the seasonal actual ET is related to the seasonal weather conditions evaluating the snowpack, summer rainfall and reference ET. This comparison will indicate if seasonal crop ET is significantly influenced by weather conditions. Secondly, the variations of seasonal actual ET that are not explained by seasonal weather are compared to changes in cropping pattern or irrigation diversions to see if this explains the variation. Thirdly, the influence of drought events with varying severity and duration (number of years) is assessed to determine the system's capacity to adapt. The paper's objectives will be achieved using a decade of remote sensing data and multi-year weather variability also referred to as cycles of dry and wet years. The METRIC surface energy balance algorithm (Allen et al., 2011a, 2007b) is applied to attain instantaneous ET estimates, which are compared with measured field data from eddy covariance towers. Seasonal crop ET is estimated using a linear interpolation method between the satellite overpass days with METRIC estimated ET. This study gives essential insight to water managers regarding the influence of seasonal water availability on water management in agricultural areas and can assist with anticipating future irrigation trends under the influence of a changing climate.

3.2 Materials and methods

This study uses a decade of satellite-based remotes sensing from 2003 to 2014. The following sections provide a description of the study area and methodology used in this study.

Study area: the Bear River Canal Company (BRCC)

The area studied for this paper is an agricultural irrigation area located in Northern Utah (41˚42'N, 112˚9'W) and is managed by the Bear River Canal Company (BRCC). It is part of the Bear River basin, which is a river system flowing from the Uintah mountain range in Utah, continuing through Wyoming and Idaho back into Utah to the Great Salt Lake after a journey of 796 km (see Appendix A). The BRCC is one of the last users of the Bear River water before terminating in the Great Salt Lake. Irrigation water is diverted from the Bear River during the growing season from May to October and feeds a canal system (see Appendix D), which is partially lined. The area irrigated by the BRCC canal system encompasses 29,500 ha in total. The irrigators mainly use border surface irrigation, with the Bear River being the sole source of irrigation water in the canals. Main crops in this area are alfalfa (37.4%) and corn (16.7%) for forage; grain crops such as wheat (29.4%); and other smaller crops (see Appendix B). The main soil types in this area are silty clay to silt loam soils, with a few small areas of sandy loam soils (see Appendix C).

The BRCC is an ideal location for this study because it encounters several similar issues existing in other agricultural irrigation areas in semi-arid regions that depend on mountain snowpack for water. One major issue is that the irrigation water availability is largely dependent on the snowpack and timing of snowmelt in the mountains. The irrigation allocation is determined according to the water levels in the reservoirs and lakes of the Bear River system. Therefore, the irrigation diversions of the BRCC are sensitive to seasonal water availability and antecedent reservoir storage levels. Hence, findings from this study in the BRCC can potentially be relevant to several other large agricultural irrigation areas globally.

Local weather, snowpack and crop data

Weather conditions during the growing season were measured at a centrally located weather station (indicated in Appendix D) operated by the Utah Climate Center (www.climate.usurf.usu.edu). The data used from the weather station to represent seasonal weather conditions are: precipitation, average daily temperature and reference ET from a well-watered alfalfa field, which was estimated with the Penman-Monteith equation. This weather station started operations in early 2003 and a time-series dataset is displayed from 2003 till 2014, shown in Appendix E.

Irrigation areas dependent on mountain snowmelt, determine the seasonal water availability by the snowpack in the mountains during early spring (February to April). The snowpack and the level of water stored in the lakes and reservoirs, determine if the BRCC irrigation district can receive their full allocations of irrigation water. For this study the snow water equivalent (SWE) of the snowpack is noted at the end of each month for February to April, as was measured by the NRCS-USDA (www.nrcs.usda.gov) and shown in Appendix E. The snowpack data was measured at Tony Grove Ranger Station (40˚N 58’48’’, 110˚W 60’0’’), which is located in the mountain range that feeds the Bear River Basin (indicated in Appendix A). This station started measurements in 1924 and is therefore useful for a historical review of seasonal water availability for this region.

The variability of cropping patterns can potentially explain differences in inter-annual seasonal crop ET depending on decisions made by individual farmers. The acreage of each major crop in the irrigation district is determined for the years 2008 to 2014, as published by the USDA National Agricultural Statistics Service (www.nassgeodata.gmu.edu/CropScape/). This gives more detailed information of crop choices during the growing season, for instance choosing a short season crop (winter wheat) over a full season crop (corn).

Categorization of seasonal water availability

Seasonal weather data and a modified drought index are used to categorize the years into dry, wet and average years. Dry and wet years are frequently labelled by local water users, but a drought index is more useful for categorization as it is less subjective and can be calculated with weather data (Tsakiris et al., 2013). The Reconnaissance Drought Index (RDI) is considered the most applicable index for agricultural areas because it incorporates both ET and precipitation data (Tsakiris et al., 2007). It is additionally simple to apply because it does not require an extensive amount of data. A modified version of RDI is used in this study, which combines both the summer precipitation and snowpack data in the equation. The modified RDI is calculated according to equation 1. The summer precipitation and reference ET are summed for the growing season from March to October. The snowpack data is included as was measured in March at the Tony Grove Ranger Station (indicated in Appendix A). The snow measurement in March is chosen for the calculation of RDI, because it occurs mid-spring and is timed at the start of the growing season. This is not necessarily the peak snowpack as is shown in Appendix E in the snowpack data.

$$\text{Modified RDI} = \frac{\text{Total summer precipitation [mm]} + \text{Snow Water equivalent in March [mm]}}{\text{Total reference ET during growing season [mm]}} \quad (\text{eq. } 1)$$

Categories are formed by calculating the first quartile and third quartile of RDI values. All years with a lower RDI than the first quartile are categorized as a dry year. Those years with a RDI higher than the third quartile are categorized as a wet year. Those years falling in between the first and third quartile are categorized as an average year. This is a rational and simplistic method for categorizing the different seasons in dry, wet and average years. Additionally, the modified RDI values are solely applicable for the Bear River Canal Company irrigation area and therefore not an indication of regional climate patterns.

METRIC surface energy balance algorithm

METRIC is based on the principles of SEBAL (Bastiaanssen et al., 1998) and the triangle method (Carlson, 2007). This approach takes extreme hot and cold pixels from the satellite image that represents well-irrigated fully-covered agricultural fields or dry soil agricultural fields. It is assumed that both extreme conditions exist in the image, which is usually a valid assumption for irrigated agricultural areas (Gonzalez-Dugo et al., 2009; Gowda et al., 2008). Several guidelines are provided for selecting the extreme pixels correctly; however it remains a manual process and is influenced by user subjectivity. Nevertheless, the impact of the user was found not to be significant in a test reported by Gonzalez-Dugo et al. (2009), which compared the results from three users and did not find significant differences. A major advantage of METRIC is that it does not require accurate surface temperature estimations and thereby atmospheric corrections of the thermal band are not necessary (Allen et al., 2007b). It is mentioned by Kalma et al. (2008) that the accurate estimation of radiometric temperature is challenging, however an internal calibration process, such as METRIC utilizes, makes results less sensitive to the accuracy of temperature estimates. METRIC has been successfully applied in several agricultural water management studies using moderate resolution imagery (Allen et al., 2007a) and is therefore the fitting choice for this study.

An elaborate description, including the equations, of the METRIC algorithm is published by Allen et al. (2011a, 2007b) and in the annex of Singh et al. (2012). The basis is the simplified surface energy balance as given in equation 2, with Rn = net radiation, G = soil heat flux, H = sensible heat flux, and LE = latent heat flux, all calculated in W m^{-2}.

$$Rn = G + H + LE \qquad \text{(eq.2)}$$

The principles from SEBAL for estimating the heat fluxes are also used in METRIC, including the internal calibration method for estimating sensible heat flux (Bastiaanssen et al., 2005). METRIC differs from SEBAL in the definition of the cold pixel, with METRIC choosing this extreme condition in an agricultural field whilst SEBAL defines cold conditions in a body of water (Gowda et al., 2008). Additionally, daily ET values are calculated in SEBAL using the evaporative fraction (EF or Λ) and in METRIC by using the reference ET fraction (ET_rF) resembling the crop coefficient from FAO56. The METRIC algorithm was processed in this study by ERDAS Imagine 2013 using model maker tools and batch options for processing a vast amount of images. The different steps of this procedure are explained in Appendix E.

The METRIC algorithm has been applied and validated in several agricultural settings. Allen et al. (2007a) validated METRIC instantaneous ET estimates with lysimeter data from a forage crop field in Idaho. Results show an average error of 30% with the error being larger in the early and late growing season. Cuenca et al. (2013) compared Bowen ratio estimates with METRIC instantaneous estimates in an agricultural area located in Oregon. The average error was 11% with larger errors occurring in non-irrigated fields. Some level of error is unavoidable with ET estimations from remote sensing, or any measurement of ET. Allen et al. (2011b) estimates a typical error of remotely-sensed ET estimations to be at 10 to 20%. Seasonal error of ET may be reduced to a typical 1 to 5% due to the reduction of random error in the calculation of seasonal ET (Anderson et al., 2012).

Seasonal crop ET estimations

Seasonal crop ET estimations are the total ET during the crop growing season, which for this study was 15th April (day of year 105) to 15th October (day of year 288). The results from METRIC are instantaneous ET estimates at the time of the satellite overpass. However, seasonal ET estimates of an agricultural area are more relevant for evaluating the agricultural water consumption than instantaneous ET results. The instantaneous results from METRIC must be combined using interpolation between image days to achieve seasonal ET estimates. In METRIC an ET_rF value is calculated for each satellite image, which represents the ratio between instantaneous ET, as calculated with METRIC, and the reference ET (ET_r) as measured at the local weather station. This ratio is also known as the crop coefficient k_c as described by Allen et al. (1998) in FAO 56. The k_c curve for each crop is divided in three stages: initial, mid and end stage, with the mid growth stage being the peak of crop development. There are three interpolation methods generally applied for estimating seasonal ET, namely the fixed ET_rF, linear and curvilinear methods. The three interpolation methods have been shown to perform similarly with no significant differences, although the curvilinear method is slightly better (Singh et al., 2012). However, in this study the major crop of the irrigation district is alfalfa and therefore the curvilinear method is presumably less suitable for calculating the timing of cuttings. Hence a linear interpolation method is chosen in this study, which is applicable when sufficient images are available during the season.

The next step is to multiply daily ET_r values from the weather station with the predicted daily ET_rF values from interpolation. The data from a local weather station (indicated in Appendix D) is provided by the Utah Climate Center (www.climate.usurf.usu.edu). Daily crop ET values are summed for the growing season from mid-April to mid-October. Interpolation of the ET_rF values and the summation of daily ET values for seasonal ET were performed using R statistical software to automate and run the process for several seasons.

It is important to note that seasonal ET estimations are achieved using a limited amount of METRIC data and is mostly approximated with an interpolation method. The METRIC results provide estimates for ET_rF and instantaneous ET throughout the season at intervals. The advantage of these results is that the spatial variability within the irrigation district is captured. The estimations from METRIC therefore guide the interpolation process for estimating seasonal ET and provide intermittent information on crop development and crop stress.

Achieving good approximations of seasonal ET requires one satellite image per month to be available (Allen et al., 2007b). Fortunately, the study area was located within two path lines of the Landsat satellite, so a scene was potentially available every 8 days. However, in some years it still remained challenging to achieve sufficient cloud-free images for running METRIC. A list of the satellite images used for this study is given in Table 3-1. Landsat 5 TM and Landsat 8 OLI/TIRS were chosen as suitable platforms. Neither platform was available in the 2012 growing season; therefore that year was excluded from the analysis. Other platforms, such as Landsat 7 ETM+, were available during the 2012, but were not used for consistency. Both Landsat 5 TM and Landsat 8 OLI/TIRS produce moderate resolution imagery with the thermal layer being 120m or 60m, respectively. This pixel size is well-suited for evaluating an agricultural irrigation area due to the large size of farm fields in the Western US (Anderson et al., 2012).

Eddy covariance field experiment and data analysis

The crop ET estimates calculated from METRIC are compared with ground measurements from an eddy covariance tower, which is considered to be the current ‘gold’ standard for directly measuring ET. This comparison indicates if the results from METRIC are consistent and if there is a general over- or underestimation in crop ET.

Eddy covariance towers were installed in the 2013 growing season in three different sites: wheat, corn and onion fields. Wheat and corn are both major crops in this irrigation district (see Appendix B). Measurements coinciding with satellite overpass were used for analysis for comparison with METRIC results. The towers measured the entire surface energy balance: net radiation, soil heat flux, sensible heat flux, and latent heat flux. Net radiation was measured with a Q6 net radiometer (Campbell Scientific, Inc.), which was cross-calibrated in a grass field with a CNR2-L (Kipp & Zonen, Inc.) to correct for a linear offset in Q6 measurements. Soil heat flux was measured with two REBS HFT3-L (REBS Inc.) heat flux plates at

Table 3-1.

List of Landsat satellite images used in this study.

Growing season	Landsat platform	Days of year for image acquisition	Total number of images
2003	Landsat 5 TM	101, 133, 140, 156, 165, 181, 188, 204, 229, 261, 277, 284	12
2004	Landsat 5 TM	095, 127, 136, 159, 168, 191, 216, 255, 280, 287	10
2005	Landsat 5 TM	106, 145, 170, 177, 186, 193, 202, 218, 241, 257, 273	11
2006	Landsat 5 TM	116, 132, 141, 157, 164, 173, 221, 228, 244, 253, 269, 285	12
2007	Landsat 5 TM	096, 128, 160, 176, 183, 199, 224, 240, 263	9
2008	Landsat 5 TM	131, 138, 170, 179, 195, 211, 227, 234, 259	9
2009	Landsat 5 TM	149, 181, 188, 197, 213, 252, 261	7
2010	Landsat 5 TM	136, 191, 200, 223, 232, 248, 255, 264, 271, 287	10
2011	Landsat 5 TM	091, 178, 194, 203, 210, 226, 235, 258, 274	9
2013	Landsat 8 OLI/TIRS	135, 144, 151, 160, 167, 183, 199, 215, 240, 247, 279	11
2014	Landsat 8 OLI/TIRS	147, 186, 195, 227, 259, 266, 282	7

* TM = Thematic Mapper; OLI = Operational Land Imager; TIRS = Thermal Infrared Sensor

a depth of 0.08 m at each system. In furrow-like systems such as the corn and onion fields, the heat flux plates were placed in both the furrow and in the crop bed. The plate heat fluxes were corrected for volumetric water storage in the soil, measured by a CS616-L reflectometer, and temperature in the layer of soil above the plates measured by TCAV-L soil thermocouples (Campbell Scientific, Inc.). The 3 components of wind were measured with a CSAT3 sonic anemometer (Campbell Scientific, Inc.), and the water vapor density fluctuations were measured with a KH20 krypton hygrometer (Campbell Scientific, Inc.). Both of these sensors were sampled at 20 Hz. Additionally, the towers were equipped with a solar panel, a CR1000 or CR5000 datalogger (Campbell Scientific, Inc.) and HMP45C-L temperature and humidity sensor (Campbell Scientific, Inc.). The Q6 net radiometer, CSAT and KH20 were placed at 2.5 m above the ground in the wheat and onion fields, and 7m above the ground and 3.5 m above the top of canopy for the corn field. All three flux towers were located in the north eastern corner of the field, because the wind direction was mainly from the southwest.

The data from the CSAT and KH20 were collected at 20 Hz frequency. The high frequency dataset was filtered for spikes using our own software modeled after known procedures for cleaning high frequency datasets (Aubinet et al., 2012; Hojstrup, 1999). Additional corrections included coordinate rotation, sensor separation, path length effects, frequency response, and effects of water vapor density and attendant small vertical velocity (aka Webb-Pearman-Leuning). Equations and procedures for the above corrections are found in Foken (2008) and Massman and Lee (2002). Finally, spectral analyses of the time series data were applied for representative periods to verify turbulence scaling properties of the boundary layer, such as the -5/3 law from Komogorov Similarity Theory.

The corrected data-set was used for calculating the fluxes for all times of day, but only daytime hours were used in this case, since ET is near zero at night. The combination of eddy covariance and available energy measurements yielded all four terms of the energy balance. This allowed a check on closing the balance, or determining how close the values matched eqn. 1. Forced closure of the energy balance was done by assuming the ratio of sensible to latent heat fluxes was correct, and adding to the fluxes in proportion to this Bowen ratio to match the available energy. This was done due to the known underestimation of the sensible and latent heat flux components of eddy covariance systems (Twine et al., 2000).

The eddy covariance data is compared with instantaneous ET estimates from METRIC using the root mean squared error (RMSE), squared bias (SB) and coefficient of determination (r^2) according to equations from Kobayashi and Salam (2000).

Irrigation system performance indicator

The operations of an irrigation system can also be indicated by decisions in irrigation diversions and performance indicators. These aspects can potentially explain part of the inter-annual variability in seasonal crop ET. Several performance indicators are used to evaluate and monitor the irrigation system, which consider either the volumetric water balance, or the quality of water delivery (Bos, 1997). In this study the irrigation system is defined as the physical canal network used for conveying the irrigation water from the diversion point to the farm fields. Evaluating and monitoring the performance of the irrigation system is necessary to determine the adequacy of the water delivery. However, in practice the water delivery is seldom monitored and rarely adapts to the fluctuations between wet and dry years (Jensen, 2007).

For this study, irrigation diversion data is provided by the BRCC and USGS (waterdata.usgs.gov). Measurements of the diversions commenced in 1912 but include a few gaps of data, including the 2011 season, which is excluded for analysis. The diversion data is used in combination with the seasonal actual ET estimates and precipitation data to evaluation the irrigation system performance. This is assessed using the depleted fraction as described by Bos et al. (2005) and shown in equation 3. This performance indicator gives insightful information for regional water managers on the year-to-year variability of water consumption in an agricultural irrigation area. The critical value for depleted fraction is considered to be 0.6 for large scale canal systems, but can fluctuate between 0.55 and 0.7 (Bos, 2004). Performance less than 0.6 indicates that water is going to groundwater storage, whilst performance higher than 0.6 indicates that additional water is required from diversions to feed the canal system and ensure adequate water delivery (Bos et al., 2005). This also indicates that a depleted fraction of 1 is not desirable, because water stress is likely occurring in the irrigation district.

$$\mathrm{DF\ (depleted\ fraction)} = \frac{\mathrm{Actual\ evapotranspiration\ ET_a}}{\mathrm{Precipitation + Irrigation\ diversions}} \qquad (\mathrm{eq.\,3})$$

3.3 Results and discussion

Categorization of wet, dry and average years

The different growing seasons were categorized in dry, wet and average years using the RDI (Reconnaissance Drought Index) and are presented in Table 3-2. In this time frame several wet and dry years occurred, but remained no longer than 2 years.

Some basic weather data are shown in Table 3-2 to provide insight on the conditions during the growing season. The reference ET during the growing season varies for each year. In general, the higher reference

ET values were found in the dry years, with the exception of 2014 which is categorized as a wet year. This year is characterized by warmer spring weather and then exceptional rainfall during the latter part of the growing season, according to weather observations in Table 3-2 and the time series data in Appendix E.

The average temperature during the peak of the growing season was generally higher for dry years compared to wet or average years. The temperature during the spring months is more variable. Average temperatures below 10˚C were only observed during wet or average years.

Snowpack as measured in March was below 200 mm for all dry years. Higher values for snowpack were only measured in wet or average years. Also high values for precipitation during the growing season were mostly observed in wet years or average years.

Table 3-2.

Categorization into dry, wet and average years from snowpack data, and additional local weather data.

Year	**April - September**		**Jun-Aug**	**Apr-May**	**SWE in March [mm]**	**RDI [-]**	**Category**
	ET_r sum [mm]	**Precipitation sum [mm]**	**Average temperature [˚C]**	**Average temperature [˚C]**			
2003	1078	119	22.6	11.1	152	0.25	dry
2004	978	85	20.7	11.3	150	0.24	dry
2005	962	290	20.6	7.6	338	0.65	wet
2006	1041	104	22.3	12.4	399	0.48	wet
2007	1107	97	22.9	12.1	46	0.13	dry
2008	1056	92	21.2	9.5	396	0.46	average
2009	1007	217	20.2	11.3	262	0.47	average
2010	1042	91	20.7	9.1	226	0.30	average
2011	971	240	20.9	8.6	536	0.80	wet
2012	1127	85	22.5	12.3	196	0.25	dry
2013	996	78	22.5	10.5	152	0.23	dry
2014	1095	182	21.1	11.5	376	0.51	wet

^ Snow Water Equivalent

* Modified RDI (Reconnaissance Drought Index) using a combination of summer precipitation and snowpack

METRIC validation with eddy covariance data

During the 2013 growing season data were collected at three eddy covariance towers. The instantaneous and daily ET estimates from METRIC were compared with those measured at the eddy covariance towers at the given days of satellite overpass. Results of this comparison are shown in Figures 3-1 and 3-2, indicating the 1:1 line and the different crop fields the data were taken from. The daily ET values from the eddy covariance systems were increased to force closure of the energy balance.

Figure 3-1 indicates the instantaneous ET comparison and shows a slightly negative overall bias. There is a larger bias from the 1:1 line for the lower ET values associated with the onion crop measurements. The onion crop is a row crop in contrast with the wheat and corn fields, which are more homogeneous. Therefore, more errors in the measurement of the different energy balance components might occur. The soil heat flux is measured by two plates with one located in the furrow and the other in the crop row. Additional heat flux plates might be needed to represent the heterogeneity of the soil heat flux better. However, inaccuracies might also lie in the observations by the satellite, which does not have a sufficient spatial resolution to distinguish between the different row crops with pixel size being 60 m for the thermal band. The correlation coefficient and RMSE of 0.07 mm hr^{-1} show that the comparison of eddy covariance and METRIC data is overall a reasonable good fit. Additionally, obvious over- or underestimation is not observed in these results.

Figure 3-2 shows the comparison of daily ET as estimated by METRIC with the daily ET as measured at the eddy covariance system using forced closure. The overall bias is relatively low, but slightly negative. There is a better overall resemblance with the 1:1 line compared to Figure 3-1. However, there is more scatter in Figure 3-2 at all values except high ET values. The RMSE error in this case was 0.56 mm d^{-1} and the correlation coefficient shows a reasonable correlation, which is slightly lower than for instantaneous ET values.

METRIC results

After conducting and evaluating the comparison of METRIC estimates with the eddy covariance measurements, the METRIC algorithm was applied to the other growing seasons from 2003 to 2014. The

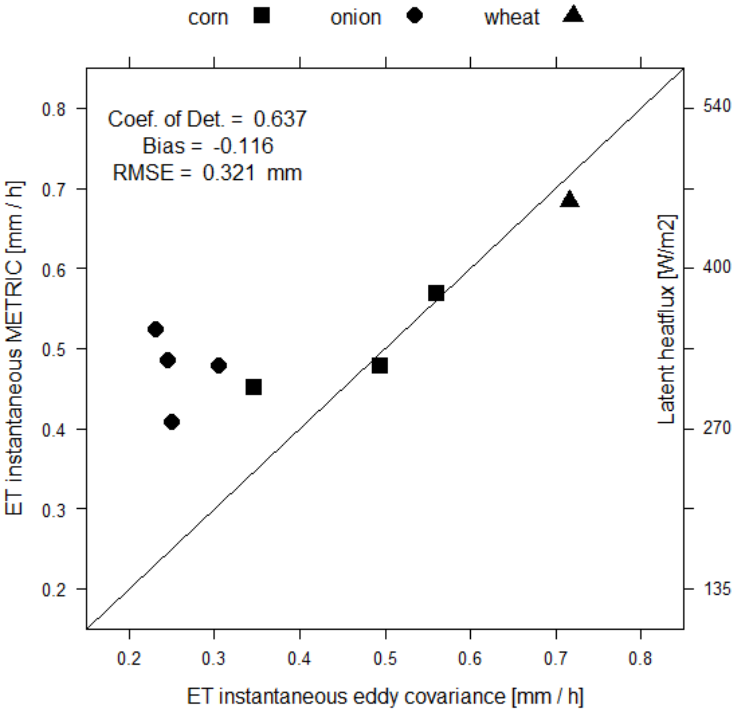


Figure 3-1. Comparison of instantaneous ET from the unforced eddy covariance data with METRIC estimates from the 2013 growing season.

results from METRIC give instantaneous ET results at the time of satellite overpass. Daily ET values are found through interpolation of instantaneous ET with ETrF values. Two images are shown as an example of the METRIC results in Figure 3-3, from 2004 and 2011 during early August. The season 2004 is a dry year whereas 2011 is a wet year, as indicated by Table 3-2. The results for 2004 show lower ET values throughout the irrigation district, whilst 2011 shows higher ET values. Additionally, the results of METRIC for the 2004 image indicate that lower ET values are evident in areas further away from the diversion point (located North East of the image, indicated in Appendix D). The Western and Southern areas are more concentrated with lower ET values, indicating that water stress might be occurring. It was also indicated by local farmers that end users of the canal water experience inconsistent water delivery due to the lengthy canal system of this irrigation district

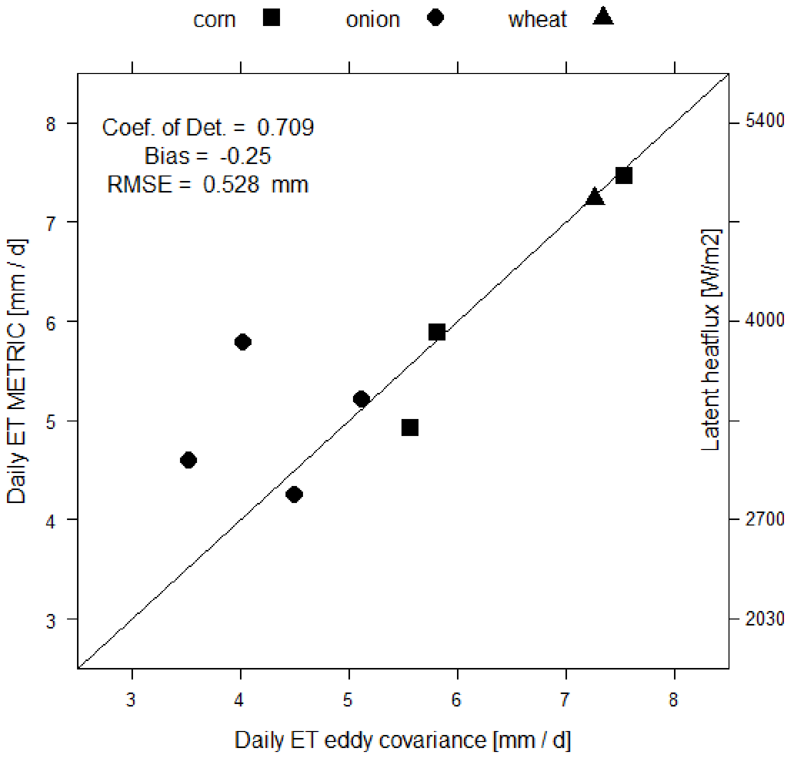


Figure 3-2. Comparison of daily ET as measured at the eddy covariance tower with forced energy balance closure, and METRIC estimates.

<u>Seasonal crop ET estimations from METRIC</u>

The results from the linear interpolation are shown in Figure 3-4, indicating the total seasonal actual ET for the whole agricultural area managed by the BRCC. The average seasonal actual ET of all the years included in this study, is 737 mm as indicated in Figure 3-4 by the dashed horizontal line. The years are categorized into dry, wet and average years according to the categorization given by Table 3-2. Additional information regarding weather conditions during the growing season is also provided in Table 3-2 and gives some necessary insights for describing certain variations in seasonal ET as presented in Figure 3-4.

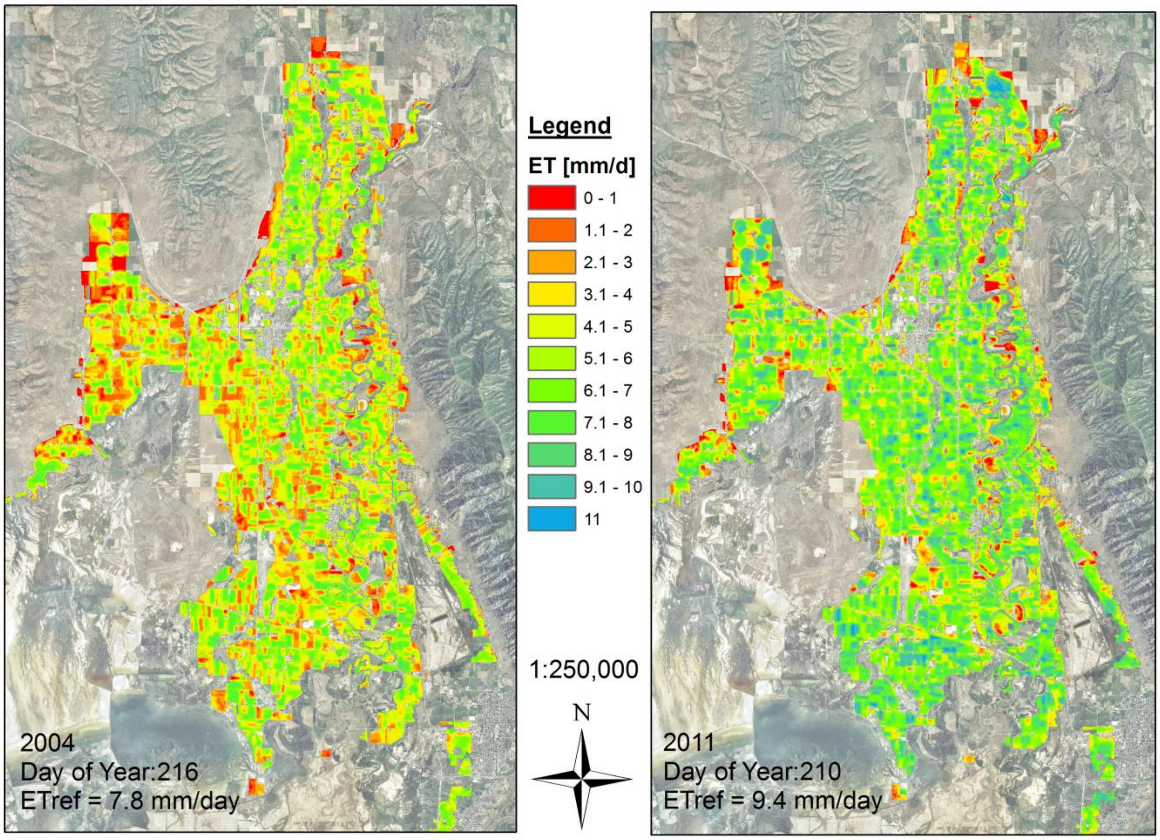


Figure 3-3. Results of daily actual ET from METRIC for the two satellite overpass days.

Figure 3-4 shows that average years display an average or above average seasonal actual ET. Both 2009 and 2010 show above average seasonal ET in Figure 3-4, whilst 2008 is close to the mean ET of 737 mm.

For dry years, Figure 3-4 indicates a large variability between the different seasons examined in this study. The seasons of 2003 and 2007 show well above average seasonal ET, whilst 2004 and 2013 are well below average. In fact, 2007 (dry year) had the largest ET value. The seasonal actual ET only decreased during the second year of drought in both cases of 2004 and 2013 (with 2012 and 2003 being a dry year, but 2012 has no results). The first year of drought was possibly provisioned by water in the reservoirs and lakes of the Bear River, whilst the consecutive year of drought the reservoir water levels had decreased and water allocations were not fully granted, as was mentioned by the canal company. The seasonal ET values during 2003 and 2007, the first dry years, are exceptionally high due to the high reference ET reported in Table 3-2. The crop water demands are high, and irrigation water was not limited in those seasons therefore seasonal crop ET is well above average. Reference ET was lower for the years 2004 and 2013, which are the second dry years and display a lower seasonal ET value in Figure 3-4. Possibly part of the lower ET value can be attributed to the lower reference ET. However, the seasonal ET shown in Figure 3-4 is considerably lower than the other years having low reference ET. Therefore, the water stress factor from limited water supplies might be an explanation for that difference.

During wet years, all the seasonal actual ET estimates were lower than or at the average 737 mm despite water availability being abundant. Two main factors can clarify this result for three wet years, but not the 2006 season. Firstly, colder temperatures are observed during the spring of the growing season as was indicated in Table 3-2. This causes delays in the growth of certain crops and some farmers might do certain activities later under warmers temperatures, such as sowing and wetting the root zone with the first irrigation. The second reason is that reference ET during the growing season was lower for some of the wet years as is indicated in Table 3-2. However, these explanations are not valid for the 2006 season and also not as obvious for the 2014 season. Additionally, the seasonal actual ET of 2006 is considerably lower than the other wet years according to Figure 3-4. There is no obvious explanation that can be derived from the weather conditions in Table 3-2 to clarify the lower seasonal actual ET of the 2006 season. It is however a second wet year, so potentially some operational decisions were made as a consequence, similar to the second dry years.

The seasonal actual ET results are examined more closely by dividing the growing season into three periods: early, mid and late season. The periods are from 15th April to 15th June for early season; 16th June to 15th August for mid-season; and 16th August to 15th October for late season. These divisions represent the various cropping patterns in the BRCC with early season growing mainly wheat and alfalfa crops; late season growing mainly alfalfa and corn; and mid-season being the peak of the growing season with all crops growing. Results for actual ET according to period and categorized in average, dry and wet years, are shown

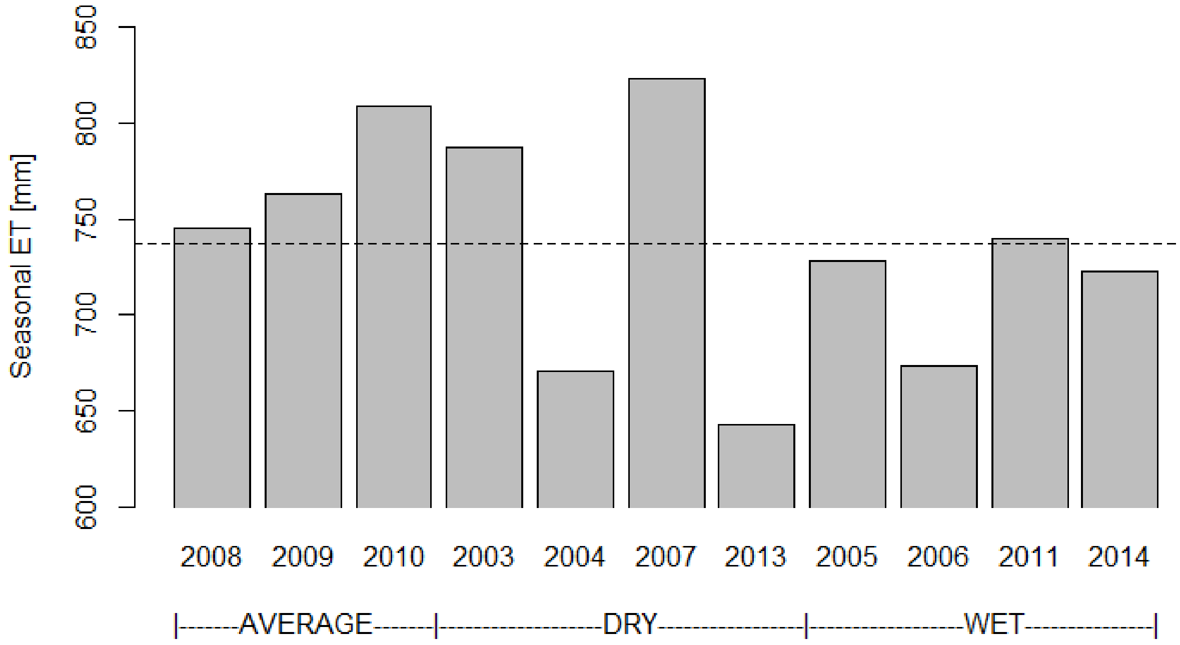


Figure 3-4. Total seasonal actual ET estimations from linear interpolation between METRIC estimated instantaneous values categorized in average, dry and wet years including the average of all 11 years indicated with a dashed line (=737 mm).

in Figure 3-5. Additionally, dry years are sub-divided into first and second dry years to examine the effects on consequential dry years better due to the large variability within the dry year category. Mean values for each sub-season are indicated by the dotted horizontal line and are 205 mm, 340 mm, and 190 mm for the early, mid, and late season, respectively.

Figure 3-5 shows that the average years have less variability in each season and especially in the late season. Furthermore, for the early and mid-seasons the estimated ET during average years was close to the mean value. During the late season the average year displayed a higher ET than the mean value. It is expected that average years are more consistent considering the lack of an extreme event.

During dry years the mean ET results are similar to those of the average years with the exception of the late season, which displays a lower ET compared to the average. However, large variability is displayed in Figure 3-5 for the dry year category due to the difference between a first and second dry year as was indicated in the discussion of Figure 3-4. First dry year events show well above average ET during the early and mid-season, and the late season actual ET is at the mean line. The high ET during the early and mid-season is associated with the high potential reference ET as shown in Table 3-2. In combination with unlimited water supply, the ET is expected to be higher because water stress is not occurring. In addition, a dry year usually has a shifted peak of cropping patterns compared to an average year due to the warmer temperatures in early spring, resulting in crops being grown earlier in the season. The second dry year displays well below average values in Figure 3-5 for the early, mid and late seasons. Limited water availability during a second dry year causes a lower ET throughout the season. Either cropping patterns were changed or water stress is occurring due to less frequent irrigation events being possible.

Figure 3-5 shows that during wet years the ET is usually close to the mean ET of all years. The variability in ET is relatively small for each season except the late season, which displays a larger variability. This might indicate a difference in crop growth stages. According to Table 3-2, wet years differ in magnitude of early season average temperature. The onset of warmer temperatures triggers the start of the growing season. Therefore, the differences in temperature cause a different timing in growth peak of the crops. This becomes apparent in the late season ET variability for wet years, with some crops still at full growth whilst some other crops are senescing or harvested.

Seasonal ET can be related to several weather conditions such as reference ET, precipitation during the growing season, and water availability from the mountain snowpack feeding the reservoir. These factors have all shown to have an amount of influence on seasonal ET as is indicated in the discussion so far. The weather conditions as stated in Table 3-2 have provided some explanation for the results of seasonal ET shown in Figures 3-4 and 3-5. However, the degree of impact of each weather condition is vague. Figure 3-6 displays the relationship between each weather condition to seasonal ET by presenting the correlation. It distinguishes between using data of all years, and excluding a 2nd year of an extreme event (i.e., 2004, 2006

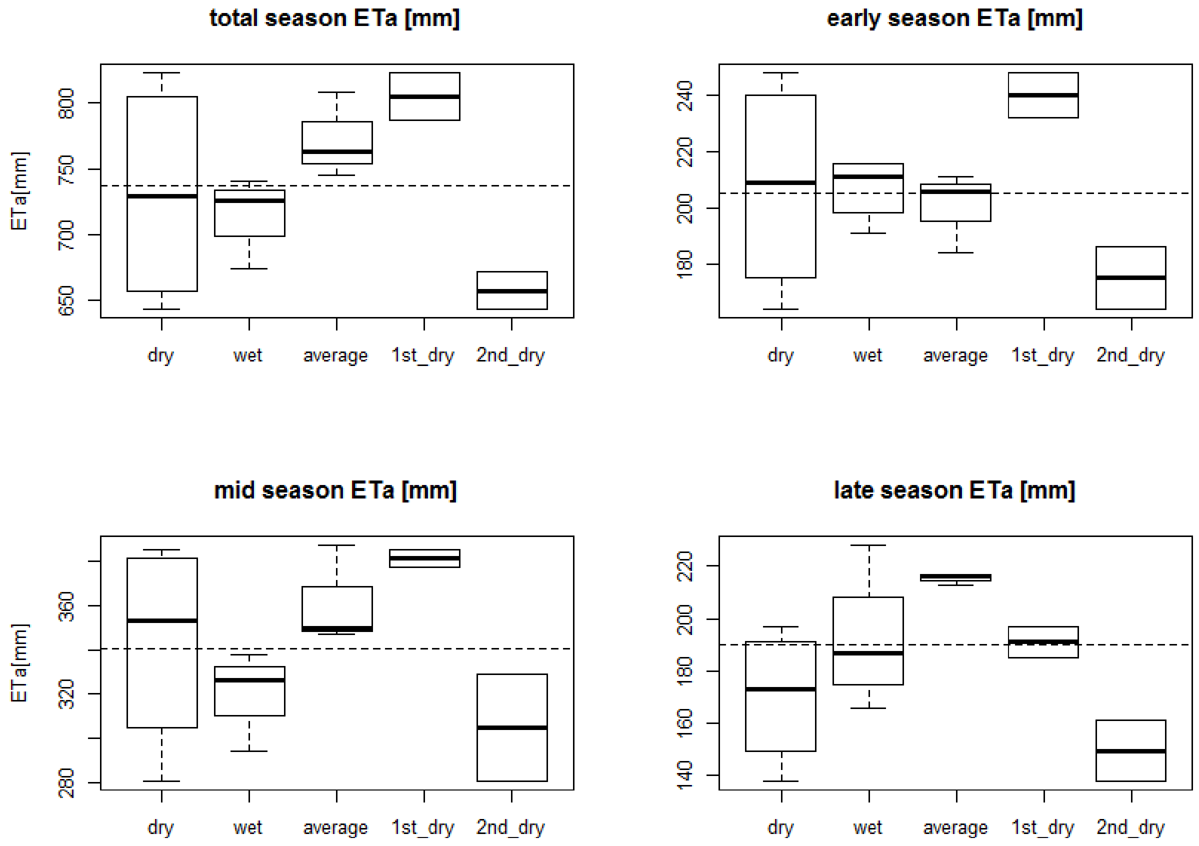


Figure 3-5. Seasonal actual ET divided into early, mid and late season using METRIC data for 2003 to 2014, with mean values indicated by the dotted horizontal line.

and 2013). This information provides insight on the weather aspect and their influence on the seasonal actual ET.

Figure 3-6 shows that the data from the first column, indicating data from all years in this study, has no significant correlation with the different weather conditions. The graphs relating seasonal actual ET with summer precipitation, snowpack and RDI lack any correlation. This demonstrates that these weather aspects and drought index do not explain the actual ET occurring in an irrigation district for each year. The reference ET shows a better correlation r^2=0.21 with seasonal ET, but not strong. This is expected because actual ET is directly related to reference ET with the k_c and k_s value differing. Apparently, these crop coefficients have a large variability therefore there is a lack of a consistent relationship between reference and actual ET. The crop choice, growth periods or water stress factor might be contributing to these differences.

Figures 3-4 and 3-5 indicated that 2nd years of either a dry or wet event display a difference in seasonal ET compared to the first year of an extreme event. Therefore, the second column in Figure 3-6 excludes the data from these years and shows great improvements in the correlation with weather conditions. The seasonal ET is best correlated with snowpack data and the RDI. The latter is a combination of precipitation, snowpack and reference ET. This indicates that snowpack as measured in March can potentially already predict the seasonal ET of the coming growing season in average years and the first year of dry or wet periods. The seasonal ET was more correlated with snowpack data than with reference ET data. An explanation for this is that snowpack measurements in spring determine a number of management decisions that farmers make at the start of the growing season. However, this should be further investigated with additional seasons of data.

The exclusion of 2nd dry and wet years from Figure 3-6 gave better correlations. This indicates that seasonal actual ET does not follow a similar pattern during 2nd years of extreme event compared to the other years of data. The three years excluded from the second column (2004, 2006, and 2013) was not sufficient to find any pattern. Additional seasons of 2nd (or more) extreme event events are required to analyze the impact of weather conditions on these years.

Seasonal crop cover

In the previous section estimations of seasonal ET were analyzed and explanations were proposed. Most of these explanations relate to weather conditions during the season or snowpack accumulated in the spring. However, the discussion of Figure 3-6 indicates that weather conditions do not explain the value of estimated seasonal ET during 2nd years of an extreme event. Therefore, explanations may be found in the management decisions typical for these years. One of these operational decisions is the cropping pattern during average, dry and wet years. The crop acreage for the major crop types is shown in Figure 3-7, displaying the results from several years examined in this study. The acreage for wheat crops is very consistent for each year varying between 28 and 29% of the total cropland. Winter wheat is planted at the end of fall during the previous season, therefore farmers cannot anticipate the seasonal water availability in the next year. The acreage of alfalfa varies between 37 and 43%, with the lowest acreage occurring in a dry year. Alfalfa is a high water-consuming crop therefore it is a better decision to change this crop to a low water-consuming crop during a dry year. However, no obvious patterns can be distinguished between the other years. The area farmed for corn seems to be similar in the latter three years. During 2008, more pasture was farmed than corn, but after this year there is a gradual increase of growing corn. Farmers testified during interviews that they grow less late season crops such as corn during a dry year due to water allocations running out at the end of the season. However, this information is not observed in the data from Figure 3-7.

The acreage of corn is similar during the 2013 dry year compared to the other years. Possibly, the majority of the farmers prefer using the warm early spring occurring during a dry year to grow corn early or choose other crops that have a longer growing season. Overall, the differences between years are not distinct and do not indicate a significant seasonal change in cropping pattern.

No obvious patterns are observed in Figure 3-7, but it is difficult to observe changes with a small set of data. More years are necessary to represent the diverse management occurring in the irrigation district. In addition, several factors influence the farmer’s decision in crop choices. Seasonal water availability might be of influence but other aspects are considered too, which causes variability.

Irrigation diversions

A third explanation given to clarify trends in season crop ET results, aside from weather patterns during the growing season (summer rainfall and potential ET) and cropping patterns, was the differences in water allocations during dry years compared to full allocations usually granted in average or wet years. Figure 3-8 indicates historical data of the annual canal diversions and snow pack during the past century.

The canal diversion data shows an overall increasing trend during the past century according to Figure 3-8. Presumably, the irrigation district expanded the irrigated cropland and experienced less competition

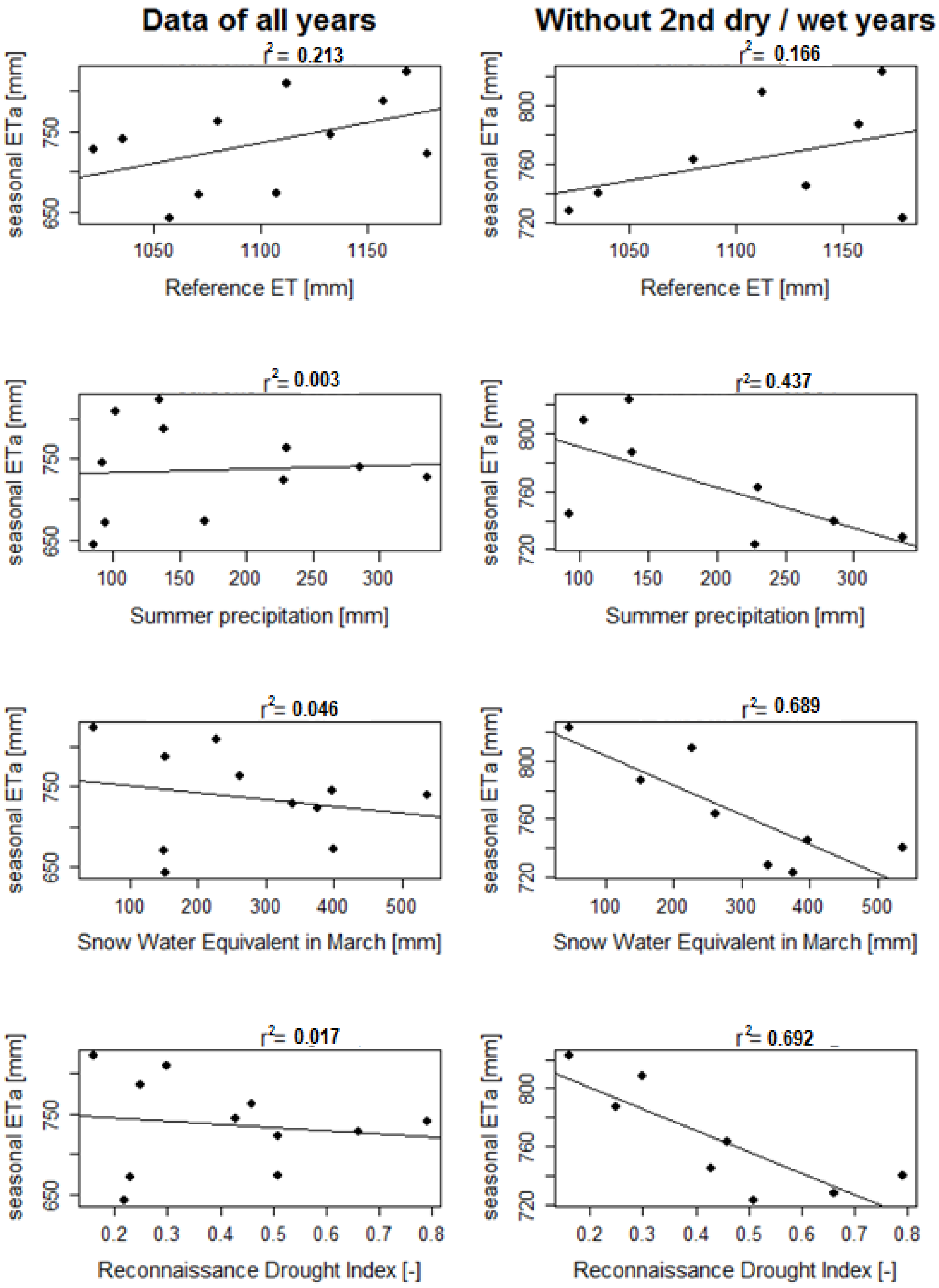


Figure 3-6. Correlation between seasonal ET and weather conditions for all years processed (1st column) and excluding consecutive (2nd) years of an extreme dry or wet event (i.e. 2004, 2006 and 2013 (2nd column)).

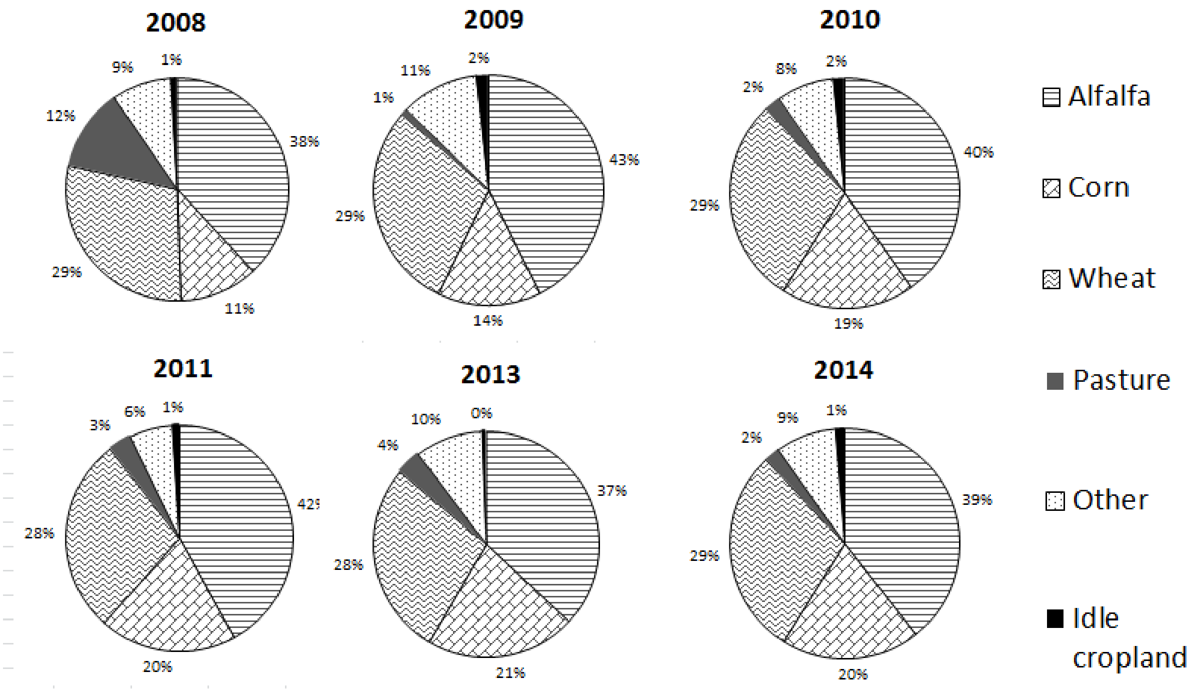


Figure 3-7. Crop acreage for the major crop types of the irrigation district, according to USDA-NASS data.

over water supplies with other users, due to low population density in the region. However during the past decades, the irrigation diversions show no pattern of gradual increase, indicating a stationary signal of water allocation. There are, however, a few cycles of upward and downward periods in irrigation diversions observed in Figure 3-8, apparently related to variations in climate. The most recent reduced water period occurred between 2000 and 2004, which coincides with consecutive dry years due to low snowpack amounts. Another downward event is observed at 1991 to 1993, which again is simultaneous to previous years of low snow pack amounts. The third distinct downward event is shown between 1980 and 1984, which is preceded by a few wet years, but followed by an extreme low snowpack in 1981. Overall, this plot indicates that diversions are influenced mainly by dry events that vary in duration or severity. This indicates that irrigation diversions are not highly sensitive to snow pack, but are only impacted during a build-up of dry years or an extreme low snowpack year. The reservoirs and lakes supplying the irrigation water decrease the sensitivity of diversions to water availability and are an important buffer for this region. This affects the capacity of a region to buffer consecutive dry years. This will give valuable knowledge of the amount of dry years required to have a major impact on the irrigation district.

Depleted fraction

The last step is to bring the different results of actual crop ET and irrigation diversions together to calculate the irrigation system performance. Using the depleted fraction to evaluate the irrigation system performance gives valuable insight for the local irrigators and also to regional water managers.

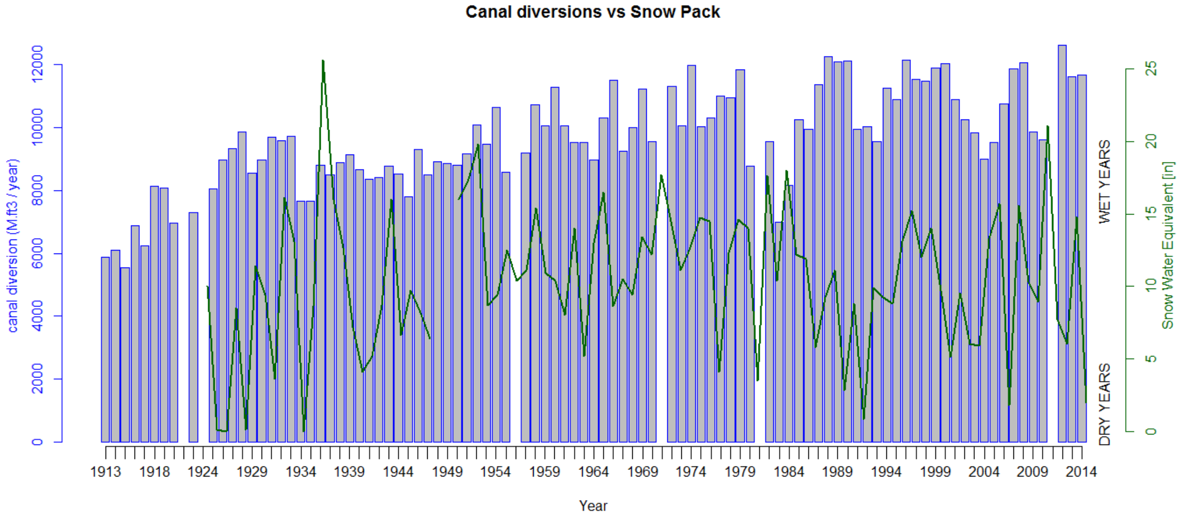


Figure 3-8. Canal diversion data of the BRCC and snow water equivalent data for a 100 year period.

The depleted fraction combines the diversion data and seasonal actual ET from the linear interpolation method assisted with METRIC instantaneous ET estimates. In addition, summer precipitation is included in the calculation of the depleted fraction, which contributes to the water available for the crops during the growing season. The results for depleted fraction are given in Figure 3-9 for the different years the seasonal actual ET was calculated for in this study. The 2011 season is excluded from this figure due to measurement disruptions occurring at the diversion point throughout the majority of the growing season.

Recall, the critical value for the depleted fraction is 0.6, above which crop water requirements are potentially not fulfilled (Bos et al., 2005). Lower than 0.6 values indicate that water is being stored in the groundwater or lost to runoff for downstream water users. Figure 3-9 indicates that most of the dry years are above the 0.6 critical threshold, which is expected due to the high crop water demands and less summer rainfall occurring as was reported in Table 3-2. This indicates that water stress might be occurring at different locations in the irrigation system due to the high water demands. There is no obvious difference observed between first (2003 and 2007) and second dry years (2004 and 2013). The 2013 growing season has a lower depleted fraction than any of the other growing seasons. This coincides with the year of management changes in the canal company, so operations might have been different.

The wet years display values lower than the 0.6 threshold, thus indicating that sufficient water is being supplied to the fields but some of the water is underused. During the wet years summer precipitation is typically higher than the other years as indicated in Table 3-2. However, the irrigation diversion presumably does not adapt, which was also indicated by local water managers. During a precipitation event less stress is put on the water delivery schedule, but the schedule remains unchanged.

The average years indicate a large variety in depleted fraction, which is potentially connected to other factors than the seasonal water availability. The 2010 season shows a higher depleted fraction than the other average years. This is probably explained by the extremely low summer rainfall occurring during that growing season, as is indicated by Table 3-2. The other two average years, 2008 and 2009, are close to the average depleted fraction.

Overall, the performance of the irrigation district is commendable with an average depleted fraction during the past decade of 0.63. Presumably neither substantial crop water stress nor water losses are occurring when the entire period is integrated. However, the scatter can be more balanced to store water during wet years and make better use of summer precipitation.

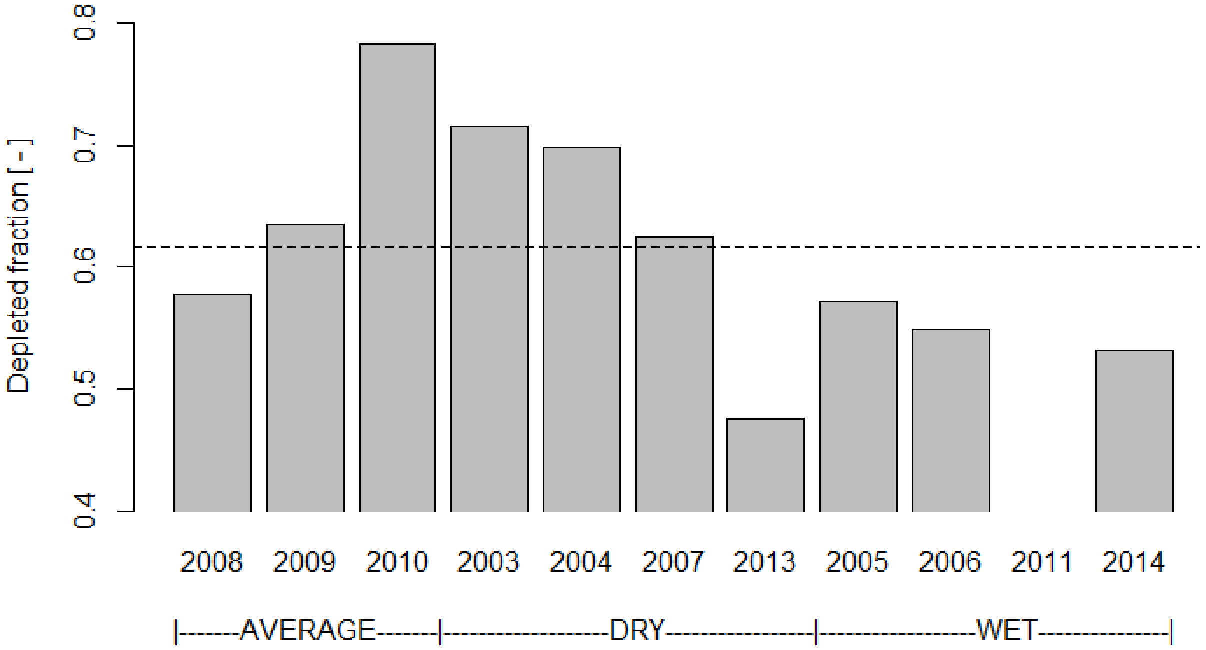


Figure 3-9. Depleted fraction of the irrigation system with the mean of all years indicated with horizontal line.

3.4 Conclusions

This paper aimed at using a decade of remote sensing data to distinguish inter-annual variability of seasonal ET from an irrigation district, and relate this to seasonal water availability. Seasonal water availability was determined using precipitation, snowpack and reference ET data, and computed a drought index to distinguish between average, wet and dry years. Seasonal ET was compared to seasonal weather conditions and to operational aspects namely cropping patterns and, irrigation diversions.

The following findings summarize the main results from this paper:

- High seasonal ET estimates were frequently connected with seasons showing a high potential reference ET, which generally occurred during dry years. Low seasonal crop ET was usually observed in a second dry year. This indicated that the capacity of the irrigation district to buffer consecutive dry years was already limited in the occurrence of two dry years.

- Wet years showed a slightly lower ET than average, however a second wet year showed a much lower than average ET.
- Seasonal ET relates better to reference ET than the other weather aspects when considering all growing seasons studied in this paper. However, when excluding the consecutive years of an extreme event (i.e. 2nd dry or wet years), the seasonal ET relates relatively strongly with snowpack data.
- Cropping patterns portrayed no distinct relation with seasonal water availability. Therefore, it can be concluded from this dataset that water availability did not have a major impact on crop choices. However, additional data from other seasons are required to better document year-to-year variability.
- Irrigation diversions were only influenced by prolonged dry events or a severe dry event. This indicates that the capacity of the irrigation system to use reservoirs as buffer is limited.
- The mean depleted fraction was close to the 0.6 critical threshold value indicating good overall performance of the irrigation system. During wet years the irrigation performance can be improved by incorporating summer precipitation in the irrigation scheduling.

Results showed that actual ET is not strongly related with reference ET when pooling the data of all seasons. This indicates that both the crop coefficient k_c and stress factor k_s are variable for each season. These factors can be influenced by both weather conditions and operational management decisions. Seasonal crop choices did not indicate an obvious pattern throughout the years. However, more data are required to be capable of distinguishing the impact of operational management, due to the diversity of farming decisions.

The results show that in most years seasonal ET can be related to snowpack. This correlation was stronger than with reference ET. Snowpack determines several major farming decisions early in the growing season, which can be a possible explanation of this finding. If this relationship can be clarified and supported with additional seasons of data, it can be a useful tool to predict seasonal ET from an irrigation district early in the season. Such predictions are a highly desirable for regional water managers for computing a water budget of the season. At present such predictions are unavailable but can be of major use. It should be noted however that this relationship is not relevant for consecutive years of an extreme event.

Findings showed that 2nd years of a dry or wet event showed differences in seasonal ET compared to the other years. Additionally, historical irrigation diversion data showed that prolonged drought events reduced irrigation diversions. The irrigation district has the capacity to buffer a first year of low seasonal water availability. However, in the 2nd year of drought the irrigation district adapts by changing irrigation diversions. This dataset can be elaborated with additional seasons to study this pattern further and potentially include a 3rd or more years of a dry or wet event.

These inter-annual differences of seasonal ET from this irrigation district gives practical insight to water managers for anticipating future climate scenario's, especially if more extreme events occur of varying duration and severity. Results showed that this irrigation district is already impacted by a two year drought event. The adaptability of the irrigation district is proven in the first year of a dry or wet event, which shows that it is hardly impacted by a decrease in water availability. Distinguishing the impact of operational decisions will require several more years of data due to the diversity within the irrigation district and the several unquantifiable operational decisions that are made throughout the growing season.

References

Al Zayed, I.S., Elagib, N.A., Ribbe, L., Heinrich, J., 2015. Spatio-temporal performance of large-scale Gezira Irrigation Scheme, Sudan. Agric. Syst. 133, 131–142. doi:10.1016/j.agsy.2014.10.009

Allen, R.G., Irmak, A., Trezza, R., Hendrickx, J.M.H., Bastiaanssen, W., Kjaersgaard, J., 2011a. Satellite-based ET estimation in agriculture using SEBAL and METRIC. Hydrol. Process. 25, 4011–4027. doi:10.1002/hyp.8408

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011b. Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agric. Water Manag. 98, 899–920. doi:10.1016/j.agwat.2010.12.015

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. FAO Irrigation and Drainage Paper No. 56 Crop Evapotranspiration. Rome.

Allen, R.G., Tasumi, M., Morse, A., Trezza, R., Wright, J.L., Bastiaanssen, W., Kramber, W., Lorite, I., Robison, C.W., 2007a. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications. J. Irrig. Drain. Eng. 133, 395–406. doi:10.1061/(ASCE)0733-9437(2007)133:4(395)

Allen, R.G., Tasumi, M., Trezza, R., 2007b. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Model. J. Irrig. Drain. Eng. 133, 380–394. doi:10.1061/(ASCE)0733-9437(2007)133:4(395)

Anderson, M.C., Allen, R.G., Morse, A., Kustas, W.P., 2012. Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources. Remote Sens. Environ. 122, 50–65. doi:10.1016/j.rse.2011.08.025

Aubinet, M., Vesala, T., Papale, D., 2012. Eddy Covariance - A practical guide to Measurement and Data Analysis, Springer Atmospheric Sciences. Springer. doi:10.1007/978-94-007-2351-1

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–9. doi:10.1038/nature04141

Bastiaanssen, W.G., Molden, D.J., Makin, I.W., 2000. Remote sensing for irrigated agriculture: examples from research and possible applications. Agric. Water Manag. 46, 137–155. doi:10.1016/S0378-3774(00)00080-9

Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A., Holtslag, A.A.M., 1998. A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation. J. Hydrol. 212-213, 198–212. doi:10.1016/S0022-1694(98)00253-4

Bastiaanssen, W.G.M., Noordman, E.J.M., Pelgrum, H., Davids, G., Thoreson, B.P., Allen, R.G., 2005. SEBAL Model with Remotely Sensed Data to Improve Water-Resources Management under Actual Field Conditions. J. Irrig. Drain. Eng. 131, 85–93. doi:10.1061/(ASCE)0733-9437(2005)131:1(85)

Bos, M., 1997. Performance indicators for irrigation and drainage. Irrig. Drain. Syst. 11, 119–137.

Bos, M.G., 2004. Using the depleted fraction to manage the groundwater table in irrigated areas. Irrig. Drain. Syst. 18, 201–209.

Bos, M.G., Burton, M.A., Molden, D.J., 2005. Irrigation and drainage performance assessment - Practical guidelines. CABI Publishing.

Carlson, T., 2007. An Overview of the "Triangle Method" for Estimating Surface Evapotranspiration and Soil Moisture from Satellite Imagery. Sensors 7, 1612–1629. doi:10.3390/s7081612

Cuenca, R., Ciotti, S., Hagimoto, Y., 2013. Application of Landsat to Evaluate Effects of Irrigation Forbearance. Remote Sens. 5, 3776–3802. doi:10.3390/rs5083776

Foken, T., 2008. Experimental Methods for Estimating the Fluxes of Energy and Matter, in: Micrometeorology. pp. 105–151.

Gonzalez-Dugo, M.P., Neale, C.M.U., Mateos, L., Kustas, W.P., Prueger, J.H., Anderson, M.C., Li, F., 2009. A comparison of operational remote sensing-based models for estimating crop evapotranspiration. Agric. For. Meteorol. 149, 1843–1853. doi:10.1016/j.agrformet.2009.06.012

Gowda, P.H., Chavez, J.L., Colaizzi, P.D., Evett, S.R., Howell, T.A., Tolk, J. a., 2008. ET mapping for agricultural water management: present status and challenges. Irrig. Sci. 26, 223–237. doi:10.1007/s00271-007-0088-6

Hojstrup, J., 1999. A statistical data screening procedure. Meas. Sci. Technol. 4, 153–157. doi:10.1088/0957-0233/4/2/003

Jensen, M.E., 2007. Beyond irrigation efficiency. Irrig. Sci. 25, 233–245. doi:10.1007/s00271-007-0060-5

Jordan, D.L., Barroll, P., 2013. Multi-Decadal Remote-Sensing Analysis of Irrigated Areas in the Lower Rio Grande Valley, New Mexico. J. Am. Water Resour. Assoc. 49, 484–497. doi:10.1111/jawr.12052

Kalma, J.D., McVicar, T.R., McCabe, M.F., 2008. Estimating Land Surface Evaporation: A Review of Methods Using Remotely Sensed Surface Temperature Data. Surv. Geophys. 29, 421–469. doi:10.1007/s10712-008-9037-z

Kobayashi, K., Salam, M.U., 2000. Comparing simulated and measured values using mean squared deviation and its components. Agron. J. 92, 345–352. doi:10.2134/agronj2000.922345x

Lenton, R., 2014. Irrigation in the Twenty-First Century: Reflections on Science, Policy and Society. Irrig. Drain. 63, 154–157. doi:10.1002/ird.1844

Massman, W.J., Lee, X., 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. Agric. For. Meteorol. 113, 121–144. doi:10.1016/S0168-1923(02)00105-3

Nam, W.-H., Choi, J.-Y., Hong, E.-M., 2015. Irrigation vulnerability assessment on agricultural water supply risk for adaptive management of climate change in South Korea. Agric. Water Manag. 152, 173–187. doi:10.1016/j.agwat.2015.01.012

Pereira, L.S., Allen, R.G., Smith, M., Raes, D., 2015. Crop evapotranspiration estimation with FAO56: Past and future. Agric. Water Manag. 147, 4–20. doi:10.1016/j.agwat.2014.07.031

Rijsberman, F.R., 2006. Water scarcity: Fact or fiction? Agric. Water Manag. 80, 5–22. doi:10.1016/j.agwat.2005.07.001

Senay, G.B., Leake, S., Nagler, P.L., Artan, G., Dickinson, J., Cordova, J.T., Glenn, E.P., 2011. Estimating basin scale evapotranspiration (ET) by water balance and remote sensing methods. Hydrol. Process. 25, 4037–4049. doi:10.1002/hyp.8379

Singh, R.K., Liu, S., Tieszen, L.L., Suyker, A.E., Verma, S.B., 2012. Estimating seasonal evapotranspiration from temporal satellite images. Irrig. Sci. 30, 303–313. doi:10.1007/s00271-011-0287-z

Taghvaeian, S., Neale, C.M.U., 2011. Water balance of irrigated areas: a remote sensing approach. Hydrol. Process. 25, 4132–4141. doi:10.1002/hyp.8371

Tsakiris, G., Nalbantis, I., Vangelis, H., Verbeiren, B., Huysmans, M., Tychon, B., Jacquemin, I., Canters, F., Vanderhaegen, S., Engelen, G., Poelmans, L., De Becker, P., Batelaan, O., 2013. A System-based Paradigm of Drought Analysis for Operational Management. Water Resour. Manag. 27, 5281–5297. doi:10.1007/s11269-013-0471-4

Tsakiris, G., Pangalou, D., Vangelis, H., 2007. Regional Drought Assessment Based on the Reconnaissance Drought Index (RDI). Water Resour. Manag. 21, 821–833. doi:10.1007/s11269-006-9105-4

Turral, H., Svendsen, M., Faures, J.M., 2010. Investing in irrigation: Reviewing the past and looking to the future. Agric. Water Manag. 97, 551–560. doi:10.1016/j.agwat.2009.07.012

Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., Houser, P.R., Meyers, T.P., Prueger, J.H., Starks, P.J., Wesely, M.L., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agric. For. Meteorol. 103, 279–300. doi:10.1016/S0168-1923(00)00123-4

Ward, F.A., 2014. Economic impacts on irrigated agriculture of water conservation programs in drought. J. Hydrol. 508, 114–127. doi:10.1016/j.jhydrol.2013.10.024

CHAPTER IV

DATA ASSIMILATION OF REMOTELY-SENSED EVAPOTRANSPIRATION IN A SIMULATION MODEL FOR EVALUATING IRRIGATION SYSTEM PERFORMANCE [2]

Abstract

The growing water scarcity issues in several regions worldwide urge agricultural areas to assess and improve their irrigation performance thereby saving water whilst achieving similar or higher crop production. The assessment of irrigation system performance requires analysis of the crop productivity and the water balance at both the farm and district scale. However, achieving sufficient field observations to assess performance at a district scale is challenging due to the diversity of farm management within an irrigation district. A data assimilation method is chosen to combine remotely sensed evapotranspiration (ET) data in an irrigation system simulation model during the calibration and validation process. This approach shows the advantage of assimilating remote sensing data and achieving estimations of irrigation performance with only a small amount of field measurements required. The irrigation performance highlights areas with low irrigation performance and yield production, which can be improved by water delivery changes or on-farm irrigation strategies. Additionally, areas are located that can potentially be stressed during peak irrigation months due to a limited water delivery capacity. Findings from this study can aid discussions with local stakeholders on improving the irrigation system performance. Additionally, this approach can be applied to other irrigation districts to rapidly and cost-effectively gain insight of the irrigation system performance.

4.1 Introduction

Water scarcity is a growing issue and impacts agricultural areas especially in arid and semi-arid climates. In these regions, the agricultural sector is typically the largest consumer of available fresh water. Future scenarios predict an increase in global population and higher food demands (Lenton, 2014). In

---

[2] Co-authored with Dr. Christopher M.U. Neale and Dr. Sergio Lecina

addition, climate scenarios predict a change in the hydrological cycle and a decrease in water supply and timing of runoff in the coming decades (Barnett et al., 2005). The agricultural sector is expected to produce more food with less water in the future. This challenge should be met by assessing and improving current irrigation systems, by encouraging measures that increase the water productivity of the system (Turral et al., 2010). Developing water conservation strategies requires a comprehensive analysis of the current irrigation system and water balance to detect potential for savings (Droogers and Bastiaanssen, 2002). These analyses include estimations of irrigation performance indicators at different spatial scales: field, farm, irrigation district and basin scale (Bos, 1997; Bos et al., 2005; Burt et al., 1997; Jensen, 2007). Information about current water use is seldom available for local water users, but is required to improve the management of irrigation systems (Levidow et al., 2014).

In this study, the irrigation system scale is defined as the physical and social entities that convey water from the source of the irrigation water to the farms (Ambast et al., 2002; Small and Svendsen, 1992). Several studies and review articles have been published emphasizing the underperformance of irrigation systems due to issues with the water delivery; in particular for surface irrigation systems operating with an arranged schedule (Pereira et al., 2002). The major issues reported are lack of flexibility of scheduling, equity of water delivery, and effective use of precipitation during the growing season. Introducing more flexibility in water delivery, with respect to flow rate, intervals, and irrigation time, can improve production by matching crop water requirements with irrigation events (Jensen, 2007; Zaccaria et al., 2010). Irrigation intervals or frequency are considered the number of days or hours between irrigation events. Irrigation time or duration is the amount of time irrigation water is being applied to the field. When the scheduled irrigation intervals are longer than optimal for the crop, water stress occurs that can lead to yield reduction (Clemmens and Molden, 2007; Pereira et al., 2012; Playán and Mateos, 2006). In general, it is challenging and impractical for a large irrigation district to provide all users with flexible irrigation times. The long canals cause delay in travel times and therefore a lag between request and delivery is unavoidable (Clemmens and Molden, 2007; Clemmens, 2006). Another issue limiting the performance of irrigation systems is the inequity and unreliability of water deliveries throughout the system. This is especially problematic for farmers who consistently receive less than their full share of water, which results in a reduction of crop yield (Clemmens and Molden, 2007). A low uniformity of water delivery in the system is usually fixed by supplying more water and thereby ensuring sufficient water delivery at the lower end of the system (Clemmens, 2006). The third issue mentioned in several studies is the exclusion of precipitation when scheduling irrigation events (Al Zayed et al., 2015; Clemmens and Molden, 2007). Sometimes effective precipitation during the growing season is negligible. However, if the amount is substantial, the arranged irrigation schedule is generally too rigid to adapt and utilize the precipitation. On-farm irrigators typically adapt to precipitation events, yet at the system level adjustments are rarely made.

Literature frequently emphasizes the importance of implementing water conservation measures at both the farm and system level (Clemmens and Molden, 2007; Pereira et al., 2012). It is challenging to involve both the farmers and irrigation district managers equally in joint steps of improvements (Pereira et al., 2012). However, there is an overall understanding that future water supplies are uncertain and that water conservation measures need to be implemented (Burt and Styles, 2000). Increasing the knowledge of the current irrigation system performance is important. Communicating this information to local water users and providing estimates on economical profits is equally essential to trigger change in management (Levidow et al., 2014).

The reason assessments, measurements and monitoring of large irrigation systems are rarely practiced is due to complexity associated with a heterogeneous area. There is a large variability in performance at the farm level considering cropping patterns, evapotranspiration, pesticide and fertilizer applications etc. (Molden et al., 2010). The required fieldwork to represent a large-scale irrigation system properly is time-consuming and expensive (Ambast et al., 2002). Additionally, irrigation systems are complex for they involve both physical and social aspects interacting dynamically (Lenton, 2014; Turral et al., 2010). Simulation models are a method to approach complex systems and provide a holistic approach for supporting farmers and districts with their water management (Knox et al., 2012; Pereira et al., 2002). Additionally, simulation models can analyze the long term effects of different measures (Ines and Droogers, 2002). Several simulation models have been developed for field or farm scale modeling, simulating the soil, vegetation, atmosphere and plant processes (Bastiaanssen et al., 2007).

Simulations at a larger scale are challenging due to the spatial heterogeneity and the existence of operated canals, which do not follow natural hydrological patterns. Acquiring information at irrigation district scale has been made possible with the use of remote sensing, which provides observations regularly and at large spatial scales (Ambast et al., 2002; Taghvaeian and Neale, 2011). Information regarding land use type, crop cover and seasonal evapotranspiration are amongst the various applications of remote sensing (Bastiaanssen et al., 2000). Evapotranspiration was traditionally estimated using point measurements, but remote sensing makes it possible to make estimations at a regional scale and provide information on spatial variability (Bastiaanssen et al., 2000; Senay et al., 2011).

Remote sensing tools for agricultural water management are becoming well-established. Recent developments have focused on data assimilation of remote sensing measurements with simulation models especially for modeling studies with limited available data (Ambast et al., 2002; Bastiaanssen et al., 2007). Several studies have been reported in literature illustrating assimilation of remote sensing data in simulation models at different spatial scales from field and farm scale to hydrology models. Some studies use a SWAP (soil, water, atmosphere and plant) field-scale model to simulate processes occurring at different individual fields in a region. The SWAP model is combined with remote sensing data by assimilating the leaf area index (LAI); soil moisture estimates from microwave bands (Ines et al., 2013; Olioso et al., 2005); or estimations of evapotranspiration (ET) using a remote sensing surface energy balance algorithm (Droogers and Bastiaanssen, 2002; Ines and Droogers, 2002; Ines et al., 2006). Findings from these studies demonstrate the usefulness of assimilating remote sensing data to simulation models when incorporating the spatial variability among fields. Adding spatial data on soil moisture was beneficial because point measurements of precipitation are not always representative for the whole region (Ines et al., 2013). Several other studies have demonstrated the assimilation of remote sensing data for a larger spatial scale such as in hydrological models (Boegh et al., 2004; Immerzeel et al., 2008). In hydrology, this approach offers a great advantage because remote sensing calculates the ET component of the water balance and the simulation model can be used to calculate the other components (Immerzeel et al., 2008). Additionally, this approach can determine the areas that displayed errors in model predictions and enhance the performance of the simulation model (Boegh et al., 2004). Studies on assimilating remote sensing data in irrigation system simulation models are limited. Ines et al. (2006) reports a study evaluating the water delivery of an irrigation system using a field scale model. However, assessing the performance of water delivery requires a thorough understanding of the canal system in relation to on-farm irrigation. Simulations with an irrigation system model that assimilates remote sensing data is a favorable approach, which can provide the much needed insight on water management in an irrigation system.

The objective of this study is to assess the current performance of a large-scale irrigation district using data assimilation of remotely-sensed ET in an irrigation system simulation model. The irrigation system simulation model is capable of simulating on-farm irrigation and water delivery from the canals. In this study field evaluations are performed to estimate several input parameters. During the calibration process, seasonal ET data from remote sensing are used to adjust parameters in the irrigation units displaying disagreements with model predictions. This approach demonstrates a cost-effective method of simulating an irrigation system and achieving insights on the current water management. In particular the quantitative information provided by the simulation model is valuable for local water users to discern the potential for water savings. This innovative approach of data assimilation with remote sensing data in a simulation model can be adopted in other studies to enable the simulation of large areas without the need for extensive fieldwork.

4.2 Study area

The irrigation district considered in this study is the Bear River Canal Company (BRCC) located in Northern Utah, U.S.A. (Appendix A). The BRCC is located within the Bear River basin, which originates in the Uinta mountain range of Utah. It flows for 796 km through the states Wyoming, Idaho and back into Utah where it terminates in the Great Salt Lake. The BRCC is one of the last users of the river water before it flows into the Great Salt Lake. Water is diverted at Cutler Dam and feeds an open canal system, which is mostly unlined. The main canals are split into the West, East and Central canal as indicated in Appendix D. The total command area under the BRCC's responsibility is 29,764 ha. The BRCC is operated by a canal company manager and ditch riders, each responsible for a canal section. These canal managers are elected by a board of local farmers from the district.

The canal company originated as a sugar beet irrigated production area in the early 20th century. At present, the main crop types planted in the BRCC are alfalfa (37%), wheat and other small grains (29%), and corn for fodder (17%). The main soil types are clay to clayey loam soils, with a few areas of sandy loam soils. The canal company provides water to the farmers on a fixed rotation schedule, which is managed by operating gates delivering water to a set of fields (herein referred to as headgates). The main irrigation method is border irrigation, with a few instances of sprinkler and basin irrigation.

The BRCC is located in a semi-arid climate characterized by warm, dry summers and cold, snowy winters. The BRCC has the senior right of the river flow; however water management is under debate due to growing pressures in the region. Northern Utah has changed in the past century from a rural area to a populated urban area (Sehlke and Jacobson, 2005). Water use and food demands in urban areas are increasing. Additionally, the water flow of the Bear River is determined mostly by snowmelt during spring. Future climate scenarios predict a change in timing and quantity of runoff, which will particularly impact regions depending on snowmelt (Barnett et al., 2005). For these reasons, analyzing the water management within the BRCC and providing quantitative information, is an important contribution to the regional discussion. In addition, the BRCC provides a good example of the major issues prevalent in other irrigation districts globally.

4.3 Methodology

Conceptual framework

There are several approaches for assimilation of remote sensing data, which can be divided in three categories: forcing, validation and re-adjustment (Fischer et al., 1997). The forcing method uses remote sensing imagery as input data to the model. Remote sensing data or information derived therefrom needs to be provided at each time step of the model, which is daily. Additionally, the remote sensing data needs to be available at the spatial scale of simulation (i.e., field scale) but also cover the spatial extent of the study area (i.e., the irrigation district). Higher resolution satellite imagery is usually available every few weeks (Moulin et al., 1998), thereby making the forcing method not ideal for this study. A more suitable method is the re-adjustment strategy, which uses remote sensing data during the calibration process of the model simulations. Model outputs are compared with results from remote sensing and parameters are adjusted to improve model results. It is important to note that the remote sensing data also contains errors, but these errors are assumed to be relatively small in comparison with the model errors. While both contain a certain level of uncertainty, the combination reduces the level of error due to the combination of information provided by both the remote sensing data and model simulations (Ines et al., 2013). The re-adjustment approach is chosen in this study as the assimilation method. The third data assimilation method is the validation method, which uses remote sensing data to validate the model simulation results.

The implementation of the data assimilation approach is illustrated in the schematic diagram of Figure 4-1. This provides an overview of the different steps taken, and at which steps remote sensing data is used in the modeling process. The different components of the process are described in the following sections. The re-adjustment process is implemented in two steps during the modelling process namely: an adjustment process and a calibration process. Additionally, the model simulation results are validated with remote sensing data using a ‘clean’ dataset. The irrigation district is divided in two main sections, the West canal and the other canals (Central and East), which can be found in Appendix D. The West canal is used in the re-adjustment process, whilst data from the other canals are only used in the validation process of the model simulations. Figure 4-1 indicates the different input datasets required for the irrigation system model, as indicated in the top row. The first step is collecting the input data and making assumptions on several parameters to make an initial run of the simulation model. The second step is comparing the simulated ET results from the initial run with the ET as estimated from remote sensing. These comparisons are made at the headgate spatial scale and the areas displaying less agreement between the remote sensing and simulated data were identified. These headgate areas are examined in more detail and the input data are adjusted in the next run of the model. Adjustments considered assumptions in field geometry, irrigated area, or soil infiltration rates. This is repeated several times until the majority of the headgate areas show good agreement and changes to the level of error are not improved for additional model runs. The third step is to calibrate the model using the seasonal estimated water use from flow gauges in the Bear River and canal diversion (indicated in Appendix D), and using the seasonal ET estimated from remote sensing from the West main canal (indicated in Appendix D). Changes are made in irrigation interval and duration for each crop type, which is the time between irrigation events and the total amount of time irrigation water is applied during an irrigation event. The combination of interval and duration that showed the best agreement with water use and remote sensing data is selected and then validated with remotely-sensed ET from the other main canals. The Pearson's correlation coefficient, bias and RMSE were calculated according to equations from Kobayashi and Salam (2000) aiding the comparison between simulations. Data management and statistics were done in R statistical software package.

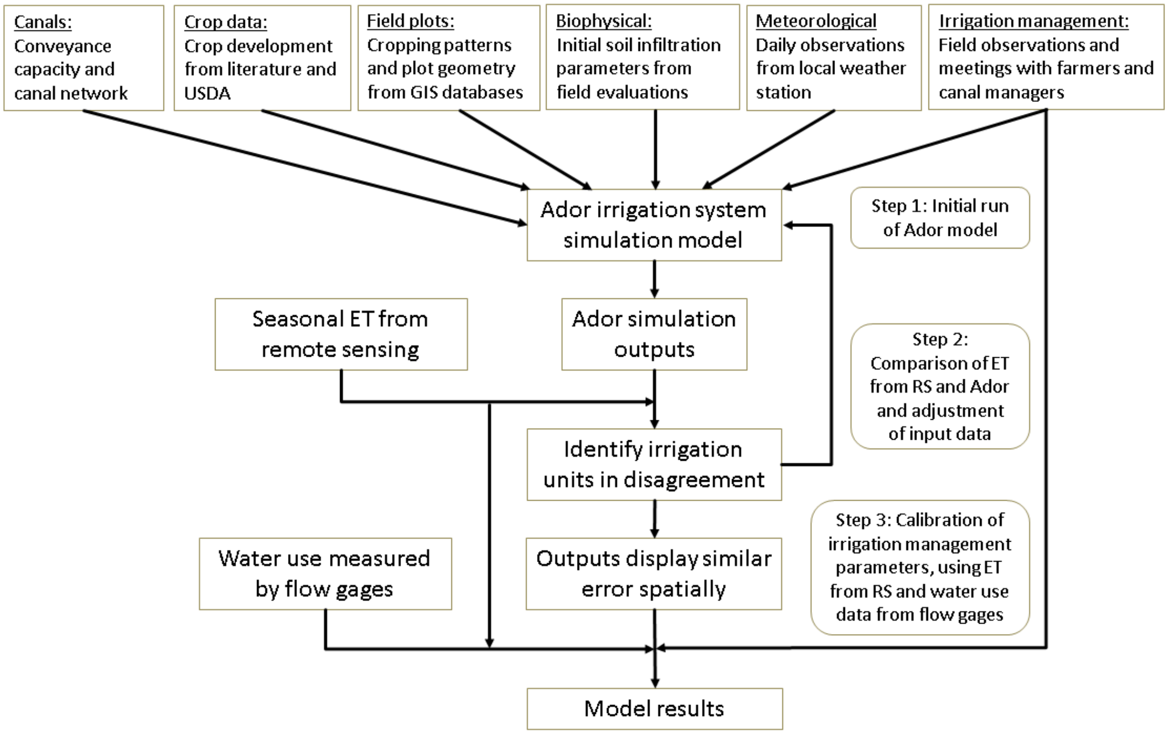


Figure 4-1. Schematic diagram of Ador simulation and calibration process using remote sensing data inputs.

Ador irrigation system simulation model

The simulation model selected in this study is the Ador-Simulation model for surface irrigation, which was developed by Lecina and Playán (Lecina and Playán, 2006a). It requires input data on meteorology, soil infiltration and other biophysical aspects, plot geometry, crops and canal network. Four different modules relate the different input parameters and simulate the water flow during on-field irrigation events and water delivery from canals, but exclude canal hydraulics. These modules are: Ador-Crop, Ador-Surface, Ador-Network and Ador-Decision. The crop development is simulated using the Cropwat method but implements degree days instead of normal days for defining growth stages (Lecina and Playán, 2006a).

The uniqueness of the Ador model is its capability to simulate water flow in the canal system and at field scale. Infiltration after irrigation events is simulated at field scale. Also the crop development and water demands are calculated at field scale. Crop water demands are then related to the canal network and the conveyance capacity of the canal segment appointed to the fields (headgates). The combination of canal system and field scale simulations is ideal for evaluating the performance of the whole irrigation system and the spatial variability between fields and headgate areas. In addition, the limitations of the water delivery schedule and conveyance capacity of the canals can be assessed. For example the conveyance capacity can be compared with the peak crop water demand. This can help identify areas, which are over allocated and can potentially experience water deficits and crop stress. Another advantage to the Ador model is the incorporation of a management module in the simulations. This enables the simulation of management decisions made by farms regarding irrigation duration and interval within the limitations of the capacity provided by the canal network. However, farm management decisions regarding fertilizer or crop management are beyond the capabilities of this module. Simulating irrigation management decisions also imposes a challenge due to the broad diversity of management decisions that can be made at farm scale. Therefore, some simplification is needed to enable the simulation of a large irrigation district.

The strengths of the Ador simulation model are demonstrated in a study conducted with an irrigation district located in Spain (Lecina and Playán, 2006b). For the two growing seasons simulated in this study, differences between observed and simulated water demand were found to be 0.9 and 1.9%. This study shows the usefulness of Ador simulation for decision-makers in irrigation districts. Additionally, it emphasizes the challenge with calibrating Ador simulation, because of the variations in management decisions made by the farmers (Lecina and Playán, 2006b). Another study implemented Ador simulation in a small section of the Bear River Canal Company (Lecina et al., 2011, 2009) with two main soil types. This study showed the potential of water savings by changing the irrigation duration and interval, whilst achieving a higher crop yield because less water stress occurs. Current irrigation intervals cause water stress for several crops in the last few days before the next irrigation event occurs. With shorter irrigation times, the frequency of irrigation can increase and ensure that crops are irrigated before stress occurs. That study indicates the suitability of implementing the Ador simulation model in the BRCC. This paper expands the simulated area to the total irrigated area under the command of the BRCC, encompassing several different soil types and their distribution.

The input datasets required for running Ador simulation are indicated in Figure 4-1. The conveyance capacity and canal network were provided by the BRCC as a database and spatial GIS (geographic information system) dataset. The GIS dataset provided the locations of the canal segments and headgates. Field observations were used to determine the fields appointed to each headgate. Crop input data regarding sowing dates was provided by USDA reports (USDA-NASS, 2010). Location and crop types for each field were provided as a GIS dataset by the Utah Division of Water Resources. Due to the large number of fields in the BRCC area (~3000), the geometry of the fields was estimated using GIS spatial analysis tools. This was especially useful for determining the length of rectangular features, non-rectangular features were more difficult to approximate. The soil infiltration parameters for the major soil types were estimated by performing field evaluations of irrigation events. This procedure is described more elaborately in the following section. Meteorological data were obtained from a local weather station operated by the Utah Climate Center. Irrigation management decisions were estimated based on field observations during the growing seasons and conversations with several local farmers and canal managers.

The calibration datasets consisted of seasonal ET estimated through remote sensing energy balance techniques, and water use estimated from flow gages. The calculation of seasonal ET is specified in a following section. The water use is estimated using flow measurements at different gages in the system (indicated in Appendix D). The canal diversion data was taken at the main diversion point at Cutler dam. Runoff is subtracted from the diversion data to achieve water use by the irrigation district. It is estimated from differences in river flow of the Bear River at an upstream and downstream location, indicated in Appendix D as flow gauges below Cutler Dam (upstream) and at Corinne (downstream). Additionally, canal seepage and leaching requirements are estimated to be 16% and 10%, respectively, based on local observations and values found in literature.

The calibration of Ador simulation model was performed using different combinations of irrigation intervals and irrigation times. Three simulations were selected for comparison in this paper that showed good correlation with the remote sensing data. The irrigation management parameters for these simulations, namely irrigation interval and irrigation time, are presented in Table 4-1 for the major soil types evaluated in this study (PdA, Fd, Co, Ho, Ld and Fv).

Table 4-1.

Input parameters regarding irrigation management for three simulations to calibrate simulation model.

Simulation #	Intervals [days]			Irrigation time [h/ha]					
	Corn	Wheat	Alfalfa and grass	PdA	Fd	Co	Ho	Ld	Fv
Simulation 13	10	14	28	5.7	7.2	3.7	3.1	6.1	2.3
Simulation 14	10	21	21	5.7	7.2	3.7	3.1	7.1	2.3
Simulation 15	10	14	28	5.8~	7.3~	3.8~	3.2~	5.8~	2.3~

~irrigation time for each soil and crop types; values indicate average for all crops

The performance indicators selected from the Ador simulation outputs to assess irrigation performance are: application efficiency (AE), distribution uniformity (DU), yield reduction, water productivity (WP) and water delivery capacity (WDC). The AE is expressed by Burt et al. (1997) as shown in equation 1, and is calculated for each field. The DU is expressed by Heermann and Solomon (2007) as shown in equation 2, and is also calculated for each field. The yield reduction is estimated using coefficients for crop stress from Doorenbos and Kassam (1979). The actual yield is calculated as fraction of maximum yield, to express the yield reduction at field scale. The WP can be expressed with numerous definitions changing between economic and biomass terms versus water consumption to water application (Pereira et al., 2012; Perry et al., 2009). This study makes use of Pereira et al. (2012)'s definition of water productivity thus using irrigation water applied as denominator, as shown in equation 3. This is more relevant for irrigation engineers and farmers alike. The WDC is estimated for each headgate area by taking the peak crop consumptive water use from July, and comparing it with the conveyance capacity. This was expressed by Molden et al. (1998) and shown in equation 4.

$$\mathrm{AE} = \frac{\text{Average depth of irrigation water contributing to target}}{\text{Average depth of irrigation water applied}} \text{ x } 100\% \qquad (\mathrm{eq.}\,1)$$

$$\mathrm{DU} = \frac{\text{Infiltrated depth of the lower quarter of the field}}{\text{Average infiltrated depth of entire field}} \qquad (\mathrm{eq.}\,2)$$

$$\mathrm{WP} = \frac{\text{Crop yield [kg]}}{\text{Gross irrigation depth } [m^3]} \qquad (\mathrm{eq.}\,3)$$

$$\mathrm{WDC} = \frac{\text{Canal capacity to deliver water to system head}}{\text{Peak consumptive demand}} \qquad (\mathrm{eq.}\,4)$$

Field evaluations and infiltration parameters

Field evaluations of irrigation events were conducted on 4 major soil types in the BRCC area: Fridlo (Fv), Lasil (Ld), Collett (Co) and Honeyville (Ho). Two other major soil types were already evaluated by Lecina et al. (2011), which were Fielding (Fd) and Parleys (PdA). Evaluations were performed in the 2009 and 2014 growing seasons. All evaluations were performed in alfalfa fields that used border irrigation with siphon tubes. A total of 14 evaluations were performed: four on Fd soils, five on Ld soils, one on Co soil, and four on Ho soils. Evaluations were conducted according to guidelines suggested by Merriam and Keller (1978).

Before the start of irrigation, soil samples were taken to 1.2 m depth at the top and bottom of the field to determine soil water storage since the previous irrigation event. During the irrigation event the advance phase of the water front was noted at each 100 feet (30.5 m.). The cutoff time was also noted, but was frequently based on the farmer's estimated cutoff time due to the long irrigation times. The water depth during irrigation was recorded at the second post (60 m) for estimating the Manning n. This approximates the surface roughness during the irrigation event and is needed for the simulation of the irrigation event. Additional measurements of the field consisted of field length and width, border width, slope with levelling equipment, and flow rate in the ditch. The flow rate in the ditch was measured with a propeller meter (Rickly Hydrological Company) or an acoustic Doppler velocimeter (Sontek).

The infiltration parameters required as input for Ador simulation were the Kostiakov k and A coefficients as shown in equation 5, where z is cumulative infiltration [m] and τ is opportunity time [min]. The coefficients k and A are specific for each soil type, with k having the dimensions m/min^A and A is dimensionless. Additionally, the coefficients change due to changes in the physical, chemical and biological properties of the soil (Walker et al., 2006).

$$\mathrm{z} = \mathrm{k} \cdot \tau^{A} \qquad \text{(eq. 5)}$$

Initial estimations of the coefficients k and A are calculated using the empirical curves as published by Walker et al. (2006). The curves are grouped according to soil composition. The soil composition of the major soil types in the BRCC area was taken from the soil survey reports by the NRCS (USDA-NRCS).

Each field evaluation was simulated using SIRMOD (Surface Irrigation Modelling) software (Walker, 2003). Initial values for Kostiakov coefficients k and A, were used and adjusted to fit the observations during the field evaluations. The resulting coefficients of k and A were averaged for each soil type and used in the Ador simulation model.

ET estimations from remote sensing

Estimating ET with remote sensing has several advantages: it provides observations of large areas and is more economic than field measurements. However, remote sensing consists of applying algorithms describing the atmospheric processes to estimate ET and is therefore not a direct measurement of ET (Allen et al., 2011b). It is therefore important to note for this study that ET estimated with remote sensing is not without error.

Evapotranspiration was estimated using the Mapping ET with Internalized Calibration (METRIC) algorithm as published by Allen et al. (2011a, 2007b). This is a surface energy balance algorithm, which calculates the different components of the energy balance: net radiation (Rn), soil heat flux (G), sensible heat flux (H), and latent heat flux (LE) is calculated as the residual of the balance. An advantage of the METRIC algorithm is the internal calibration method used to estimate H. This calibration method eliminates the need for accurate estimations of aerodynamic stability corrections and surface roughness (Allen et al., 2007b). A disadvantage of METRIC is the subjectivity in selecting extreme hot and cold pixels (Anderson et al., 2012), which is done manually but according to well-described guidelines. A test as published by Gonzalez-Dugo et al. (2009) showed no significant differences in results between three individuals running the METRIC algorithm. The METRIC algorithm has been applied in several agricultural water management studies and validated with field observations (Allen et al., 2007a; Cuenca et al., 2013; Gowda et al., 2008).

The results from METRIC give instantaneous ET and ET_rF (similar to crop coefficient) values, for the time of satellite overpass. The instantaneous values need to be interpolated to achieve daily and seasonal values for ET. There are different methods of interpolation using the ET_rF, namely cubic spline, linear and fixed. All three methods perform similarly with cubic spline performing slightly better but not significantly (Singh et al., 2012). However, for this study a linear interpolation method was chosen, because it is more suitable for an area with alfalfa cuttings dominating the growing season. Seasonal ET estimations with METRIC using an interpolation scheme shows a lower degree of uncertainty compared to daily values, due to less random errors (Anderson et al., 2012). Therefore, in this study seasonal ET or monthly ET was chosen to compare with simulation data.

In this study 11 Landsat 8 OLI (Operational Land Imager) images are selected in the 2013 growing season. The thermal resolution of the image is 60m, whilst the multi-spectral resolution is 30m. The instantaneous values of ET estimated by METRIC were compared with eddy covariance flux tower data to confirm the confidence in METRIC results. Three eddy covariance flux towers were part of a field experiment during the 2013 growing season and provided data for the several days of satellite overpass. The methodology and results of the eddy covariance flux towers and comparison with METRIC results is presented in chapter 3. The estimated ET_rF values were interpolated and multiplied with daily reference ET values provided by a local weather station (operated by the Utah Climate Center). The implementation of the METRIC algorithm was done in the ERDAS Imagine software. Data management and calculations of seasonal ET were performed in R statistical software package.

4.4 Results and discussion

Field evaluations and infiltration parameters

Results of the field evaluations are shown in Table 4-2 for four of the major soil types. Elaborate field reports of the field evaluations are found in Appendix F. Two major soil types were already evaluated and published in Lecina et al. (2011). The slope and geometry of the fields showed considerable variation within the soil types. The local farmers and canal managers indicated that slope was more related to location. Most farmers in the area practice laser levelling of their fields, but select a slope that is the most economic for levelling. It was also mentioned by the canal managers that border width was connected linearly to flow as provided by the headgate. The irrigation time as presented in Table 4-2 also showed some variation within the soil types

Kostiakov infiltration parameters were estimated using SIRMOD software. The average and variation of the infiltration parameters are grouped for each soil type and shown in Table 4-2. Unfortunately, the parameters for the soil type Co were estimated from merely one field evaluation. However, the Co soil type was similar in composition to the Ho soils therefore the parameters can be compared to confirm reasonable estimates.

Infiltration curves are computed from the average Kostiakov k and A values and are shown in Figure 4-2. The soil types evaluated by Lecina et al. (2011) are also added to the figure for comparison. The heavier soils containing a higher percentage of clay are Ho and Co, namely 27 to 35% according to the USDA-NRCS soil surveys. In Figure 4-2 the infiltration curves for these soils indicate less infiltration occurring over a given time compared to the other soil types. Due to the slower infiltration rate of this soil, a lower flow rate is more suitable to reduce runoff. This is implemented according to the field evaluation data in Table 4-2. Additionally, local farmers indicated that block-ends are frequently implemented in fields to capture the drainage at the end of the field. Figure 4-2 also indicates that the infiltration curves for Fd and Ld are similar, and display the largest infiltration rate. This can also be related to the percentage of clay, which is lowest for these soil types being between 15 to 25%. Soil types PdA and Fv display infiltration curves between the other soil types. They have a slightly higher clay percentage than the Fd and Ld soil types, namely 18 to 27%.

Table 4-2.

Results from field evaluations conducted during irrigation events in 2009 and 2014.

		Soil types			
		Fv	Ld	Ho	Co
Number of evaluations		4	5	4	1
Slope	Average (m/m)	0.0011	0.0017	0.0018	0.0012
	CV(%)	36	47	31	
Border width	Average (m)	54	47	69	58
	CV(%)	58	29	49	
Border area	Average (ha)	2.5	1.7	2.7	1.1
	CV(%)	20	39	52	
Unit flow	Average (m^3/s)	0.118	0.094	0.087	0.091
	CV(%)	76	29	56	
Irrigation time	Average (h/ha)	2.4	5.5	1.9	2.3
	CV(%)	31	29	12	
Kostiakov k	Average (m/min^a)	0.0160	0.0191	0.0114	0.0110
	CV(%)	17	14	3	
Kostiakov A	Average (-)	0.331	0.360	0.310	0.305
	CV(%)	7	6	1	
Manning n	Average (-)	0.10	0.15	0.09	0.10
	CV(%)	8	26	13	

Seasonal ET from remote sensing

Estimations of instantaneous ET were calculated with METRIC and interpolated to daily ET values for the day of satellite overpass, using the ET_rF value. Results from the 11 images processed with METRIC are shown in Figure 4-3, indicating the daily ET of pixels located in the agricultural area and masking out the urban, wetland and other areas irrelevant to this study.

Figure 4-3 shows low daily ET values for the first image of the growing season on day of year (DOY) 135 (15th May). This is associated with lower vegetative cover and cooler temperatures in the early season. The next images show an increase in daily ET values. The peak ET values are observed on DOY 183 (2nd July). At that time all major crops are at full cover, and the winter wheat crop is starting to senesce.

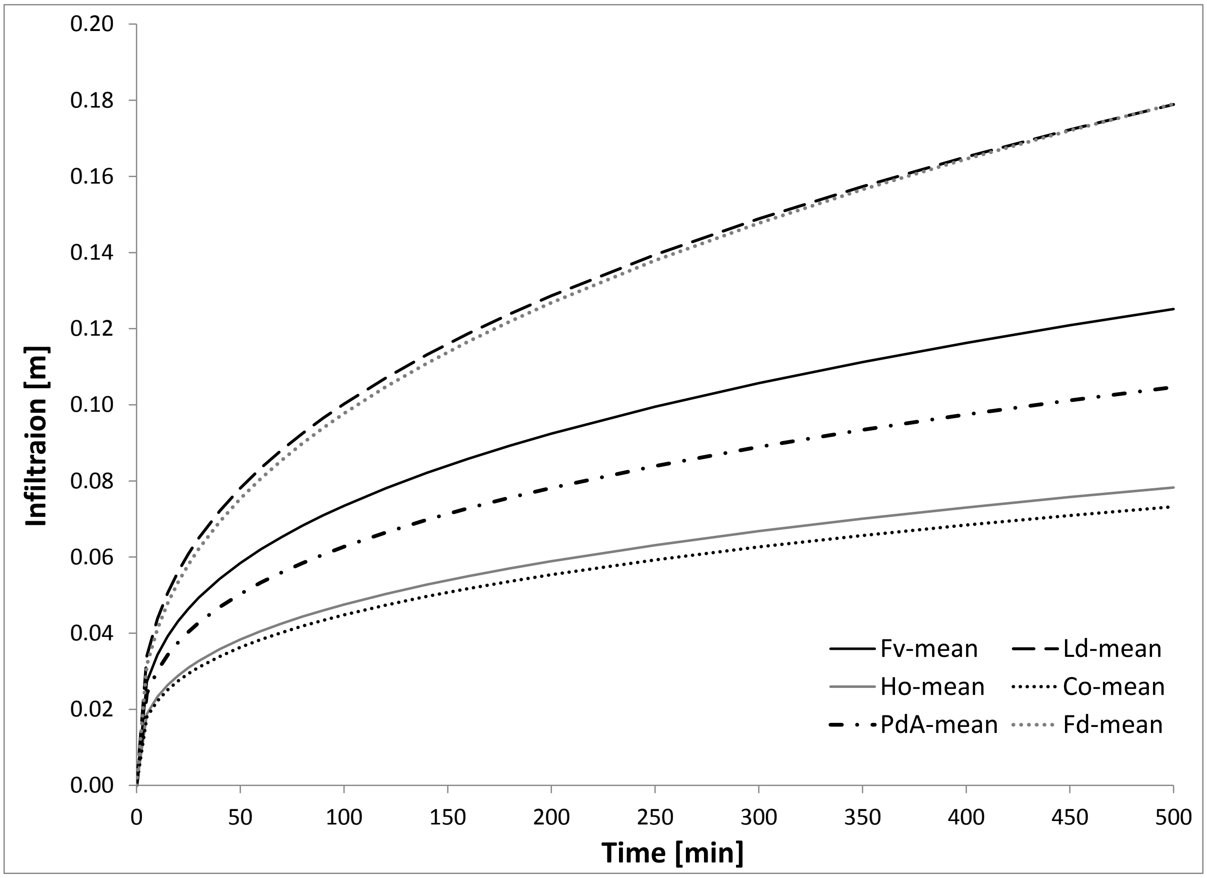


Figure 4-2. Average infiltration curves for each major soil type in the BRCC district as estimated with SIRMOD.

Additionally, the air temperatures are higher, which amplifies the higher ET values. After the peak the images show a gradual decrease in crop ET and several fields show close to zero ET values indicating that the crop has been harvested. Crop growing season for alfalfa continues through October, therefore the last image on DOY 279 (6th October) shows moderately high ET values.

The gaps in between images are reasonable making it possible to interpolate the ET_rF values and estimate monthly and season ET. The only problematic gap was between DOY 215 and 240, which is a 25 day gap due to cloud cover during the days of satellite overpass. An alfalfa cutting cycle in this irrigation district is on average 28 days therefore this gap might have skipped one alfalfa cutting. This should be taken into consideration when assimilating the data with the Ador simulations.

There are several fields observed in Figure 4-3, which have a low ET values throughout the growing season. These fields indicate the areas that are set fallow for the season, or might be agricultural lands which are used temporarily for wild rangeland. These fields are frequently situated close to the riverbanks or at the boundary of the BRCC regulated area.

Additionally, it can be observed that there is spatial variability of estimated ET within the BRCC command area. The higher ET values are usually found in the central part of the irrigation district. Generally, the South and West parts of the district are at the end of lengthy canals and can experience some stress due to the limited water delivery. This was indicated by the local farmers and can be partially observed in Figure 4-3 for the Western region, however is less pronounced for the Southern region. These differences might also be associated with differences in crop choice, because there is not an obvious pattern of less ET during the growing season. The results from METRIC with satellite remote sensing does demonstrate the capability of distinguishing between fields and clearly shows the plots containing early season crops, compared to those containing alfalfa or late season.

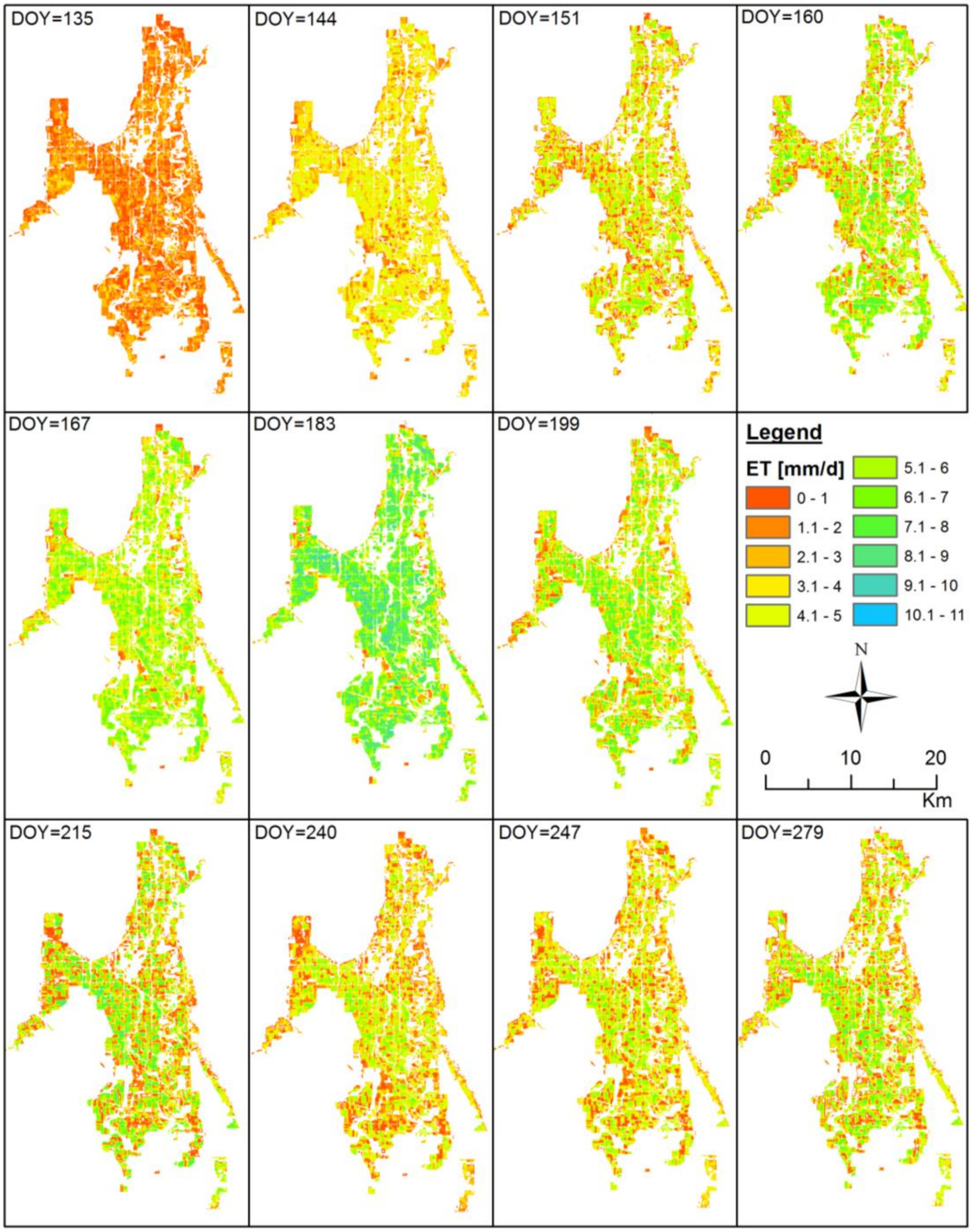


Figure 4-3. Results of daily ET from METRIC for 11 satellite images in the 2013 growing season.

Data assimilation for re-adjustment

The sum of seasonal ET for each headgate area from the Ador simulations were compared with the remote sensing results for the same areas. Headgate areas displaying a considerable disagreement with seasonally integrated remote sensing results were identified and adjusted for the next simulation run, by changing the approximations of the input data namely field geometry, slope, irrigated area or soil infiltration. Results of the comparisons after each run are shown in Figure 4-4 and show improvement after each simulation run for most headgate areas. A few individual units showed a slight decline, which is unavoidable due to the several links in the input data and parameters between headgate units. Changes to improve certain headgate areas will most likely influence the outcomes for other headgate areas. The overall results of the simulation runs shows improved agreement between simulated and remotely-sensed seasonal ET represented as a fraction. This fraction is defined as difference between remotely-sensed and simulated seasonal ET, divided by remotely-sensed ET. The last two simulation runs in Figure 4-4 (third and fourth run) display little improvements in units and therefore the next step of the data assimilation process can commence.

Data assimilation for calibration

The irrigation timing and intervals for each major crop and soil types were adjusted to determine a good agreement with the seasonal remotely sensed ET at different scales within the irrigation system. Combinations of irrigation management for three simulations were shown in Table 4-1 of the methodology. These simulations focus on calibrating the irrigation timing and interval of on-farm irrigation events. Results of the three simulations at the later laterals, headgate areas and plot scales are displayed in Figure 4-5 including the Pearson’s correlation coefficient, bias and RMSE for each simulation.

The results for calibration at lateral or secondary canal scale show a good correlation for all three the simulations. There is a slightly negative bias for all three simulations but the bias is negligible when compared to magnitude of the values. The RMSE also shows values that are reasonable compared to the values portrayed on each axis. Simulation #14 displays the smallest bias but the largest RMSE of all three

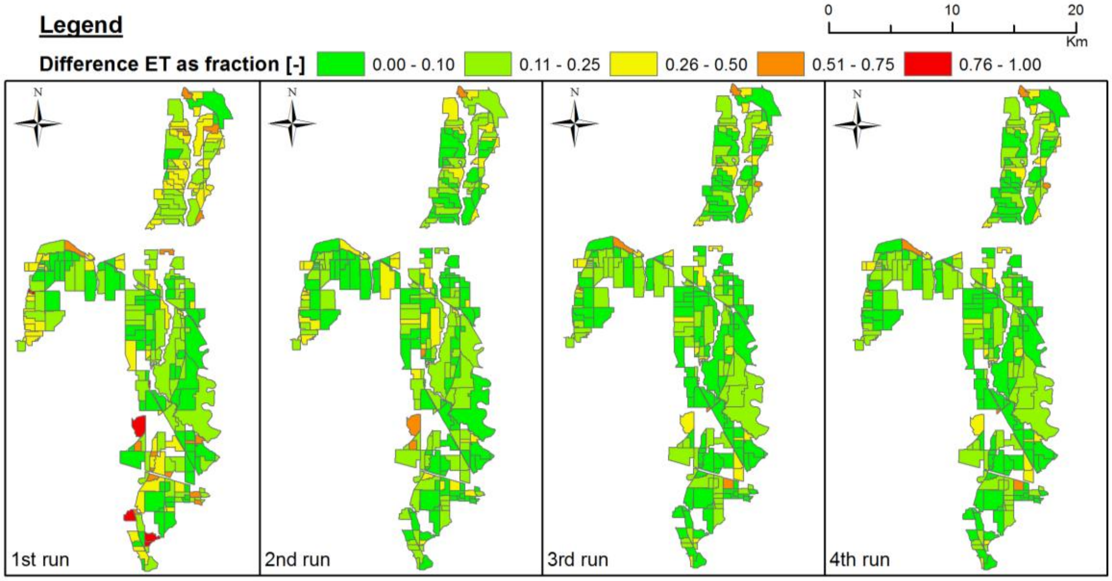


Figure 4-4. Identification of headgate areas displaying disagreement, and improvements after each simulation run using the difference in remotely-sensed ET and simulated ET as fraction of remotely-sensed ET.

the simulations. Simulation #13 is the opposite with the largest bias but the smallest RMSE, whilst simulation #15 is in-between the two simulations considering the bias and RMSE. However, information at the lateral scale might not be ideal for a good comparison. There are a total of seven laterals in the irrigation district (shown in Appendix D) therefore the ET at lateral scale can cause random errors to be reduced due to the summation of ET values at this larger scale.

The comparison of remotely-sensed and simulation actual ET at headgate scale is portrayed in Figure 4-5. The simulations #13 and #15 display a similar correlation coefficient with #15 performing slightly better. This is expected due to the similarities of irrigation management parameters shown in Table 4-1. Simulation #14 shows a lower correlation coefficient compared to the other two simulations. The RMSE is also similar for simulations #13 and #15, whilst the RMSE for simulation #14 is higher. The bias however shows the difference between simulations #13 and #15 with simulation #13 having a lower bias. However, both the bias and RMSE values are almost negligible considering the magnitude of values on the axes.

The third spatial level analyzed in Figure 4-5 is the actual ET at the plot level. The correlation coefficient displays very similar results for all three simulations. Simulation #13 differs with a relatively higher bias compared to the bias from the other two simulations. The bias for all three simulations was negative. The RMSE is higher for simulation #14, whilst the RMSE of the other two simulations are similar.

Overall both simulations #13 and #15 show better performance than simulation #14. These two simulations had similar irrigation intervals and only different irrigation times as shown in Table 4-1. This indicates that the irrigation interval chosen for both simulations #13 and simulation #15 are more applicable compared to those intervals chosen for simulation #14. The small differences between the performance of simulations #13 and #15 indicate that irrigation times had less impact on ET than irrigation intervals.

Actual ET and water use results

Both simulations #13 and #15 showed similar performance for the regression analysis at different spatial scales within the system. For further calibration a choice between the two simulations is made based on its performance of monthly ET and water use. Results of the Pearson's correlation coefficient are given in Table 4-3, with data from the West canal taken as a calibration dataset and the other (Central and East canals as a validation dataset.

The correlation coefficients regarding actual ET in the West canal, show no difference between the two simulations. This is expected considering the similarities evident at the other spatial scales as were presented in Figure 4-5. The correlation coefficients calculated for the water use data showed trivial differences with simulation #15 indicating a slightly better performance. Simulation #15 is therefore selected to be the better fit and will be used for analyzing the irrigation performance. It should be noted that water use was more sensitive to changes in irrigation timing than ET. The calibration process with remotely-sensed ET assisted the process. However, it remains essential to achieve flow data to achieve the correct combination of managerial variables regarding irrigation interval and timing.

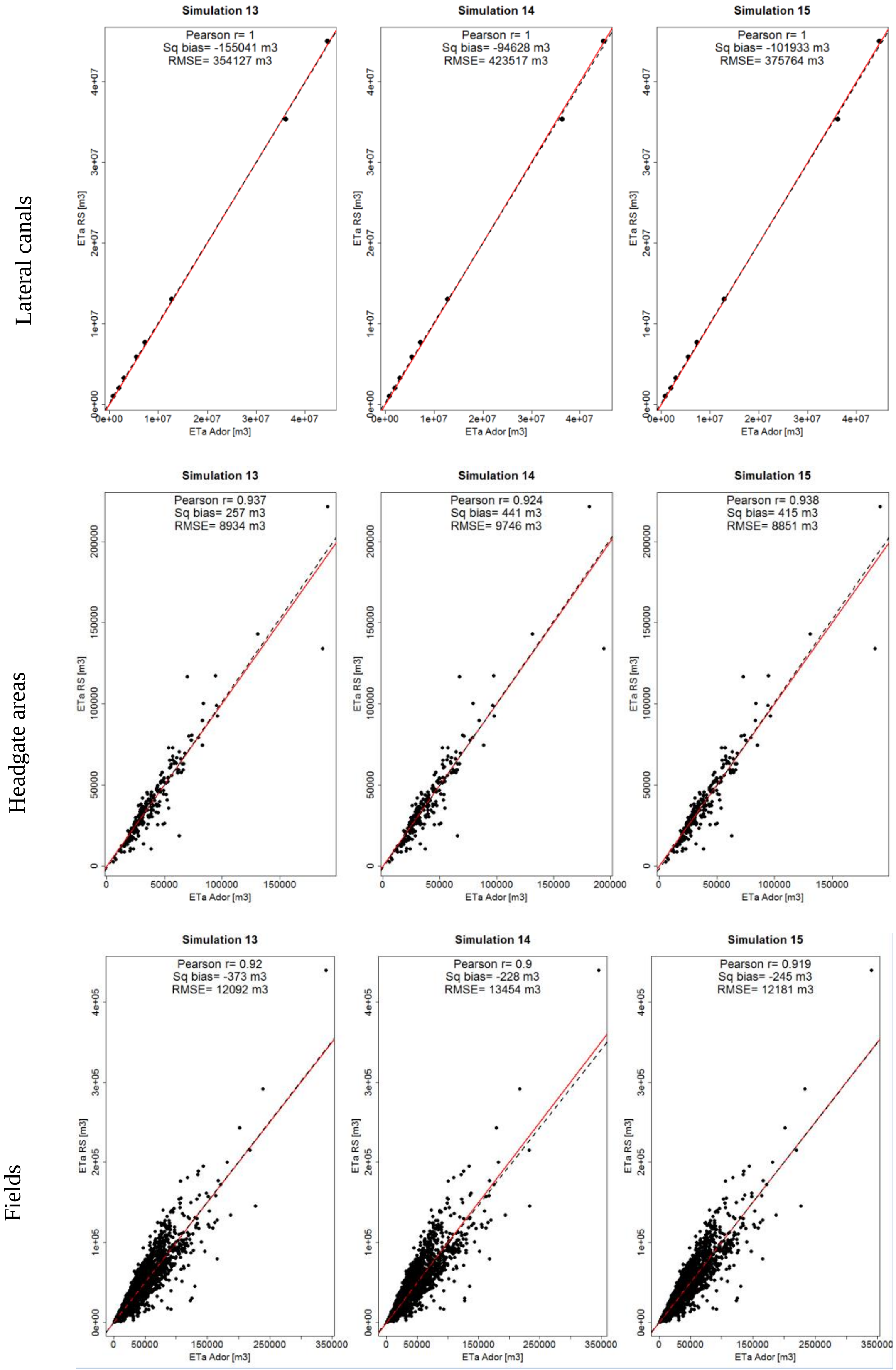


Figure 4-5. Regression analysis of actual ET from Ador and remote sensing at different spatial scales of the irrigation system.

Table 4-3.

Pearson's correlation coefficient for calibration and validation data sets comparing simulated ET and water use, with remotely-sensed ET and water use estimated with flow gauges.

Simulation #	Main canals monthly ET		Water use
	West (calibration)	Others (validation)	
Simulation #13	0.981	0.981	0.928
Simulation #15	0.981	0.981	0.930

The results of simulation #15 are shown in Figures 4-6 and 4-7 for monthly actual ET and water use. Both the results from the calibration dataset (West canal) and validation dataset (other canals) are shown in Figure 4-6. The results between remote sensing data and Ador simulations show good correspondence for each month. The only exception is the data for September, which showed a higher value for remote sensing data compared to Ador. This might be associated with a missed alfalfa cutting, which was likely not observed in the remote sensing data due to the gap in August, as was mentioned previously.

The good correlation of the Ador simulation ET as is presented in both Table 4-3 and Figure 4-6, is an indication of the capability to simulation actual ET at the district level. Ador makes use of Cropwat for the simulation of crop water use and production. Results show that this approach of data assimilation from remote sensing with a crop model is effective at the district level. The development stages and other factors are incorporated successfully in the simulation throughout the growing season.

The result for water use, as shown in Figure 4-7, displays reasonable resemblance between simulated water use and that approximated by flow data. The pattern throughout the season is similar, but the peak of water use is higher for the Ador simulations. The water use from flow gage data shows a lower peak but is spread over several months, in particular during the months after the peak demand in August to October. This might be due to the size of the area, which causes errors in the estimation of water use flow gages. Additionally, choices for irrigation interval and duration might be different during peak irrigation in July, with shorter intervals applied to avoid crop water stress. The fixed water delivery schedule sets the irrigation intervals, but farmers can make the decision to skip a scheduled irrigation event during the early or late crop growth season. Additionally, the irrigation district has some retention time to buffer peak water demands by storing water in the root zone and making use of capillary rise. This buffering capacity might explain the reason for a flatter and broader peak for the water use as estimated by flow data.

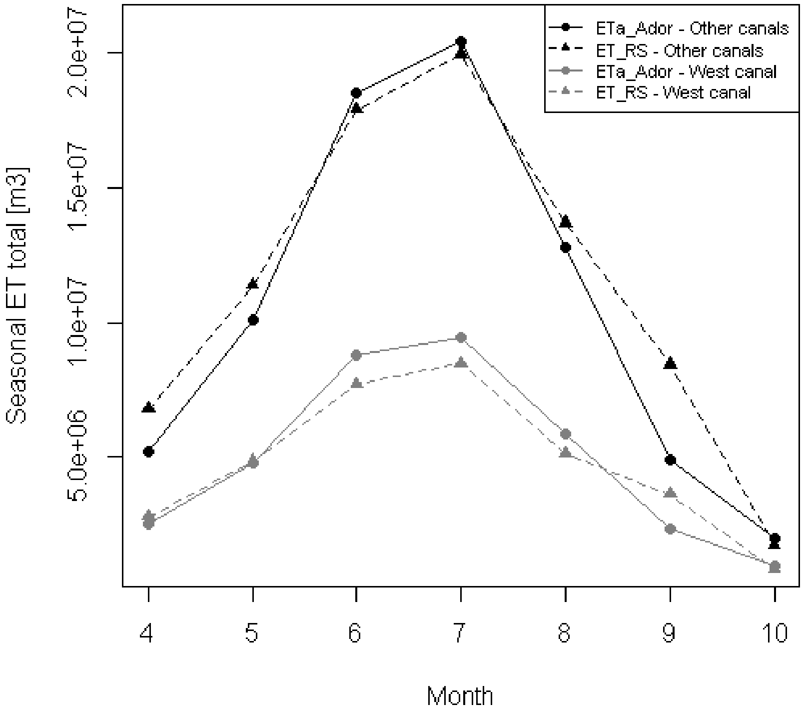


Figure 4-6. Results for simulated (#15) and remotely sensed ET from West canal (calibration) and other main canals (validation).

Ador simulation irrigation performance

Ultimately the irrigation performance is the relevant output dataset for the different stakeholders. Despite the best attempts to achieve accurate results, there remains some unavoidable uncertainty in the simulation results as was pointed out in the previous sections. Therefore, these results should be assessed with a level of scrutiny and not be taken as absolutes but a good means for comparison within the irrigation system and assist in further discussions with local farmers and canal managers.

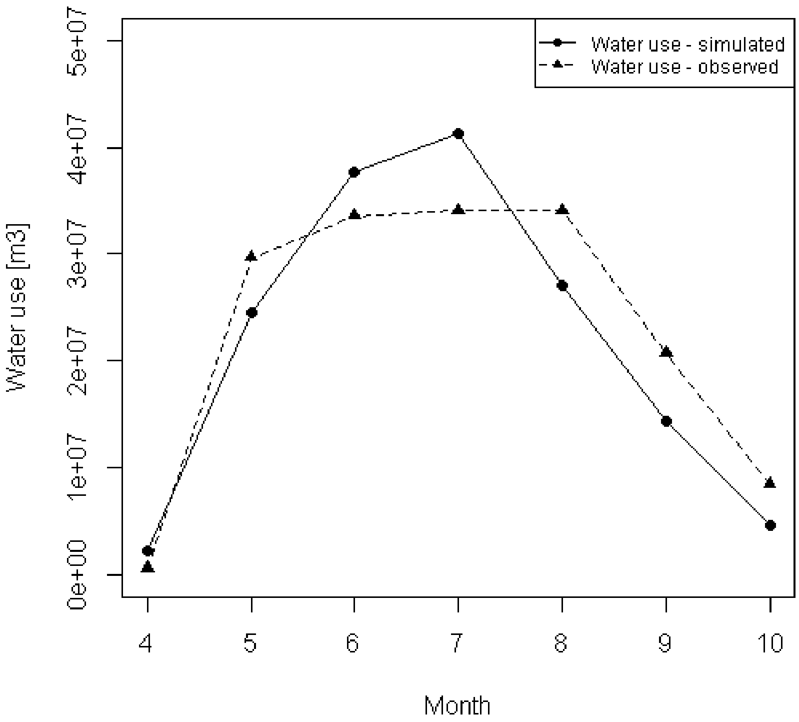


Figure 4-7. Results for water use from model simulation (#15) and approximated with flow data.

The application efficiency in Figure 4-8 shows large variation in the irrigation system, with exceptionally low values in the downstream (Southern) areas. These areas have some issues with saline soils due to the Salt Lake being in the vicinity, which causes salty groundwater to be closer to the root zone. Different irrigation management strategies might be necessary to cope with the salinity. Additionally, some plots close to the rivers (see Appendix D) especially in the Northern part of the district show lower application efficiency. These areas are sandier and have therefore a higher infiltration rate. The irrigation scheduling imposed by the canal company is usually not adapted to sandier soils therefore the flow rate and irrigation timing might not be the best combination for these plots. These lower application efficiencies indicate that irrigation events are not sufficient to sustain crop water requirements according to simulations. Potentially most of the irrigation water applied ends up as runoff from the field or percolates to groundwater.

The distribution uniformity as shown in Figure 4-8, displays low values in the areas that are associated with the Ho and Co heavier soil types due to a higher clay content. Findings in the previous sections showed that Ho and Co have a lower infiltration rate and are characterized as heavier soils. Farmers frequently observe that infiltration depths are not uniform in these fields. In particular maize fields displayed a large variability in crop height along the length of the field with higher stalks at the top and bottom ends of the field and the middle showing shorter stalks. The bottom end receives more water due to the block-ends installed to capture the drainage.

Overall Figure 4-8 indicates several areas where irrigation management can be improved. However, improvements in water delivery scheduling will require a collective decision. Currently the irrigation schedule is set according to the alfalfa rotations and is more applicable to the loamier soils, which represents the majority of the district. However, potential improvements of the district can be achieved if irrigation scheduling is adapted to enable more efficient irrigation for sandier or clayey soils. These modifications should be analyzed with a water accounting approach, however, to determine the change in the district's water balance and the influence on the surrounding (mainly downstream) environment.

The yield reduction in Figure 4-9 showed some variability within the irrigation system, with high yield reduction occurring mostly in the downstream areas. These areas seem to coincide partially with the low application efficiency areas from Figure 4-8. Additionally, it is expected that more water stress will occur at the tail end of the canal system. As was mentioned in the introduction, long canal systems experience a delay in water flow adjustments due to the travel time lag. If downstream areas request more water, there might be a lag time of a few days causing crop water stress to occur.

Figure 4-10 displays the water productivity for the three major crops: corn, grasses (i.e. alfalfa) and wheat. Water productivity was defined in the equation 3 as the crop production per volume unit of irrigation water applied. Corn production was simulated as biomass instead of harvestable product, which displays higher values for production because it is a larger crop. Several areas in the South and Eastern part of the district show higher water productivities. However, lower water productivity values are also widespread throughout the valley indicating the diversity of irrigation management between farms. The low water productivity rates are a sign of irrigation water not being used effectively by the crops and might be a sign of over-irrigation. These findings need to be confirmed with field observations and input from farmers before measures can be discussed to improve water productivity. Additionally, the explanations for lower water productivity values can be diverse and can be contributed by on-farm management and the water delivery service of the canal company. However, the results show that improvements can be made to potentially increase production and achieve water savings simultaneously.

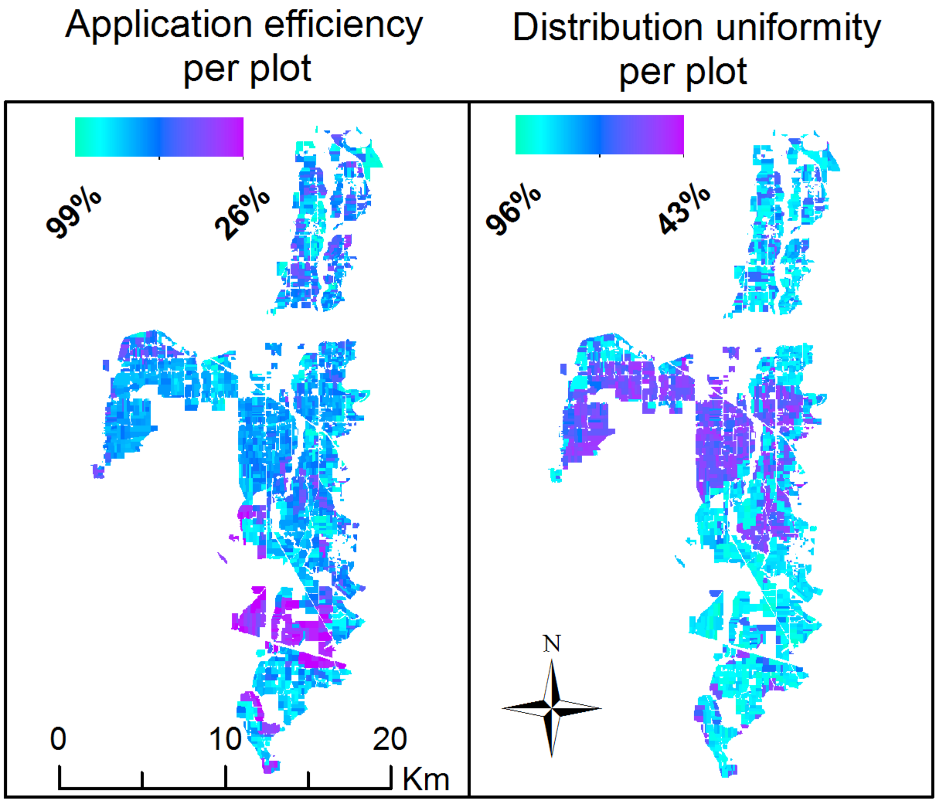


Figure 4-8. Application efficiency and distribution uniformity for 2013 growing season as simulated by Ador.

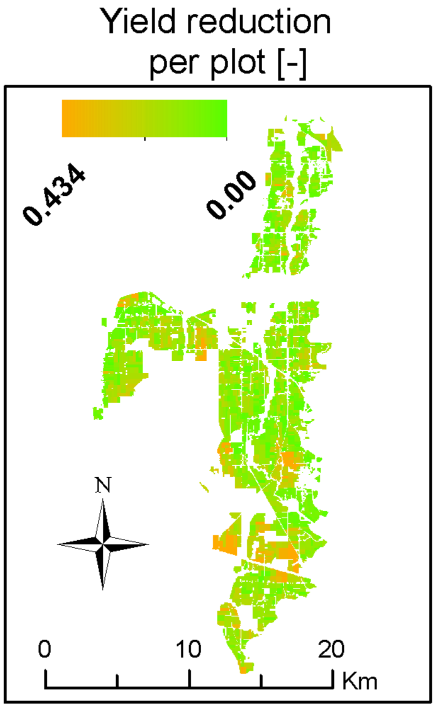


Figure 4-9. Yield reduction for 2013 growing season as simulated by Ador.

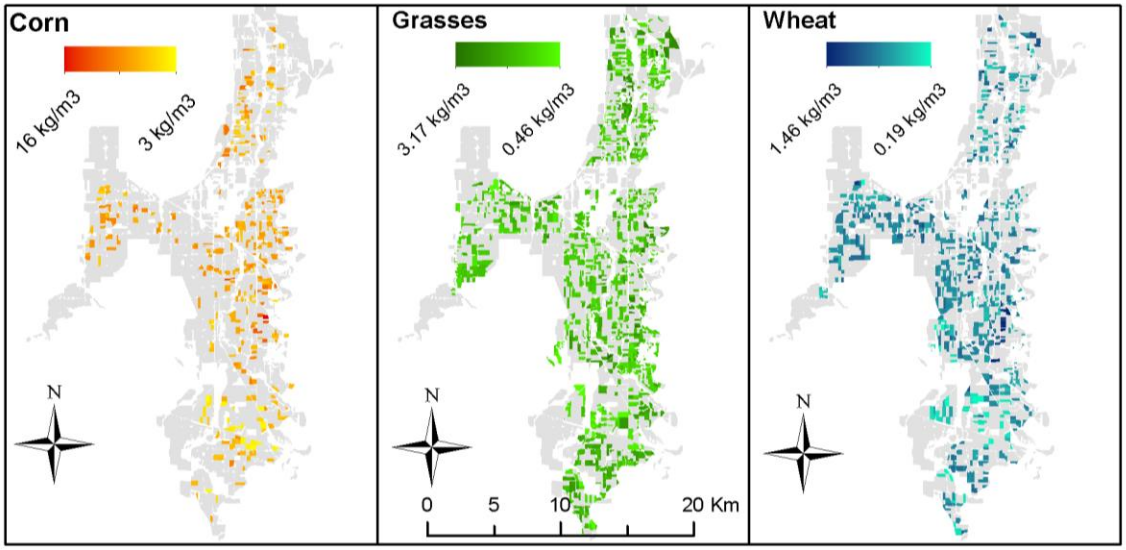


Figure 4-10. Water productivity for corn, grasses (i.e., alfalfa), and wheat for 2013 growing season as simulated by Ador.

The findings of water delivery capacity (WDC) are shown in Figure 4-11 for each headgate area. This is a useful measure to identify areas under pressure during the peak crop water demand month (namely July). The areas classified with a WDC below 100% have a larger water demand compared to the conveyance capacity appointed to that headgate. Local farmers indicated that in those situations water is diverted from neighboring headgates to irrigate the fields. Several farmers have fields in various locations and under different headgate areas, therefore these farmers can be flexible in switching to other headgates. Fortunately, there are also several headgate areas experiencing a WDC larger than 100% so there is the capacity to buffer over-allocations with other headgates. However, this WDC map is a useful output for discussion with district managers and local farmers about the current schedule and flow rates. Changes to the irrigation scheduling might be useful for future seasons. Currently, farmers within low WDC headgate areas are capable of negotiating a solution. However, if dry years occur more frequently conflicts might occur regarding the division of water flows within the headgate areas. It is therefore recommendable to make arrangements before such a situation can escalate.

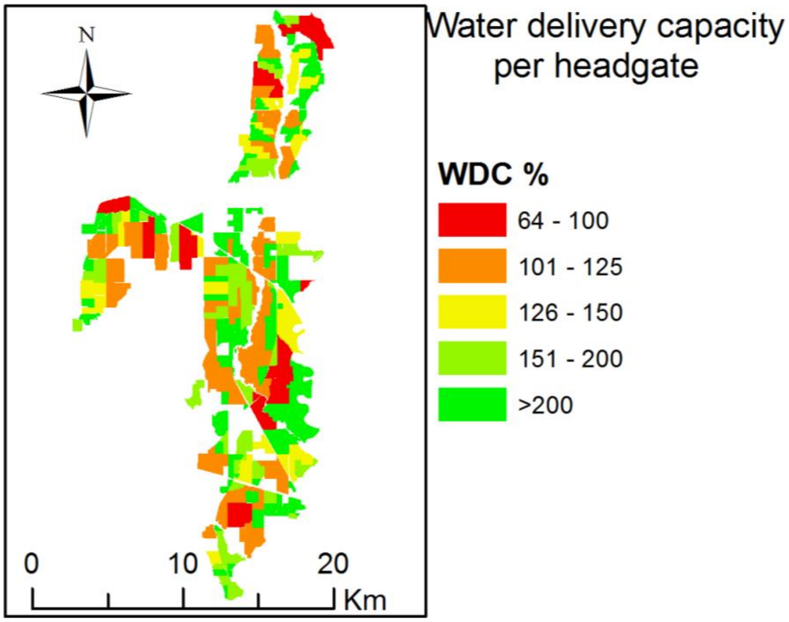


Figure 4-11. Water delivery capacity for each head gate during 2013 growing season as simulated by Ador.

4.5 Conclusions

This study demonstrated a successful implementation of data assimilation using remote sensing data in an irrigation system model. Some field observations of irrigation events were conducted to obtain data for making initial assumptions characterizing the water management in the irrigation district. Additionally, field evaluations of irrigation events were conducted to get infiltration parameters for each major soil type in the area. However, achieving a sufficient level of certainty with fieldwork for simulating a large irrigation district is time-consuming and expensive. This has resulted in a limited amount of research studies conducted to evaluate the operations of an existing irrigation system.

Data assimilation with remotely-sensed ET estimations was used to aid and improve the modelling process. Most studies in data assimilation have focused on field scale or hydrological models, therefore this study is unique because it applies data assimilation as input to an irrigation system simulation model. Ador simulations are capable of tracking or predicting water flow at the field and canal scale, which enables the evaluation of irrigation performance both at the plot and system scale. The data assimilation process used for this study was the re-adjustment approach, which incorporates remote sensing data in the calibration process. In addition, a remote sensing dataset was used for validation of the model. The findings of the data assimilation process indicate the improvements made at a spatial scale to enhance model simulations. Additionally, this method provided a supplemental dataset for calibration and selecting the irrigation management that showed better agreement with observations. The combination of irrigation management parameters that showed the best fit with remote sensing data at different spatial scales were selected. It was found that irrigation interval had a larger impact on the simulated ET results than irrigation timing. Additionally, the calibration with water use data showed that irrigation management parameters had more influence on water use than on ET. Therefore, it remains necessary to use a combination of ET and water use data to calibrate the simulation model.

The actual ET from the validated simulation showed good correspondence with remotely-sensed ET during the growing season. This shows the capability of the Cropwat equations, which was used in the Ador model, for estimating actual crop ET at a district scale. The method of coupling remote sensing with a

Cropwat-based model achieved good results and simulated crop development agreeably during the growing season.

The simulated water use during the growing seasons showed differences considering the magnitude of peak water use. The simulated water use was higher than the water use approximated by flow gages. A possible explanation for this is the buffer capacity of the irrigation district to store water in the soil and therefore cause a lag time in flow measurement of drainage water compared to the simulated water use. However, field measurements are required to confirm this observation.

The final output of the Ador model gave insight on the irrigation system performance both at plot level and at headgate areas. The application efficiency and yield reduction were found to be lower in the downstream areas. This can be explained by the salinity issues in those areas as well as reduced water deliveries causing crop water stress at the end of the long canal system. The water productivity at these locations was lower in these areas when compared to the rest of the district. Distribution uniformity was found to have lower values on heavier soils due to low infiltration rates. Potential improvements in water delivery scheduling can be made to adapt to these heavier soils. Either flow rates or irrigation times can be adapted to these sections. Additionally, the sandier soils close to the rivers showed low application efficiency, due to the high infiltration rates. The water delivery schedule is mainly focused on the loamier soils and alfalfa fields, which is the majority of the region. However, changes in the delivery schedule to adapt to the sandier and clayey soils can lead to improvements of both irrigation performance and crop productivity.

The water delivery capacity indicated several headgate areas that are under pressure during the peak irrigation month. Currently the solution mentioned by the farmers is to negotiate within the headgate area or make use of a neighboring headgate area which is not under pressure. However, this can potentially lead to conflict situations especially during an extreme drought year. It is recommendable to assess the water delivery schedule and make improvements to avoid stressed headgate areas.

These findings on irrigation performance are of importance for starting discussions on irrigation scheduling in the district. They provide insights at different scales of the current irrigation management and the limitations of the current water delivery schedule. It should be noted that there is a level of uncertainty in the output of the Ador model. Errors can occur due to combining imperfect datasets. Yet this approach also dissolves some uncertainty due to the aggregation of datasets. The data assimilation method has demonstrated to be a cost-effective method to calibrate and validate the model, which is required to evaluate the operation of a large irrigation system. This can potentially provide essential insights for several irrigation districts and accelerate the process of assessing current irrigation management. Such findings are needed for starting discussions with local water managers.

References

Al Zayed, I.S., Elagib, N.A., Ribbe, L., Heinrich, J., 2015. Spatio-temporal performance of large-scale Gezira Irrigation Scheme, Sudan. Agric. Syst. 133, 131–142. doi:10.1016/j.agsy.2014.10.009

Allen, R.G., Irmak, A., Trezza, R., Hendrickx, J.M.H., Bastiaanssen, W., Kjaersgaard, J., 2011a. Satellite-based ET estimation in agriculture using SEBAL and METRIC. Hydrol. Process. 25, 4011–4027. doi:10.1002/hyp.8408

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011b. Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agric. Water Manag. 98, 899–920. doi:10.1016/j.agwat.2010.12.015

Allen, R.G., Tasumi, M., Morse, A., Trezza, R., Wright, J.L., Bastiaanssen, W., Kramber, W., Lorite, I., Robison, C.W., 2007a. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications. J. Irrig. Drain. Eng. 133, 395–406. doi:10.1061/(ASCE)0733-9437(2007)133:4(395)

Allen, R.G., Tasumi, M., Trezza, R., 2007b. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Model. J. Irrig. Drain. Eng. 133, 380–394. doi:10.1061/(ASCE)0733-9437(2007)133:4(395)

Ambast, S.K., Keshari, A.K., Gosain, A.K., 2002. Satellite remote sensing to support management of irrigation systems: concepts and approaches. Irrig. Drain. 51, 25–39.

Anderson, M.C., Allen, R.G., Morse, A., Kustas, W.P., 2012. Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources. Remote Sens. Environ. 122, 50–65. doi:10.1016/j.rse.2011.08.025

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–9. doi:10.1038/nature04141

Bastiaanssen, W.G., Molden, D.J., Makin, I.W., 2000. Remote sensing for irrigated agriculture: examples from research and possible applications. Agric. Water Manag. 46, 137–155. doi:10.1016/S0378-3774(00)00080-9

Bastiaanssen, W.G.M., Allen, R.G., Droogers, P., D'Urso, G., Steduto, P., 2007. Twenty-five years modeling irrigated and drained soils: State of the art. Agric. Water Manag. 92, 111–125. doi:10.1016/j.agwat.2007.05.013

Boegh, E., Thorsen, M., Butts, M., Hansen, S., Christiansen, J., Abrahamsen, P., Hasager, C., Jensen, N., van der Keur, P., Refsgaard, J., Schelde, K., Soegaard, H., Thomsen, A., 2004. Incorporating remote sensing data in physically based distributed agro-hydrological modelling. J. Hydrol. 287, 279–299. doi:10.1016/j.jhydrol.2003.10.018

Bos, M., 1997. Performance indicators for irrigation and drainage. Irrig. Drain. Syst. 11, 119–137.

Bos, M.G., Burton, M.A., Molden, D.J., 2005. Irrigation and drainage performance assessment - Practical guidelines. CABI Publishing.

Burt, C., Clemmens, A., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Eng. 123, 423–442.

Burt, C.M., Styles, S.W., 2000. Irrigation district service in the Western United States. J. Irrig. Drain. Eng. 126, 279–282.

Clemmens, A.J., 2006. Improving irrigated agriculture performance through an understanding of the water delivery process. Irrig. Drain. 55, 223–234. doi:10.1002/ird.236

Clemmens, A.J., Molden, D.J., 2007. Water uses and productivity of irrigation systems. Irrig. Sci. 25, 247–261. doi:10.1007/s00271-007-0067-y

Cuenca, R., Ciotti, S., Hagimoto, Y., 2013. Application of Landsat to Evaluate Effects of Irrigation Forbearance. Remote Sens. 5, 3776–3802. doi:10.3390/rs5083776

Doorenbos, J., Kassam, A.H., 1979. FAO Irrigation and Drainage Paper No.33 Yield response to water. Food and Agriculture Organization of the United Nations, Rome.

Droogers, P., Bastiaanssen, W., 2002. Irrigation Performance using Hydrological and Remote Sensing Modeling. J. Irrig. Drain. Eng. 128, 11–18. doi:10.1061/(ASCE)0733-9437(2002)128:1(11)

Fischer, a., Kergoat, L., Dedieu, G., 1997. Coupling satellite data with vegetation functional models: Review of different approaches and perspectives suggested by the assimilation strategy. Remote Sens. Rev. 15, 283–303. doi:10.1080/02757259709532343

Gonzalez-Dugo, M.P., Neale, C.M.U., Mateos, L., Kustas, W.P., Prueger, J.H., Anderson, M.C., Li, F., 2009. A comparison of operational remote sensing-based models for estimating crop evapotranspiration. Agric. For. Meteorol. 149, 1843–1853. doi:10.1016/j.agrformet.2009.06.012

Gowda, P.H., Chavez, J.L., Colaizzi, P.D., Evett, S.R., Howell, T. a., Tolk, J. a., 2008. ET mapping for agricultural water management: present status and challenges. Irrig. Sci. 26, 223–237. doi:10.1007/s00271-007-0088-6

Heermann, D.F., Solomon, K.H., 2007. Efficiency and uniformity, in: Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L. (Eds.), Design and Operation of Farm Irrigation Systems. ASABE, pp. 108–119.

Immerzeel, W.W., Gaur, A., Zwart, S.J., 2008. Integrating remote sensing and a process-based hydrological model to evaluate water use and productivity in a south Indian catchment. Agric. Water Manag. 95, 11–24. doi:10.1016/j.agwat.2007.08.006

Ines, A., Droogers, P., 2002. Inverse modeling to quantify irrigation system characteristics and operational management. Irrig. Drain. Syst. 16, 233–252.

Ines, A.V.M., Das, N.N., Hansen, J.W., Njoku, E.G., 2013. Assimilation of remotely sensed soil moisture and vegetation with a crop simulation model for maize yield prediction. Remote Sens. Environ. 138, 149–164. doi:10.1016/j.rse.2013.07.018

Ines, A.V.M., Honda, K., Das Gupta, A., Droogers, P., Clemente, R.S., 2006. Combining remote sensing-simulation modeling and genetic algorithm optimization to explore water management options in irrigated agriculture. Agric. Water Manag. 83, 221–232. doi:10.1016/j.agwat.2005.12.006

Jensen, M.E., 2007. Beyond irrigation efficiency. Irrig. Sci. 25, 233–245. doi:10.1007/s00271-007-0060-5

Knox, J.W., Kay, M.G., Weatherhead, E.K., 2012. Water regulation, crop production, and agricultural water management—Understanding farmer perspectives on irrigation efficiency. Agric. Water Manag. 108, 3–8. doi:10.1016/j.agwat.2011.06.007

Kobayashi, K., Salam, M.U., 2000. Comparing simulated and measured values using mean squared deviation and its components. Agron. J. 92, 345–352. doi:10.2134/agronj2000.922345x

Lecina, S., Neale, C.M.U., Merkley, G.P., Dos Santos, C.A.C., 2009. Increasing field work productivity in irrigation evaluation processes through the use of combined irrigation models, in: World Environmental and Water Resources Congress. ASCE, pp. 4250–4262.

Lecina, S., Neale, C.M.U., Merkley, G.P., Dos Santos, C.A.C., 2011. Irrigation evaluation based on performance analysis and water accounting at the Bear River Irrigation Project (U.S.A.). Agric. Water Manag. 98, 1349–1363. doi:10.1016/j.agwat.2011.04.001

Lecina, S., Playán, E., 2006a. Model for the Simulation of Water Flows in Irrigation Districts I : Description. J. Irrig. Drain. Eng. 132, 310–321.

Lecina, S., Playán, E., 2006b. Model for the Simulation of Water Flows in Irrigation Districts II : Application. J. Irrig. Drain. Eng. 132, 322–331. doi:10.1061/(ASCE)0733-9437(2006)132:4(310)

Lenton, R., 2014. Irrigation in the Twenty-First Century: Reflections on Science, Policy and Society. Irrig. Drain. 63, 154–157. doi:10.1002/ird.1844

Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A., 2014. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. Agric. Water Manag. 146, 84–94. doi:10.1016/j.agwat.2014.07.012

Merriam, J.L., Keller, J., 1978. Farm irrigation system evaluation: A guide for management. Logan, UT.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agric. Water Manag. 97, 528–535. doi:10.1016/j.agwat.2009.03.023

Molden, D., Sakthivadivel, R., Perry, C., de Fraiture, C., Kloezen, W.H., 1998. Indicators for comparing performance of irrigated agricultural systems - Research report no.20.

Moulin, S., Bondeau, A., Delecolle, R., 1998. Combining agricultural crop models and satellite observations: From field to regional scales. Int. J. Remote Sens. 19, 1021–1036. doi:10.1080/014311698215586

Olioso, a., Inoue, Y., Ortega-FARIAS, S., Demarty, J., Wigneron, J.-P., Braud, I., Jacob, F., Lecharpentier, P., OttlÉ, C., Calvet, J.-C., Brisson, N., 2005. Future directions for advanced evapotranspiration modeling: Assimilation of remote sensing data into crop simulation models and SVAT models. Irrig. Drain. Syst. 19, 377–412. doi:10.1007/s10795-005-8143-z

Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manag. 108, 39–51. doi:10.1016/j.agwat.2011.08.022

Pereira, L.S., Oweis, T., Zairi, A., 2002. Irrigation management under water scarcity. Agric. Water Manag. 57, 175–206. doi:10.1016/S0378-3774(02)00075-6

Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. Agric. Water Manag. 96, 1517–1524. doi:10.1016/j.agwat.2009.05.005

Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manag. 80, 100–116. doi:10.1016/j.agwat.2005.07.007

Sehlke, G., Jacobson, J., 2005. System dynamics modeling of transboundary systems: the Bear River basin model. Ground Water 43, 722–730. doi:10.1111/j.1745-6584.2005.00065.x

Senay, G.B., Leake, S., Nagler, P.L., Artan, G., Dickinson, J., Cordova, J.T., Glenn, E.P., 2011. Estimating basin scale evapotranspiration (ET) by water balance and remote sensing methods. Hydrol. Process. 25, 4037–4049. doi:10.1002/hyp.8379

Singh, R.K., Liu, S., Tieszen, L.L., Suyker, A.E., Verma, S.B., 2012. Estimating seasonal evapotranspiration from temporal satellite images. Irrig. Sci. 30, 303–313. doi:10.1007/s00271-011-0287-z

Small, L.E., Svendsen, M., 1992. A framework for assessing irrigation performance (No. 1), IFPRI Working Papers on Irrigation Performance. Washington D.C.

Taghvaeian, S., Neale, C.M.U., 2011. Water balance of irrigated areas: a remote sensing approach. Hydrol. Process. 25, 4132–4141. doi:10.1002/hyp.8371

Turral, H., Svendsen, M., Faures, J.M., 2010. Investing in irrigation: Reviewing the past and looking to the future. Agric. Water Manag. 97, 551–560. doi:10.1016/j.agwat.2009.07.012

USDA-NASS, 2010. Field Crops - Usual Planting and Harvesting Dates, National Agricultural Statistics Service. doi:October 2010

Walker, W.R., 2003. Surface Irrigation Simulation, Evaluation and Design - Guide and Technical Documentation. Utah State University, Logan, UT.

Walker, W.R., Prestwich, C., Spofford, T., 2006. Development of the revised USDA-NRCS intake families for surface irrigation. Agric. Water Manag. 85, 157–164. doi:10.1016/j.agwat.2006.04.002

Zaccaria, D., Oueslati, I., Neale, C.M.U., Lamaddalena, N., Vurro, M., Pereira, L.S., 2010. Flexible delivery schedules to improve farm irrigation and reduce pressure on groundwater: a case study in southern Italy. Irrig. Sci. 28, 257–270. doi:10.1007/s00271-009-0186-8

CHAPTER V

MODEL SIMULATIONS OF DIFFERENT WATER DELIVERY STRATEGIES TO IMPROVE THE WATER PRODUCTIVITY OF AN IRRIGATION DISTRICT[3]

Abstract

The agricultural sector is pressured to maintain or reduce their water use whilst increasing food production to fulfill demands of a growing global population. Increasing the water productivity of agricultural areas is seen as the best answer for these issues. This study conducts several simulations of water delivery strategies to improve water productivity at district and farm scale. Strategies consist of changing irrigation times, frequencies and flow rate. Optimizing the irrigation times provided shorter intervals between irrigation events and introduced more flexibility for the farmers to decide on the best timing for irrigation events. Major improvements in irrigation performance and water productivity were achieved with the changes in water delivery. Water savings of up to 11.6% were achieved compared with the current situation. Additionally, water productivity increased up to 17% with alternative strategies. There were no substantial differences found between alternative strategies concerning management changes and those incorporating infrastructure changes. This indicates that simple management changes can achieve similar benefits in comparison with infrastructure changes to expand the flow rate.

5.1 Introduction

Water scarcity is a growing issue worldwide and especially impacts agricultural areas in arid and semi-arid regions. Agriculture in these regions is dependent on irrigation during the growing season. However, sources of freshwater are becoming limited and unreliable. Future climate scenarios expect that an increase of temperature will lead to alterations in runoff patterns particularly in mountainous areas where snowmelt is the main source for lakes and rivers. The winters will be shorter resulting in less snow accumulation and an earlier peak of spring runoff (Barnett et al., 2005). Additionally, the growing global population increases

---

[3] Co-authored with Dr. Christopher M.U. Neale and Dr. Sergio Lecina

food demands and therefore requires a higher production from the agricultural sector. With the limitations of water resources, agricultural areas are expected to increase productivity without increasing their water use (Rijsberman, 2006; Turral et al., 2010). Focus needs to be laid on the water productivity of agricultural areas, which is the crop yield or biomass achieved for the volume of water used or consumed (Pereira et al., 2012; Perry et al., 2009).

Water productivity can be studied at different scales within the irrigation system. At the plant scale, crop physiologists consider water productivity to be the amount of carbon assimilation per unit of transpired water (Molden et al., 2010). At field scale water productivity is expressed with different terms in the nominator and denominator varying between biomass, crop yield to economic value in the nominator and water consumption expressed as transpiration or evapotranspiration (ET) to applied irrigation depth in the denominator (Pereira et al., 2012; Perry et al., 2009; Playán and Mateos, 2006). Within an irrigation district, individual fields can display considerable variability due to the differences in farm practices such as fertilizer and irrigation management, pest and disease control and several other factors (Molden et al., 2010). The choice of crop variety can also cause variations in crop yields (Pereira et al., 2012). Additionally, the timing and duration of water delivery from the canal system to the fields has an impact on the crop production (Clemmens, 2006; Pereira et al., 2012).

Farmers usually do not have control of the water delivery service, which is the responsibility of a centralized agency such as a canal company. The water delivery scheduling can be organized in an on-demand system, arranged or a rigid rotation schedule (Bos et al., 2005). These differ in the level of flexibility for the timing of water delivery to the fields. However, it has been observed that even districts practicing an on-demand system, which is considered more flexible, have difficulty with the timing of the water delivery (Burt and Styles, 2000). Flexibility of water delivery is desirable for the farmers, because they can control the irrigation application to their fields and manage their farms as an integrated unit without restrictions made by a fixed water delivery scheduling (Merriam et al., 2007). Soil infiltration rates and crop water requirements change throughout the growing season and it is recommended to adapt to these changes in water demands to avoid poor irrigation performance (Burt and Styles, 2000; Jensen, 2007; Merriam et al., 2007). Flexibility of the water delivery is determined by timing, duration and flow rate of water delivery to the farm fields (Clemmens and Molden, 2007). Several studies have been reported analyzing the potential of water savings when adjusting the frequency and duration of water delivery. Zaccaria et al. (2010) reported a study conducted in Southern Italy with model simulations and farmer interviews. Farmers indicated that they prefer applying less irrigation water during an irrigation event, but have a higher frequency of water delivery thereby fulfilling crop water requirements more adequately during the growing season. Another study conducted by Tromboni et al. (2014) in Northeast Italy indicated the impact on the water balance with different scenarios of irrigation frequency and duration. The scenario with a higher frequency of irrigation events resulted in more water being used by the plants and less drainage from the field. Khan and Abbas (2007) conducted a study with the SWAP model and upscaling with GIS, to quantify potential water savings by changing from surface irrigation to pressurized irrigation. These findings indirectly indicate the advantages for crop production with a change of irrigation frequency, duration or method, by analyzing the water balance and irrigation efficiency at field scale. The potential advantages of water delivery changes for increasing water productivity have been described in conceptual studies. For example, it is reported that timing of water delivery is especially important for several high-value crops, or for certain crops during the flowering or fruit set stage (Clemmens and Molden, 2007). Additionally, water productivity at both the district and farm scale can be increased if distribution uniformity is improved (Clemmens, 2006). However, studies specifically quantifying changes in water productivity at the irrigation district scale influenced by water delivery scheduling alterations have been limited.

Clemmens (2006) mentions the challenge of connecting on-farm irrigation performance to the water delivery service. On-farm irrigation performance, such as water productivity, is influenced by the quality of the water delivery service in an irrigation district, which is assessed with the reliability, equity and flexibility of service to the fields. The impact of both the uniformity and flexibility of water delivery on crop production needs to be understood. This understanding can enable improvements in water productivity at irrigation district scale. Playán and Mateos (2006) emphasize that improvements in irrigation performance does not necessarily need technical changes in infrastructure as has been done traditionally. In many cases, improvements can be achieved by making management changes in the scheduling, which is better adapted to crop water requirements. A suggested change of management is introducing flexibility of water delivery at the tertiary canal sections, which is the distribution of water to the farm fields. This can be done by increasing the storage, which buffers the peak water demand periods (Merriam et al., 2007). Another suggestion for improvements in water delivery is implementing control at the secondary level of the canal system, and providing flexibility of water delivery at the tertiary level (Clemmens, 2006). However, this requires a hydraulic analysis to determine the capacity of canals to compensate with fluctuating water flows. Additionally, improvements that can be achieved by changing the scheduling need to be quantified. A study by Pereira et al. (2007) conducted in an irrigation district in China, showed the potential improvements that can be achieved by adapting the irrigation scheduling and maximizing yields. The importance of making changes in both the on-farm irrigation management and the scheduling at district scale was stressed in this exercise, as both are interlinked and necessary for the new strategies to succeed (Clemmens and Molden, 2007). For any changes to the irrigation district, a water balance analysis is also required to determine the impact on the surrounding environment (Contor and Taylor, 2013). It is of importance to determine changes in water flows from the irrigation district when choosing a new irrigation strategy. Some strategies that can potentially achieve good irrigation performance might be less beneficial at a basin scale (Perry et al., 2009; van Halsema and Vincent, 2012).

The objective of this paper is to quantify potential improvements in water productivity that can be achieved by making changes in the water delivery schedule of a large irrigation district in Northern Utah, mostly under surface irrigation and a fixed water delivery schedule. The first strategy that will be analyzed is the optimal combination of irrigation duration and frequency. The second strategy is the changes in flow rate delivered to the headgate areas, which is a group of fields irrigated using the same ditch. Improvements in water productivity at both the farm and irrigation district scale are analyzed to determine potential benefits of water delivery changes.

5.2 Materials and methods

Study area

This study is conducted in the district known as the Bear River Canal Company, which is located in Northern Utah, as indicated on the map in Appendix A. It is situated within the Bear River Basin, which has its source in the Uintah Mountains of Utah; flows into Wyoming, Idaho and back into Utah where it terminates in the Great Salt Lake. Bear Lake is the major reservoir for the Bear River Canal Company, which is fed by spring snowmelt. The major crop types in this irrigation area are alfalfa and pasture, wheat and corn. The soil types are indicated in Appendix C, with the major soil type being silty loam soils. A few areas consist of a heavier soil type, referred to as silty clay loam. Areas located close to the river are sandier as indicated on the soils map.

The canal company diverts water from the Bear River at Cutler dam and conveys the water to the farmers through a canal system as indicated in Appendix D. There are three main canals on the Western side of the Bear River, namely West, East and Central canal. On the Eastern side of the Bear River, another diversion from Cutler dam feeds the Hammond canal. These canals have a few secondary canals, but most of the headgates take water directly from the main canals. The headgates are operated by the farmers and convey irrigation water through ditches to several farm fields. These headgates are managed with a fixed rotation schedule, according to the water rights of the irrigators. Ditchriders appointed to each main canal are responsible for checking the headgates and ensuring that they are operated according to the schedule. The fixed rotation schedule provides limited flexibility. Therefore, this canal company provides an interesting case study to investigate the potential impact of changing the water delivery scheduling.

The region of the Bear River Canal Company experiences cycles of wet and dry years according to snow accumulation in the mountains. Future climate scenarios predict that this region can expect earlier spring runoff and less snow accumulation (Barnett et al., 2005). This will impact the water use of the region especially agricultural areas. Additionally, the urban areas around Salt Lake City have been rapidly expanding and increase water demands. The Bear River Canal Company and local farmers frequently discuss these developments and are searching for strategies to cope with a reduced and fluctuating future water availability. These issues make a study of water delivery strategies relevant for the local stakeholders and a suitable case study for this paper.

Ador irrigation system simulation model

The Ador irrigation system simulation model is selected to be well suited for this study due to its capability of simulating both on-farm irrigation events and water flow in the canal system. The Ador model was developed and published by Lecina and Playán (2006b). It has been applied and validated in several irrigation districts such as the Bardenas located in Spain (Lecina and Playán, 2006a) and a section of the Bear River Canal Company (Lecina et al., (2011). These studies indicate the applicability of using the Ador model for simulating an irrigation district and the capability of quantifying potential improvements of the irrigation district. The model consists of several modules: Ador-surface, simulating on-farm surface irrigation events; Ador-crop, simulating crop growth based on Cropwat; Ador-network, simulating water flows in the canal network; and Ador-decision, simulating management choices. Ador-decision is a useful module for simulating irrigation planning and adjusting management choices to improve the irrigation performance. It is limited to decisions made regarding the water balance, such as irrigation time, which is the duration of one irrigation event. The decision module does not incorporate other farm decisions, such as fertilizer application or crop variety selection. It is also challenging to incorporate the various decisions made by each individual farmer (Lecina and Playán, 2006a). In the previous chapter, the spatial heterogeneity of the BRCC irrigation district, including various management decisions were taken into account and the model was calibrated and validated using remote sensing data to capture the variability between farm management and water distribution within the system. The potential for water savings in a section of the Bear River Canal Company located on the West main canal was reported by Lecina et al. (2011). For that study the cutoff time for irrigation events was optimized, which achieved water savings of 2.64 Mm^3 in irrigation diversions, whilst halving of the yield reduction. The increase in production was achieved due to a higher frequency of irrigation events thereby reducing crop water stress to occur. This study indicates the potential for improvements of irrigation performance and the capability of Ador model to simulate these strategies for the entire BRCC irrigation district.

Performance indicators

Several performance indicators have been reported in literature to assist the assessment of an irrigation district (Bos, 1997; Bos et al., 2005; Burt et al., 1997). These indicators mainly focus on the efficiency and uniformity of on-farm irrigation; and the quality of water delivery service at the district scale. Water productivity has been defined in literature but shows great variability in its calculations with production (nominator) and water use (denominator) having several interpretations (Pereira et al., 2012; Perry et al., 2009; Playán and Mateos, 2006). The following equations are implemented in this paper to assess the irrigation performance and improvements made with different irrigation strategies.

At farm scale the irrigation events are evaluated using the distribution uniformity (DU) and application efficiency (AE) as formulated by Burt et al. (1997) and shown in equations 1 and 2. The infiltration and irrigation depths required for calculating AE and DU were computed in the Ador model for each field and irrigation event. The seasonal average AE and DU of each plot was used in this study, thereby combining the performance of the different irrigation events throughout the growing season.

$$\mathrm{DU} = \frac{\text{Infiltrated depth of the lower quarter of the field [mm]}}{\text{Average infiltrated depth of entire field [mm]}} \qquad (\mathrm{eq.}\,1)$$

$$\mathrm{AE} = \frac{\text{Average depth of irrigation water contributing to target depth [mm]}}{\text{Average depth of irrigation water applied [mm]}} \qquad (\mathrm{eq.}\,2)$$

The water productivity (WP) was calculated based on the definition from Pereira et al. (2012) and shown in equation 3. Crop yield was computed in the Ador model based on Cropwat for simulating crop growth, developed by the Food and Agriculture Organization (FAO, Land and Water Development Division) using the equations from FAO Irrigation Papers 56 and 33 (Allen et al., 1998, Doorenbos and Kassam, 1979). The potential yield and yield reduction due to water stress were calculated. The irrigation water use of each plot is the total amount of water applied during the growing season, and therefore includes the irrigation water that did not contribute to crop growth such as spills and deep percolation.

$$\mathrm{WP} = \frac{\text{Actual crop yield achieved [kg]}}{\text{Irrigation water use [m}^3\text{]}} \qquad (\mathrm{eq.\,3})$$

Irrigation strategy scenarios

Different irrigation strategies are analyzed in this paper to find improvements in irrigation performance and productivity. The first two strategies (scenario 1a and 1b) are irrigation management improvements, which are more cost-effective than infrastructure improvements. These strategies focus on optimizing the irrigation duration of on-farm irrigation events to achieve the highest water productivity. Shorter irrigation events will increase the frequency of irrigation events possible within a growing season and thereby limits crop water stress occurring. Farmers commonly cut off the irrigation when the water reaches the end of the field. This method does not account for the irrigation water still stored on the field after cut off. With the simulations for scenario 1a and 1b this water is taken into account, thereby making a shorter irrigation time possible.

The second set of strategies (scenario 2a and 2b) focus on changes in the infrastructure. The conveyance capacity of selected headgates is increased to make a higher flow rate at some fields possible. Fields located near the Great Salt Lake displayed low application efficiencies due to the low water holding capacity of the Lasil (=Ld) soil (NRCS soil database). A change in flow rate was simulated to assess the benefit and possibility for increasing the irrigation frequency at these locations. Additionally, this scenario can indicate the advantage of increasing the flexibility in flow rate at the headgate. Soil infiltration rates change throughout the growing season, so it is desirable to apply a suitable flow rate accordingly. However, this requires some hydraulic analysis on the capabilities of the infrastructure and an economical assessment for expanding the canal system.

Current scenario: The current scenario is the benchmark for this study. It is the current irrigation management of the irrigation district as was approximated in the previous chapter using remote sensing data for calibration and validation. Assumptions were made considering the irrigation duration and timing according to conversations with local farmers and canal managers. These assumptions were incorporated in the current scenario. The previous chapter indicated the fine tuning process of the parameters during the calibration process. The growing season used for the current scenario was 2013, which is characterized as a dry year but full irrigation allocations were permitted.

Scenario 1a: This scenario finds the minimum irrigation time necessary for each plot to fulfill the target irrigation depth, which is the irrigation requirement of the crops. The minimum irrigation time was found through an optimization process built in the Ador model.

Scenario 1b: This scenario finds the optimal irrigation time to achieve the highest water productivity for each plot. The minimum irrigation time was used as a starting point. Increments of 5% were added to the minimum irrigation time up to 50% to achieve a variety of options.

Scenario 2a: This scenario increases the flow rate of selected headgates irrigating Ld soils (located near the Great Salt Lake) to 0.2 m^3/s. Additionally, the slope of plots located in Ld soils is increased to 0.002 m/m, which is practically possible using laser levelling. The minimum irrigation time for achieving target irrigation depth is found for these plots and used achieving the model outputs.

Scenario 2b: This scenario includes the modifications from scenario 2a. In addition, other headgates are selected for increasing the flow capacity because these headgates displayed a low water delivery capacity indicating that the flow rate is not sufficient during the peak month. An increase of the flow rate is necessary to avoid crop water stress. Flow rates were increased to achieve sufficient flow during the peak months and the conveyance was doubled to allow for two fields to irrigate simultaneously.

5.3 Results and discussion

Minimum irrigation time

The minimum irrigation time to fulfill the target irrigation depth was found for each field within the BRCC system. The comparison between the current irrigation times and minimum irrigation time (scenario 1a) is displayed in Figure 5-1.

Figure 5-1 shows that several areas can apply a shorter irrigation time according to simulations. In particular, the plots on the heavier silty clay loam soils located centrally in the district (see soil map in Appendix C) can apply irrigation water for a shorter time. Heavy soils having a higher clay content typically have lower infiltration rates. Therefore, long irrigation events will likely cause an amount of water to runoff the field instead of infiltrating to the root zone. In several instances this situation was confirmed by local farmers during conversations. However, the existing delivery schedule appoints a fixed amount of time for irrigation so farmers usually apply the full amount of time allotted to their plots.

The majority of the heavier soils indicate that a minimum irrigation time of up to 4 hours for each irrigation event is possible. Other areas indicate that some reductions in irrigation times are possible. The longer minimum irrigation times (from scenario 1a) are found in the Northern and Southern parts of the irrigation district, and additionally some plots in the West at the edge of the district. There are several factors that can cause this requirement of longer irrigation times, such as soil infiltration, slope of the plot and plot geometry.

The histograms in Figure 5-1 indicate that for both scenarios, the majority of irrigation times are below 10 hours. The peak for the current scenario is at 4 to 6 hours irrigation time, whilst for scenario 1a this is at 2 to 4 hours. Maximum irrigation times in the current situation were indicated by local farmers to be no more than 24 hours. The simulation of the current scenario indicated a few fields with more than 24 hours irrigation, which need to be adjusted according to specific input from the local farmers. Scenario 1a also displayed one field requiring more than 24 hours of irrigation time. In Figure 5-1 this field is perceived to be relatively large, which can explain the longer irrigation time required. The farmer probably irrigates this field in several irrigation units, thereby requiring less irrigation time per unit.

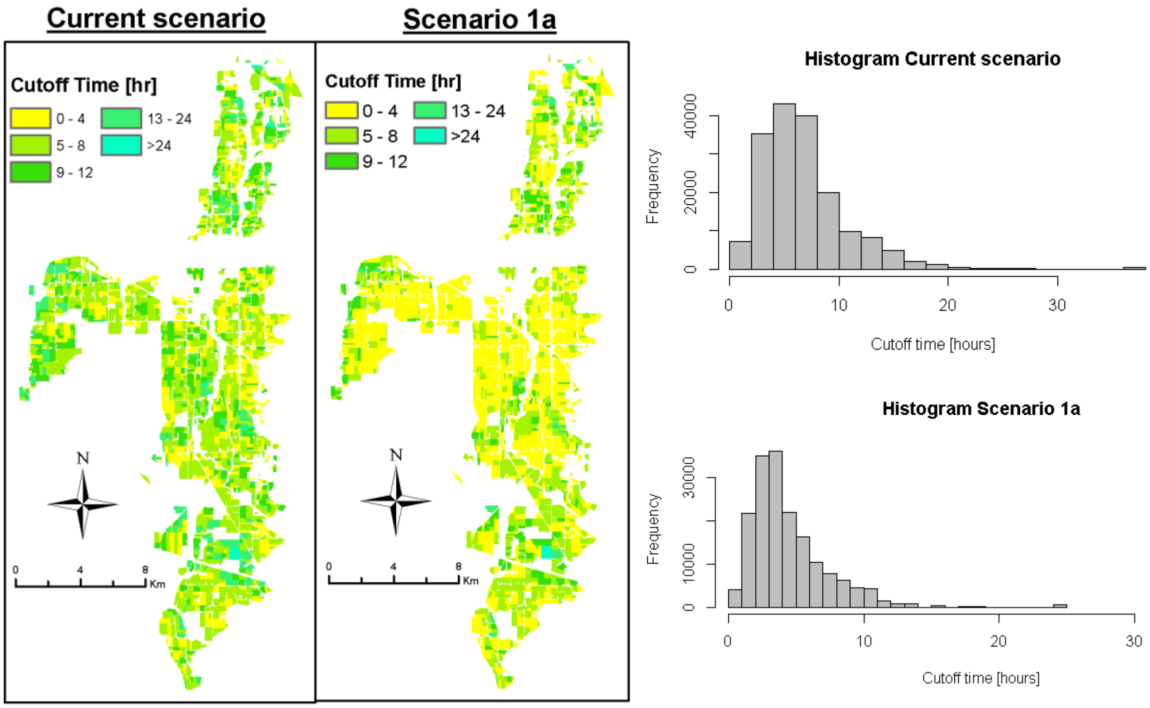


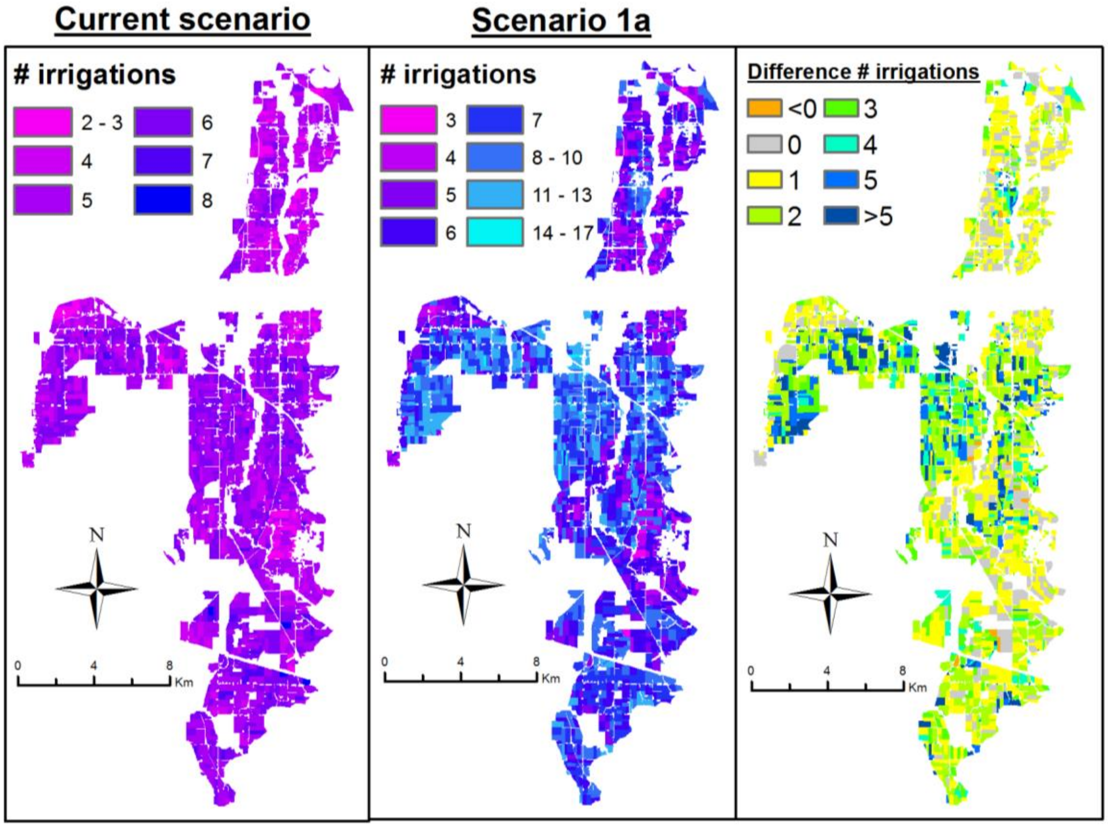
Figure 5-1. Irrigation time [hours] for an irrigation event in the current scenario and scenario 1a and frequency histograms.

The shorter irrigation times makes it possible to provide irrigation at a higher frequency. This is quantified with the number of irrigation events in total during the growing season as shown in Figure 5-2.

The current scenario shows that most fields receive irrigation 4 to 6 times during the growing season. Some plots in the Southern part of the district apply a higher number of irrigation events. In general, there is no distinctive spatial pattern in the district for areas with higher or lower number of irrigations. This is expected with a rigid rotation schedule, which determines the irrigation interval for the district. The flexibility is limited for increasing the frequency of irrigations due to the set times in the schedule.

In scenario 1a results from Figure 5-2 indicate that if the option were available, several fields would require more irrigation events during the growing season. In particular, the fields located in the central part of the district, associated with silty clay loam soils (Appendix C), shows a higher number of irrigation events for the season.

Figure 5-2 also indicates the difference in number of irrigation events between the current scenario and scenario 1a. Results indicate that several areas could increase the number of irrigations by at least 1 event. The major increases are observed in the central part of the district. The plots that displayed no change or a negative change were marginal.



Current scenario

Scenario 1a

Figure 5-2. Number of irrigation events for the growing season in the current scenario and scenario 1a, and the increase of irrigations possible with the shorter irrigation time from scenario 1a.

Irrigation performance and water use

Potential changes in irrigation time and frequency were indicated in the previous section. This section elaborates on the benefits in irrigation performance and water use that can be achieved with changes in water delivery.

Figure 5-3 displays the simulation results of the different strategies quantifying water use for irrigation and the irrigation performance of on-farm irrigation. The application efficiency and distribution uniformity was calculated for each plot and then averaged using the weight of the plot area to find a representative value for the district.

Major reductions in water use of up to 17.6 Mm^3 can be achieved with alternative strategies. This is a considerable part of the current water use, namely 11.6%. Despite the increase in irrigation frequency for several plots, the total water use was reduced, indicating that frequency was compensated by shorter irrigation times. The largest reduction in water use was found for scenario 1b, which simulated an optimized irrigation time for higher farm water productivity. However, scenarios 1a, simulating the minimum irrigation time, and 2a, simulating increases in flow rate of fields with low application efficiency, display similar levels of water use. Scenario 2b, which simulated increases in flow rate for selected headgates, shows a slightly higher water use, compared to the other alternative scenarios, due to the increase in flow rate at several headgates. Scenario 2a also simulated increases of flowrates, but this was possibly compensated with shorter irrigation times, thereby balancing the total water use.

Considerable improvements were also achieved for on-farm application efficiency as shown in Figure 5-3. The current scenario displays an application efficiency of 70%, whilst an efficiency of 83 to 86% can be achieved with alternative strategies. The highest application efficiency was achieved in scenario 2a, which aimed at increasing flow rates for selected headgate areas displaying low application efficiencies. This shows that the strategy of increasing the flow rate for these headgates was successful. Scenario 1b displayed a lower application efficiency relative to the other alternative scenarios. This scenario aimed to improve water productivity and not necessarily application efficiency. This resulted in slight decreases of application efficiency. The distribution uniformity improved substantially from the current scenario to the alternative scenarios as shown in Figure 5-3. The potential distribution uniformity that can be achieved with the alternative strategies ranges between 88 and 89%, indicating little variability between the scenarios.

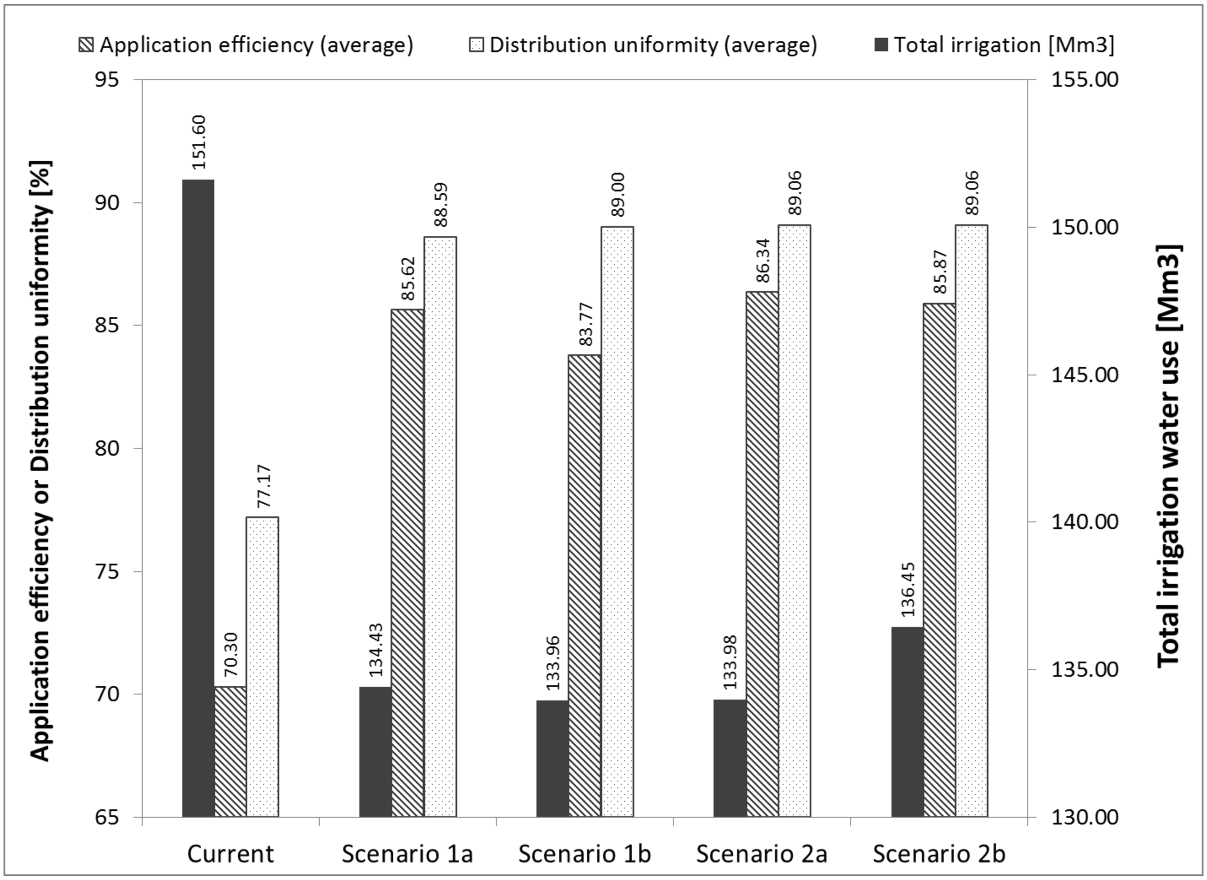


Figure 5-3. On-farm irrigation performance averaged for the district scale and total district water use for each scenario.

Application efficiency and distribution uniformity are simulated for on-farm irrigation events. It is therefore relevant to determine the spatial variability of the irrigation performance for the different scenarios. Results for application efficiency and distribution uniformity are displayed in Figures 5-4 and 5-5.

Figure 5-4 shows that the application efficiency was lower throughout the district in the current scenario. The improvements in irrigation time achieve increases in application efficiency for the majority of the district as shown in scenarios 1a. However, a small area in the south of the district, close to the Great Salt Lake, showed lower application efficiencies. These plots are mostly located in an Ld soil type with a lower water holding capacity relative to the other soils in the district. Changes in flow rate and slope specifically for these plots were simulated in scenario 2a with no noticeable improvements according to Figure 5-4. An optimization process for flow rate will be necessary to determine if flow rate can achieve improvements in application efficiency for these areas.

The distribution uniformity as shown in Figure 5-5 shows major improvements between the current scenario and the alternative scenarios. Particularly the distribution uniformity of the plots located in the central part of the district is improved with changes in irrigation time and frequency. The results from the alternative scenarios show that distribution uniformity is fairly similar throughout the district, displaying hardly any spatial variability. This is desirable because most of the land is used productively and not under-irrigated. It is emphasized in irrigation literature that uniformity of irrigation is important for crop production (Clemmens, 2006).

Water productivity

The production and water productivity are calculated for the irrigation district and shown in Figure 5-6 for the different scenarios simulated in this study. Ultimately, production is of most interest to the farmers to achieve increases in profitability. Additionally, agricultural areas are urged to increase water productivity, thereby achieving higher crop yields with less water.

The total crop production increased for the alternative scenarios compared to the current scenario. The level of crop production for scenarios 1a and 1b were similar and increased the crop production with 1.9% (percentage increase compared to current scenario). Further increases in production were achieved for scenario 2a with 3.4% and scenario 2b with 4.5%. Increases in flow rate simulated in scenarios 2a and 2b had a beneficial impact on crop production.

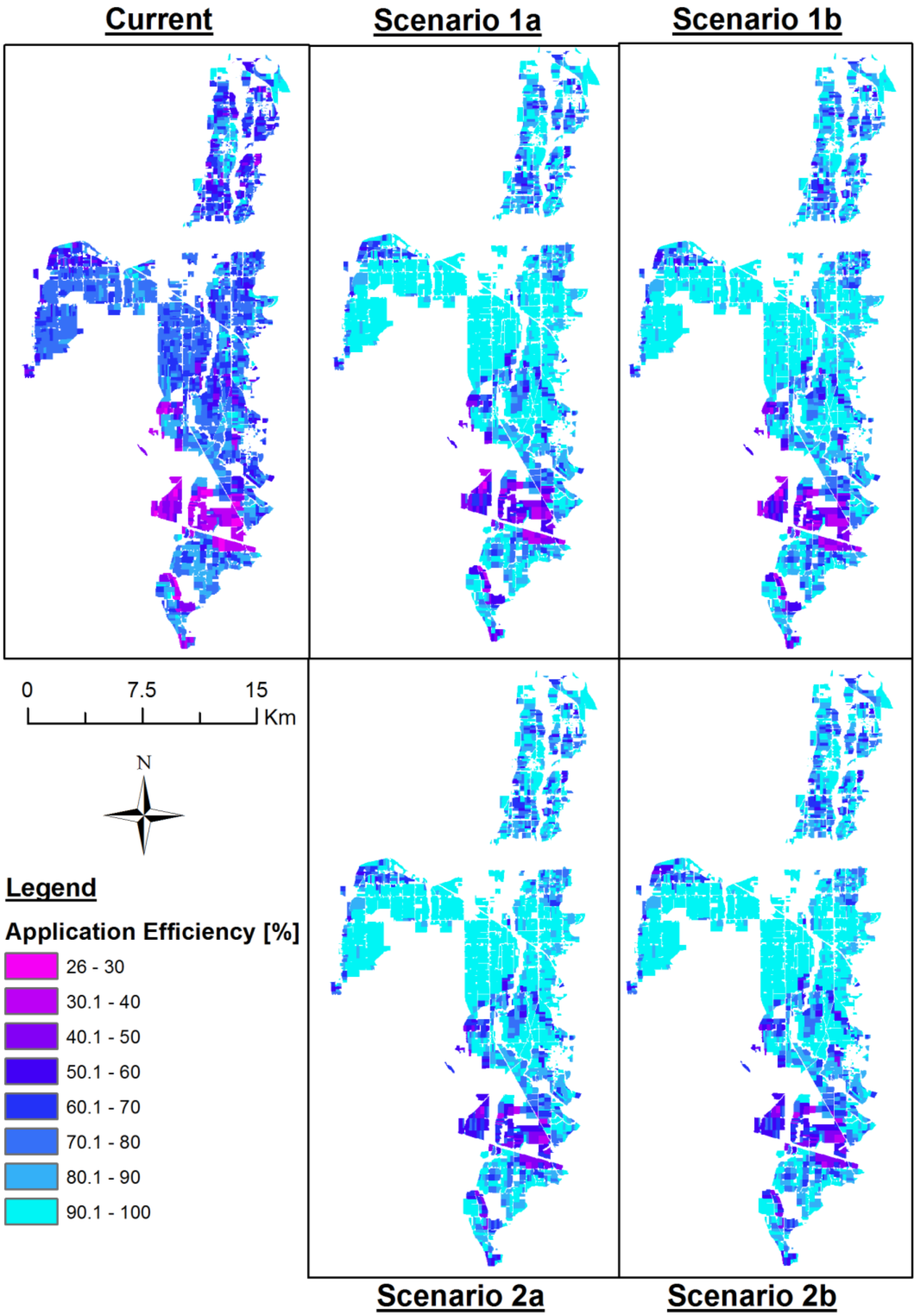


Figure 5-4. Results for application efficiency in the Bear River Canal Company for each simulated scenario.

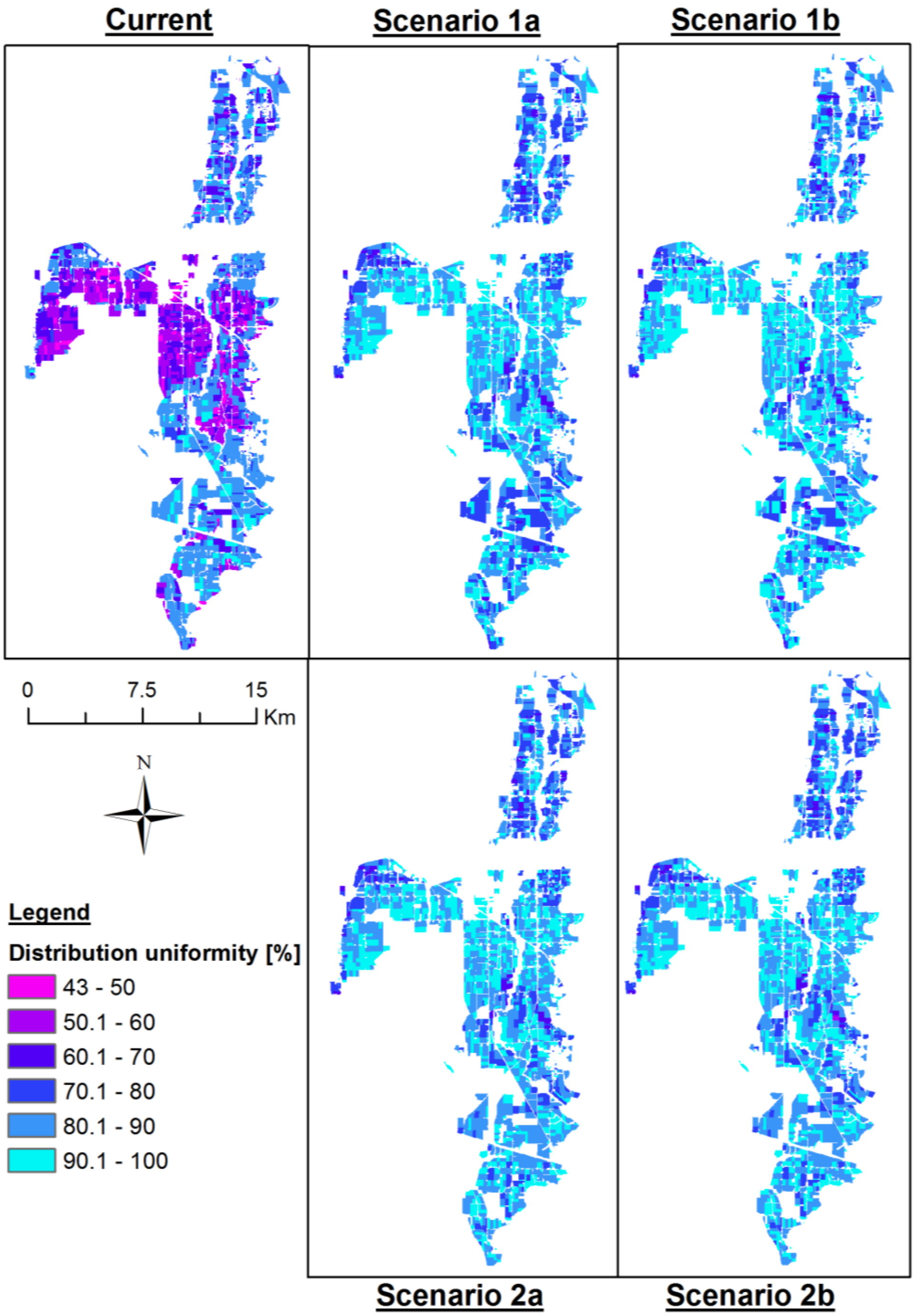


Figure 5-5. Results for distribution uniformity in the Bear River Canal Company for each simulated scenario.

However, the larger gains were in water productivity, which increased substantially for each scenario of 15% to 17%. Major improvements were achieved in scenarios 1a and 1b. This indicates that simple management changes in cutoff time and irrigation frequency can already provide considerable benefits. Scenario 1b displayed a slightly higher water productivity, due to the optimization process in cut-off time aiming at the highest water productivity. However, the difference with scenario 1a is miniscule indicating that the minimum cut-off time already achieved close to optimal water productivity. The flow rate changes simulated in scenario 2a showed another increase in water productivity, indicating that these flow rates were beneficial for crop production in selected headgates. However, the level of water productivity is not substantially different to the water productivity achieved with scenarios 1a and 1b. Therefore, it is arguable if infrastructure changes to increase flow rate is profitable regarding the limited advantages that can be achieved. Scenario 2b showed the highest crop production, but a slightly lower water productivity compared to scenario 2a. This is due to the increase in irrigation water use as was shown in Figure 5-3. This reinforces the need for analyzing water productivity in combination with irrigation water use and performance. It provides a different perspective to selecting more beneficial scenarios.

Insight on the spatial variability of water productivity between plots is required to make additional improvements in irrigation strategies, which are more location specific. The results of water productivity at field scale are shown in Figure 5-7, 5-8 and 5-9 for each crop type. Crop types can achieve different levels of water productivity with corn being relatively higher compared to grasses (i.e., alfalfa and pasture) or wheat. Therefore, water productivity is displayed for each crop type to indicate increases achieved for certain crops at specific locations in the irrigation district.

The largest improvements in water productivity were achieved in the central part of the district, which is in agreement with previous findings for irrigation performance. There is potential for improvement in the Southern areas of the district. This can potentially be achieved by optimizing the flow rate.

Differences between the alternative strategies were small and no distinguishable patterns are observed in Figures 5-7, 5-8 and 5-9. This is in accordance with the results from Figure 5-6, which showed some differences in water productivity, but there were not substantial enough to argue for costly infrastructure changes.

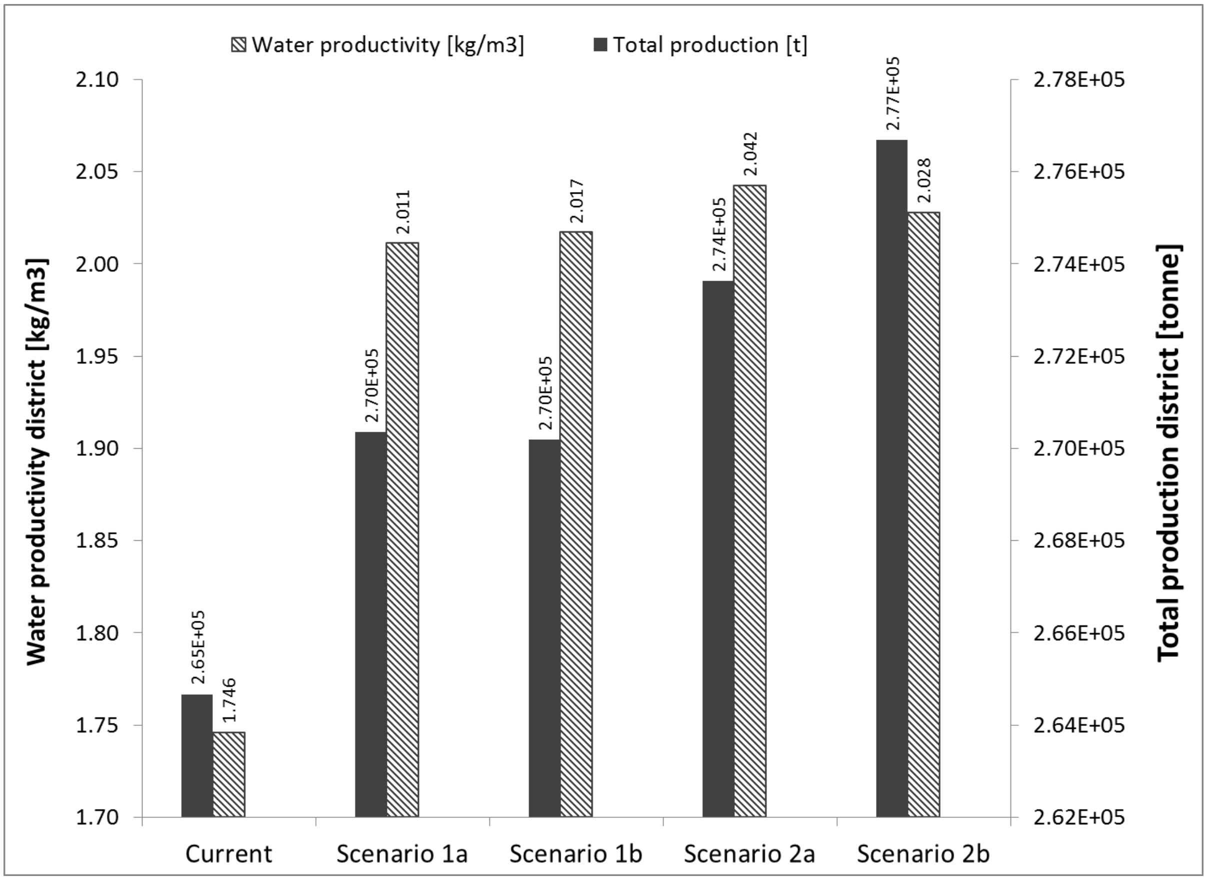


Figure 5-6. Total production and water productivity of the irrigation district for the simulated scenarios.

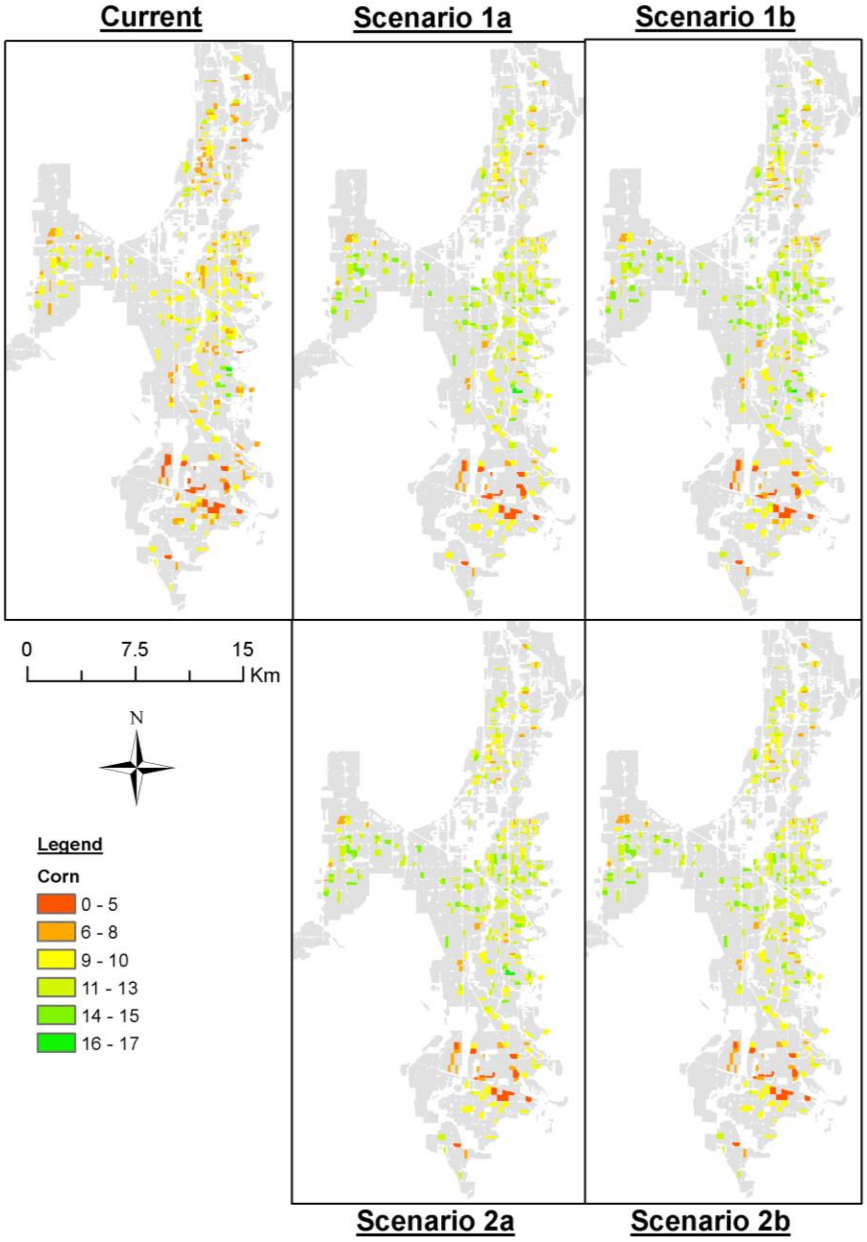


Figure 5-7. Corn water productivity for each plot and calculated for the different simulated scenarios.

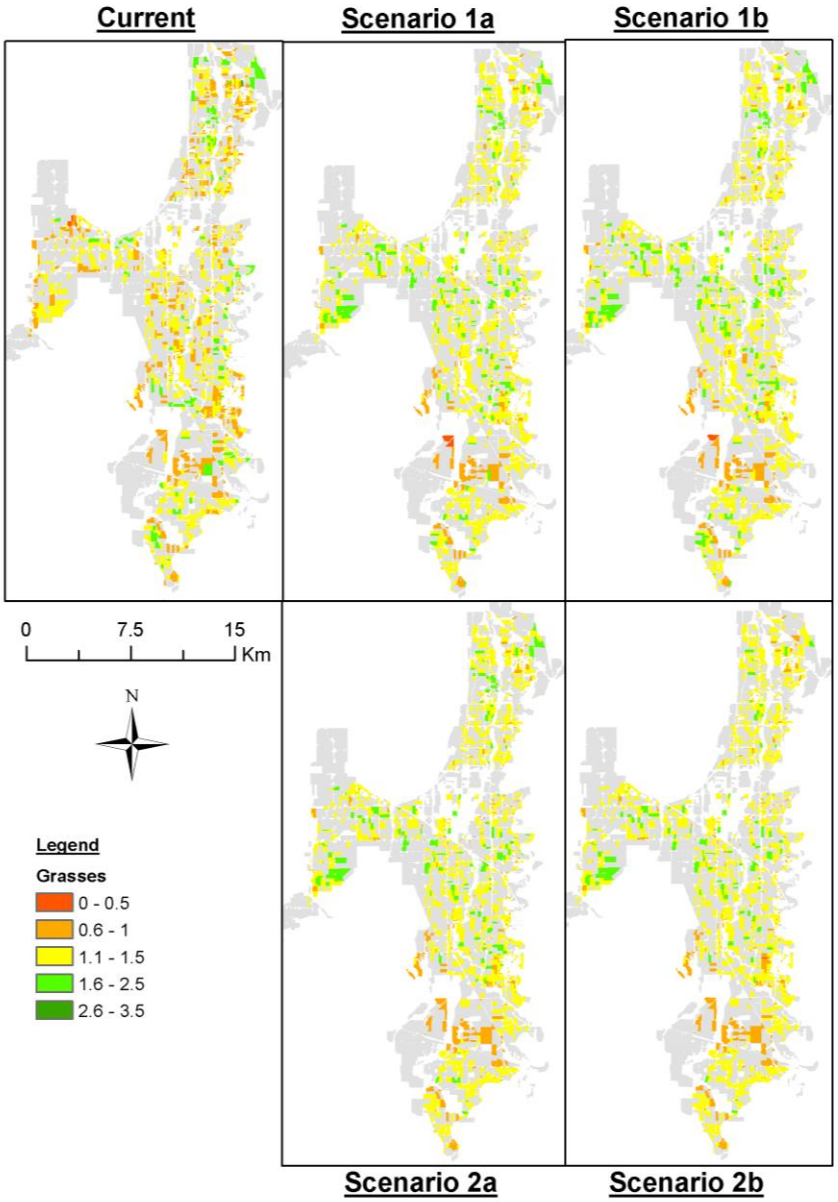


Figure 5-8. Grasses (i.e., alfalfa) water productivity for each plot and calculated for the different simulated scenarios.

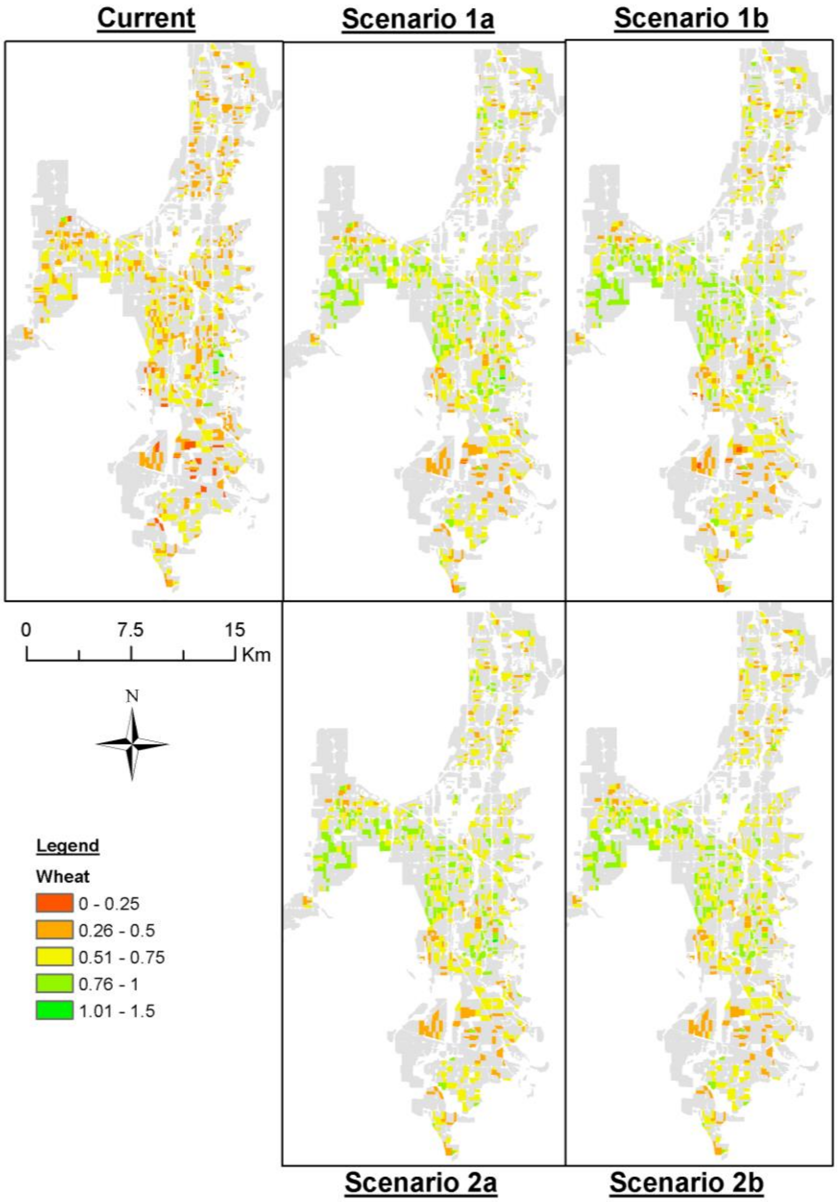


Figure 5-9. Wheat water productivity for each plot and calculated for the different simulated scenarios.

5.4 Conclusions

The strength and uniqueness of this study is in the analysis of water delivery scenarios at both the plot and district scale. This enables the impact of water delivery improvements for a diversity of farms. Additionally, the overall benefits at the district scale are quantified for each water delivery scenario. The analysis indicates that irrigation times can be reduced for the majority of the plots and irrigation frequency can thus be increased. This leads to substantial improvements in irrigation performance and water productivity. However, this change in water delivery scheduling is a collective effort and cannot be carried by individual farmers. It is necessary for farmers at similar headgates or canal sections to find an agreement in the scheduling and operate the headgates accordingly within the constraints of the canal company and their water rights. The canal company distribution schedule could be changed to match the necessary strategies in different parts of the system.

The shorter irrigation times and increase in irrigation frequency provides farmers with more flexibility in water delivery. The shorter intervals between scheduled irrigation events, enables farmers to decide the best timing for irrigation events. Currently, the intervals between scheduled events does not allow for an irrigation event to be skipped, because crop water stress can occur. Therefore, farmers are forced to over-irrigate with the current schedule. Increases in irrigation frequency can promote better irrigation management, with the additional benefit of considering eventual precipitation events in the summer.

Another form of flexibility in water delivery was analyzed by changing the flow rate to one more suitable for a soil infiltration rate. However, in practice changing the flow rate can be costly due to the changes in canal capacity that are necessary to convey a larger flow rate. Results displayed only slight improvements in irrigation performance and water productivity compared to the other scenarios. Therefore, implementing a costly infrastructure change is potentially not the most profitable. This also indicates that simple management changes in water scheduling can already achieve several major benefits without requiring substantial investments.

This study provides insight on the connection between external performance, such as water productivity, and internal performance namely the quality of water delivery service. Improvements can be made in water delivery scheduling regarding the duration and frequency of water provided by the canal company. This is predicted to result in substantial improvements being achieved both at farm and district level in water productivity. Additionally, water savings were achieved whilst providing a higher frequency of irrigation events. There is a need to determine the effect of these irrigation management changes on the surrounding environment by conducting a water budget analysis. Findings from this study can aid local farmers and the canal company with improving water delivery. Additionally, water managers can achieve insight in cost-effective changes that irrigation districts can undergo to achieve a higher water productivity.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. FAO Irrigation and Drainage Paper No. 56 Crop Evapotranspiration. Rome.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–9. doi:10.1038/nature04141

Bos, M., 1997. Performance indicators for irrigation and drainage. Irrig. Drain. Syst. 11, 119–137.

Bos, M.G., Burton, M.A., Molden, D.J., 2005. Irrigation and drainage performance assessment - Practical guidelines. CABI Publishing.

Burt, C., Clemmens, A., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Eng. 123, 423–442.

Burt, C.M., Styles, S.W., 2000. Irrigation district service in the Western United States. J. Irrig. Drain. Eng. 126, 279–282.

Clemmens, A.J., 2006. Improving irrigated agriculture performance through an understanding of the water delivery process. Irrig. Drain. 55, 223–234. doi:10.1002/ird.236

Clemmens, A.J., Molden, D.J., 2007. Water uses and productivity of irrigation systems. Irrig. Sci. 25, 247–261. doi:10.1007/s00271-007-0067-y

Contor, B. a., Taylor, R.G., 2013. Why Improving Irrigation Efficiency Increases Total Volume of Consumptive Use. Irrig. Drain. 62, 273–280. doi:10.1002/ird.1717

Doorenbos, J., Kassam, A.H., 1979. FAO Irrigation and Drainage Paper No.33 Yield response to water. Food and Agriculture Organization of the United Nations, Rome.

Jensen, M.E., 2007. Beyond irrigation efficiency. Irrig. Sci. 25, 233–245. doi:10.1007/s00271-007-0060-5

Khan, S., Abbas, A., 2007. Upscaling water savings from farm to irrigation system level using GIS-based agro-hydrological modelling. Irrig. Drain. 56, 29–42. doi:10.1002/ird

Lecina, S., Neale, C.M.U., Merkley, G.P., Dos Santos, C.A.C., 2011. Irrigation evaluation based on performance analysis and water accounting at the Bear River Irrigation Project (U.S.A.). Agric. Water Manag. 98, 1349–1363. doi:10.1016/j.agwat.2011.04.001

Lecina, S., Playán, E., 2006a. Model for the Simulation of Water Flows in Irrigation Districts I : Description. J. Irrig. Drain. Eng. 132, 310–321.

Lecina, S., Playán, E., 2006b. Model for the Simulation of Water Flows in Irrigation Districts II : Application. J. Irrig. Drain. Eng. 132, 322–331. doi:10.1061/(ASCE)0733-9437(2006)132:4(310)

Merriam, J.L., Styles, S.W., Freeman, B.J., 2007. Flexible Irrigation Systems: Concept, Design, and Application. J. Irrig. Drain. Eng. 133, 2–11. doi:10.1061/(ASCE)0733-9437(2007)133:1(2)

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agric. Water Manag. 97, 528–535. doi:10.1016/j.agwat.2009.03.023

Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manag. 108, 39–51. doi:10.1016/j.agwat.2011.08.022

Pereira, L.S., Gonçalves, J.M., Dong, B., Mao, Z., Fang, S.X., 2007. Assessing basin irrigation and scheduling strategies for saving irrigation water and controlling salinity in the upper Yellow River Basin, China. Agric. Water Manag. 93, 109–122. doi:10.1016/j.agwat.2007.07.004

Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. Agric. Water Manag. 96, 1517–1524. doi:10.1016/j.agwat.2009.05.005

Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manag. 80, 100–116. doi:10.1016/j.agwat.2005.07.007

Rijsberman, F.R., 2006. Water scarcity: Fact or fiction? Agric. Water Manag. 80, 5–22. doi:10.1016/j.agwat.2005.07.001

Tromboni, F., Bortolini, L., Martello, M., 2014. The use of water in the agricultural sector: a procedure for the assessment of large-scale irrigation efficiency with GIS. Irrig. Drain. 63, 440–450. doi:10.1002/ird.1833

Turral, H., Svendsen, M., Faures, J.M., 2010. Investing in irrigation: Reviewing the past and looking to the future. Agric. Water Manag. 97, 551–560. doi:10.1016/j.agwat.2009.07.012

Van Halsema, G.E., Vincent, L., 2012. Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. Agric. Water Manag. 108, 9–15. doi:10.1016/j.agwat.2011.05.016

Zaccaria, D., Oueslati, I., Neale, C.M.U., Lamaddalena, N., Vurro, M., Pereira, L.S., 2010. Flexible delivery schedules to improve farm irrigation and reduce pressure on groundwater: a case study in southern Italy. Irrig. Sci. 28, 257–270. doi:10.1007/s00271-009-0186-8

CHAPTER VI

ARE ‘REAL’ WATER SAVINGS ACHIEVED?

- ANALYSIS FOR THE REBOUND EFFECT -

Abstract

Improvements in the water delivery of an irrigation district can be beneficial both at farm and district scale. However, a water budget analysis is required to estimate if ‘real’ water savings are achieved at the catchment scale. It is expected that an increase in water efficiency can cause the rebound effect to occur, which is associated with an increase of water consumption. The water budget analysis in this study indicated that increases in water efficiency were indeed accompanied with an increase of water consumption thereby confirming that the rebound effect is relevant even with simple changes in irrigation management and water delivery. In addition, the water budget analysis found that reductions in irrigation diversions caused a larger decrease in drainage from the district thereby negatively impacting downstream water users dependent on this source of water. Results for water productivity indicated the difference between farmer’s perspective and regional water manager perspectives. Major improvements in water productivity were achieved when expressed in terms of irrigation water applied. However, in relation with crop ET the water productivity remained similar and showed marginal decreases in the alternative scenarios. Regional water managers are challenged to make decisions for increasing the productivity of agricultural areas, whilst limiting negative consequences. This study provides quantifiable insight of the impact of irrigation management changes on downstream water users.

6.1 Introduction

Improvements in irrigation management require a water balance analysis to determine the potential consequences of these changes. Individual farmers altering their management strategies have a marginal effect on the surrounding environment. However, collective changes in a large scale irrigation district can have a substantial impact on the environment. The previous chapter concluded that district water savings can be achieved by diverting less irrigation water while implementing changes in the water delivery scheduling. The magnitude of potential water savings was up to 11.6%, which in volume terms is 17.6 Mm^3. This can provide a full year of average water use for approximately 82,000 Americans (WBSCD, 2006), which is almost half of the population of Salt Lake City. On the other hand, this water could be stored upstream for use in future years in the event of droughts.

It is frequently emphasized that water savings is a subjective term which needs to consider the spatial scale. Certain improvements in efficiency acquired at farm scale, might be less beneficial at the district or catchment scale due to the decrease of drainage to downstream areas (Perry et al., 2009; van Halsema and Vincent, 2012). Therefore, it is important to distinguish between 'dry' water savings and 'wet' or 'real' water savings (Seckler, 1996). Dry water savings are beneficial at a local scale but do not provide water savings at a larger scale. Wet water savings are considered to reduce water use at a larger scale by reducing consumption or non-recoverable losses. Determining the type of water savings that are achieved in an irrigation district through management changes requires a water budget analysis (Jensen, 2007).

The objective of this paper is to compute a water accounting of the irrigation district to determine the in- and outflows with the surrounding environment. A hydrological analysis studying the water flow at the watershed scale and determining the volume and direction of the flow for both ground and surface water, is beyond the scope of this study. Therefore, the water balance is computed in simple terms for the district area, quantifying the in- and outflows of the irrigation district. The inflows are the precipitation and canal diversion from the reservoir (location indicated in Appendix D). The outflows from the irrigation district are the crop evapotranspiration (ET) and drainage through runoff or percolation.

The objective of this chapter is to quantify the impact of irrigation management changes on downstream water users. These findings will indicate if 'real' water savings are achieved or if downstream users will be negatively impacted by a decrease in water availability due to irrigation management changes. The simulation results for the current scenario, as presented in chapter 4, are compared with the simulation results of alternative water delivery scenarios, as presented in chapter 5. The changes in irrigation diversion, crop evapotranspiration and drainage of the irrigation district for each scenario are quantified

6.2 Background information

Water accounting approach

The terminology associated with water accounting was first published by Burt et al. (1997) and Pereira et al. (2002). A water accounting approach at catchment scale is important to determine if water savings will provide or limit water availability for other water users (Pereira et al., 2012). Water flows are divided into consumed and non-consumed fractions. The consumed fraction can then be subdivided into beneficial consumption such as transpiration contributing to crop growth; or non-beneficial such as soil evaporation or transpiration from weeds. The non-consumed fraction is subdivided into recoverable and non-recoverable water flows. Recoverable water flows can be used elsewhere in the system. Non-recoverable water flows are not suitable for further use due to deterioration of the water quality or inaccessibility (Pereira et al., 2012; Perry et al., 2009).

In practice it is challenging to categorize the water flows correctly. For instance the distinction between evaporation and transpiration in crop fields is difficult to measure or quantify with a simulation model (Perry et al., 2009). Additionally, distinguishing between recoverable and non-recoverable water flows requires an in-depth hydrological analysis of the catchment.

In this paper it is assumed that the majority of the drainage from the irrigation district is recoverable and used by downstream water users. This assumption is based on conversations with the local farmers, who indicated that the drainage water is captured using a network of tile drains and ditches. The drainage water is then diverted to the Bear River Bird Refuge or water fowl hunting clubs, which are water users located downstream of the Bear River Canal Company. The assumption that the drainage water is recoverable and usable for downstream water user should be tested with an analysis of the regional hydrology including the flow direction and quantity of surface and groundwater. It is necessary to conduct such a hydrological analysis for a detailed water accounting of the irrigation district. However, a study of the regional hydrology is beyond the scope of this chapter. Therefore, an initial water accounting is conducted to indicate potential impacts for downstream water users and can be used as preliminary work for further research and discussion.

Rebound effect concept

The ‘rebound effect’ concept was originally used in the energy sector. Several measures were taken to improve energy efficiency and reduce greenhouse emissions thereby limiting the effects of climate change. However, these improvements in energy efficiency are at times associated with an increase in energy consumption instead of the expected decrease (Herring and Sorrell, 2009).

This concept was later used in the context of water resources management by the European Commission (E.C., 2012). In this report the rebound effect for water management is defined as the increase of water use and consumption due to efficient water management or technologies. Berbel et al. (2014) later specifies the rebound effect for irrigation districts and limits the definition to studying water consumption, which is considered a ‘real’ loss of water to the catchment because it is not recoverable.

Rebound effect in irrigation areas

Evidence for the rebound effect occurring in irrigation areas is limited (Berbel et al., 2014). Some studies have studied this phenomenon or described the conceptual possibility of this effect occurring in irrigation areas. The basic concept of the rebound effect is found in the yield or production curve as presented by Contor and Taylor (2013). The relationship between yield and evapotranspiration (ET) is generally linear therefore an increase in ET is expected to be associated with an increase in yield. Therefore, if an irrigation district aims at improving efficiency of water use to achieve higher crop yields, it can be expected that ET thus water consumption increases simultaneously.

A case study reported by Berbel et al. (2014) analyzed the effect of changing from surface to pressurized irrigation in a district located in Spain. This study indicated that the rebound effect does not occur if the expansion of irrigated area is limited and the water saved by transforming to pressurized irrigation is made available for other water users.

Playán and Mateos (2006) argue that increases in water consumption are sometimes necessary to increase crop production and sustain future crop demands. Yields are expected to increase with changing cropping patterns and expansion of irrigated area under irrigation modernization scenarios. This is necessary to substantially increase the food production and meet future demands. Molden et al. (2010) agrees that for some regions it is necessary to increase ET when other measures have already been implemented for increasing plant production. Other methods for increasing productivity are through plant genetics, fertilizer application or pest and disease management.

6.3 Methodology

Seasonal water balance

The seasonal water balance was computed for the total irrigated area under the command of the Bear River Company as indicated in Appendix D. The water balance considers five components in this study namely: precipitation, irrigation diversion, crop evapotranspiration (ET), drainage, and change in soil water storage.

Precipitation was measured at the weather station located in the study (see Appendix D). The precipitation was summed for the water year, starting on 1st November 2012 to 31st October 2013.

Irrigation diversion is the sum of irrigation water diverted during the irrigation season. This is calculated for the current and alternative water delivery scenarios using the Ador simulation model. It consists of the total volume of irrigation water applied to each field, and the volume of water lost from the canal system due to leaks.

The seasonal crop ET is calculated as the total crop ET from each field for the irrigation system. It is computed by the Ador simulation model for both the current and alternative water delivery scenarios. For the water balance calculations, the crop ET from each field is summed to achieve the total seasonal crop ET for the irrigation district.

Drainage in this study consists of the runoff, spills and percolation from the irrigation district. The runoff is considered to be the runoff from the fields, which are collected in ditches flows out of the irrigation district into the Malad River, Bear River, or wetland area. The canal spills are the volumes of water at the end of the canal system, which was not used by the irrigators. These spills are collected and used by downstream water users. Percolation is the water that drains to the groundwater during the irrigation event.

In this study, the three components are combined due to the lack of a hydrological analysis. The runoff and percolation is simulated by the Ador model for each field and summed to achieve a seasonal value for runoff and percolation. Additionally, the total runoff and percolation for the irrigation district is found by summing seasonal values from each field. The canal spills are computed by the Ador model by subtracting the water diverted by headgates and estimating the losses due to leakages.

The change in soil water storage is estimated for each field by the Ador simulation model. It indicates the change in soil moisture from the start of the growing season to the end of the season. This is variable for each field according to the planting and harvesting date of the field. The data from each field is summed to achieve the total soil water storage for the irrigation district.

Water productivity

Improvements in water delivery were aimed at increasing water productivity as was defined and analyzed in the previous chapter. However, there are various definitions for water productivity applicable for different stakeholders. Farmers and canal managers are interested in increasing productivity per unit of irrigation water applied. The findings in this paper so far have indicated that water consumption is increased for the different alternative scenarios. It is therefore relevant to study the water productivity relative to water consumption or crop ET. This term is of more interest to water managers aiming at achieving higher food production with less consumption of water. Equations 1 and 2 indicate the terms used for calculating the two different water productivities (WP). Both equations use the total production and volumes of water at the district scale.

$$\text{WP (irrigation)} = \frac{\text{Actual crop yield achieved [kg]}}{\text{Irrigation water use [m}^3\text{]}} \qquad \text{(eq. 1)}$$

$$\text{WP (ETc)} = \frac{\text{Actual crop yield achieved [kg]}}{\text{Crop evapotranspiration [m}^3\text{]}} \qquad \text{(eq. 2)}$$

6.4 Results and discussion

Seasonal water balance

The results of the seasonal water balance for the current situation of the Bear River Canal Company and alternative water delivery scenarios are shown for 2013 in Figure 6-1. An elaborate description of the alternative scenarios was presented in the previous chapter. The first two alternative scenarios (1a and 1b) simulate the minimum and optimum irrigation times for each field thereby achieving a higher frequency of irrigation events. The second set of scenarios (2a and 2b) implement changes in flow rates from selected headgates indicating under performance. The major conclusions from the previous chapter were that both application efficiency and distribution uniformity increased with the alternative scenarios. It is therefore valid to examine the potential of the rebound effect, which is associated with an increase of water efficiency.

Figure 6-1 indicates a decrease in irrigation water use of up to 17.6 Mm^3 for scenario 1b. Both scenarios 2a and 2b display similar reductions. The crop ET as simulated by Ador is shown in Figure 6-1 and indicates a slight increase for the alternative scenarios of 4.8 to 6.4 Mm^3. The smallest increase of ET was found for scenarios 1a and 1b, whilst scenarios 2a and 2b displayed slightly higher crop ET values. This small increase in water consumption suggests a small rebound effect is maybe occurring when efficient irrigation management is implemented. The rebound effect is usually associated with a transformation to pressurized irrigation. However, these findings indicate that simple management changes in water delivery or infrastructure can also potentially increase water consumption and cause some rebound effect. This small increase should be checked with the uncertainty of model simulations.

Figure 6-1 also indicates that the drainage from the district (assumed to be runoff, spills and percolation) decreased for each alternative scenario. For this irrigation district the majority of drainage is used for the Bird Refuge wetland areas downstream and is therefore considered recoverable water flows. The reduction in drainage as indicated in figure 6-1 is therefore a decrease in water availability for downstream water users. However, water availability is compensated with the decrease of irrigation diversions of potentially higher quality water.

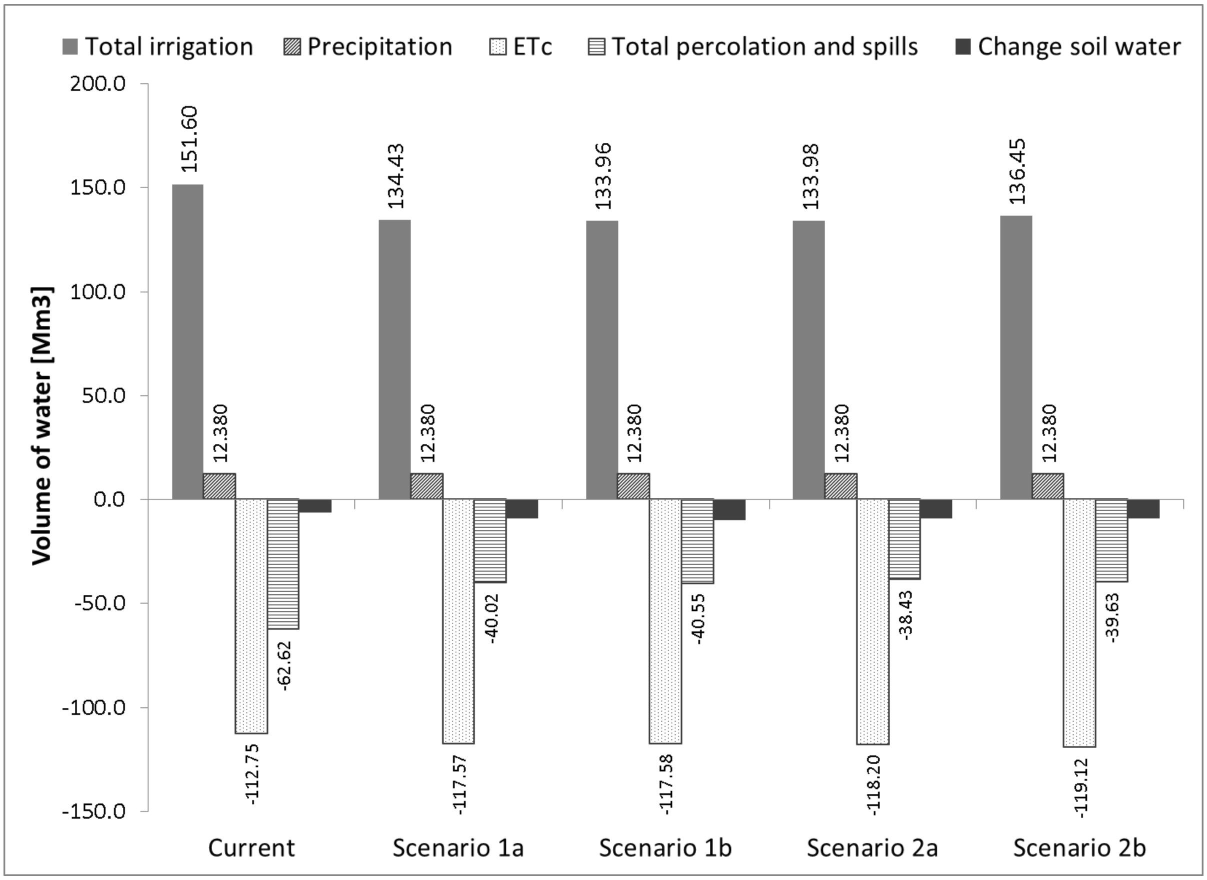


Figure 6-1. Seasonal water balance for the district in 2013 according to the current and alternative scenarios as simulated with Ador.

The tallying of water flow changes for each scenario compared with the current scenario is shown in Table 6-1. The reduction in irrigation diversions are calculated and related to the change in drainage. The net reduction of drainage is the total decrease minus the water made available by reduced irrigation diversions. This assumes that the water not diverted by the district remains in the river system and is available for downstream users. If this is not the case, the impact on downstream users is more substantial. If the downstream areas are compensated with river water from reduced irrigation diversions, the net reduction of drainage water is still 4.43 to 7.84 Mm^3. This is a sizeable 7% to 12.5% change from the original drainage volume in the current scenario. It can be concluded that in any scenario the downstream water users are negatively impacted. This is a tradeoff for regional water managers to decide if improvements of water delivery resulting in higher productivity compensates with changes of water availability to downstream areas. Issues of water quality and timing of water availability would also need to be examined.

Table 6-1.

Difference in water balance components compared to current scenario.

	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b
Reduction drainage [Mm^3]	22.6	22.1	24.2	23.0
Reduction irrigation [Mm^3]	17.2	17.6	17.6	15.2
Net reduction drainage [Mm^3]	5.4	4.4	6.6	7.8
Increase consumption [Mm^3]	4.8	4.8	5.5	6.4

Water productivity

Results for water productivity using irrigation depth and water consumption are displayed in Figure 6-2. Major improvements in water productivity were achieved for all alternative scenarios when using irrigation depth applied, which is the volume of water applied to the field. The water productivity when expressed with crop ET shows marginal variability. There is even a very slight decrease in water productivity observed in the alternative scenarios compared with the current scenario. This indicates that the increase in crop production achieved in the alternative scenarios was associated with an increase in water consumption. Other management options such as fertilizer application or pest management were not an option in the model simulations. Therefore, the model simulations of this study are limited to achieving higher crop production by irrigation management and other farm management decisions are excluded.

These results clearly point out that the great benefits achieved at farm and district scale are advantageous to the farmers through increased crop yield and potentially other benefits such as reduced losses of fertilizer and other inputs. However, at the larger basin scales the benefits of irrigation improvements are marginal, unless stakeholders agree to managing the quantity and quality of the water resources as a whole. This shows the differences in perspectives between farmers, canal managers, and regional water managers.

6.5 Conclusions

Alternative scenarios were simulated to improve the water delivery and achieve higher crop productivity and better irrigation performance. This paper used a model to perform a water budget analysis to determine the impact on the surrounding environment from irrigation management changes in a large-scale irrigation district.

The seasonal water balance indicated that water consumption by crops increased for each alternative scenario compared with the current scenario. This is an indication that improvements in efficiency resulted in a higher consumption and confirms the potential for the rebound effect to occur.

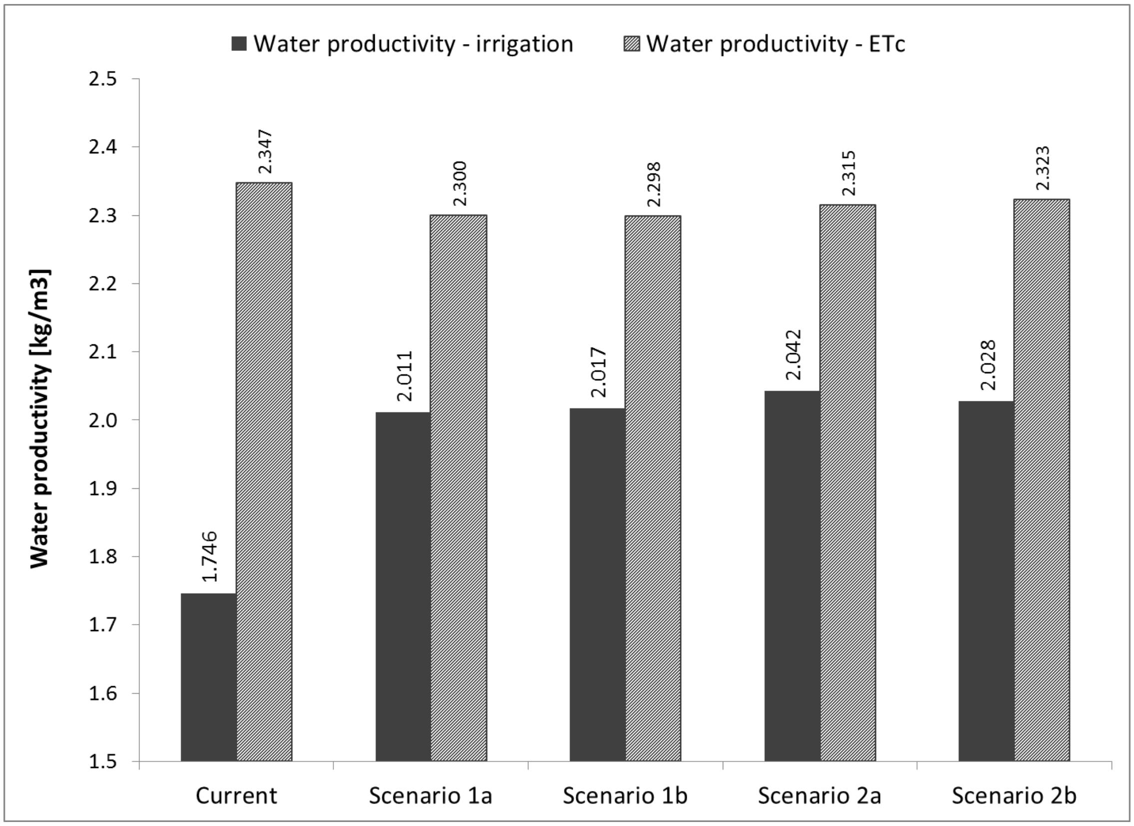


Figure 6-2. Results for water productivity expressed with irrigation applied and crop ET for the entire irrigation district including alfalfa, grains and corn as the major crop types.

Results in the water balance also indicated that the reduction in irrigation diversions does not reduce water use at the catchment scale due to the reduction in drainage from the district. Several water users downstream are dependent on the drainage from the irrigation district. The drainage changed substantially but is slightly compensated with the decrease in irrigation diversions. The net reduction of drainage was still considerable being from 7% to 12.5% for the different alternative scenarios. If regional water managers choose to use the reduction in irrigation diversions for other purposes, the impact on water availability for downstream water users will be more substantial.

Water productivity is analyzed using two definitions, namely in terms of irrigation applied and crop ET. The first is of relevance for farmers and canal managers, whilst the latter is important for regional water managers who aim at increasing food productivity whilst maintaining similar water consumption. Findings showed that substantial increases in water productivity were achieved for the alternative scenarios when calculating with irrigation use. However, water productivity in terms of crop ET remained similar and showed marginal decreases in the alternative scenarios. Other methods can be used to increase water productivity in terms of crop ET, such as deficit irrigation during certain parts of the growth cycle. This can reduce water consumption without causing significant losses in yield.

Advantages to improving the water delivery in the irrigation district are considerable for farmers and canal managers. However, the bigger picture shows that several disadvantages can be listed for the regional water management. Water savings were expected due to the reduction in irrigation diversions. A water budget analysis indicated that these water savings are diminished when relating them to the decrease of drainage. Regional water managers are faced with the challenge to make decisions in this situation that does not provide an ideal solution for all stakeholders. Fortunately, this study quantifies the effects of the different scenarios, providing the necessary insight for aiding the decision-making process. This approach can be used in upstream irrigation systems to quantify the consequences of similar water management improvements. This can identify the possibility for a basin-wide water storage and adaptive management strategies to cope with multi-year drought events.

References

Berbel, J., Gutiérrez-Martín, C., Rodríguez-Díaz, J. a., Camacho, E., Montesinos, P., 2014. Literature Review on Rebound Effect of Water Saving Measures and Analysis of a Spanish Case Study. Water Resour. Manag. doi:10.1007/s11269-014-0839-0

Burt, C., Clemmens, A., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Eng. 123, 423–442.

Contor, B. a., Taylor, R.G., 2013. Why Improving Irrigation Efficiency Increases Total Volume of Consumptive Use. Irrig. Drain. 62, 273–280. doi:10.1002/ird.1717

EC, 2012. A blueprint to safeguard Europe’s water resources. Brussels, Belgium.

Herring, H., Sorrell, S., 2009. Introduction, in: Energy Efficiency and Sustainable Consumption - The Rebound Effect. Macmillian Distribution Ltd., Hampshire, UK, pp. 1–20.

Jensen, M.E., 2007. Beyond irrigation efficiency. Irrig. Sci. 25, 233–245. doi:10.1007/s00271-007-0060-5

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agric. Water Manag. 97, 528–535. doi:10.1016/j.agwat.2009.03.023

Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manag. 108, 39–51. doi:10.1016/j.agwat.2011.08.022

Pereira, L.S., Oweis, T., Zairi, A., 2002. Irrigation management under water scarcity. Agric. Water Manag. 57, 175–206. doi:10.1016/S0378-3774(02)00075-6

Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. Agric. Water Manag. 96, 1517–1524. doi:10.1016/j.agwat.2009.05.005

Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manag. 80, 100–116. doi:10.1016/j.agwat.2005.07.007

Seckler, D., 1996. The new era of water resources management: From “dry” to "wet’ water savings (No. 1), Research Report. Colombo, Sri Lanka.

van Halsema, G.E., Vincent, L., 2012. Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. Agric. Water Manag. 108, 9–15. doi:10.1016/j.agwat.2011.05.016

WBSCD, 2006. Water facts and trends - UN factsheet.

CHAPTER VII

GENERAL SUMMARY AND CONCLUSIONS

General summary

This dissertation was divided into four sections. The first two presented the practical application and use of remote sensing tools to estimate the current operation of an irrigation system. The spatial diversity of farm management within an irrigation system makes estimation of operation and performance challenging. Fortunately, remote sensing with satellite imagery can provide data at regular intervals and has the capability of distinguishing between farm fields that enables the analysis of the irrigation system at both field and district scales. The last two parts of the dissertation discuss the possible impacts of changes in water delivery at farm, district and basin scale. The study area for this dissertation was the Bear River Canal Company located in Northern Utah. However, the methodology and conclusions are relevant to several irrigation districts within the Bear River Basin, and likely many other cases for surface irrigation systems in regions with an uncertain or limited future water availability.

A decade of remote sensing data was used to determine inter-annual changes in ET (evapotranspiration) and year-to-year changes in operation. It was found that this irrigation system has the capability to buffer one year of drought. However, a two year drought event showed substantial differences in the second year indicating the limitations in the buffering capacity of the irrigation system and the present basin-wide management of water resources.

On-farm irrigation and water flows in the canal system were simulated with the Ador irrigation system simulation model to assess current operations and performance. An assimilation approach was applied using remote sensing data to improve the calibration and validation process. This approach provided a cost-effective method of simulating a large-scale irrigation system without requiring an extensive amount of field observations. Assessment of current irrigation performance indicated the variability of performance in the irrigation system and potential areas for improvement.

Results suggest that irrigation performance can be improved by adjusting the water delivery scheduling or infrastructure. Several alternative water delivery scenarios were simulated with Ador and compared with the current scenario to assess the potential for increasing irrigation performance and productivity. Findings indicated that substantial improvements can be achieved in productivity, efficiency and reductions of irrigation diversions when applying shorter irrigation times. This enabled a higher frequency of irrigation events and reductions in crop water stress. In addition, the shorter irrigation times gave farmers more flexibility in deciding the best timing for an irrigation event due to the faster return rate of their timeslot and the consideration of rainfall events. A change in flow rate capacity of selected headgates also showed improvements in irrigation performance, but are less economical.

Irrigation management improvements of an irrigation district need to be accompanied with a water accounting analysis to determine changes in water flows from and into the irrigation district. The simulated water balance indicated that implementing some of the modeled scenarios, a change in drainage flows from the irrigation district would result in less water availability to downstream users. This implies that water savings at the district scale resulted in less available water for other downstream water users despite the reductions in irrigation diversions. Additionally, improvements in water delivery increased efficiency but resulted in a higher crop water consumption thereby demonstrating the potential of the rebound effect occurring with simple management changes.

Conclusions

This study indicated that the buffering capacity of this irrigation system is limited to 1 year drought events although this can depend on the severity of the drought. This limited buffering is a cause for concern especially with future climate scenarios predicting less and fluctuating water availability for regions depending on snowmelt for irrigation. This requires the assessment and discussion for finding improvements in irrigation management by first benchmarking the current operation and then quantifying the benefits of changes to the irrigation system. The inter-annual variability in seasonal ET shows the importance of using several years for benchmarking an irrigation system.

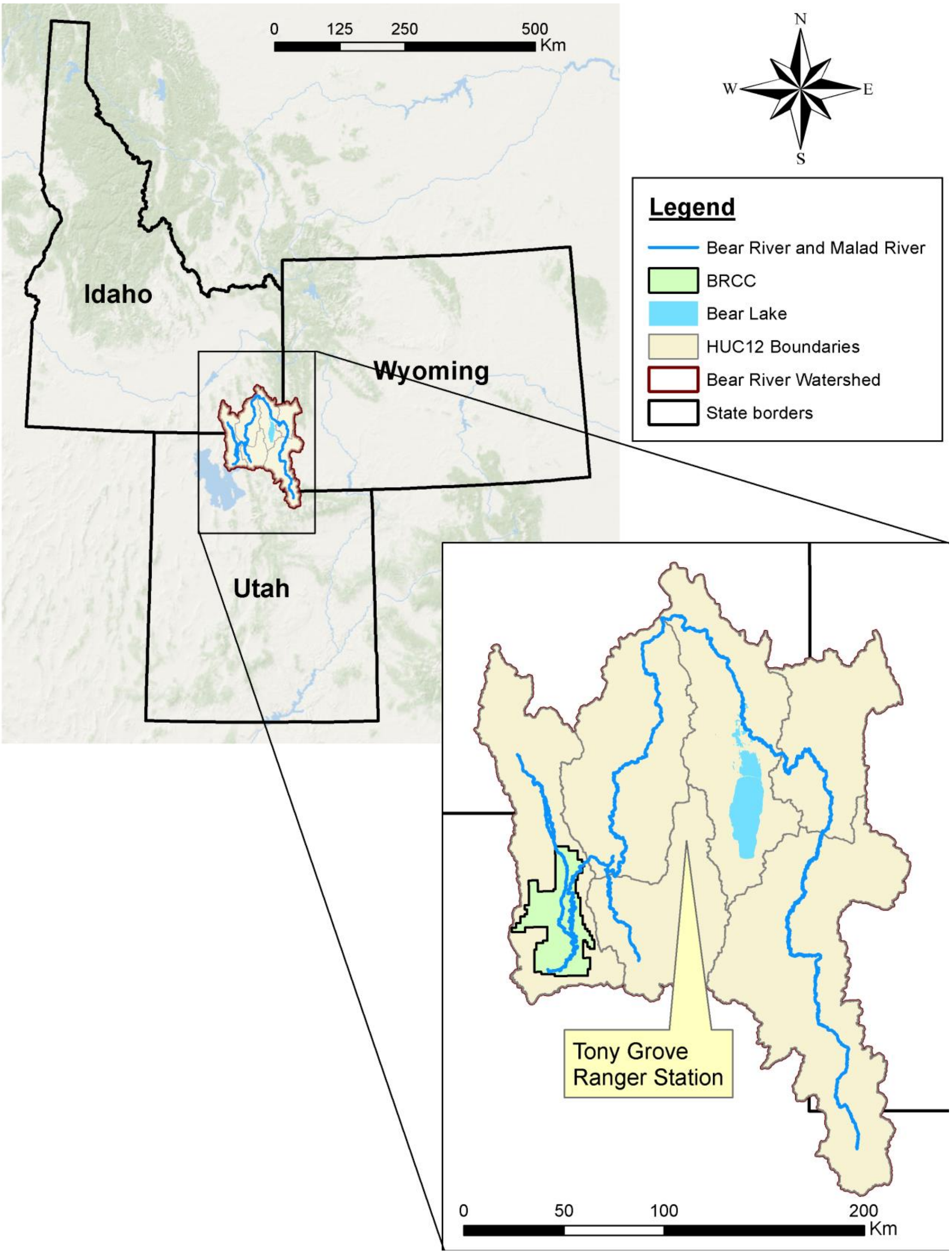
This study showed the capability of evaluating the current operation of a large scale irrigation system and distinguishing the spatial diversity of individual fields within the district. This was made possible by applying remote sensing data and combining this data with a simulation model. The ability of the Ador model to simulate both on-farm irrigation and water delivery from the canal system enabled this study to analyze and establish connections between farm and district performance. The effect of the water delivery on external performance indicators such as application efficiency and water productivity was quantified using different scenarios of water delivery. The quantification of potential benefits achieved through simple management changes can motivate the irrigation district to achieve higher water productivities.

Future food demands need to be met at least partially by improving the water productivity of agricultural areas especially in regions coping with limited water supplies. Management changes to minimize irrigation time thereby increasing irrigation frequency resulted in higher water productivities and less crop water stress. This is an important finding for other irrigation districts searching for cost-effective methods of improving water productivity. However, each irrigation district is different and an analysis is required to quantify the potential for improvements.

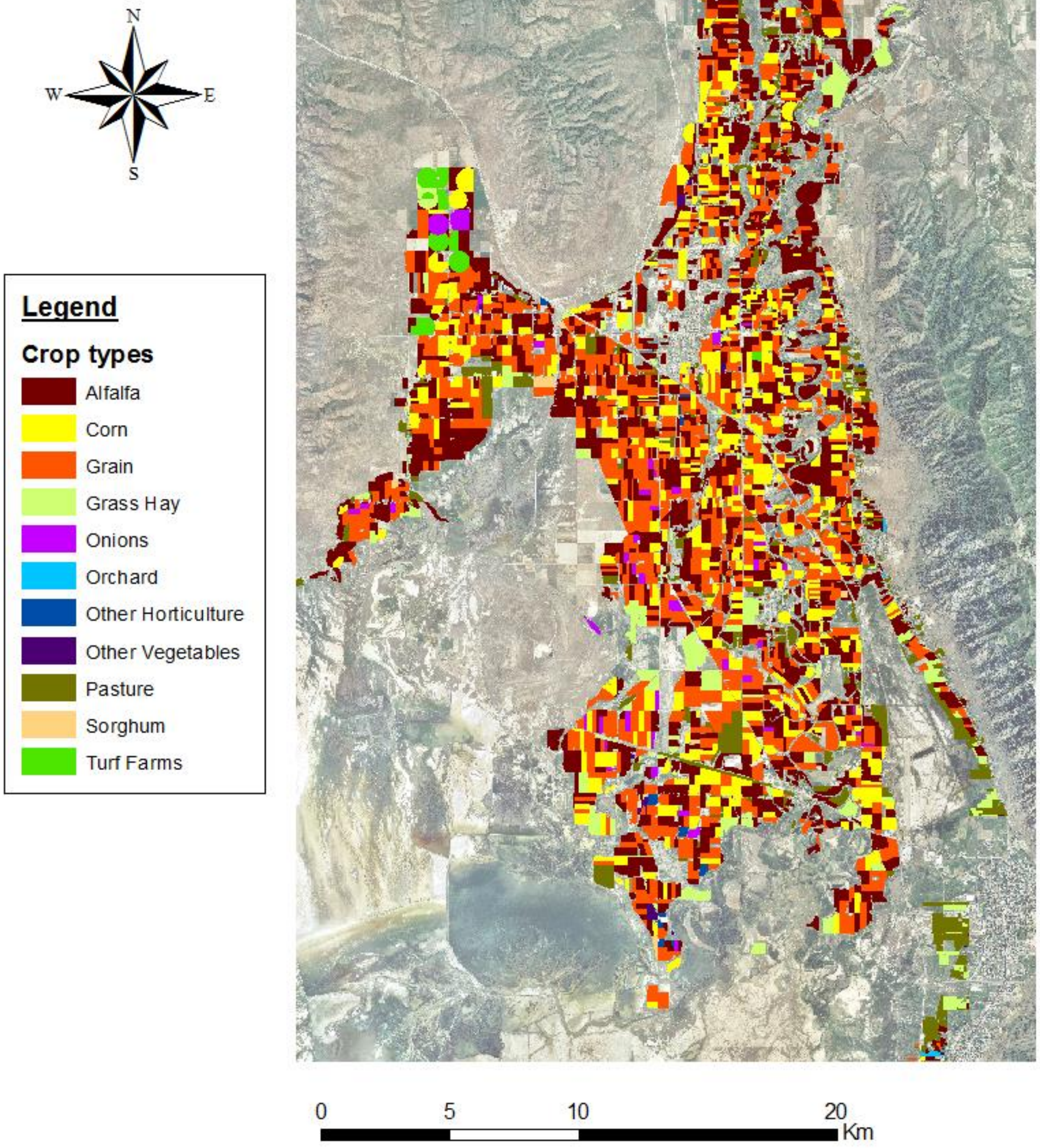
The water savings for the farmers and the irrigation district were diminished at the basin scale in this case after conducting a water accounting analysis with downstream water users being negatively impacted. Regional water managers might need to make tough decisions in balancing the advantages of increasing food production with the reduction of water availability for other water users. This study provided quantifiable insights useful as input to the discussion with regional water managers, farmers and canal managers. In addition, this study demonstrates the necessity of conducting a water accounting analysis when assessing potential improvements in the irrigation system. The water accounting analysis can be elaborated with a hydrological analysis to improve estimations of water flows. This can aid the categorization of drainage water from the district into recoverable and non-recoverable water flows. The comprehensive approach of this study, incorporating the variability across both temporary and spatial scales, indicates the importance for scientists and engineers to take account of these aspects and adapt the operation and design of irrigation systems to these dynamics.

APPENDICES

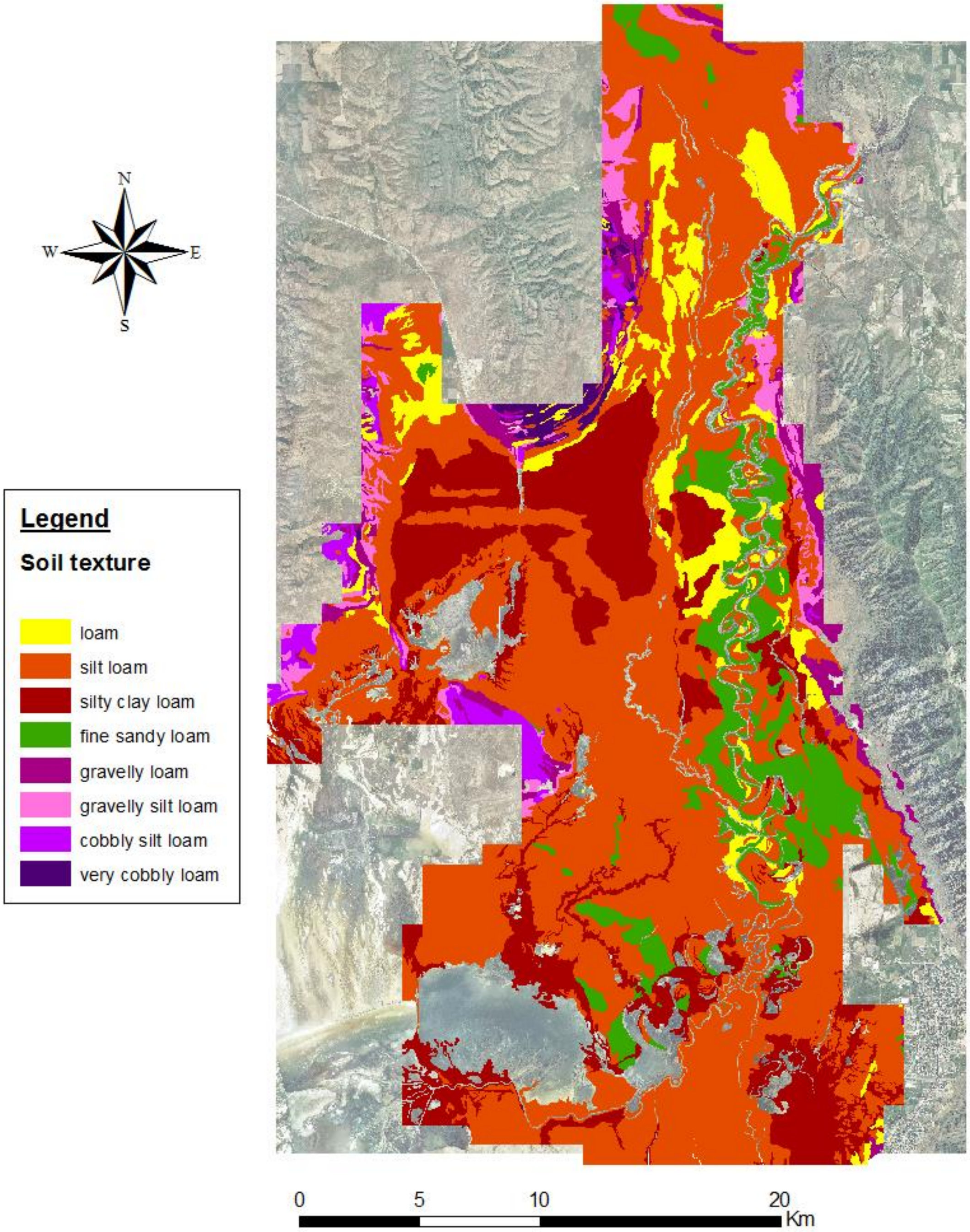
Appendix A – Location of the Bear River Watershed



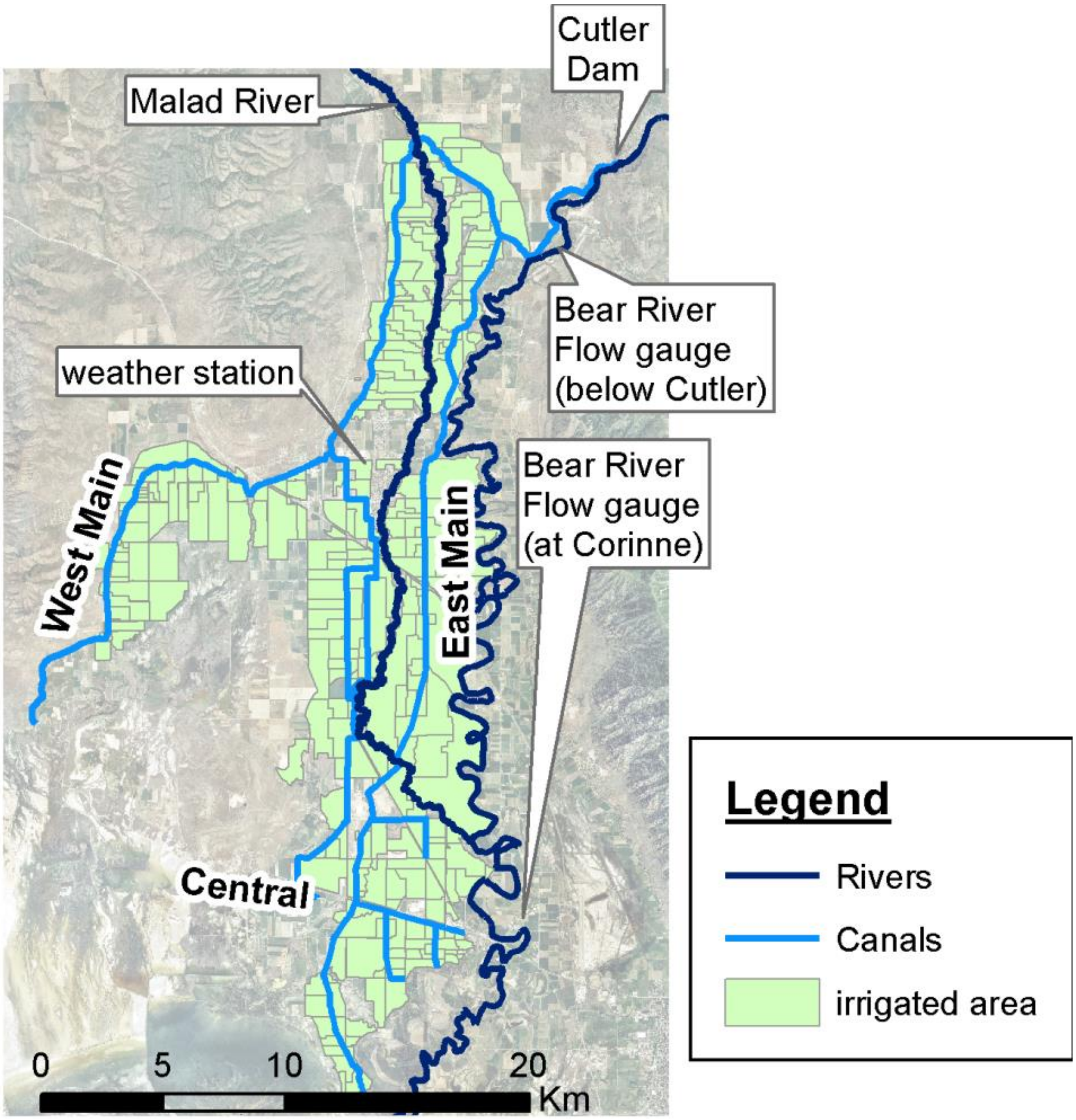
Appendix B – Crop distribution map of the Bear River Canal Company area as surveyed in 2009



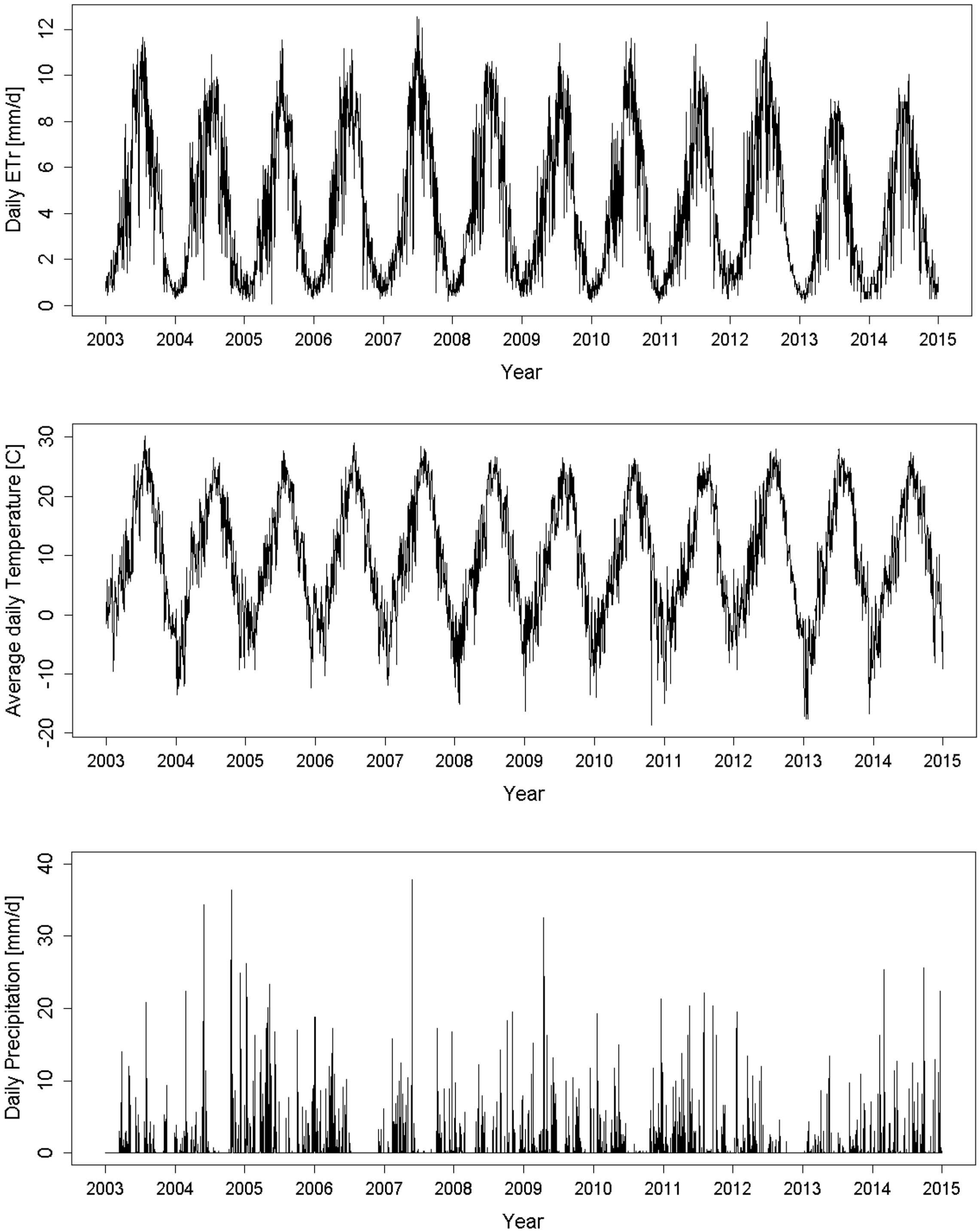
Appendix C – Soil distribution map of the Bear River Canal Company area



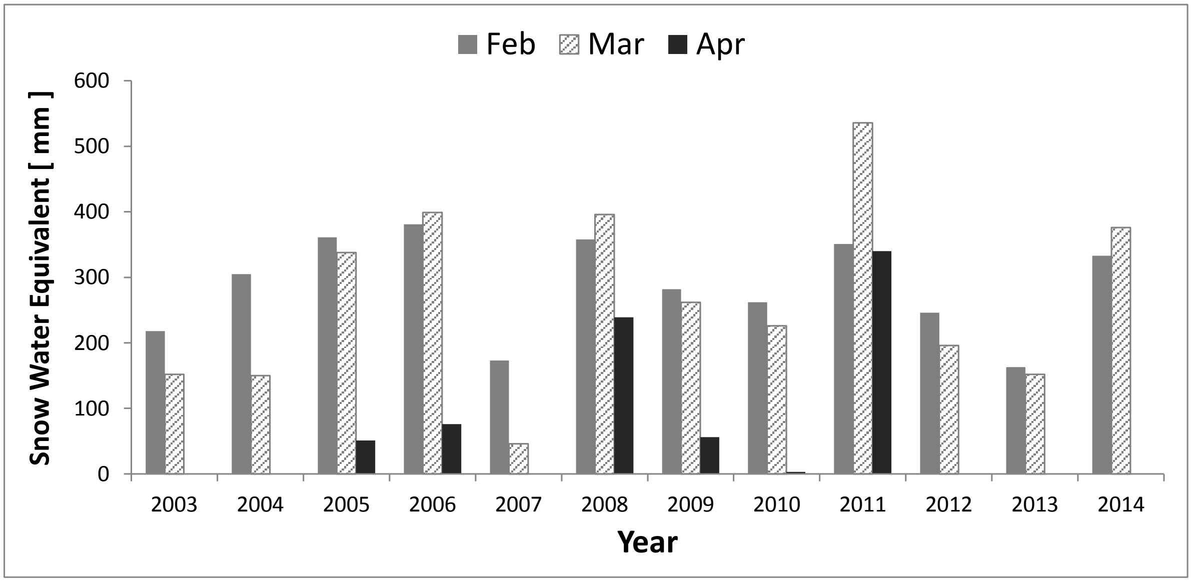
Appendix D – Main canals and rivers in the Bear River Canal Company area



Appendix E – Time series of reference ET, temperature, precipitation and snowpack data



Time series of weather data (reference ET, precipitation and daily temperature) for 2003 to 2014. Data provided by the Utah Climate Center (www.climate.usurf.usu.edu)



Snow water equivalent as measure at Tony Grove Ranger Station at the end of the month (February, March, April) for 2003 to 2014. Data provided by the NCRS-USDA (www.nrcs.usda.gov)

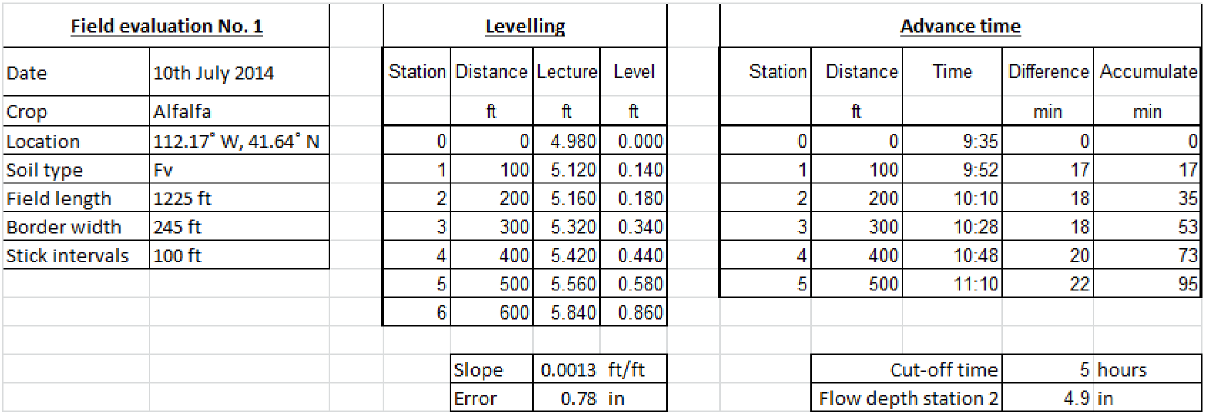
Appendix F – Results of the field evaluations and SIRMOD simulations

Field evaluations 2014

During the 2014 growing season 5 field evaluations were conducted by Rose Long and Jonna van Opstal. The number of field evaluations during this season was limited due to the summer precipitation making irrigation events infrequent.

The observations and measurements made during the field evaluations are reported below. The flow in the ditch was measured with an acoustic Doppler velocimeter (Sontek). The advance was simulated using SIRMOD software and an iterative process of adapting the infiltration parameters to match the simulated advance with the observed advance from the field evaluations.

Field evaluation No.1



Field evaluation No. 1	
Date	10th July 2014
Crop	Alfalfa
Location	112.17° W, 41.64° N
Soil type	Fv
Field length	1225 ft
Border width	245 ft
Stick intervals	100 ft

Levelling

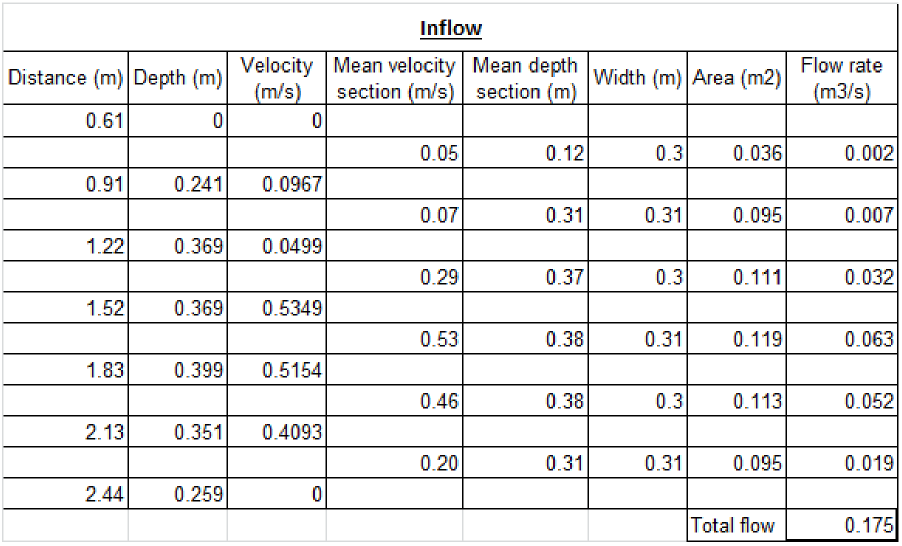
Station	Distance	Lecture	Level
	ft	ft	ft
0	0	4.980	0.000
1	100	5.120	0.140
2	200	5.160	0.180
3	300	5.320	0.340
4	400	5.420	0.440
5	500	5.560	0.580
6	600	5.840	0.860

Slope	0.0013	ft/ft
Error	0.78	in

Advance time

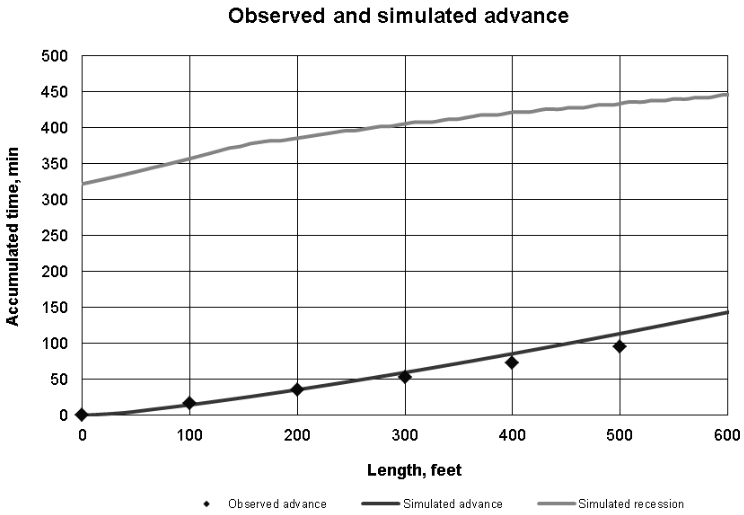
Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	9:35	0	0
1	100	9:52	17	17
2	200	10:10	18	35
3	300	10:28	18	53
4	400	10:48	20	73
5	500	11:10	22	95

Cut-off time	5	hours
Flow depth station 2	4.9	in



Inflow

Distance (m)	Depth (m)	Velocity (m/s)	Mean velocity section (m/s)	Mean depth section (m)	Width (m)	Area (m2)	Flow rate (m3/s)
0.61	0	0					
			0.05	0.12	0.3	0.036	0.002
0.91	0.241	0.0967					
			0.07	0.31	0.31	0.095	0.007
1.22	0.369	0.0499					
			0.29	0.37	0.3	0.111	0.032
1.52	0.369	0.5349					
			0.53	0.38	0.31	0.119	0.063
1.83	0.399	0.5154					
			0.46	0.38	0.3	0.113	0.052
2.13	0.351	0.4093					
			0.20	0.31	0.31	0.095	0.019
2.44	0.259	0					
						Total flow	0.175



Field evaluation No.2

Field evaluation No. 2	
Date	15th July 2014
Crop	Alfalfa
Location	112.17˚ W, 41.57˚ N
Soil type	Ld
Field length	1150 ft
Border width	127 ft
Stick intervals	100 ft

Levelling

Station	Distance	Lecture	Level
	ft	ft	ft
0	0	4.940	0.000
1	100	5.080	0.140
2	200	5.140	0.200
3	300	5.420	0.480
4	400	5.500	0.560
5	500	5.680	0.740
6	600	5.800	0.860

Slope	0.0015	ft/ft
Error	0.53	in

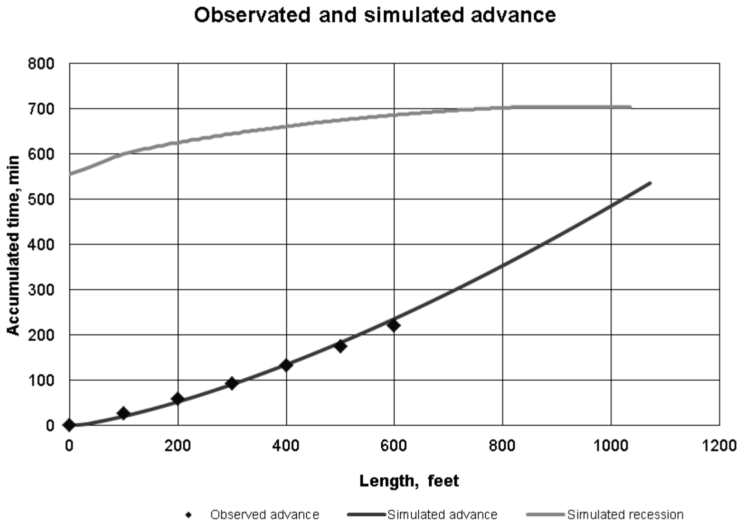
Advance time

Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	9:40	0	0
1	100	10:07	27	27
2	200	10:34	31	58
3	300	11:08	34	92
4	400	11:49	41	133
5	500	12:30	41	174
6	600	13:17	47	221

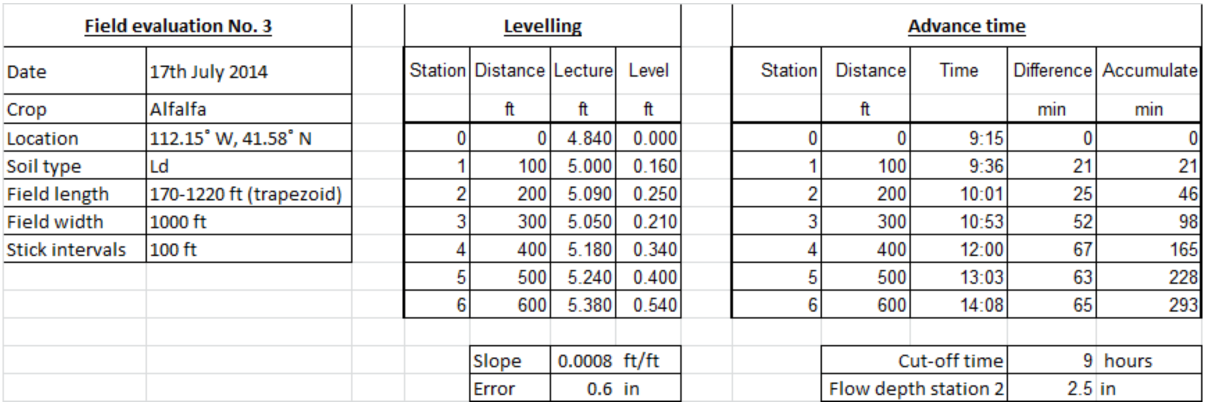
Cut-off time	18:30	
Flow depth station 2	3.5	in

Inflow

Distance (m)	Depth (m)	Velocity (m/s)	Mean velocity section (m/s)	Mean depth section (m)	Width (m)	Area (m2)	Flow rate (m3/s)
0.61	0	0					
			0.02	0.20	0.3	0.060	0.001
0.91	0.399	0.0366					
			0.44	0.54	0.31	0.167	0.073
1.22	0.68	0.8406					
			0.44	0.66	0.3	0.199	0.088
1.52	0.649	0.0451					
			0.02	0.59	0.31	0.184	0.004
1.83	0.54	0					
			0.00	0.41	0.3	0.123	0.000
2.13	0.28	0.0033					
			0.00	0.14	0.16	0.022	0.000
2.29	0	0					
						Total flow	0.167



Field evaluation No.3



Field evaluation No. 3	
Date	17th July 2014
Crop	Alfalfa
Location	112.15˚ W, 41.58˚ N
Soil type	Ld
Field length	170-1220 ft (trapezoid)
Field width	1000 ft
Stick intervals	100 ft

Levelling

Station	Distance	Lecture	Level
	ft	ft	ft
0	0	4.840	0.000
1	100	5.000	0.160
2	200	5.090	0.250
3	300	5.050	0.210
4	400	5.180	0.340
5	500	5.240	0.400
6	600	5.380	0.540

Slope	0.0008	ft/ft
Error	0.6	in

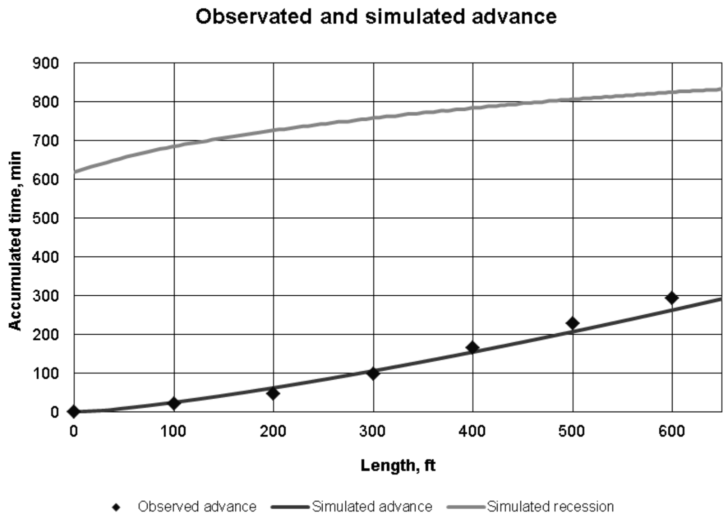
Advance time

Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	9:15	0	0
1	100	9:36	21	21
2	200	10:01	25	46
3	300	10:53	52	98
4	400	12:00	67	165
5	500	13:03	63	228
6	600	14:08	65	293

Cut-off time	9	hours
Flow depth station 2	2.5	in

Inflow

Distance (m)	Depth (m)	Velocity (m/s)	Mean velocity section (m/s)	Mean depth section (m)	Width (m)	Area (m2)	Flow rate (m3/s)
0.46	0	0					
			0.00	0.09	0.15	0.014	0.000
0.61	0.18	0.0065					
			0.04	0.25	0.15	0.038	0.001
0.76	0.32	0.0709					
			0.12	0.39	0.15	0.059	0.007
0.91	0.469	0.1706					
			0.20	0.52	0.16	0.082	0.016
1.07	0.561	0.2241					
			0.25	0.58	0.15	0.087	0.022
1.22	0.601	0.2763					
			0.29	0.59	0.15	0.089	0.026
1.37	0.579	0.3083					
			0.30	0.57	0.15	0.086	0.026
1.52	0.561	0.2935					
			0.24	0.48	0.16	0.077	0.019
1.68	0.399	0.1908					
			0.20	0.34	0.15	0.051	0.010
1.83	0.28	0.2169					
			0.11	0.14	0.3	0.042	0.005
2.13	0	0					
						Total flow	0.132



Field evaluation No.4

Field evaluation No. 4	
Date	30th July 2014
Crop	Alfalfa
Location	112.17˚ W, 41.64˚ N
Soil type	Fv
Field length	1225 ft
Border width	245 ft
Stick intervals	100 ft

Levelling

Station	Distance	Lecture	Level
	ft	ft	ft
0	0	5.740	0.000
1	100	5.950	0.210
2	200	5.980	0.240
3	300	6.120	0.380
4	400	6.220	0.480
5	500	6.400	0.660
6	600	6.540	0.800

Slope	0.0013	ft/ft
Error	0.48	in

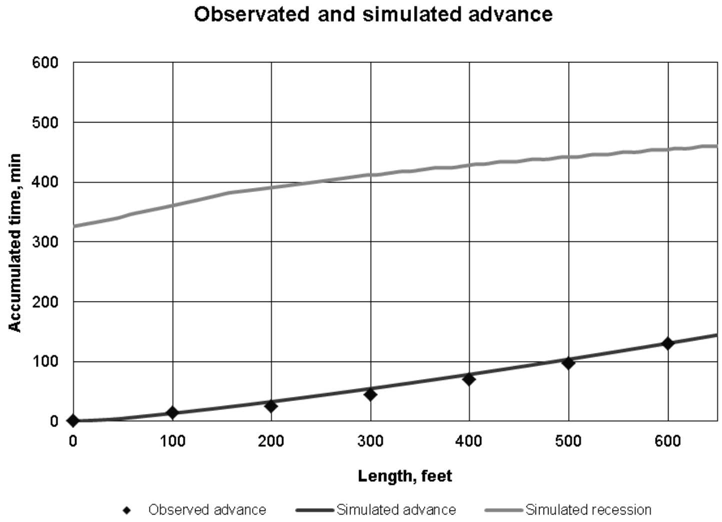
Advance time

Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	7:26	0	0
1	100	7:40	14	14
2	200	7:50	10	24
3	300	8:10	20	44
4	400	8:35	25	69
5	500	9:03	28	97
6	600	9:35	32	129

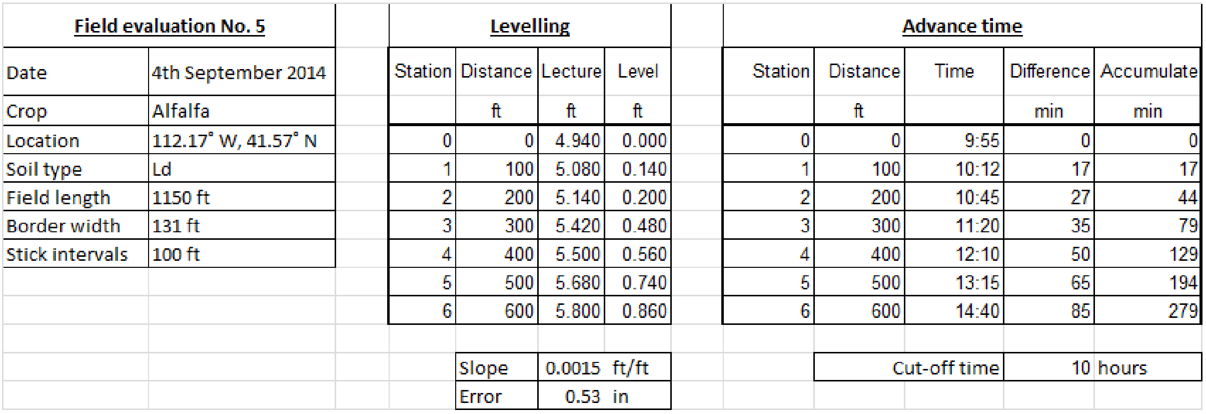
Cut-off time	5	hours
Flow depth station 2	2	in

Inflow

Distance (m)	Depth (m)	Velocity (m/s)	Mean velocity section (m/s)	Mean depth section (m)	Width (m)	Area (m2)	Flow rate (m3/s)
0.46	0	0					
			0.04	0.11	0.3	0.033	0.001
0.76	0.22	0.0795					
			0.21	0.32	0.31	0.099	0.020
1.07	0.421	0.3325					
			0.38	0.42	0.3	0.126	0.049
1.37	0.421	0.4359					
			0.43	0.45	0.31	0.140	0.060
1.68	0.479	0.4271					
			0.42	0.44	0.3	0.132	0.056
1.98	0.399	0.4202					
			0.21	0.20	0.46	0.092	0.019
2.44	0	0					
						Total flow	0.206



Field evaluation No.5



Field evaluation No. 5	
Date	4th September 2014
Crop	Alfalfa
Location	112.17˚ W, 41.57˚ N
Soil type	Ld
Field length	1150 ft
Border width	131 ft
Stick intervals	100 ft

Levelling

Station	Distance	Lecture	Level
	ft	ft	ft
0	0	4.940	0.000
1	100	5.080	0.140
2	200	5.140	0.200
3	300	5.420	0.480
4	400	5.500	0.560
5	500	5.680	0.740
6	600	5.800	0.860

Slope	0.0015	ft/ft
Error	0.53	in

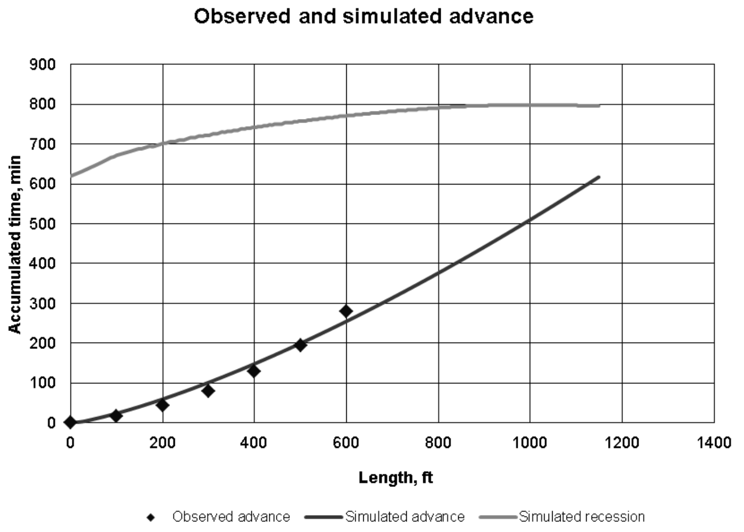
Advance time

Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	9:55	0	0
1	100	10:12	17	17
2	200	10:45	27	44
3	300	11:20	35	79
4	400	12:10	50	129
5	500	13:15	65	194
6	600	14:40	85	279

Cut-off time	10	hours

Inflow

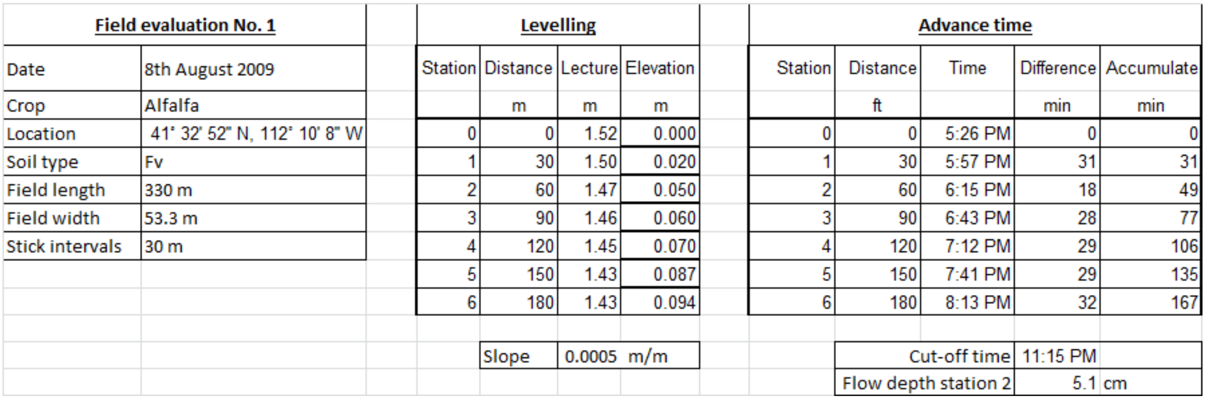
Distance (m)	Depth (m)	Velocity (m/s)	Mean velocity section (m/s)	Mean depth section (m)	Width (m)	Area (m2)	Flow rate (m3/s)
0.61	0	0					
			0.00	0.08	0.15	0.012	0.000
0.76	0.159	0.0009					
			0.03	0.19	0.15	0.029	0.001
0.91	0.229	0.0494					
			0.11	0.27	0.16	0.044	0.005
1.07	0.32	0.1632					
			0.18	0.33	0.15	0.050	0.009
1.22	0.341	0.2013					
			0.21	0.34	0.15	0.051	0.011
1.37	0.341	0.2105					
			0.21	0.34	0.15	0.051	0.011
1.52	0.341	0.2059					
			0.22	0.34	0.16	0.055	0.012
1.68	0.341	0.2318					
			0.23	0.34	0.15	0.051	0.012
1.83	0.341	0.2356					
			0.22	0.33	0.15	0.050	0.011
1.98	0.32	0.1946					
			0.18	0.30	0.15	0.045	0.008
2.13	0.28	0.1596					
			0.15	0.24	0.16	0.038	0.006
2.29	0.201	0.1359					
			0.07	0.10	0.15	0.015	0.001
2.44	0	0					
						Total Flow	0.085



Field evaluations 2009

During the 2009 growing season 8 field evaluations were conducted by Sekar Ramu and others from the Remote Sensing Services Lab in the Civil Engineering department. Observations and measurements are reported below. Flow in the ditch was measured with a mechanical propeller meter (Rickly Hydrological). Advance curves were simulated with SIRMOD software using an iterative process of adapting the infiltration parameters to obtain a simulated curve close to the observations during the field evaluation.

Field evaluation No.1



Field evaluation No. 1	
Date	8th August 2009
Crop	Alfalfa
Location	41° 32' 52" N, 112° 10' 8" W
Soil type	Fv
Field length	330 m
Field width	53.3 m
Stick intervals	30 m

Levelling

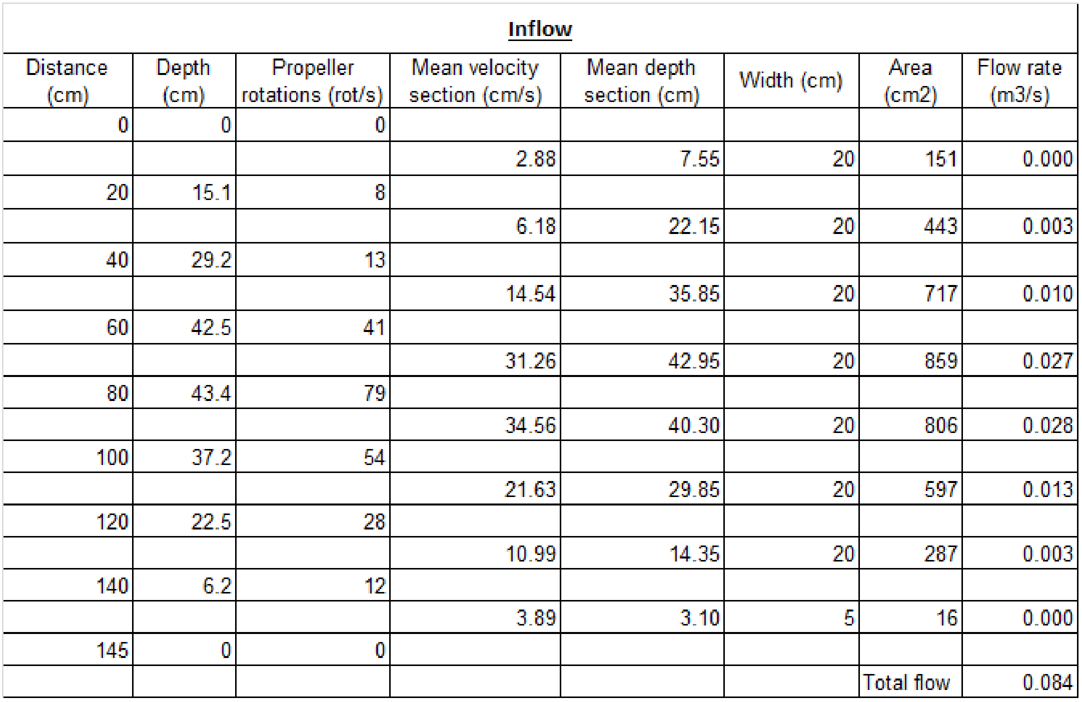
Station	Distance	Lecture	Elevation
	m	m	m
0	0	1.52	0.000
1	30	1.50	0.020
2	60	1.47	0.050
3	90	1.46	0.060
4	120	1.45	0.070
5	150	1.43	0.087
6	180	1.43	0.094

Slope	0.0005	m/m

Advance time

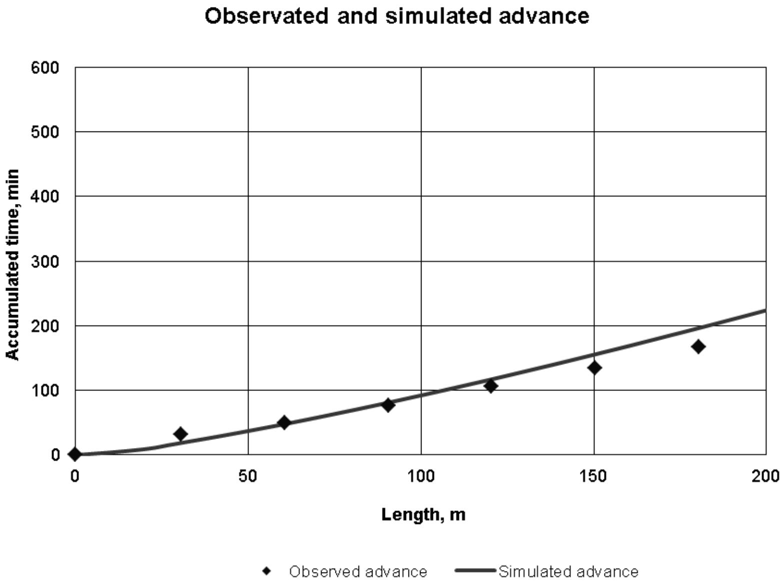
Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	5:26 PM	0	0
1	30	5:57 PM	31	31
2	60	6:15 PM	18	49
3	90	6:43 PM	28	77
4	120	7:12 PM	29	106
5	150	7:41 PM	29	135
6	180	8:13 PM	32	167

Cut-off time	11:15 PM	
Flow depth station 2	5.1	cm

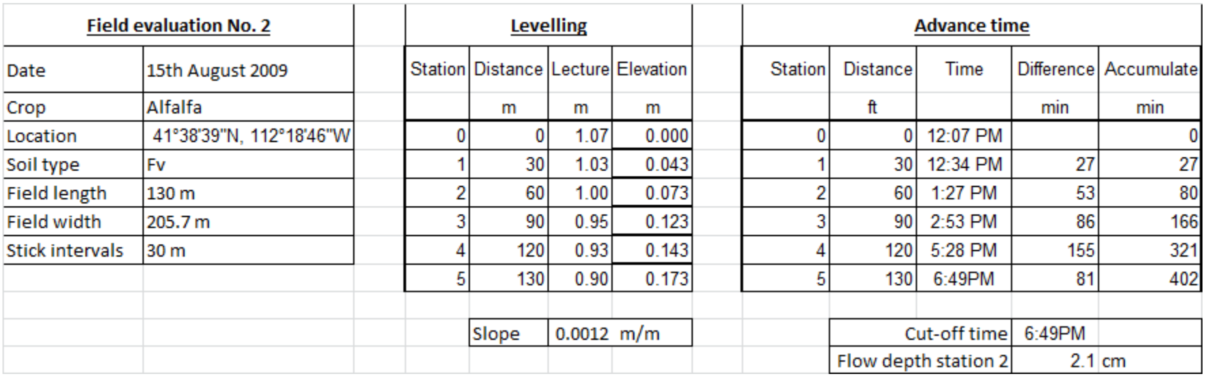


Inflow

Distance (cm)	Depth (cm)	Propeller rotations (rot/s)	Mean velocity section (cm/s)	Mean depth section (cm)	Width (cm)	Area (cm2)	Flow rate (m3/s)
0	0	0					
			2.88	7.55	20	151	0.000
20	15.1	8					
			6.18	22.15	20	443	0.003
40	29.2	13					
			14.54	35.85	20	717	0.010
60	42.5	41					
			31.26	42.95	20	859	0.027
80	43.4	79					
			34.56	40.30	20	806	0.028
100	37.2	54					
			21.63	29.85	20	597	0.013
120	22.5	28					
			10.99	14.35	20	287	0.003
140	6.2	12					
			3.89	3.10	5	16	0.000
145	0	0					
						Total flow	0.084



Field evaluation No.2



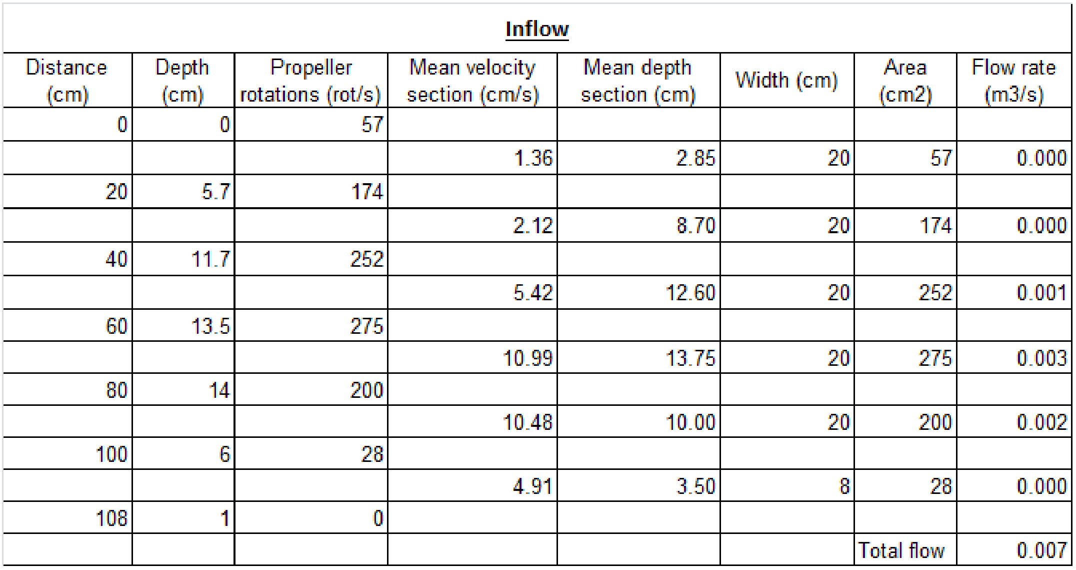
Field evaluation No. 2	
Date	15th August 2009
Crop	Alfalfa
Location	41°38'39"N, 112°18'46"W
Soil type	Fv
Field length	130 m
Field width	205.7 m
Stick intervals	30 m

Levelling

Station	Distance	Lecture	Elevation
	m	m	m
0	0	1.07	0.000
1	30	1.03	0.043
2	60	1.00	0.073
3	90	0.95	0.123
4	120	0.93	0.143
5	130	0.90	0.173
Slope	0.0012 m/m		

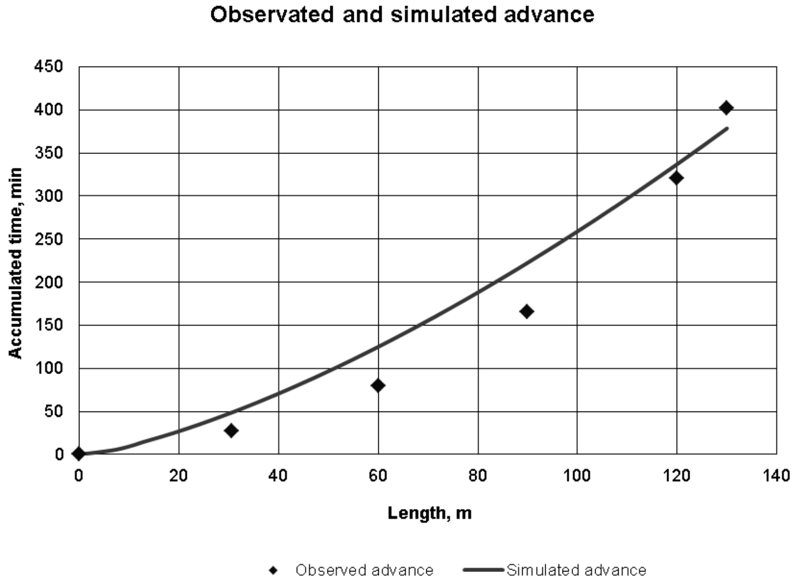
Advance time

Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	12:07 PM		0
1	30	12:34 PM	27	27
2	60	1:27 PM	53	80
3	90	2:53 PM	86	166
4	120	5:28 PM	155	321
5	130	6:49PM	81	402
	Cut-off time	6:49PM		
	Flow depth station 2	2.1	cm	

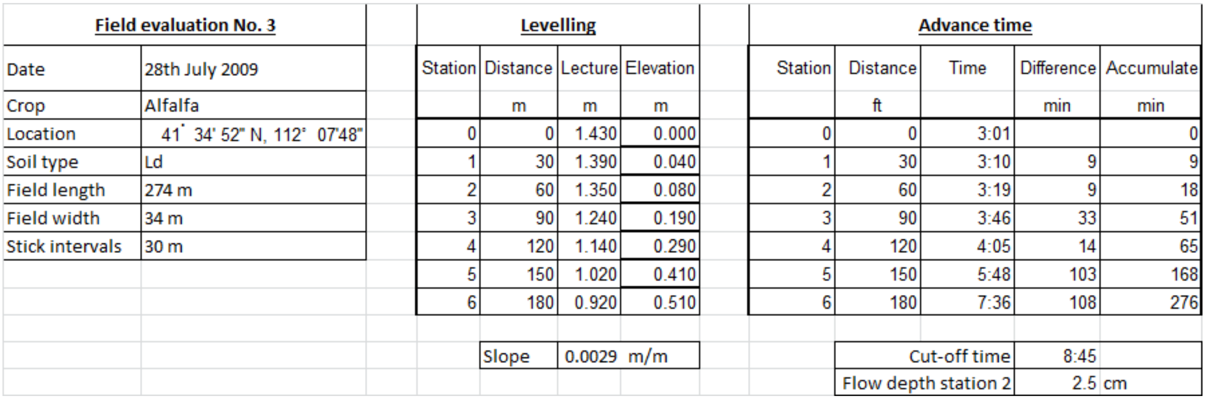


Inflow

Distance (cm)	Depth (cm)	Propeller rotations (rot/s)	Mean velocity section (cm/s)	Mean depth section (cm)	Width (cm)	Area (cm2)	Flow rate (m3/s)
0	0	57					
			1.36	2.85	20	57	0.000
20	5.7	174					
			2.12	8.70	20	174	0.000
40	11.7	252					
			5.42	12.60	20	252	0.001
60	13.5	275					
			10.99	13.75	20	275	0.003
80	14	200					
			10.48	10.00	20	200	0.002
100	6	28					
			4.91	3.50	8	28	0.000
108	1	0					
						Total flow	0.007



Field evaluation No.3



Field evaluation No. 3

Date	28th July 2009
Crop	Alfalfa
Location	41˚ 34' 52" N, 112˚ 07'48"
Soil type	Ld
Field length	274 m
Field width	34 m
Stick intervals	30 m

Levelling

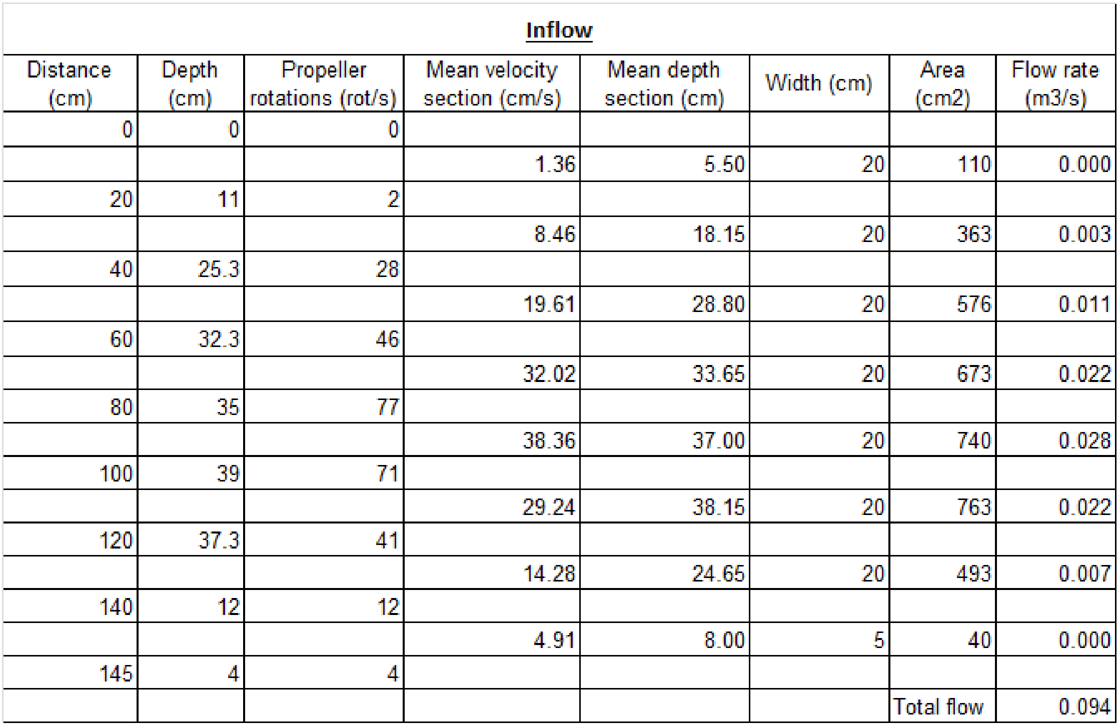
Station	Distance	Lecture	Elevation
	m	m	m
0	0	1.430	0.000
1	30	1.390	0.040
2	60	1.350	0.080
3	90	1.240	0.190
4	120	1.140	0.290
5	150	1.020	0.410
6	180	0.920	0.510

Slope	0.0029 m/m

Advance time

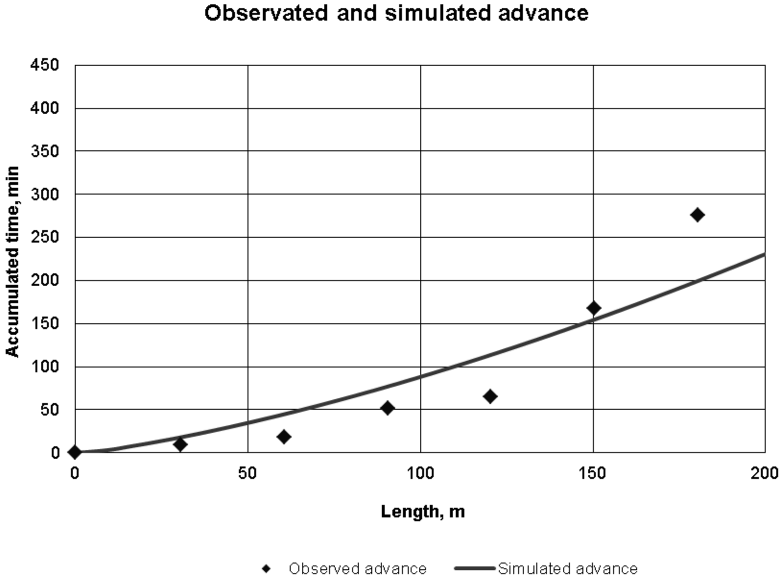
Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	3:01		0
1	30	3:10	9	9
2	60	3:19	9	18
3	90	3:46	33	51
4	120	4:05	14	65
5	150	5:48	103	168
6	180	7:36	108	276

Cut-off time	8:45
Flow depth station 2	2.5 cm



Inflow

Distance (cm)	Depth (cm)	Propeller rotations (rot/s)	Mean velocity section (cm/s)	Mean depth section (cm)	Width (cm)	Area (cm2)	Flow rate (m3/s)
0	0	0					
			1.36	5.50	20	110	0.000
20	11	2					
			8.46	18.15	20	363	0.003
40	25.3	28					
			19.61	28.80	20	576	0.011
60	32.3	46					
			32.02	33.65	20	673	0.022
80	35	77					
			38.36	37.00	20	740	0.028
100	39	71					
			29.24	38.15	20	763	0.022
120	37.3	41					
			14.28	24.65	20	493	0.007
140	12	12					
			4.91	8.00	5	40	0.000
145	4	4					
						Total flow	0.094



Field evaluation No.4

Field evaluation No. 4	
Date	15th July 2009
Crop	Alfalfa
Location	41°34'10"N/112°12'29"W
Soil type	Ld
Field length	426 m
Field width	110 m
Stick intervals	30 m

Levelling

Station	Distance	Lecture	Elevation
	m	m	m
0	0	1.45	0.000
1	30	1.41	0.039
2	60	1.30	0.145
3	90	1.25	0.197
4	120	1.22	0.228
5	150	1.21	0.240
6	180	1.12	0.325

Slope	0.0013 m/m

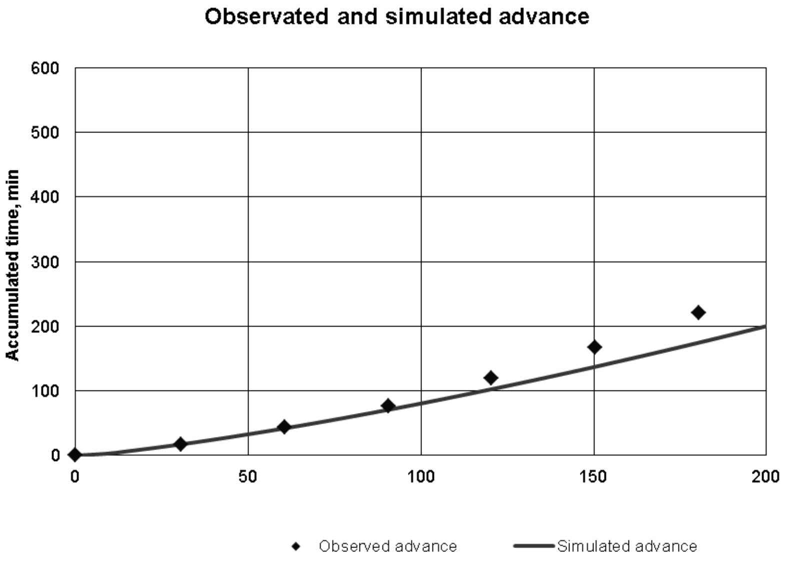
Advance time

Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	1.15 pm		0
1	30	1.32 pm	17	17
2	60	1.58 pm	26	43
3	90	2.32 pm	34	77
4	120	3.14 pm	42	119
5	150	4.02pm	48	167
6	180	4.56 pm	54	221

Cut-off time	7.25 hours
Flow depth station 2	3.7 cm

Inflow

Distance (cm)	Depth (cm)	Propeller rotations (rot/s)	Mean velocity section (cm/s)	Mean depth section (cm)	Width (cm)	Area (cm2)	Flow rate (m3/s)
0	0	0					
			2.12	7.55	20	151	0.000
20	15.1	5					
			9.98	21.20	20	424	0.004
40	27.3	31					
			22.65	32.90	20	658	0.015
60	38.5	55					
			35.57	39.90	20	798	0.028
80	41.3	82					
			40.13	39.35	20	787	0.032
100	37.4	73					
			33.54	28.70	20	574	0.019
120	20	56					
			22.14	13.35	20	267	0.006
140	6.7	28					
			10.23	3.35	5	17	0.000
145	0	9					
						Total flow	0.105



Field evaluation No.5

Field evaluation No. 5	
Date	16th August 2009
Crop	Alfalfa
Location	
Soil type	Ho
Field length	244 m
Field width	549 m
Stick intervals	30 m

Levelling

Station	Distance	Lecture	Elevation
	ft	ft	ft
0	0	1.45	0.000
1	30	1.41	0.040
2	60	1.41	0.040
3	90	1.40	0.050
4	120	1.38	0.072
5	150	1.26	0.194
6	180	1.14	0.310

Slope	0.0022	m/m

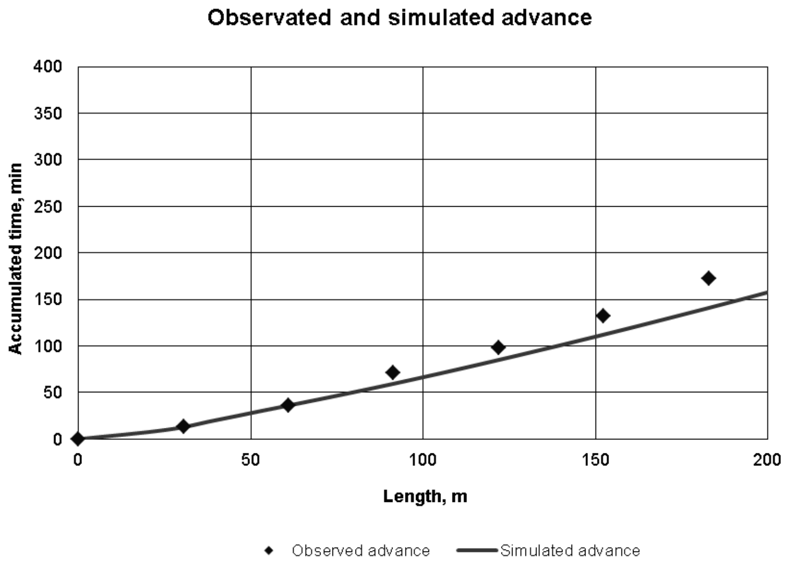
Advance time

Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	2.59 PM	0	0
1	30	3.12 PM	13	13
2	60	3.35 PM	23	36
3	90	4:10 PM	35	71
4	120	4:37 PM	27	98
5	150	5:11 PM	34	132
6	180	5:51 PM	40	172

Cut-off time	10:30 PM	
Flow depth station 2	4.3	cm

Inflow

Distance (cm)	Depth (cm)	Propeller rotations (rot/s)	Mean velocity section (cm/s)	Mean depth section (cm)	Width (cm)	Area (cm2)	Flow rate (m3/s)
0	0	0					
			2.88	10.00	20	200	0.001
20	20	8					
			6.43	29.25	20	585	0.004
40	38.5	14					
			13.78	39.25	20	785	0.011
60	40	37					
			18.59	30.90	20	618	0.011
80	21.8	33					
			9.22	10.90	20	218	0.002
100	0	0					
						Total flow	0.029



Field evaluation No.6

Field evaluation No. 6

Date	6th August 2009
Crop	Alfalfa
Location	41° 41' 00" N, 112° 8' 54" W
Soil type	Ho
Field length	360 m
Field width	88 m
Stick intervals	30 m

Levelling

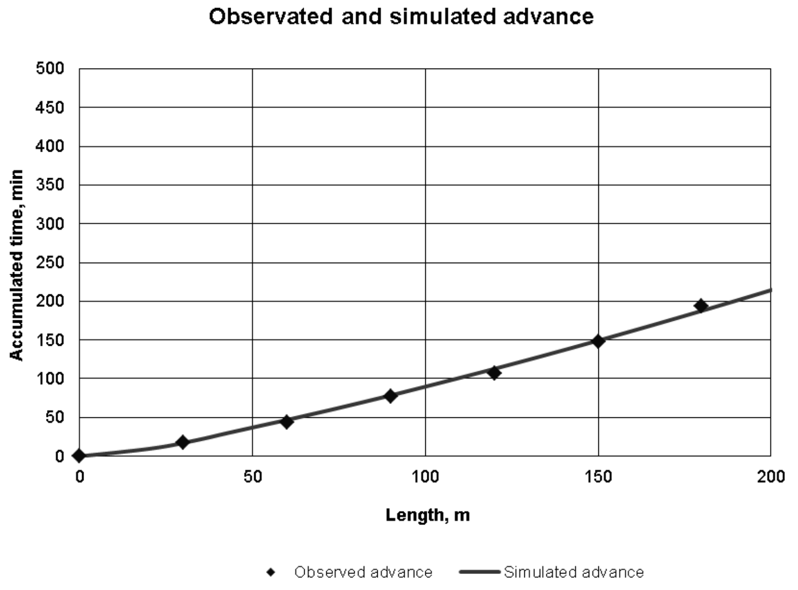
Station	Distance	Lecture	Elevation
	m	m	m
0	0	1.62	0.000
1	30	1.59	0.030
2	60	1.56	0.060
3	90	1.56	0.060
4	120	1.54	0.080
5	150	1.52	0.100
6	180	1.51	0.111
	Slope	0.0006	m/m

Advance time

Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	1:30 PM	0	0
1	30	1:48 PM	18	18
2	60	2:13PM	25	43
3	90	2:47PM	34	77
4	120	3:17PM	30	107
5	150	3:58PM	41	148
6	180	4:43PM	45	193
		Cut-off time	7:28 PM	
		Flow depth station 2	3.2	cm

Inflow

Distance (cm)	Depth (cm)	Propeller rotations (rot/s)	Mean velocity section (cm/s)	Mean depth section (cm)	Width (cm)	Area (cm2)	Flow rate (m3/s)
0	0	0					
			7.44	21.00	20	420	0.003
20	42	26					
			16.82	48.50	20	970	0.016
40	55	37					
			28.22	56.00	20	1120	0.032
60	57	71					
			30.25	57.50	20	1150	0.035
80	58	45					
			19.61	33.60	20	672	0.013
100	9.2	29					
			8.20	4.60	20	92	0.001
120	0	0					
						Total flow	0.100



Field evaluation No.7

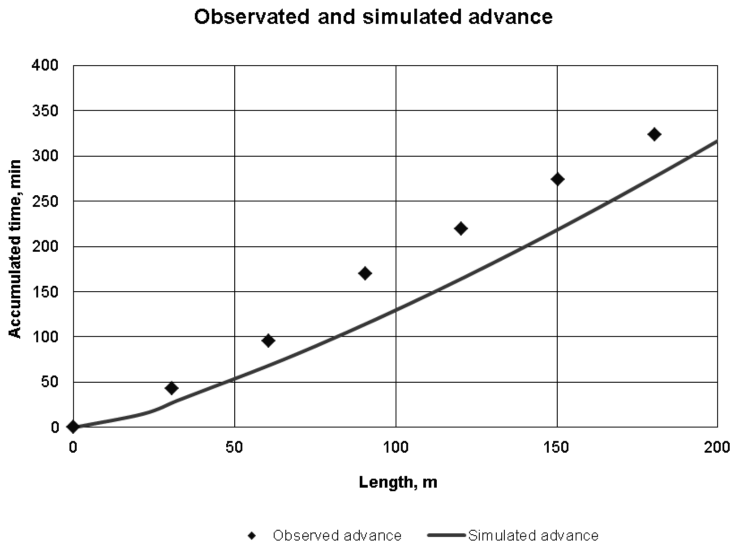
Field evaluation No. 7	
Date	30th July 2009
Crop	Alfalfa
Location	41° 41'21"N/112° 9'27"W
Soil type	Ho
Field length	580 m
Field width	200 m
Stick intervals	30 m

Levelling			
Station	Distance	Lecture	Elevation
	m	m	m
0	0	1.73	0.000
1	30	1.58	0.150
2	60	1.32	0.220
3	90	1.43	0.300
4	120	1.35	0.380
5	150	1.24	0.490
6	180	1.14	0.590
	Slope	0.0023 m/m	

Advance time				
Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	1:58 PM		0
1	30	2:41 PM	43	43
2	60	3.34 PM	53	96
3	90	4:48 PM	74	170
4	120	5:37 PM	49	219
5	150	6:32 PM	55	274
6	180	7:22 PM	50	324
	Cut-off time		6:00 AM	
	Flow depth station 2		3.3 cm	

Inflow

Distance (cm)	Depth (cm)	Propeller rotations (rot/s)	Mean velocity section (cm/s)	Mean depth section (cm)	Width (cm)	Area (cm2)	Flow rate (m3/s)
0	0	0					
			1.36	2.50	20	50	0.000
20	5	2					
			10.99	8.60	20	172	0.002
40	12.2	38					
			26.19	15.90	20	318	0.008
60	19.6	62					
			31.52	18.90	20	378	0.012
80	18.2	59					
			22.65	13.55	20	271	0.006
100	8.9	27					
			7.70	4.45	20	89	0.001
120	0	0					
						Total flow	0.029



Field evaluation No.8

Field evaluation No. 8	
Date	18th August 2009
Crop	Alfalfa
Location	41°42'29"N/112°16'5"W
Soil type	Co
Field length	185 m
Field width	58 m
Stick intervals	30 m

Levelling

Station	Distance	Lecture	Elevation
	m	m	m
0	0	1.31	0.000
1	30	1.20	0.110
2	61	1.17	0.140
3	91	1.10	0.216
4	122	1.09	0.229
5	152	1.08	0.232
6	183	1.08	0.232

Slope	0.0012 m/m

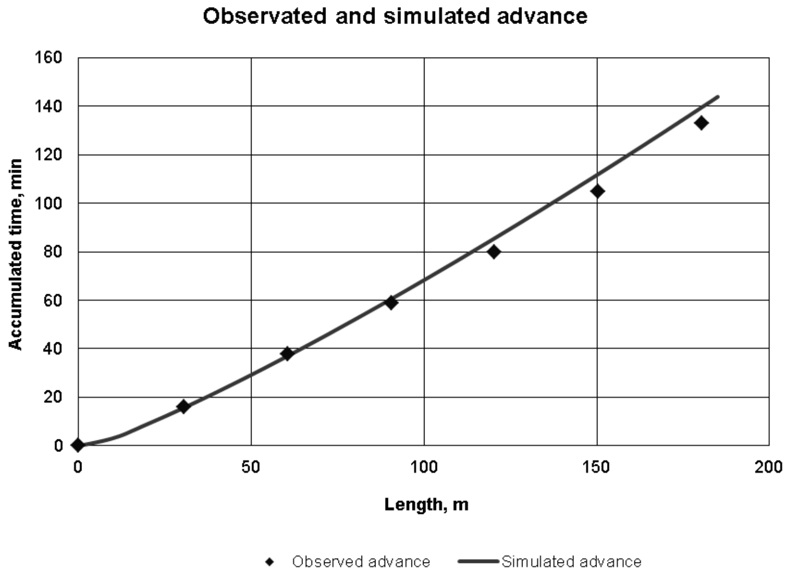
Advance time

Station	Distance	Time	Difference	Accumulate
	ft		min	min
0	0	9.15 AM		0
1	30	9.31AM	16	16
2	60	9.53AM	22	38
3	90	10.14AM	21	59
4	120	10.35AM	21	80
5	150	11.00AM	25	105
6	180	11.28 AM	28	133

Cut-off time	11.28 AM	
Flow depth station 2	3.7	cm

Inflow

Distance (cm)	Depth (cm)	Propeller rotations (rot/s)	Mean velocity section (cm/s)	Mean depth section (cm)	Width (cm)	Area (cm2)	Flow rate (m3/s)
0	0	0					
			1.87	9.25	20	185	0.000
20	18.5	4					
			4.15	27.35	20	547	0.002
40	36.2	9					
			12.00	37.55	20	751	0.009
60	38.9	35					
			18.34	30.10	20	602	0.011
80	21.3	34					
			9.47	10.65	20	213	0.002
100	0	0					
						Total flow	0.025



CURRICULUM VITAE **linkedin.com/in/jonnavopstal**

JONNA D. VAN OPSTAL

EDUCATION

2011 – 2015

PhD Irrigation Engineering
Utah State University
GPA: 3.94/4.0
Emphasis: remote sensing of irrigation areas, water delivery scheduling

Logan, UT
USA

2008 - 2010

MSc International Land and Water Management
Wageningen University
Major: Irrigation and Water Management
Thesis: "Irrigation with reclaimed water down under: a bottom-up approach" research was conducted in Australia (graded 9/10)
Internship: "The use of fertigation in Israel for the production of olive oil" research was conducted in Israel (graded 9/10)

Wageningen
The Netherlands

2004 – 2008

BSc International Land and Water Management
Wageningen University
Major: Irrigation and Water Management
Minor: Water Quality and Treatment
Thesis: "Farmer Field Schools for irrigation management"
Excursions: Spain and Tunisia

Wageningen
The Netherlands

WORK EXPERIENCE

MAY, 2011 - DEC, 2015

Utah Water Research Laboratory
Research assistant

Logan, UT
USA

- using remotely sensed imagery to estimate evapotranspiration and assess irrigation district performance
- fieldwork: setting up eddy covariance systems, monitoring water flow of main and lateral canals, performing field evaluations of irrigation events, taking water quality samples of irrigation and drainage water
- model simulations of the irrigation system schedule and alternative strategies

JAN – MAY, 2011

Peutz bv
Project assistant, Department of Fire Safety

Zoetermeer
The Netherlands

OCT – DEC, 2010

ARCADIS
Project assistant, Department of Water

Hoofddorp
The Netherlands

- report the findings of a project on water management of the Ijsselmeer lake

Sep, 2009 – Mar, 2010

CSIRO Land and Water Division **Brisbane, QLD Australia**

MSc thesis

- farm-system modelling of the social and biophysical aspects of introducing reclaimed wastewater irrigation
- interviewing and performing case studies for 6 local farmers

Mar – Jul, 2008

Agricultural Research Organisation **Gilat Israel**

MSc internship

- monitoring irrigation solution and N, P and K nutrient concentrations
- conducting growth measurements of olive trees

PUBLICATIONS AND CONFERENCES

J.D. van Opstal, F.P. Huibers, R.G. Cresswell 2012 'A participatory modelling approach to define farm-scale effects of reclaimed wastewater irrigation in the Lockyer Valley, Australia' *Water International* Vol.37 Iss.7

R. Erel, U. Yermiyahu, J. van Opstal, A. Ben-Gal, A. Schwartz, A. Dag 2013 'The importance of olive (*Olea europaea* L.) tree nutritional status on its productivity' *Scientia Horticulturae* Vol. 159

J.D. van Opstal, C.M.U. Neale 2013 'Potential savings of water and nutrients for the Bear River Canal Company' *USCID Conference Proceedings,* 7th International Conference on Irrigation and Drainage, Phoenix AZ (Oral presentation and publication)

J.D. van Opstal, C.M.U. Neale, S. Lecina 2014 'Improvements in irrigation system modelling when using remotely sensed ET for calibration' *Proceedings SPIE 9239*, Remote Sensing for Agriculture, Ecosystems, and Hydrology XVI (Oral presentation and publication)

ACS Meetings, Cincinnati OH (Oral presentation) 2012 'Comparison of evapotranspiration calculated with a conservation of mass and energy balance method in an irrigated agricultural area in Utah'

American Geophysical Union, San Francisco CA (Oral presentation) 2014 'Irrigation dynamics and tactics – developing a sustainable and profitable irrigation strategy for agricultural areas'

ASABE ET symposium, Raleigh NC (Oral presentation) 2014 'Learning from the past, looking at the future – irrigation ET estimation using remote sensing during wet and drought years'

Spring Runoff Conference, Logan UT (Oral presentation) 2012 'Integrating water quality and quantity aspects of irrigation management for an area in the Lower Bear River watershed'

Spring Runoff Conference, Logan UT (Poster presentation) 2013 'Estimating potential savings of water for the Bear River Canal Company using spatial analysis tools'

Spring Runoff Conference, Logan UT (Oral presentation) 2014 'The influence of spring runoff water availability on irrigation performance'