URBAN AGRICULTURE AND SMALL FARM IRRIGATION:
CASE STUDIES FROM CACHE VALLEY, UTAH

by

Tyler Pratt

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ABSTRACT

Urban Agriculture and Small Farm Irrigation:
Case Studies from Cache Valley, Utah

by

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Utah State University, 2016

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The landscape of water in Utah is changing due to population growth, conversion of agricultural land to urban development, and increasing awareness of water scarcity. The Utah Division of Water Resources forecasts that the currently developed water supplies will not be enough to provide for Utah’s future population, and is pursuing conservation and new development to meet the state’s anticipated needs.

Along with the urban growth Utah is experiencing a growing urban and small farm agricultural sector, but knowledge of water use in these operations is limited. Further research in this area aids in understanding the impact of land use change on the state’s hydrology, aids the state water authorities in water use estimates, assists farmers in moving towards wiser water management, and helps Utah State University Extension better meet the needs of small irrigators.

My research creates a clearer picture of urban and small farm agricultural irrigation in Utah. For the 2015 growing season I performed irrigation evaluations for 24 urban and
small farms in Cache Valley, and I explore the results from both case study and statistical perspectives. My results show a great degree of heterogeneity with irrigation efficiencies ranging from 6% to 100%. In general, small fields had greater irrigation depths than large fields, and surface irrigated fields applied higher depths than sprinkle and drip irrigated fields. Yet a big influence on efficiency was management, as fields relying on a set schedule had higher depths than fields that were irrigated inconsistently due to other factors. Therefore, water conservation programs focused on reducing irrigated area or providing technological alternatives may not result in true water savings if the effect of management is ignored. In particular, urban and small farmers need increased awareness of how management can result in savings of time and money, and improved knowledge of how to measure application rates, improve application uniformity, and scheduling techniques. With improvements in these areas, water management on urban and small farms can be improved, therein helping the urban and small farm irrigators themselves as well as the state in meeting its future water needs.

(162 pages)
PUBLIC ABSTRACT

Urban Agriculture and Small Farm Irrigation:

Case Studies from Cache Valley, Utah

Tyler Pratt

The socioeconomic landscape of water in Utah is rapidly changing due to population growth, conversion of agricultural land to urban development, and increasing awareness of future water scarcity. The Utah Division of Water Resources (DWRe) forecasts that the currently developed water supplies will not be enough to provide for Utah’s future population, and is pursuing conservation and new development to be able to meet the state’s needs.

Along with the urban growth Utah is experiencing a quickly growing sector of urban and small farm agriculture, but knowledge of water use and current practices in this area is limited. Further research in this area aids in understanding the impact of land use change on the state’s hydrology, aids the state water authorities in current and future water use estimates, assists farmers in moving towards wiser agricultural water management, and gives insight to USU Extension as how to better meet the needs of small irrigators.

My research creates a clearer picture of urban and small farm agricultural irrigation in Utah. For the 2015 growing season I performed thorough irrigation evaluations for 24 urban and small farm fields in Cache Valley, Utah, and I explore the results from both case study and statistical perspectives. My results show a great degree of heterogeneity with irrigation efficiencies ranging from 6% to 100%, signifying that for single-use river basins
significant water savings could be possible by addressing inefficiencies at the urban and small farm scale. I observe and compare trends in efficiencies in order to identify which factors (e.g. size, crop, irrigation method, scheduling) led to efficient and inefficient irrigation practices. Additionally, I explore the unique circumstances of the few outliers with exceptionally high application depths, and I provide recommendations for improvement that these irrigators as well as others with similar circumstances can benefit from. Insight into water use in this sector, and recommendations for the improved management thereof, are provided to numerous parties including the DWRe, Utah State University Extension, and the urban and small farm irrigators that took part in my study.

The funding for this research was provided by the Utah Water Research Laboratory in Logan, Utah.
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I must mention the many farmers, both here in the U.S. and abroad, whose stories and ambitions inspired in me a passion for growing food, which led to my interest in irrigation and eventually engineering school. Seven years of university later, I would not have changed this path for anything.

I owe my great experience in university to my professors that over the years have spent countless office hours with me, patiently helping me grasp new concepts and gain new skills that I hope to someday be teaching others. I will be forever grateful to them, not to mention the funding that I have received through them to help make this dream come true. In particular I would like to thank Dr. Niel Allen for his extensive knowledge, insight, and open door for whenever I needed direction or to bounce an idea off of him. I also wish to thank Dr. David Rosenberg, Dr. Kelly Kopp, and Dr. Andy Keller for their involvement on my graduate committee and the sound advice they gave to guide my research, and to the irrigators themselves for working with me to collect the data I needed for this study.

Tyler Pratt
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INTRODUCTION

The socioeconomic landscape of water in Utah is undergoing a transformation, and there is much debate about how water should be managed to meet the present and future needs of the state. According to the U.S. Census Bureau, the 2010 Utah population is expected to more than double by 2060, giving the state the fourth highest growth rate in the country (United States Census Bureau 2016). The growth is happening largely by sprawl of new residential and commercial land onto agricultural land at the edge of urban boundaries, creating a mosaic of mixed agricultural, residential, and commercial land use (Li 2013; McGinty 2009). A study by NumbersUSA in 2014 found that Utah has the second highest rate of urban sprawl by percentage in the U.S. (Kolankiewics et al. 2014). Urban sprawl is defined as the increase in physical area of a town over time as undeveloped land is developed. Over 64,500 acres of farmland converted to urban use in Utah between the years 1982 and 2012, an increase in developed land of 16%, and the Utah Division of Water Resources (DWR) estimates that by 2050 an additional 10% of farm land will be urbanized (Utah Division of Water Resources 2013). As the agricultural land is developed the spatial and temporal water use on the landscape changes, which can have major implications to other water users in the basin by changing the quantities and timing of water demands, the environmental flows in rivers and wetlands, and the quantity and destination of return flows associated with agriculture. How this change in water use will affect the future of Utah is a subject of much research as the state tries to balance the ever evolving needs of municipalities, agriculture, the environment, and industry.

Simultaneous with urban growth, Utah is experiencing a quickly growing sector of
urban and small farm agriculture. Urban agriculture is defined as “the growing, processing, and distribution of food and other products through intensive plant cultivation and animal husbandry in and around cities” (Brown et al., unpublished manuscript, 2003). In this study I define a small farm as being less than or equal to 20 acres. Although total acreage in agriculture in Utah is decreasing as agricultural land is converted to urban development, the total number of farms in Utah is actually increasing. For example, in Weber, Davis, and Salt Lake counties, mostly urbanized areas and the primary counties comprising the Wasatch Front, the number of farms between one and nine acres has increased 245% from 1974 to 2007 (Downen 2009). A recent survey by New York University of 253 urban farms found that the median income of the farms in their study was $5,000, suggesting that the recent growth is not related to economics but rather a combination of concerns including interest in locally produced foods, nutrition and health, food security, education, environmental benefits, and community building (Dimitri et al. 2016; Curtis et al. 2013). Salt Lake City, for example, set a goal of increasing direct access to fresh foods, and community groups and public officials are actively working to identify vacant lots that can be used to grow food in the city (Utah Division of Water Resources 2003). None of these documents, however, investigate the quantities and efficiency of water use in urban and small farm irrigation.

The DWRe currently divides water use into two main categories, agricultural and municipal and industrial (M&I). At present, the fraction of the state’s water used for urban and small farm agriculture is unknown due to the variety of water sources used, the aforementioned rapid shift in land use, the confusion in definitions of what is and is not agriculture, a lack of knowledge of the amount of urban land being farmed as well as typical
water use and efficiencies of such farms, and difficulties with the identification of these plots. The fact that these urban and small farms are in urbanized areas means their water use is often likely to be considered M&I. However, there are efforts being made in Salt Lake City to classify this water as agricultural so as to restructure water prices to make urban agricultural irrigation more affordable, thereby encouraging the urban farm movement because of the aforementioned benefits (K. Kopp, personal communication, November, 2014).

The DWRe estimates that agriculture diversions comprise 82% of the total diversions in the state (Utah Division of Water Resources 2013). The agricultural water depletion (i.e. the portion of water that is evapotranspirated by crops and thereby depleted from the watershed) is estimated from basin scale water balances using remote sensing for land classification, PRISM Climate Data for evapotranspiration (ET) and precipitation estimates, hydrologic measurements at agricultural water diversions and select return flow locations, and basin efficiency estimates from Utah State University (USU) research from 2003. When DWRe’s calculated basin efficiencies do not match the USU 2003 paper efficiencies, the various model inputs, outputs, and efficiencies are adjusted by their best judgement until the water balance is satisfied (C. Miller, personal communication, April, 2016). However, at the basin scale it is very difficult to account for such hydrological factors as capillary action from high groundwater tables, lateral groundwater flows, and other variables that can influence the basin water balance. Due to the scope of estimating agricultural water use across the state at a higher resolution than the basin level, the DWRe has yet to assess agricultural water use at the district or field levels.

In 2015 Utah ranked the second highest state in M&I per capita water use (USGS
2014). Being the second driest state in the nation, this exceptionally high use is due to the large volumes of water used for outdoor irrigation coupled with a culture that encourages verdant landscapes and gardens. Of the estimated 18% of water that goes to M&I use, 60% is thought to be used for outdoor irrigation (Utah Division of Water Resources 2013). Typical values of culinary (i.e. treated, potable water) M&I water used for outdoor irrigation were determined in a DWRe study of 17 communities throughout the state for the years 2001 through 2007 (Utah Division of Water Resources 2009). According to the study the average seasonal irrigation depth and irrigation efficiency (defined in the study as $ET_{net}$/irrigation depth) were approximately 32.5 inches and 79% respectively for households having heard of the state’s “Slow the Flow” conservation program, and approximately 35 inches and 72% respectively for households that had not heard of the program. However, these results are for culinary water on landscapes only, and numerous unmetered secondary systems deliver water to urban areas where the water is being used for urban and small farm agriculture as well as landscaping. The term secondary water system is used in Utah to describe any non-potable water delivery system (i.e. untreated to drinking water standards), typically intended for irrigation purposes, and consists of either a canal network or a piped, pressurized supply. While these secondary systems are usually metered at the original diversion, the actual water delivered to each end user is unknown and is therefore estimated by the DWRe as being twice the ET requirement of the landscaped area (i.e. an irrigation efficiency of 50%) (E. Klotz, personal communication, April, 2016). Currently, the DWRe estimates that secondary systems serving M&I areas comprise 23% of the total M&I water use (Office of the Legislative Auditor General 2015).

Using the current methods of agricultural and M&I water use estimation described
above, the DWRe forecasted that the present day developed water supplies will not be enough to provide the same per capita water supply to Utah’s future population. Recently the DWRe projected that, based on previous conservation efforts, the state’s demand for water would exceed the developed supply by 2040, and that by 2060 there would be a shortage of 283,000 acre-feet of water if further measures to meet the demand are not taken (Utah Division of Water Resources 2013). To meet the future demands the DWRe set a new conservation goal of a 25% reduction of the 295 gallons per capita per day (gpcd) of M&I use in 2000 by 2025 (Utah Division of Water Resources 2013). Additionally, they anticipate needing to spend $33 billion over the next couple of decades to repair existing systems and develop new supplies including such projects as the Bear River project and the Lake Powell Pipeline project (Utah Division of Water Resources 2015). Another source of water to help meet the future M&I water demand lies in the transfer of agricultural water rights to urban water rights. When agricultural land is developed for urban use the water rights associated with the agricultural land are often acquired by a municipality and become part of the urban water supply. In addition to this shift in water rights holdings from land use changes, increasing attention is focused on the purchase of existing agricultural water rights to meet urban demands.

In 2015 the Utah state Legislative Auditor General conducted an audit of the DWRe water use estimates and future use projections and found that numerous of the state’s methods needed improvement. Here I briefly explain two of the areas highlighted in the audit in which outdoor irrigation play an important role.

The first issue raised in the audit is that the state is not sufficiently promoting (and accounting for) the potential of outdoor water use conservation in meeting future needs.
Numerous studies show that conservation is often the more economical solution than development of new supplies (California Department of Water Resources 2010; Inman and Jeffrey 2006; Rosenberg and Lund 2009; Vickers 2001). The audit cites research by USU that residents in a study applied as much as twice the water their landscapes needed, and that outdoor use could be reduced by 26% with better practices (Office of the Legislative Auditor General 2015). But why is Utah’s outdoor water use efficiency so poor? Currently more than half of the public water systems in Utah provide secondary water alongside culinary water, and in 30% of the systems secondary water is the main source used for irrigation. To date the vast majority of secondary systems in the state are unmetered with the water users typically paying a flat rate, resulting in some of the lowest water prices in the country (Office of the Legislative Auditor General 2015). Yet numerous studies have shown that providing unmetered water results in an increase in use. A 2003 study by Colorado State University found that 39% more water was used by flat rate users than those who had their water metered and paid according to their use (Cole 2015). A 2004 study by the DWRe determined that Utahns with unmetered water generally use twice the water necessary to irrigate lawns (Richards 2009). In fact, the DWRe suggested as early as 2003 that metering of all secondary systems should be done as soon as possible (Utah Division of Water Resources 2003). The legislative audit suggests that metering of all service connections will give more value to water and is encouraging the legislature to adopt policies to phase in universal metering, as numerous other dry states including Arizona, California, Colorado, and Washington have done (Office of the Legislative Auditor General 2015).

The DWRe has invested in numerous conservation programs which promote
reducing outdoor irrigation water use through efficient irrigation practices. Yet, in order to be effective conservation programs must be able to identify existing and future capacities to conserve (Endter-Wada 2014). Therefore, the context of irrigation efficiency and how it pertains to agro-hydrology must be kept in perspective (Levidow et al. 2014). This warrants a brief discussion of a few irrigation efficiency metrics.

Irrigation efficiency (IE) is defined as the ratio of the volume of irrigation water beneficially used to the volume applied minus the change in storage, as shown in equation 1 below (Burt et al. 1997).

\[
IE = \frac{vol.\,irrig.\,water\,beneficially\,used}{vol.\,irrig.\,water\,applied - \Delta \,storage\,of\,irrig.\,water} \times 100\% \tag{1}
\]

While this definition of efficiency is important from a field irrigation design point of view, it should not generally be used for measuring or identifying areas for actual water savings in the context of a river basin (A. Keller and J. Keller, Effective Efficiency: A Water Use Efficiency Concept for Allocating Freshwater Resources, unpublished report). When viewing water quality and quantity on a river basin scale, this irrigation efficiency metric ignores the contribution of irrigation return flows in meeting other user’s needs. Therefore, the water saved by conservation programs may not be “real” water, but rather only shift the distribution of water in space and time (Allen et al. 2005). For example, deep percolation resulting from over-irrigating does not consume (i.e. evapotranspirate) more water than if no deep percolation occurred, but simply transfers water from the surface to the groundwater. This groundwater may be extracted by wells elsewhere in the watershed, or it may even resurface as springs. Water that is recovered and reused may not be a good target for water conservation as no water is actually saved, although it may result in other
benefits such as reduced pumping costs, improved water quality, or maintaining environmental flows. Therefore, conservation efforts should focus on where water is unrecoverable, such as entry of water into a saline body, large depths to groundwater, or evaporation and transpiration losses (Allen et al. 2005). This concept is often misunderstood by the public and government working to effect water conservation and has resulted in billions of dollars of proposed investments to improve irrigation efficiencies which will not address the true water problems. In fact, improvements in farm scale water management can actually increase the water lost in the basin because of increased evapotranspiration due to better crop health (Allen et al. 2005). This concept led to the development of an efficiency metric termed “effective efficiency”, which is the ratio of water consumed to the volume diverted minus the reusable portion of return flows, which more closely represents efficiency at the scale of a river basin (A. Keller and J. Keller, Effective Efficiency: A Water Use Efficiency Concept for Allocating Freshwater Resources, unpublished report).

To help understand this hydrology one can think of river basin systems consisting of two types, those with a multiple-use cycle and those with a single-use cycle. For example, high in the watershed the hydrology could be considered multiple-use, as return flows are available for other users lower in the watershed, but at the bottom of the watershed the hydrology could be considered single-use, as return flows are unlikely to be recoverable by other users. A good portion of the Wasatch Front could be considered to have a single-use hydrology, as the water that drains from the front feeds the saline Great Salt Lake, although these flows are important for environmental and industrial purposes (Wurtsbaugh 2016). Other urbanizing areas, such as Box Elder and Cache County, are high
enough in the watershed that they could be considered to have multiple-use cycles. Because of Cache Valley’s location in the watershed and its relatively saline free soils and water, conditions are such that appreciable degradation in water quality in agricultural return flows does not occur. Therefore, return flows from irrigation are likely to be available for other users lower in the watershed, and efforts targeting improved irrigation methods, while likely having many of the aforementioned benefits, will not result in water savings for the basin. Thus, efficiencies at the field level scale and how these equate to the potential for water savings in a particular region need to be considered in the context of their location in the watershed.

Additionally, it is important to consider the concept of efficiency in the context of a canal company or irrigation district. Return flows in the form of deep percolation from irrigators with a shared canal as their water source may not be available to other users downstream on the canal, and thus return flows may result in a loss of water to the canal company. In this paper I use the term “district” to describe an area with a shared single irrigation conveyance network (such as a canal), and “district efficiency” as the efficiency metric for this area. A poor district efficiency at the urban and small farm scale may be an incentive for the water planners and managers of the district to encourage efficient field irrigation practices.

A second critique raised in the legislative audit is that the state water agencies are understating growth in the available water supply as agricultural lands and their associated water rights are converted from farmland to urban development (Office of the Legislative Auditor General 2015). This issue is comprised of two parts: 1) the proper forecasting of urban development and 2) the water made available by that development. Here I discuss
the latter. According to a 1993 study by the Colorado Water Resources Research Institute, the quantity of the water historically used by a water right often differs from the actual amount of the right, which has led to over-appropriation of Colorado’s waters as unused portions of water rights are thought to be surplus flows and are sold to new rights seekers. Technically, the unused portion of a right has not been “fully developed”, and therefore has not been “claimed” and should not be available for sale by the water right holder (Rice and MacDonnell 1993), but rather awarded to a new user by the state. However, this situation also occasionally results in over-irrigation when shareholders concerned of losing their unused portion may irrigate beyond the beneficial use required by their crops (Rice and MacDonnell 1993).

According to the audit, the Utah state engineer has historically assigned a one-to-one value for water rights transfers, meaning that when transferred one share of agricultural water rights becomes an equivalent quantity of M&I rights (Office of the Legislative Auditor General 2015). According to my conversation with the Utah Division of Water Rights (DWRi), the actual historical use is only investigated if the transfer is occurring in a basin where there is a concern of over-allocation of water. Otherwise, they assume the beneficial use of water on the land is the water required to grow alfalfa in that particular region. The DWRi, said this assumption gives the benefit of the doubt to the water right holder, as alfalfa is considered to have higher water requirements than most other crops (B. Clayton, personal communication, April, 2016). However, in cases where the historical beneficial use of the crop is different than that of alfalfa (e.g. a crop other than alfalfa was grown), it seems that this method could lead to misrepresentation of the water volumes actually historically consumed. Ideally, the method should be based on an understanding
of actual consumptive use based on the crops grown, not theoretical use of an assumed crop.

To address the issues raised in the audit improved quantitative and qualitative data from actual urban and small farm agricultural operations is needed. However, at present very little is known about urban and small farm agricultural irrigation in the U.S. as most of the academic literature pertaining to urban and small farms is focused on developing countries where the farmers face very different situations than in developed countries. In the U.S. the majority of studies focus on large farm scenarios which have very different circumstances than urban and small farms including higher levels of agricultural education, economies of scale, and higher operational costs (although operational costs per unit area may be less) which yield a faster return on investment for changes in irrigation technology and management. However, of the limited documentation that does exist for small farms two particular trends stand out. First, there is a general shortage of knowledge exchange between academia and small farmers and second, there is a lack of adoption of more efficient practices when the benefits are not perceived to result in economic gains. I now explore each of these in turn.

Most of the documents intended for farms in the U.S. tend to be from state extension services, and these documents often target the small farm sector with helpful manuals, design guidelines, rules of thumb, scheduling methods, and more. But to what extent are urban and small farmers using these resources? According to Levidow (2014), there is often a default assumption that farm irrigation practices are already adequately efficient, and therefore farmers often don’t take responsibility for efficient water management. Thus, amongst farmers there often exists an unknown efficiency and thus there are weak
incentives to improve irrigation practices. A continuous knowledge exchange between all stakeholders (including farmers, academia, and resource managers) is needed so that all users can share in responsibility for the water. According to Levidow et al. (2014), the knowledge-exchange needs the following three components: 1) expert scientific knowledge, 2) links between farmer perspectives and practices and their incomes, and 3) means to lower resource burdens from inputs and pollutants.

The reason for lack of adoption of changes to irrigation management is because farmers are often convinced by advertising that improvement requires new technology, the benefits of which can only be fully met with the assistance of technical advice (Perry 2009). Additionally, farmers are unlikely to change their management practices if there is a lack of perceived economic benefits, and they may lack the knowledge to anticipate the effects of changing their practices (Levidow et al. 2014). Rather, most growers make their irrigation decisions by subjective judgement, based on their practical experience and observations (Knox et al. 2012).

In Utah most urban and small farms use secondary water systems, and because most of these systems are unmetered, there is very little data with which to quantify irrigation water use in this sector. It remains unknown the volumes of water typically used on urban and small farms in Utah, whether or not the water use is efficient, and whether the water use is likely to increase or decrease with time as the population grows and more pressure is put on the state’s food and water supplies.

My research aims to create a clearer picture of urban and small farm irrigation water use in northern Utah by conducting season long comprehensive evaluations of a sample of urban and small farms. For the entirety of an irrigation season I measured the volume of
applied irrigation water and performed full field irrigation evaluations for 24 urban and small farm fields in Cache Valley, Utah. Numerous parties will benefit from this research. The DWRe can use my results when they eventually move from a basin level agricultural water use analysis to a field level analysis, as well as to better understand typical volumes of agricultural return flows which could improve the accuracy of their current basin level predictions. It will also aid the DWRe to better understand how demographic and land use changes will affect the state water balance, improve its accounting and reporting of water use methods, and to help create effective and informed conservation goals. Additionally, my methods can serve as a guide for how to conduct such a study in other locations that wish to gain a better understanding of small farm water use. The irrigators that participated in my study will benefit by having direct insight into their water use in order to know what they are doing well and what they can improve on. The result will be possible improvements in yield and savings in water, energy, and time, or, if no substantial improvements are identified, they can continue their current practices with the knowledge that they are doing a good job. Other small farmers that have similar circumstances to the participants in my study will benefit by my recommendations for the case studies as well as the general trends I identify. USU Extension will have insight that will help them better understand situations faced on urban and small farms in order to better develop effective technical programs and workshops, presentations, and factsheets that are targeting the real issues and providing help where it is really needed.
DATA COLLECTION AND METHODOLOGY

Collect Field Data

Find Participants

Using the snowball sampling approach I began my search for participants by contacting numerous canal companies (i.e. irrigation districts), local organizations, and regional water planners to inquire if they knew of any irrigators that may be interested in my study. The participants needed to be producing an agricultural product either for their own consumption or sale, and to be greater than 1000 square feet and less than 20 acres in area. After contacting the recommended irrigators, through word of mouth and further solicitation I found 20 participants irrigating a total of 24 fields.

Install Measurement Devices

After initial contact with each prospective participant I conducted a personal interview with the irrigator and arranged a visit to the field. The visit entailed collecting field metadata including farm crop types, irrigation method and system configuration, and details on irrigation management practices, which gave me a starting point to determine how to best measure the irrigation flow rates and schedules. Four of the 24 fields used surface irrigation, so based on the irrigation channel geometry and slope I installed two flumes and one weir and gave the irrigators a table for filling out the irrigation schedule and staff gauge reading. The remaining 20 systems were pressurized systems, nine of which were conducive to installing a single flow meter which would measure water to the entire field. The flow meter types installed included electromagnetic flow meters and mechanical flow meters. The electromagnetic flow meters included the Seametrics AG2000 with an
internal datalogger, the Seametrics WMP totalizer, the McCrometer Mc Mag 3000 with an internal datalogger, and the Sensus iPERL. The mechanical meters included turbine meters and the EKM 1” pulse output meter. Twelve of the fields had piping configurations that would have required multiple meters to measure all the water use. For example, numerous fields had multiple risers off of a mainline that supplied other users downstream, and designating a meter for each riser would have been too costly of an approach. For ten of these fields I made a single manual flow rate measurement with either a portable Seametrics AG2000 flow meter or the volumetric method (collecting water from each sprinkler nozzle with a hose, bucket, and timer), and recorded the irrigation schedule with a Lascar Electronics EL-USB-5 datalogger and Dwyer A2 discrete pressure switch assembly installed underneath a sprinkler nozzle on each lateral. For two fields where upwards of a dozen pressure switch data loggers would have be required, I asked the irrigator to manually fill out the schedule in a table.

Conduct Field Measurements

Once I determined the flow measurement method and installed the measurement device I collected field measurements. I determined the field area using visual observations of field edges and measured the areas by tracing the field boundaries in ESRI’s ArcMap GIS software. Then, I collected crop data from a combination of visual observations and communication with the irrigators, which included crop types, planting dates, and harvest dates.

Next I collected the required data to calculate the application uniformities of the sprinkle and drip irrigated fields. The distribution uniformity of the surface irrigated fields was not evaluated. For the single drip irrigated field I took a pressure reading at the inlet
of each drip tape and made an estimate of field slope in order to calculate the emission uniformity (EU) using theoretical equations and specifications from the drip tube model datasheet. For the sprinkle irrigated fields attempting to achieve application uniformity (not all irrigated with this intention), I conducted a catch can test in order to calculate the coefficient of uniformity (CU) and distribution uniformity (DU).

Other field measurements I made included sprinkler system lateral spacing, nozzle types, diameters, operating pressures and spacing, as well as estimation and/or measurement of the flow rate of leaks. Additional observations included whether system maintenance was lacking, whether surface runoff occurred, and whether there was anything unusual about the system configuration and components.

**Calculate Irrigation Performance**

To aid the reader in comprehending the below concepts and calculations, a glossary of terms is provided in Appendix A.

**Gross Irrigation Depth**

The volumetric readings collected in the study were of two types: those with time series data (flow meter dataloggers, pressure switch dataloggers, and manual tables) and those with totalized readings (turbine, EKM, and iPERL meters) that were collected every couple of weeks throughout the season. I calculated the average depth of water applied to the irrigated area over the season by dividing the total applied volume by the irrigated area, giving me a season gross irrigation depth (GID).

For flow meter accuracies I used the percent accuracies with a 95% confidence interval found in the instrument datasheets. For the fields using flumes and weirs, I used
conservative estimates of the accuracies of each device as found in the textbook *Irrigation Fundamentals* by Hargreaves and Merkley. For the accuracy of the area of large fields I calculated the area of a +/- 5 foot swath around the field perimeter and divided that by the area estimate. For small gardens I used a +/- 2 foot swath.

**Time Series Water Balance**

In order to include the many variables that should be involved in a detailed irrigation water balance, I created a spreadsheet that uses a time series with a daily time step to account for irrigation and precipitation events, changing soil moisture, ET with crop coefficients and adjustment factors, and the timing and quantity of return flows. The calculations include all inputs (irrigations $I$, precipitation $P$), outputs ($ET$, return flow $RF$), and the change in soil moisture storage $\Delta SM$ in units of inches using a control volume of field area by mature rooting depth of the crop.

$$RF = I + P - ET_{crop} - \Delta SM$$ (2)

The daily time step of the water balance allows for the temporal variability to be observed, and the cumulative results are presented for a seasonal time frame. All equations used in the spreadsheet and described in this section are included in *Appendix B*.

For the irrigation input variable $I$, for fields with flow meter dataloggers, I converted the time step to days and imported the data into the spreadsheet. For totalized meter readings read every couple weeks, I divided the depth applied in that time interval by the probable number of irrigations within the interval to estimate the application depth of each irrigation, and assigned that depth to the respective number of days spaced evenly throughout the interval.
Precipitation $P$ and reference ET ($ET_{ref}$) data for each field were collected from the Utah Climate Center (UCC) Agricultural Weather Network station with the closest proximity to the field, which was typically less than five miles. I assumed that 80% of the precipitation was effective, meaning that 80% of the rainfall was not evaporated before it could infiltrate into the soil. I chose this percentage because this is a common assumption used in irrigation water balances (Utah Division of Water Resources 2009). Note that the precipitation in the valley during the season was of sufficient depth that this assumption plays a significant role in the calculated return flows and efficiencies.

The UCC $ET_{ref}$ estimate uses the ASCE standardized reference ET equation, also known as the Penman-Monteith equation. To calculate the crop ET ($ET_{crop}$) I used procedures from Food and Agriculture Organization Irrigation and Drainage Paper 56 (FAO-56) including such factors as single crop coefficients ($K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$), the water stress coefficient $K_s$, and reductions is $K_c$ for plastic mulch conditions. When available I used crop coefficients found in the USU Crop and Wetland Consumptive Use and Open Water Surface Evaporation for Utah document, which includes a “garden” coefficient specifically meant to represent mixed vegetable gardens in Utah, as well as alfalfa coefficients for multiple cuttings during the growing season (Hill et al. 2011). To calculate the theoretical reduction in yield from plant water stress I used the yield-moisture stress relationship with the seasonal yield response factor $K_Y$ from Table 24 in FAO-56.

For the $\Delta SM$ component of the water balance I calculated the total available water (TAW) of the soil (the maximum water that can be stored in the soil that is available for uptake by plants) from the available water capacity (AWC) times the rooting depth of the crop. The available water (AW) for plants at any one time is a maximum at TAW and zero.
at the point where permanent plant wilting occurs. For all crops I used an estimate of mature rooting depth from FAO-56 Table 22, and for annual crops I included a root zone adjustment factor to account for the changing depth of root zone throughout the growing season. I determined the AWC using the USDA’s online Web Soil Survey (WSS) database by finding the AWC for each soil type on the property for the mature rooting depth of the crop (USDA 2016). If more than one soil type was within the field I calculated an area weighted average AWC.

The readily available water (RAW) is the depletion ($D_r$) below the soil field capacity (FC) at which plant water stress begins to occur. It is calculated as the product of the TAW and the depletion fraction, also referred to as the management allowed depletion (MAD). Values for the depletion fraction for different crops are found in the FAO-56 in Table 22 (Allen et al. 1998). The AW at this point where water stress begins is simply the TAW minus the RAW. To maximize crop yield and prevent plant water stress the $D_r$ should be kept below the RAW.

The precipitation in Cache Valley in April and May of 2015 was 2.48 and 5.29 inches respectively, which was significantly higher than the April and May average precipitation of 2.05 and 2.10 inches, respectively (UCC 2016). Therefore, I assumed the root zone depletion ($D_r$) at the beginning the time series was 0 inches for annuals and 25% of the TAW for perennials because annuals are typically planted into a barren field where no ET for the year would have yet occurred, and perennials would likely have been evapotranspirating and depleting the soil moisture before the beginning of the time series. Note that these assumptions will not always be valid, and an accurate estimate of initial depletion should take into context the precipitation of a particular year and ideally rely on
actual soil moisture measurements. Therefore, the calculations I used for the time series water balance allow for any initial depletion. An example of a time series plot with an annual crop is shown below in Fig. 1.

![Example Time Series Water Balance](image)

**Fig. 1. Example - Time series water balance**

The plot shows the TAW, AW, RAW, irrigation events, precipitation events, and return flow events for an annual crop from May 1st through early September. The black dashed line represents the TAW within the crop rooting depth, and the red line represents the AW, or if referenced to the TAW, the Dr. The distance between the TAW and the grey dashed line represents the RAW. Ideal irrigation water management would not allow the AW to drop below the grey dashed line (i.e. not let the Dr exceed the RAW). Below this line the ET decreases because of plant water stress. The irrigation events, irrigation return flows, and precipitation events are represented by the green, blue, and orange bars,
respectively. When an irrigation or precipitation event occurs the AW increases until the FC of the soil is reached, at which point return flows occur. For example, if the AW is 2 inches, the TAW is 4 inches, an irrigation event applied 3 inches, and the ET was 0 inches, the actual AW would be recharged to the TAW at 4 inches and there would be 1 inch of return flow.

To determine the accuracy of each water balance variable (other than for flow measurement, which was usually found on the model datasheet) I used common accuracy values found in Clemmens and Burt (1997), and for each dependent variable I used statistical equations for addition, multiplication, and division of accuracies as found in the same paper. The equations used, along with a table showing the calculated accuracies of each independent and dependent variable for each field, are included in Appendix C.

**Application Uniformity**

A properly designed irrigation system will attempt to achieve a high application uniformity in order to minimize under and over-watering parts of the field. High sprinkler system uniformity is accomplished by achieving head to head coverage and is achieved with proper nozzle selection and proper operating pressure. Head to head coverage along the lateral is achieved with proper spacing (usually 40 feet due to the common length of irrigation pipe) and head to head coverage between laterals is best achieved with triangular spacing, although for ease of moving pipe and to minimize capital costs most irrigation systems use 60 foot rectangular spacing. Values of DU and CU less than 0.6 and 75%, respectively, are considered low for low-value crops like alfalfa and hay, and for higher value crops like vegetables DU and CU greater than 0.75 and 84%, respectively, are recommended (Merriam and Keller 1978). The equations used to determine the CU and
DU values are given in Appendix D.

For fields using sprinkle irrigation and attempting to achieve application uniformity, I calculated the field CU and DU using data from a catch can test. In the catch can test, plastic cans are set in the field in a rectangular grid with 10 foot spacing between cans, offset 5 feet from the nozzles, to determine the spatial distribution of water application. After a set irrigation run time, the volumes of water collected in each can are measured and then converged to depth by dividing the volume of water by the area of can opening. For fields operating with only a single lateral at a time, I set up the cans between nozzles (with the two cans closest to the nozzle at 7.07 feet diagonal from the nozzle) and on both sides of the lateral covering the entire radius of throw. For fields with more than one lateral operating at a time, I set up the grid in the rectangular area between four nozzles.

A couple of computer programs have been designed specifically to analyze overlapped catch can data (e.g. Catch3D) but these programs only analyze uniformity in the overlapped area of the field or on the edge, but do not easily calculate both of these areas together. Because the uniformity on the field edges is usually low, I expected the uniformities of small fields with a high perimeter to surface area ratio to be lower than uniformities for large fields. To simulate overlapping as the set moved across the field in addition to the field edges I entered the catch can depths as an array in MATLAB software and wrote a script to simulate overlapping of the array down the length of a lateral, across the field, and on the field edges (MATLAB 2016). This procedure creates an array of depths throughout the entire field and can easily be visualized with a 3D plot. My MATLAB script is included in Appendix D, and the 3D plots are included Appendix F.

It is important to recognize that 100% uniformity is impossible to achieve, and even
with the best practical uniformity different areas of the field will receive different depths of water. Therefore, unless the entire field is excessively over-irrigated, some portions of the field will be under-irrigated and experience water stress (and a reduction in yield) and other parts of the field will be over-irrigated and have return flows. To assist in the use of CU values in irrigation design and scheduling an efficiency metric called the “water distribution efficiency” (DE\textsubscript{pa}) was developed. This metric is used to calculate the average application depth required by a field with a known CU so that a certain percentage of the field receives a minimum depth of water. A table listing the DE for a range of CU values and percentage of area adequately irrigated is provided in Keller and Bliesner (1995). For example, using this table, if a sprinkle system has a CU of 70%, and 85% of the field is to receive a minimum depth of water, the DE\textsubscript{85} is read to be 61%. Therefore, if the minimum desired depth in 85% of the field is 1 inch, then the average depth applied to the field will need to be 1 inch divided by 61%, or 1.64 inches. Thus, the average application depth is significantly higher than the minimum desired depth. If the CU of the system is raised to 80%, the DE\textsubscript{85} is read to be 74%, and the average depth applied to the field will need to be 1 inch divided by 74%, or 1.35 inches, a difference of 0.29 inches. Therefore, a high CU is very desirable to minimize the need to over-irrigate the majority of a field just to provide enough water to a lesser portion of the field. An example of the use of this efficiency metric is provided in Case Study 1 of the Results section.

Only one of the fields in my study used drip irrigation, as detailed in Case Study 2. I calculated the emission uniformity (EU) using equations from Keller and Bliesner (1990) and iteration to converge on the flow rates and pressures in the tubing. Some of the important variables used in the calculations include the friction loss gradient J, the
reduction coefficient $F$, the head loss through a length of pipe, the field slope $\Delta E_L$, and the emitter spacing $S_e$, discharge exponent $x$, constant of proportionality $K_d$, and coefficient of manufacturing variability $v_s$. The algorithm and equations are provided in Appendix D. Recommended values of EU vary depending on the method of drip irrigation used.

**Irrigation Efficiency**

As I explained in the *Background* section, irrigation efficiency at the farm, district, and basin scales can be very different depending on whether the basin is a single-use or multiple-use basin. In this analysis I assume Cache Valley acts as a multiple-use basin because return flows are available to other users lower in the basin, which gives rise to a high effective efficiency of all of the fields in my study. Therefore, the main metric of efficiency analyzed for the fields in my study is the field irrigation efficiency given in equation 1. While there are numerous field efficiency metrics to choose from, I chose this metric because of the inclusion of the change in soil moisture, which I calculated in my time series water balance. The district efficiency differs from the irrigation efficiency only if return flows reenter the district conveyance system, usually as surface runoff.
RESULTS

Overview

In this section I provide the results of my study, starting with a description of the fields. In the first section I provide detailed case studies for six of the fields in my study. Three of the six case studies had exceptionally high gross irrigation depths (GIDs) which resulted in very low irrigation efficiencies (making them outliers among the 24 fields of my study) and I provide a discussion of what technical and management issues likely led to them being outliers. In the second section I present the GIDs, gross return flow depths (GRFs), and irrigation efficiencies for all fields in my study, along with some statistics including the area-weighted average gross irrigation depths for different crop types, irrigation methods, and field sizes. Additionally, I explore the relationship between sprinkle system uniformities and GID and field size. I used the visualization software tool DiscoveryDV to discover relationships among variables (DiscoveryDV 2016). Finally, observations of the condition and management of the systems are discussed.

Field Metadata

The participants of my study were located in numerous towns in the valley including, from most southern to most northern, Paradise, Wellsville, Nibley, River Heights, Logan, North Logan, Hyde Park, Benson, Smithfield, and Richmond. A map showing these municipalities is shown in Fig. 2.

To maintain the anonymity of the participants I arranged the fields in alphabetically order by either the owner’s last name or farm name and provided each field in the list an
Fig. 2. Map of municipalities in study area

identification letter from A through X. The fields consisted of small commercial farms selling CSA shares at local grocery stores and farmer’s markets, community gardens, backyard gardens, orchards, pastures, alfalfa fields, and university research farms. The crops included mixed vegetables, grass pasture, grass hay, alfalfa hay, apples, wheat, corn, quinoa, tomatoes, peppers, winter squash, and watermelon. Four fields used surface
irrigation, one field used drip irrigation, and 19 fields used sprinkle irrigation. A wide range of methods were used for the sprinkler systems including hand-move, side-roll, hose-fed, and fixed systems. Almost all of the sprinkle irrigated fields had varying nozzle sizes throughout their systems of which the irrigators were unaware, and most of the fixed sprinkler systems had more than one clogged nozzle at the time of the field evaluation. Few of the irrigators had any official irrigation education or training, and none used flow measurement devices or soil moisture measurements for irrigation scheduling. Therefore, they either irrigated by feel or based on a set schedule either dictated by their own weekly schedule or their irrigation turn. The field metadata is listed in Table 1.

Case Studies

In this section I provide a detailed look at the evaluations for six of the 24 fields in my study and provide recommendations for improving the irrigation configuration and management. I chose the six cases to illustrate two examples of good irrigation practices (one field with sprinkle and one field with drip), and four examples of irrigation practices resulting in poor irrigation efficiencies. To provide a means of comparison between the performance and management of different fields, I begin by analyzing a field with a good GID, schedule, low return flows, and a decent uniformity. Next, I analyze the one field in my study using drip irrigation. I then analyze four additional fields with poor performance, three of which were the outliers in my study. The analysis can be used to identify potential irrigation issues that could be found on fields with similar circumstances.

Case Study 1 - Sprinkle Irrigated Pasture with Good Performance - Field W

Field W is a 0.93-acre pasture of mixed grasses and legumes. The field is one of
two fields irrigated by the landowner and is located in North Logan surrounded by other urban hay fields intermixed with new residential developments. The pasture is grazed by horses and cut and bailed in late June, late July, and late September. The water supply is a secondary system pressurized piped supply that runs through the property, and the irrigator can irrigate whenever he chooses. The field is long and narrow and is irrigated from two risers with periodic-move 3” aluminum hand-move pipes. To avoid the irrigator having to move a heavy meter when moving pipe between the two lateral positions, and because no

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<th>Crop Type(s)</th>
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<td>Alfalfa</td>
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<td>Surface</td>
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<td>Garden</td>
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<td>Orchard</td>
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<tr>
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<td>Cereal</td>
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<td>Sprinkle - hand-move</td>
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<td>0.50</td>
<td>Grass Pasture/Hay</td>
<td>Pasture</td>
<td>Sprinkle - hand-move</td>
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</table>
single easy location existed to install the meter, I determined the application rates with a one-time field analysis of the flow rate with the Seametrics AG2000 electromagnetic flow meter and verified the measurement with the manual volumetric method. I recorded the schedule with the EL-USB datalogger and Dwyer A2 pressure switch assembly. For the time series I assumed an initial soil moisture depletion of 25% of the TAW because the crop was perennial pasture with an established root zone. The time series plot is shown in Fig. 3.

![Field W - Time Series Water Balance](image)

**Fig. 3. Field W - Time series water balance**

The plot shows that precipitation continually recharged the soil AW in May, and irrigation did not begin until mid-June. The field only received seven irrigations during the season, six of which applied around two inches of water, and one that applied nearly four
inches of water. The calculated irrigation return flows only happened on two occasions in early July and late August, and the total depth of these flows (calculated as the difference between irrigation depth and the initial depletion on that day) was minimal. Because no surface run off or standing water was ever observed on this field, the return flows most likely went to deep percolation. Additionally, the soil moisture was kept well above the MAD, so assuming that the sprinkler system had a decent application uniformity the majority of the field was never water stressed and thus the crop yield was maximized.

Looking at the data from a season long cumulative perspective confirms the above observations. Fig. 4 shows four cumulative water balance variables: 1) the cumulative irrigation depth (green line), 2) the total crop ET (purple line), 3) the total sum of irrigation and precipitation (magenta line), and 4) the total irrigation return flows (blue line). Note how the total water received by the field closely follows the slope of the ET line, signifying that the irrigator made good use of both the precipitation and irrigation water to provide the crop water demand. Additionally, there were very little irrigation return flows. The positive difference between the received water and the ET at the end of the time series, in combination with very little return flows, resulted in a soil moisture at the end of the season that was greater than at the beginning of the season. The cumulative irrigation depth was calculated to be 15.7 inches, with total return flows from irrigation of 1.4 inches. The change in soil moisture from irrigation was a positive 2.7 inches, meaning that the final two irrigations (which combined applied roughly 3.1 inches) were not necessary. However, the irrigation management was still very good, resulting in an irrigation efficiency of 90%.

The 3D plot of the application uniformity is shown in Fig. 5, and the CU and DU are 71.8% and 0.49 respectively, fairly good values for a field with such a small area to
perimeter ratio, yet still lower than the recommended values. The x and y axis are field length and width, respectively, in units of 10 feet (e.g. 30 units equals 300 feet) and the z axis is irrigation depth from the catch can test in inches. The color scale ranges from lowest depth (blue) to highest depth (red). The label “SW” in the upper left corner of the image indicates that this corner corresponds to the southwest corner of the field. Note how the field receives the most water in the strip down the middle, and how the south and east edges receive significantly less water than the rest of the field. This is due to the lack of overlap that occurs at the field edge. In this case the center of the field had almost three times the application rate as the left edge. The lateral on the right side of the field provided overspray into the adjacent corral and field, so a portion of that overthrow was likely beneficially used. I left the top side of the field out of the uniformity analysis because of the field

Fig. 4. Field W - Cumulative seasonal water balance
irregularity on that end and the difficulty of integrating irregular shapes into the MATLAB calculations.

![3D plot of sprinkler uniformity](image)

**Fig. 5. Field W – 3D plot of sprinkler uniformity**

To consider the areas over and under-irrigated from the non-uniformity, it is important to consider the distribution efficiency (DE_{pa}) in the analysis. Fig. 4 showed that there were very few return flows during the season, so I know this field was not excessively over-irrigated. Assuming the water depths through the field are symmetrical around the average depth, 50% of the area will receive more water than the average depth and 50% will receive less than the average depth. Referring to DE_{pa} values from Keller and Bliesner (1990), with a CU of 71.8%, I applied DE_{pa} values for different areas of the field to the average depth of 15.7 inches and plotted the result in Fig. 6. The figure shows the average depth and the net ET of 12.5 inches (or ET – P_{eff}), which is the ET required by the crop that must be provided by irrigation. Note that only 72% of the area of the field receives
more than the net ET and 28% of the field receives less. Therefore, 28% of the field is likely water stressed and has a reduction in yield.

**Fig. 6. Depth in different areas of field due to non-uniformity**

In summary this irrigator applied adequate but not excessive irrigation depths to avoid crop water stress and yet still minimize return flows, resulting in a high field efficiency. Whether intentional or not, the soil moisture depletion was timed perfectly with the rain events so that all of the precipitation was utilized. However, this irrigator could have saved some water and time by adjusting his schedule in three ways. First, the AW in the soil at the end of the season was almost equal to the TAW (i.e. the soil was at FC) so the final irrigation could have been avoided without dropping the AW below the MAD. Second, the AW was higher at the end of the season than at the beginning of the season, so
this irrigator did not utilize the previous off-season’s precipitation, nor allow storage space for the upcoming off-season. Lastly, the AW stayed well above the MAD all season, so the irrigator could have irrigated for longer durations at longer intervals, thereby avoiding the work of the moving hand-move sprinkler laterals more than necessary. The field CU was low but decent considering the challenging field geometry, and 28% of the field received less than the net ET. It is up to the irrigator whether the potential increase in yield from improving the uniformity is worth the costs and challenges of doing so. Still, although the irrigator could have improved his irrigation scheduling and application uniformity, this was one of the best managed fields in my study.

**Case Study 2 - Drip Irrigated Vegetable Field with Good Performance - Field L**

Field L is a 2.51-acre vegetable field using plastic mulch and 5/8 inch line-source drip tube irrigation with a flow rate of 0.22 gpm/100 feet on uniform topography. The crops included tomatoes, sweet peppers, winter squash, and watermelons that are sold at grocery stores, CSA shareholders, and farmer’s markets. The water supply comes from an irrigation pump pumping from an open water body, which can be operated at the irrigator’s discretion. The pump feeds the line-source drip tape through a 4” riser to a sand media filter, pressure regulator, and lay-flat hose manifold. The drip tubes consist of two lengths for different sections of the field with 950 foot and 560 foot runs. I recorded the flow rates and irrigation schedule with a Seametrics AG2000 electromagnetic flow meter with an internal datalogger, which I installed at the riser for the duration of the irrigation season. For the time series water balance I used an area-weighted average of the four crops for the depletion fraction, rooting depth, and crop coefficient. The water balance for the field is shown below in Fig. 7.
The plot shows that once the rooting depth was fully established in mid-July the soil moisture closely followed the MAD, signifying that the crops may have been on the threshold of beginning to experience water stress. The soil moisture could have moved away from this threshold with a single longer duration irrigation in early July to get the soil moisture up closer to the mid-point of the MAD. Note how the soil moisture does not oscillate much at all, indicating that the sum of irrigation and precipitation almost perfectly matched the crop ET, making the total water received by the crop nearly optimal. However, the irrigation scheduling could easily have been adjusted to result in less labor for the irrigator by irrigating for twice the duration but half the frequency, utilizing more of the water storage capacity of the soil. Disregarding the effect of uniformity in the irrigation efficiency calculation, not a single return flow event from precipitation nor irrigation occurred during the season, which led to a very high irrigation efficiency.
A plot showing the cumulative variables is shown below in Fig. 8. The total applied irrigation depth was only 7.7 inches, the precipitation was 2.1 inches, and the seasonal ET was 12.9 inches, indicating that the difference of 3.1 inches required by ET likely came from depleting the soil moisture throughout the season. Therefore, the irrigator effectively used off-season precipitation to provide nearly 23% of their crop needs.

![Field L - Cumulative Seasonal Water Balance](image)

**Fig. 8. Field L - Cumulative seasonal water balance**

For the 560 foot and 950 foot runs I calculated the drip system emission uniformity (EU) to be 81% and 72% respectively. The 81% EU for the 560 foot drip tape is above the minimum recommended value for of 80% for line source tubing on uniform topography, and thus is performing well. The EU of the 950 foot length however was significantly lower than ideal (Merriam and Keller 1990). To improve the EU of the 950 foot runs the irrigator could either 1) increase the size of the drip tubing from 5/8 inch to 7/8 inch, 2) decrease
the flow rate from 0.22 gpm/100 feet to 0.11 gpm/100 feet, or 3) run more lay-flat hose manifold to reduce the length of the 950 foot run to 560 foot or less. Because decreasing the flow rate on a pumped system (option 2) would change the operating point on the pump head-capacity curve, and running more lay-flat hose (option 3) requires more fittings and complicates the tubing layout, increasing the tubing size (option 1) is most likely the preferable option. According to my calculations both options 1 and 2 would increase the EU to 80%.

**Case Study 3 – Sprinkle Irrigated Garden with Low Efficiency – Field D**

Field D is a small 0.04-acre backyard garden and orchard in North Logan surrounded by quickly growing urban development. The garden is irrigated with a fixed sprinkler system from an irrigation pump that draws water from an adjacent ditch. Seven sprinkler nozzles are set at varying heights, with those on the edge on ~4 foot risers and the others at ground level, and the nozzles were of mixed types including turf rotators nozzles and brass and plastic impact nozzles. The crops included mixed vegetables planted densely in beds and half a dozen apple and pear trees, all of which appeared to provide a decent yield. I used a $\frac{3}{4}$” iPERL totalizer magnetic flow meter to measure the irrigation volume and took meter readings approximately every three weeks. To determine the depth applied at each irrigation I divided the difference between each meter reading into the number of likely irrigation events in that time period. The time series plot is shown in Fig. 9. The plot shows that before late July, when the root zone reached its full development, irrigation events occurred close to when the soil moisture dropped to the MAD, making the frequency of irrigations close to ideal. However, the depths of water
applied during each irrigation were extremely high, with the majority of irrigations contributing 75% or more of the total depth to return flows in the form of deep percolation, while two irrigations went almost entirely to return flow. Therefore, although the irrigation frequency was nearly perfect, the irrigation duration could have been significantly reduced.

The cumulative plot in Fig. 10 shows that the over-irrigation occurred consistently throughout the year, rather than just during a few events. The cumulative irrigation depth was calculated to be 54.4 inches, with irrigation return flows of 41.0 inches. These excessive applications led to a field efficiency of only 25%.

I determined the uniformity of the garden by placing catch cans in a 10 x 10 grid throughout the garden wherever the space would allow. No cans were placed in areas where plant growth was too dense and would likely interfere with water catchment. Therefore I
calculated the CU and DU using data only from the locations that could accommodate the catch cans. The CU and DU were 66% and 0.41, respectively. Because of the incomplete grid of cans, no 3D image was created. The nozzles were in very poor shape, with two completely clogged, the spray of one immediately blocked by vegetation, and two rotating 360 degrees when they should have been set to 180 degrees and 90 degrees respectively. The low uniformity may have been a part of the reason that this garden received so much water, because in order to adequately irrigate the dry spots the majority of the garden had to be excessively over-watered.

My suggestions for improving irrigation in this garden is to fix the clogged and improperly rotating nozzles to achieve a better uniformity, and then to irrigate at the same frequency of once per week but for only a fraction of the duration that was done in 2015. Additionally, lower durations of irrigation early in the season when the root zone is still

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**Fig. 10. Field D - Cumulative seasonal water balance**

![Field D - Cumulative Seasonal Water Balance](image_url)
shallow would avoid excessive return flows and nutrient leaching.

**Case Study 4 – Sprinkle Irrigated Community Garden with Low Efficiency – Field N**

Field N is a small community garden adjacent to a city park and surrounded by residential development. In 2015 the cultivated portion of the garden was only 0.08 acres, and numerous beds were left fallow. The garden crops included mixed vegetables and a couple of patches of corn. The garden is irrigated with both culinary and secondary water sources. The culinary water is metered with a permanently installed city approved water meter and is available for gardeners to irrigate their plots by hose whenever they wish. The secondary source is a fixed sprinkler system with brass impact sprinklers mounted on evenly spaced posts in a 50 foot grid throughout and on the edges of the garden and is turned on by a control valve and timer that is part of the adjacent city park irrigation system. The park’s pump system is fed by a canal. The secondary water schedule is set by a city employee who adjusts the schedule based on his understanding of the gardeners’ needs.

I calculated the total applied water for the culinary water supply using monthly utility meter readings, and for the secondary water supply via a one-time volumetric test in conjunction with the irrigation schedule provided by the city employee. During the field measurements, I observed that the post mounted sprinklers had good head to head coverage but irrigated not only the garden beds but the entire community garden area, the majority of which was grass. I visually observed the edges of the irrigated area and determined the area measurement in ArcMap to be 0.35 acres. Therefore only 23% of the irrigated area was growing crops. Although this may have been intentional because of the aesthetic and other benefits of grass in pathways and common areas, some of the irrigated area was far beyond the cultivated areas where there was likely very little benefit. In order to not distort
the total volume of water received by the garden beds, the turf area was left out of the
analysis, and I calculated the flow rate of secondary water applied to the garden beds by
multiplying the total measured secondary system flow rate by 23%. I determined the total
irrigation depths to be the sum of the secondary and culinary sources.

The time series water balance is shown in Fig. 11. Evident from the plot is the fact
that the majority of each irrigation is going towards return flows, which in this case are
deep percolation.

![Field N - Time Series Water Balance](image)

**Fig. 11. Field N - Time series water balance**

A plot of the cumulative water balance is shown in Fig. 12 below. The
disaggregated irrigation depths from the secondary and culinary sources (omitted in the
figure for simplicity) showed that the majority of the applied water came from the culinary
source, which comprised 90% of the total irrigation in July and August, and more than 95%
in September. Therefore, the excessive irrigation depth was applied by the gardeners themselves and not the automated secondary system. The total irrigation depth was 116.9 inches, with irrigation return flows of 97.7 inches, leading to a very poor irrigation efficiency of 16%.

![Field N - Cumulative Seasonal Water Balance](image)

**Fig. 12. Field N - Cumulative seasonal water balance**

To determine the garden secondary system CU and DU I conducted a catch can test where cans were placed in a 10 x 10 grid throughout the garden wherever space would allow. The CU and DU were 64% and 0.45 respectively, both well below the recommended values. The low uniformities were potentially related to the fact that the crop heights varied considerably throughout the garden, with the tall crops (e.g. corn) blocking sprinkler spray on numerous beds.

Improving the irrigation efficiency of this community garden would require
education of the gardeners and/or collaboration between the gardeners and the city employ
responsible for the secondary sprinkler system. If the gardeners are under the impression
that they need to provide the majority of the irrigation water, then they should be informed
as to the extent of their over-irrigation and educated about basic soil moisture storage
principals and rooting depth. Another alternative is that the majority of irrigation
responsibility shifts towards the secondary system and city employee, who could learn
proper irrigation scheduling methods and assure the gardeners that he is taking care of the
lion’s share the irrigation needs so that they do not need to participate as much in the
irrigating. Additionally, this site would be a good candidate for automated or manually
controlled drip irrigation in the vegetable beds with mulched paths between beds.

Case Study 5 – Surface Irrigated Pasture with Surface Return Flows - Field K

Field K is a 3.67-acre field with pasture and orchard comprising 72% and 28% of the
area, respectively. The field is heavily grazed and is not cut and bailed. The water
source is a canal with the head gate directly adjacent the field, and the field is surface
irrigated via sheet flow with the water directed to different areas of the field via gates, sand
bags, and furrows. To measure irrigation flow rates I installed a broad crested weir (BCW)
and staff gauge in the ditch beneath the head gate, and had the irrigator manually fill out a
table of the schedule along with the staff gauge reading. A picture of the BCW in operation
is shown below in Fig. 13. The time series water balance is shown below in Fig. 14.

The plot shows that return flows occurred almost during every irrigation throughout
the season, with extremely high applications occurring at the beginning of the season (when
canal flow was high) and decreasing until late July. The irrigation frequency was very
consistent, with irrigation occurring at every turn provided by the canal company. Yet even
Fig. 13. Field K - Broad crested weir for surface irrigation measurement

Fig. 14. Field K - Time series water balance
after the irrigations depths decreased to a more reasonable level (late July) the vast majority of applied water went to return flows.

The cumulative plot of inputs and outputs shown in Fig. 15 confirms the above statement about application depths throughout the season. The majority of return flows occurred early in the season during the first six irrigations, with a much lower quantity occurring after July.

**Fig. 15. Field K - Cumulative seasonal water balance**

The cumulative irrigation for this field was 118.2 inches, with 95.1 inches going towards return flows, resulting in a field irrigation efficiency of 19%. However, this field is unique to my study because it appeared that the majority of return flows directly reentered the canal just down slope of the field via surface runoff. Therefore, the field irrigation efficiency is not a useful metric because the district efficiency, assuming very
little water goes towards deep percolation and that the surface runoff has no decrease in quality, is high. Therefore, applying less irrigation depths via more precise application methods (e.g. sprinklers) would not save much water.

According to the water balance in Fig. 14, the irrigator does not need to irrigate with his current frequency, as there still exists approximately 50% of the MAD every week when he begins irrigating. Therefore, I recommend that if he wishes to save time irrigating he adjust his schedule to irrigate the same duration but at half the frequency. This would result in lower return flows, which although it would not necessarily save water, would result in considerable savings in time and less loss of pasture fertilizers and amendments. This is a classic situation with surface irrigation where surface runoff return flows are not lost to other irrigators downstream, and thus there is little incentive for water conservation. However, savings in time from better management can be substantial.

**Case Study 6 – Surface Irrigated Garden with Low Efficiency - Field V**

Field V is a small but very productive 0.19-acre backyard garden growing a wide variety of crops including mixed vegetables, grains, berries, cover crops, and fruit trees. The garden is surface irrigated via an open ditch secondary system with a head gate. The main distribution channel in the garden is lined with plastic to reduce seepage losses. I measured the irrigation flow rates with an S-M flume designed by Samani and Magallanez (2000) and the irrigation schedule and staff gauge reading was recorded by the irrigator. The S-M flume in operation is shown in Fig. 16. The time series water balance is shown below in Fig. 17.

The plot shows that the vast majority of irrigations went directly to return flows.
Fig. 16. Field V – S-M flume for surface irrigation measurement

Fig. 17. Field V - Time series water balance
The excessive return flows is likely due to a combination of two factors. First, according to the Web Soil Survey the soil in this area contains 58% sand and has a drainage class of *somewhat excessively drained*, which leads to high infiltration rates that make efficient flood irrigation without careful control very difficult (Soil Survey Staff 2016). Second, the field has a very low AWC of only 1.08 inches/foot (the third lowest of all the fields in my study), which means very little water can be stored in the soil. Therefore, irrigation events need to be rather frequent to avoid crop water stress. The need for high frequency of irrigation along with a fast draining soil makes surface irrigation in this location very difficult.

Also evident from Fig. 17 is that the irrigation frequency for this field was very consistent. This is because the garden was irrigated at almost every irrigation turn allowed by the canal company, which in this case was three times per week. Additionally, the soil moisture seldom approached even 50% of the MAD. Therefore, once the crops had reached full rooting depth (mid-August) the irrigation frequency could have likely have been halved. Still, there were a couple of occasions in the summer where the soil moisture dropped slightly below the MAD.

The cumulative seasonal water balance is shown in Fig. 18. The total irrigation depth was the highest of all fields in my study at 188.3 inches, with calculated return flows of 176.8 inches, resulting in an irrigation efficiency of only 6%. Because there was no observed surface runoff on the property the return flows went to deep percolation, thus the field efficiency is the same as the district efficiency because the return flows are not available to other users of the canal.
Improving the irrigation efficiency early in the season, when the rooting zone of vegetable crops is very shallow and the soil surface and germinating seeds most prone to erosion, would be very difficult with surface irrigation. If the irrigator wishes to save time and water during this period I would recommend sprinkle irrigating (with culinary water if need be) the shallow rooted crops until they become more developed. Depending on how surface irrigation is controlled throughout the garden the deep rooted crops (e.g. trees, berries, and perennials) could still be surface irrigated. Once the full rooting zone of vegetables crops is developed (approximately mid-August) the irrigator could surface irrigate with half the frequency and, depending on how the water is advanced through the garden, significantly less duration. To ensure adequate water distribution with a changed schedule the rate of advance of the water towards the far side of the garden should be increased as much as possible in order to reduce deep percolation losses that occur during
the advance stage of flooding. This could be accomplished by lining more of the
distribution furrows with plastic sheeting, by installing more pipes and gates for better flow
control, or by creating berms parallel to the water flow to allow higher flow rates over
smaller areas. Additionally, the far side of the garden could be diked, which would prevent
water from flowing out of the garden and allow the inflow to be cut off sooner.

**Summary Statistics**

*Gross Irrigation Depth and Gross Return Flow of Each Field*

The gross irrigation depth (GID) and gross return flow (GRF) for each field,
determined via the time series mass balance approach, is shown in Fig. 19. The vertical
black bars on the plot represent the 95% confidence interval of the each value.

![Gross Irrigation Depth & Gross Return Flow vs Field ID](image)

*Fig. 19. Field gross irrigation depth (GID) and gross return flow (GRF)*
From the figure note the spread of GID among the fields. The bar chart shows that there are three distinct outliers (fields K, N, and V) that had GID and GRF significantly higher than average field. Aside from the outliers however, three of the fields applied around 50 inches, while the majority applied less than 25 inches, with some applying significantly less. Additionally, the majority of fields had some fraction of return flows, but seven of the fields had no return flows at all.

**Change in Soil Moisture**

On numerous fields in my study the water balance calculated that the crop demanded even more water than was provided by irrigation and precipitation. The deficit between the demand and supply in my calculations, assuming no lateral or vertical movement of groundwater, comes from either a depletion in soil moisture or crop water stress. Since none of the crops appeared stressed to the naked eye, I assume that the deficit comes from a depletion in soil moisture. A depletion in soil moisture means that the soil moisture was used up throughout the season, leaving it drier in the fall than it was found in the spring. If the soil is left dry and depleted of water in the fall usually a portion of late fall, winter, and early spring precipitation will go towards recharging the soil moisture. This water can be used by the irrigator to help meet a portion of the crop water demand during the growing season, so it can be advantageous for an irrigator to leave the soil in the fall drier than they found it in the spring. On the other hand, as positive change means that the soil was left wetter in the fall than it was found in the spring, so a portion of water inputs (irrigation and precipitation) went towards filling up the soil reservoir at some point during the season. Using irrigation water to fill up the soil moisture in the fall at the end of the growing season is likely to have little benefit (with the exception of some field crops
such as alfalfa and wheat) as off-season precipitation alone will often adequately recharge it. The change in soil moisture from the beginning to the end of the season, as calculated with the time series water balance, is shown in Fig. 20.

![Fig. 20. Field change in soil moisture](image)

**Irrigation Efficiency**

The field irrigation efficiency (IE) is defined in the *Data Collection and Methodology* section as the ratio of irrigation water beneficially used to the irrigation water applied minus the change in storage. By this definition an efficiency of 100% is obtainable if all of the irrigation water applied, minus any irrigation water stored in the soil, was beneficially used to grow the crop. Leaching salts out of the soil by intentionally applying water beyond that which can be stored in the soil is required in areas with water high in dissolved salts, and thus is considered a beneficial use. However, in Cache Valley the water is low enough in salts that leaching is not typically necessary. Therefore, any quantity of
return flows for the fields in my study would result in an irrigation efficiency less than 100%. Fig. 21 shows a bar chart of the irrigation efficiency for each field.

![Participant Irrigation Efficiency (%)](image)

**Fig. 21. Field irrigation efficiency**

The chart shows that seven of the fields had an IE of 100%. Although achievement of 100% IE can be beneficial in regards to reducing labor, pumping costs, and fertilizer inputs it is important to recognize that an irrigation efficiency of 100% is misleading for two reasons. First, under-irrigation results in a high efficiency value, because according to the definition of IE (equation 1) if the ET is higher than the applied water then the efficiency is >100%. However, under-irrigating a significant amount can result in crop water stress and be detrimental to yield, and so the 100% IE does not mean that no
improvements are needed. On the contrary, if the difference between ET and the applied depth is great then the irrigator should probably apply more water than they are. Second, because an application uniformity of 100% is not physically possible (even the highest efficient traveling sprinkler systems only achieve a CU of 95%), different areas of the field will receive different depths. For the sites where ET was much higher than the applied depths the whole field was likely under-irrigated (i.e. even the wettest areas). For those sites which applied close to the right depth to match the crop ET, approximately 50% of the field will be under-irrigated and the remaining portion will be over-irrigated. Therefore, the irrigators with 100% IEs should still try to achieve the minimum recommended uniformities of their crops and if the ET differs greatly from the applied depth they should consider applying more water.

A high field efficiency, as explained above in the Background section, can be beneficial on the field scale in regards to reducing labor, pumping costs, and fertilizer inputs, but a low field efficiency does not necessarily indicate a need for improvement. For example, as explained in Case Study 5, field K, a surface irrigated pasture, has an incredibly low field efficiency of 19%, but the return flows go directly back into the canal, resulting in no loss to the district other than the portion evapotranspirated by the crop and whatever might have deep percolated. Field I is another unique situation where the irrigation water is pumped from a groundwater well supplied by a high water table just a few meters deep, and return flows from deep percolation directly return to the water table. The resultant low field efficiency of 60% means unnecessary energy costs and perhaps loss of fertilizers and inputs, but does not result in any change in water available to the farm nor other users of the aquifer. The return flows for field N on the other hand, a sprinkle irrigated field on a
pumped system fed from a canal, are in the form of deep percolation. Thus, improving the field efficiency is a good target as the low efficiency results in high pumping costs and perhaps even waste of fertilizers and other agricultural inputs being leached from the soil, in addition to lost water from the district. Therefore, the field efficiency for each field must be taken in its own context.

The district efficiency for these fields, except for field K and I, is the same as the field efficiency. A poor field efficiency from deep percolation leads to a poor district efficiency. The effective efficiency for these fields, however, all located within a multiple-use basin, is 100% assuming there are no ET losses from vegetation or evaporation losses from standing water in the return flow paths. Since the determination of these losses would in and of themselves be a study, and are not easily estimated, they are assumed negligible, and in my analysis the only portion of water lost to the basin is that evapotranspirated by the crops.

*Area and Gross Irrigation Depth*

For any non-automated irrigation system it takes more labor to irrigate a large field than a small field. I hypothesized that the larger a field is the less likely it is to be over-irrigated, as the hours that would be required to over-irrigate the larger area are unlikely to be spent doing so. For example, it takes very little effort to run a backyard sprinkler system for a small vegetable garden, but it takes a lot of effort to move hand-move irrigation pipe across a large pasture. Therefore, it seems it would be easier to over-irrigate the backyard garden than the pasture. To explore this hypothesis I created a scatter chart of GID and GRF vs field size, shown in Fig. 22 below. In addition to depths the plot shows the distribution of field sizes in my study sample, with field sizes as small as 0.08 acres up to
roughly 12.3 acres, with a slight concentration towards small fields.

**Fig. 22. Gross irrigation depth (GID) and gross return flow (GRF) vs field size**

Note that two of the three fields with the highest GID were less than 0.25 acres, and the third field was less than 4 acres. Fields only slightly larger than 0.25 acres tended to have much lower GID and GRF. Additionally, with the exception of two fields all of the fields greater than 2 acres had a GIDs less than 20 inches and calculated GRFs of zero. Therefore, my hypothesis that small fields are more likely to be over-irrigated than large fields appears to have some validity. To verify this with any level of certainty a more extensive study of small fields would be needed. However, this finding leads to an interesting insight regarding a statement made in the legislative audit that “smaller lot sizes should reduce outdoor landscape water use” (Office of the Legislative Auditor General
Although smaller lot sizes will inarguably have less irrigated area and therefore require less water if managed properly, as my study shows if the irrigation is not managed well they may be even more prone to over-irrigation than larger lots. Therefore, the solution to reducing outdoor irrigation lies not only in less landscaped area but also better irrigation management.

The bars connecting the GID and GRF in Fig. 22 approximately represents the net ET (ET minus precipitation minus the change in soil moisture as calculated from the water balance in equation 2). Note that all of the bars have a similar magnitude, indicating that the net ET does not change much based on field size.

**Method and Gross Irrigation Depth**

The methods used by an irrigator are a result of many variables including the method of water delivery (e.g. pressurized supply line, groundwater well, or open ditch), the crop type and cropping techniques, field size, soil types, topography, the cost of water and electricity, equipment capital costs, labor availability, farm history, level of education, and more. 19 out of the 24 areas in my study used sprinkle irrigation, four used surface irrigation, and one used drip irrigation. Note that I would have preferred more fields using drip irrigation but that this method is still not nearly as common in Cache Valley as sprinkle and surface methods. In Fig. 23 a three dimensional plot (created using DiscoveryDV software) of GID vs field size and irrigation method shows how most of the larger farms used sprinkle irrigation, and that two of the three outliers with excessive GID used surface irrigation. Note that in the figure a couple of the points are so close to each other than they appear as a single point. It appears that in Cache Valley there is indeed some correlation between GID, farm size, and method, with larger farms in general having less GID than
smaller farms and more likely to use sprinkle than surface methods.

Fig. 23. Three dimensional plot of gross irrigation depth (GID) vs field area and irrigation method

A bar chart of GID for each field and its irrigation method is shown below in Fig. 24. The only field using drip irrigation (Field L) applied 7.7 inches, giving this field the second to the least GID of all the fields. The fields using sprinkle systems had one outlier (Field N) with excessive GID of 116.9 inches, which was a result more of management than method, as I explained in Case Study 4. However, 14 of the 19 fields applied less than 30 inches, and 9 of the fields had few to none return flows at all. With the single outlier N removed, the weighted average GID for the sprinkle irrigated fields is 19.5 inches.
The variability among GID for the four surface irrigators was much higher than for the other two methods. The surface irrigated fields K and V had a GID of 118.2 and 188.3 inches, respectively, and a GRF of 95.1 and 176.8 inches, respectively. Note that in the case of field K the return flows went directly back into the canal via surface runoff, leading to a high district efficiency. For field V on the other hand, all of the return flows were deep percolation in a very sandy soil. The remaining two fields (B and C) irrigated only 27.5 inches each, performing better than many of the sprinkle irrigated fields. This shows that surface irrigation can have a wide spread of GID, and that the depending on the destination of return flows, may or may not have large depletions of water. As fields B and C show, if managed well surface irrigation systems can perform better than poorly managed sprinkler systems, and may perform equivalently well to properly managed sprinkler systems.
However, the area-weighted average GID for sprinkler systems show that super excessive irrigation with sprinklers is less likely to occur than with surface methods.

**Crop Type and Gross Irrigation Depth**

To compare GID for the different crop types in the study I categorized the crop types into the six groups: alfalfa, cereal crops, mixed vegetable gardens, orchard, pasture, and vegetables with plastic mulch. Fig. 25 shows the bar chart of GID vs. crop type for each field. Three of the five fields with the highest GID were mixed vegetable gardens, one was pasture, and one was alfalfa.

![Gross Irrigation Depth & Gross Return Flow vs Crop Type](image)

**Fig. 25. Field gross irrigation depth (GID) vs crop type**

As is explained in the case studies the outliers are more a result of irrigation management than crop types and their related water requirements. Therefore, in order to
observe the relationships between GID and crop type, I removed the three outliers K, N, and V. Fig. 26 shows the area-weighted GID, seasonal ET, and GRF as a function of crop type.

**Fig. 26. Area weighted average gross irrigation depth (GID), gross return flow (GRF), and evapotranspiration (ET) vs crop type**

Both the *Cereal* category and *VegetablesMulch* category each include only one field and are therefore included as interesting data points, but should not be used as a means of comparison with the other crops. As shown in the chart, both the *Cereal* crop and the *VegetablesMulch* crop received less irrigation than the crop water requirements and had zero return flows. Therefore, the difference between seasonal ET and GID likely came from a combination of precipitation and a depletion in soil moisture throughout the season. In both cases capillary rise from a shallow water table was unlikely. For the *Alfalfa* and
Mixed Vegetable Garden crops there was less applied water than the crop water demand, but both of these categories had some return flows, indicating that the return flows were likely due to poor scheduling. The Orchard crops had the highest ET but also received the most irrigation with roughly 33% of irrigation going to return flows. Pasture also had approximately 33% of its irrigation go towards return flows. The numerical results of the weighted average GID, GRF, IE as defined in this paper, and irrigation efficiency as defined in the DWRe’s 2009 Residential Water Use Study for each crop type is shown in Table 2.

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>GID (inches)</th>
<th>IE (%)</th>
<th>Irrigation efficiency = ETnet/GID, used in 2009 DWRc study (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>20.9</td>
<td>89%</td>
<td>89%</td>
</tr>
<tr>
<td>Cereal</td>
<td>9.7</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Garden</td>
<td>19.4</td>
<td>86%</td>
<td>86%</td>
</tr>
<tr>
<td>Orchard</td>
<td>31.1</td>
<td>68%</td>
<td>68%</td>
</tr>
<tr>
<td>Pasture</td>
<td>22.7</td>
<td>72%</td>
<td>67%</td>
</tr>
<tr>
<td>VegetablesMulch</td>
<td>7.7</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Uniformity and Gross Irrigation Depth

For fields using sprinkle irrigation that were attempting to achieve uniformity I wanted to determine if there was any correlation between the uniformity coefficients and GID and field size. Fig. 27 shows a three dimensional plot of coefficient of uniformity (CU) (y-axis) vs field area (x-axis) and GID (marker size) for all fields that received catch can tests. Recall that the recommended CU values for high-value crops, low-value crops,
and tree crops is 84%, 75%, and 70%, respectively (Merriam and Keller 1990).

The largest point (field with the highest GID) on the left edge of the plot is the outlier explained in Case Study 4, which has both a small field area and a poor CU. This field’s excessive GID was a result of over-irrigation by community garden members who obviously did not know the needs of their crops. For the single point at approximately seven acres and CU of 82%, the GID was high because of excessive irrigation durations all season long, illustrating how even with a high CU over-irrigation can result from poor scheduling. With the exception of this one field, all of the points larger than 2.5 acres had
high CUs and are on the small end of the size scale (indicating they had relatively low GIDs), while the points smaller than 2.5 acres had worse CUs and are significantly larger in size (indicating they had relatively high GIDs). Therefore, the following three trends become evident: 1) CU increases with increasing field size, 2) GID increases with decreasing area, and 3) GID increases with decreasing CU.

**Scheduling and Gross Irrigation Depth**

Irrigators aiming to improving irrigation efficiency often think the only solutions lie in technological improvements, thereby overlooking the role of management. However, poorly managed high tech systems can be less efficient than well managed low tech systems (Perry, 2009). To gain insight into the role of irrigation scheduling (a management issue) in GID and IE, I gave each field two qualitative ratings. The first rating is of schedule interval which includes the ratings fixed (irrigations occurred at a fixed interval all season), partially fixed (irrigations occurred at a fixed interval for most of the season), variable (irrigations occurred at no discernable interval), and random (irrigations occurred seemingly at random). The second rating is the frequency of return flow occurrence for each field and includes the ratings RF every IRR (return flows occurred on every irrigation event), RF early season (return flows occurred only early in the season but not late in the season), RF late season (return flows only occurred late in the season but not early in the season), and zero RF (not a single return flow event occurred during the season). Table 3 shows the two ratings for each field along with their respective GIDs and irrigation efficiencies, ranked in decreasing order of GID.

Two significant patterns are evident from the table. The fields at the top of the table with the highest GID and lowest efficiencies received irrigations at fixed intervals, and
Table 3. Field Gross Irrigation Depth (GID), Irrigation Efficiency (IE), Schedule Interval, and Return Flow Frequency

<table>
<thead>
<tr>
<th>ID</th>
<th>GID (in)</th>
<th>IE (%)</th>
<th>Schedule Interval</th>
<th>Return Flow (RF) frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>188.3</td>
<td>6</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>K</td>
<td>118.2</td>
<td>19</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>N</td>
<td>116.9</td>
<td>16</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>D</td>
<td>54.4</td>
<td>25</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>R</td>
<td>51.1</td>
<td>37</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>Q</td>
<td>44.0</td>
<td>27</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>O</td>
<td>35.2</td>
<td>71</td>
<td>variable</td>
<td>RF early season</td>
</tr>
<tr>
<td>T</td>
<td>29.5</td>
<td>75</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>M</td>
<td>28.9</td>
<td>42</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>X</td>
<td>27.8</td>
<td>51</td>
<td>partially fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>B</td>
<td>27.5</td>
<td>62</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>C</td>
<td>27.5</td>
<td>62</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>A</td>
<td>25.8</td>
<td>55</td>
<td>fixed</td>
<td>RF every IRR</td>
</tr>
<tr>
<td>U</td>
<td>18.9</td>
<td>94</td>
<td>fixed</td>
<td>zero RF</td>
</tr>
<tr>
<td>P</td>
<td>18.0</td>
<td>86</td>
<td>partially fixed</td>
<td>NA</td>
</tr>
<tr>
<td>F</td>
<td>17.7</td>
<td>100</td>
<td>fixed</td>
<td>zero RF</td>
</tr>
<tr>
<td>W</td>
<td>15.7</td>
<td>90</td>
<td>partially fixed</td>
<td>zero RF</td>
</tr>
<tr>
<td>I</td>
<td>14.1</td>
<td>81</td>
<td>partially fixed</td>
<td>RF early season</td>
</tr>
<tr>
<td>G</td>
<td>13.7</td>
<td>100</td>
<td>fixed</td>
<td>zero RF</td>
</tr>
<tr>
<td>H</td>
<td>11.8</td>
<td>100</td>
<td>fixed</td>
<td>zero RF</td>
</tr>
<tr>
<td>S</td>
<td>9.7</td>
<td>100</td>
<td>variable</td>
<td>zero RF</td>
</tr>
<tr>
<td>E</td>
<td>9.4</td>
<td>100</td>
<td>partially fixed</td>
<td>NA</td>
</tr>
<tr>
<td>L</td>
<td>7.7</td>
<td>100</td>
<td>partially fixed</td>
<td>zero RF</td>
</tr>
<tr>
<td>J</td>
<td>7.2</td>
<td>100</td>
<td>random</td>
<td>zero RF</td>
</tr>
</tbody>
</table>

Return flows occurred on almost every irrigation throughout the season, rather than in a few events. These fields were irrigating according to a set schedule, whether set by the irrigation district or based on their own judgement and experience. The fact that return flows occurred on almost every irrigation indicates that they either did not know the depths
of water they were applying or how much water their soil was capable of holding, or both. However, there were a few irrigators with fixed interval schedules that had zero return flows, so in these cases the fixed interval did not result in over-irrigating. For the majority of fields without fixed interval schedules, there was generally low return flows. For these irrigators the schedule interval was a matter of choice because the water was available for more frequent irrigations if they had wanted it. Therefore, the lack of a fixed interval meant they were relying on their judgement based on weather, time constraints, knowledge of their field conditions, etc. These results indicate that the role of irrigation scheduling and frequency is very significant in regards to GID and IE.

Also worth noting is that a few of the fields had return flows early in the season (perhaps because they were unaware of shallow rooting depths and low ET early in the season) but none had return flows late in the season. This makes evident a potentially important difference between the temporal variability of water demand for irrigation use vs landscaping use, where according to a DWRe study in 2009, the majority of over-watering on residential landscapes occurs in early fall as a result of tenants not adjusting their irrigation timer schedules to respond to reduced ET in the fall (Utah Division of Water Resources 2009). All of the agricultural irrigators in my study had either only early season over-irrigating or season long over-irrigating, but not late season over-irrigating alone.
DISCUSSION

Utah Division of Water Resources

As discussed in the Introduction, the DWRe currently estimates agricultural water use at the basin scale only, using basin efficiency estimates from a USU paper in 2003 and basin water inputs and outputs from available hydrologic measurements and estimates. When the water balance calculated efficiency does not match the basin efficiency in the paper, the basin efficiency and other inputs and outputs are adjusted until the water balance is satisfied. While this method may be a feasible means of estimating agricultural water use with limited engineering hours and water flow, land use, and ET data, it is very prone to error and misrepresentation of the actual water use and efficiency of a basin. Therefore, the DWRe should begin increasing the precision of their agricultural water use estimation methods to the field scale on a basin by basin basis to be able to identify areas with high potential for water savings as well as to help validate their current basin estimates. In doing so it is important that they consider average efficiencies for different farm sizes, irrigation methods, crop types, and the destination and quantity of return flows by conducting studies similar to this one and/or using data from this report. Increased metering of secondary water sources would provide invaluable data to help in this effort.

For M&I water the DWRe does use some average irrigation depths and field level efficiencies in their water use estimates. As I explained in the Background section, from the DWRe 2009 Residential Water Use Study the average outdoor irrigation depth and irrigation efficiency for metered culinary water users having heard of the “Slow the Flow” campaign was 32.5 inches and 79%, respectively (Utah Division of Water Resources
Although this data comes from 17 communities across the state with varying ET, and my study area of Cache Valley has lower ET than most areas of the state, it is interesting to note that not a single one of the crop types in my study received as much water as the landscapes in the DWRe study, as is shown in Table 2. Additionally, all of the crop type categories in my study except for *Pasture* and *Orchard* have higher average efficiencies than the average landscape efficiency in the study, and all of the categories have significantly higher efficiencies than the aforementioned 50% estimate used by the DWRe for unmetered secondary systems. Therefore, because all except one of the fields in my study were using secondary water systems, it reasons that it is very likely that the DWRe’s 50% efficiency estimate is significantly lower than it should be.

The values in Table 2 also lead to an interesting comparison between residential landscapes and agriculture. The average irrigation depth and efficiency for the *Garden* category (the crop type most likely to occur in residential landscapes) in my study were 19.4 inches and 86%, respectively, much better than the average landscape values in the DWRe’s 2009 study. Therefore, it could reason that encouraging urban agriculture as an alternative to conventional landscaping could potentially save water in the M&I sector (thereby contributing to the state’s 25% reduction in M&I gpcd goal), not to mention simultaneously accomplish many of the community building, nutrition, and food security benefits of urban and small farms.

For conservation programs to be effective they must be informed as to the real causes of inefficiency in water use. As the results of my study show, conservation efforts aimed at reducing irrigated area alone may not result in true water savings if the role of irrigation management is ignored because small irrigated areas, if improperly managed,
can have incredibly poor efficiencies. In my study, the areas of management most needing improvement were knowledge of irrigation system flow rates, irrigation scheduling, and obtaining decent application uniformities. Programs aimed at educating water users about wise irrigation need to incorporate these management issues into their efforts. Additionally, prioritizing the water users most prone to over-watering will likely result in the largest return on investment, and small fields with unmetered secondary sources certainly fall into this category. I believe that these conservation efforts are most likely to be received well by urban and small farm irrigators if they are sponsored and promoted by Extension rather than the DWRe alone, as most irrigators are already familiar with Extension services and many are skeptical of state departments having insight into their water use.

**Irrigators**

From my study the three aforementioned areas of irrigation system management that stand out as needing improvement are 1) knowledge of irrigation system flow rates, 2) proper irrigation scheduling and 3) achieving a decent application uniformity. Knowledge of their flow rate would give farmers an idea of the depths of water they are applying at each irrigation, which is a prerequisite for proper irrigation scheduling. Determining system flow rates for drip and sprinkle systems could be as simple as conducting a volumetric test to provide a decent baseline measurement. For surface systems a simple S-M flume or rectangular weir can be built and installed cheaply, but even use of the float method (to measure stream velocity) and a staff gauge (to measure stream area) in a uniform part of the channel would be an improvement no measurement device. Second, irrigators should be aware of and able to quickly and easily use basic irrigation scheduling
tools. At present, perhaps the easiest scheduling tool for use in Utah is Washington State University’s mobile phone application “Irrigation Scheduler”, which uses a series of weather networks that together cover a large portion of the western U.S. and Canada. This user-friendly applications allows the irrigator to input a small amount of data including the field location, soil type, and crop type (along with numerous more detailed inputs available) and helps estimate the ideal irrigation schedule, soil moisture, crop water stress, and more. I recommend that the irrigators sit down and take a couple of hours to learn how to use this tool, and believe that the effort spent will quickly pay off in savings of water, energy, and time irrigating.

Lastly, irrigators should be aware of their application uniformity. If the average applied depth equals the calculated crop water requirements, a poor uniformity will mean that some areas of the field are under-watered, likely reducing yield, while other areas of the field are over-watered, resulting in waste of fertilizers and soil amendments. If the crop water requirements of the entire field are met for a system with poor uniformity, significant volumes of water will go directly to return flows, also wasting resources. Application uniformities can be improved by utilizing matching nozzles spaced properly for head to head coverage, and by simple maintenance such as ensuring nozzles are not clogged, are set to the correct arc, and are properly rotating. Together, improvement in these three areas (knowledge of flow rates, improved scheduling, and application uniformities) would quickly pay off on the farm scale by reducing labor and energy costs, minimizing the leaching of nutrients, and potentially even increasing yield.

Table 4 shows some of the benefits that could result from improved irrigation scheduling for each field in my study. Note that these descriptions are rough and
approximate, and for a more precise analysis I recommend the reader refer to the time series plots provided in Appendix F. The table is provided here not to give explicit recommendations, but rather to give an approximate feel for potential scheduling improvements and the costs and savings that could result from these.

**Table 4. Recommended Schedule Changes and Associated Benefits and Costs**

<table>
<thead>
<tr>
<th>ID</th>
<th>Recommended Schedule Change</th>
<th>Approximate On-farm Water Savings (Acre-feet)</th>
<th>Benefits &amp; Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Discontinue use of 1 of the irrigation systems</td>
<td>0.29</td>
<td>Reduced manual labor, reduced leaching</td>
</tr>
<tr>
<td>B</td>
<td>Reduce duration 50%</td>
<td>1.39</td>
<td>50% of hrs saved, reduced leaching</td>
</tr>
<tr>
<td>C</td>
<td>Reduce duration 50%</td>
<td>1.34</td>
<td>50% of hrs saved, reduced leaching</td>
</tr>
<tr>
<td>D</td>
<td>Reduce duration 75%</td>
<td>0.13</td>
<td>75% less pumping costs, reduced leaching</td>
</tr>
<tr>
<td>E</td>
<td>Increase duration 25%</td>
<td>0.00</td>
<td>25% more pumping costs, slightly increased yield</td>
</tr>
<tr>
<td>F</td>
<td>Increase duration 20%</td>
<td>0.00</td>
<td>20% more pumping costs, slightly increased yield</td>
</tr>
<tr>
<td>G</td>
<td>Begin irrigating 2 weeks earlier in season, increase duration 25%</td>
<td>0.00</td>
<td>25% more pumping costs, increased yield</td>
</tr>
<tr>
<td>H</td>
<td>Begin irrigating 2 weeks earlier in season, increase duration 25%</td>
<td>0.00</td>
<td>Significantly more labor, increased yield</td>
</tr>
<tr>
<td>I</td>
<td>Increase duration 50% starting mid-July</td>
<td>0.20</td>
<td>50% more pumping costs, increased yield</td>
</tr>
<tr>
<td>J</td>
<td>Begin irrigating 1 month earlier, add 1 irrigation late season, increase irrigation duration 25%</td>
<td>0.00</td>
<td>100% more labor, increased yield</td>
</tr>
<tr>
<td>K</td>
<td>Reduce frequency 50%, reduce duration early season by 75%</td>
<td>NA</td>
<td>50% of irrigation days saved, reduced leaching</td>
</tr>
<tr>
<td>L</td>
<td>Reduce frequency 50%, increase duration 125%</td>
<td>0.00</td>
<td>50% of irrigation days saved</td>
</tr>
<tr>
<td>M</td>
<td>Increase frequency 25%, reduce duration 50%</td>
<td>0.41</td>
<td>25% more irrigation days, slightly increased yield, reduced leaching</td>
</tr>
<tr>
<td>N</td>
<td>Reduce frequency 50%, reduce duration 75%</td>
<td>0.67</td>
<td>50% of irrigation days saved, reduced leaching</td>
</tr>
<tr>
<td>O</td>
<td>Reduce frequency 50%, reduce duration 100% starting mid-July</td>
<td>1.15</td>
<td>50% of irrigation days saved, reduced leaching</td>
</tr>
<tr>
<td>P</td>
<td>Reduce frequency 50%, increase duration 50% starting mid-July</td>
<td>0.11</td>
<td>10 irrigation days saved</td>
</tr>
<tr>
<td>Q</td>
<td>Reduce frequency 50%, increase duration 50% starting mid-July</td>
<td>1.98</td>
<td>6 irrigation days saved</td>
</tr>
<tr>
<td>R</td>
<td>Begin irrigating 1 month earlier, reduce duration 50%</td>
<td>17.07</td>
<td>Increased yield, increased labor early season, 50% of hours saved starting mid-July, reduced leaching</td>
</tr>
<tr>
<td>S</td>
<td>Reduce frequency 50%, increase duration 100% starting mid-June</td>
<td>0.00</td>
<td>Slightly increased yield</td>
</tr>
<tr>
<td>T</td>
<td>Reduce duration 20%</td>
<td>0.31</td>
<td>20% of hours saved, reduced leaching</td>
</tr>
<tr>
<td>U</td>
<td>Reduce frequency 75%, increase duration 300% starting mid-June</td>
<td>0.31</td>
<td>50% of irrigation days saved</td>
</tr>
<tr>
<td>V</td>
<td>Reduce frequency 50%, reduced duration 50% starting mid-June</td>
<td>2.77</td>
<td>50% of irrigation days saved, 50% of hours saved</td>
</tr>
<tr>
<td>W</td>
<td>Reduce frequency 50%, increase duration 100%</td>
<td>1.11</td>
<td>50% of irrigation days saved</td>
</tr>
<tr>
<td>X</td>
<td>Reduce frequency 50%, increase duration 50%</td>
<td>0.53</td>
<td>50% of irrigation days saved</td>
</tr>
</tbody>
</table>
Utah State University Extension

My recommendations to USU Extension is to focus irrigation training and education efforts at helping irrigators understand the link between improved irrigation management and savings in time and money in addition to the above three issues relating to irrigation flow rates, scheduling, and uniformity. To address the lack of measurement and proper scheduling (until universal metering is phased in), programs should focus training irrigators how to conduct simple flow rate and uniformity measurements on their systems, whether it is a one-time field measurement or a homemade or low cost measurement method or device.

Once irrigators have knowledge of their flow rates they should be trained how to use online scheduling tools. Although many such tools are already offered free online, their use does still not seem to be widespread, an illustration of the gap between academia and practice. For northern Utah, the best source for the weather data needed to create an irrigation schedule is the Utah Climate Center’s Agricultural Weather Network, but to make use of this data the irrigator must understand irrigation water balances, the application of crop coefficients, and make numerous estimates of soil and crop characteristics, which makes this option difficult and unlikely to be used in practice. WSU’s “Irrigation Scheduler – Mobile” tool may be the best user-friendly online tool for irrigators at present. I recommend that Extension begin promoting the use of this or other tools in irrigation education efforts, keeping in mind that for the use of any tool to become widespread it is important that it be fast, reliable, and easy to use.

Addressing application uniformities is slightly more difficult, as constraints such as farm shape and size, labor and equipment costs can prohibit improvements to irrigation
system layouts. However, although most sprinkle irrigators are aware of the importance of head to head coverage, they are often unaware of the importance of nozzle size, so encouraging simple low cost measures such as nozzle maintenance (e.g. cleaning clogged nozzles and making sure all nozzles have the correct arc and rotate smoothly) and the use of standardized and uniform nozzles would most likely be the most effective approach.
CONCLUSION

The results of my study provide valuable insight into the water use and irrigation efficiencies of the urban and small farm agricultural sector in Cache Valley, Utah. In this study I conducted comprehensive season long evaluations of 24 urban and small farm agricultural plots in Cache Valley, Utah, gathered time series data of applied irrigation depths and calculated the volume and timing of return flows and the changing soil moisture throughout the season. With this data I calculate a seasonal irrigation efficiency for each field and consider whether crop yield was compromised from water stress. To calculate the gross irrigation depth I used a variety of methods to measure system flow rates and schedules including installing measurement devices and dataloggers where practical, conducting one-time flow rate measurements, and having irrigators manually fill out a table. I then divided the total volume applied at each irrigation by the field area as measured in ArcMap to yield an irrigation depth for each irrigation event. With soil data from the USDA’s Web Soil Survey and precipitation and reference ET data from the Utah Climate Center’s Agricultural Weather Network I calculated a simple irrigation water balance at a daily time step. For sprinkle systems I determined the application uniformities with a catch can test.

With the above evaluation data for each field I identified three outliers that had extremely high irrigation depths. My report provides six detailed case studies including one field with good performance, one field with drip irrigation, and the four fields with the highest gross irrigation depths (three of which are the outliers), and investigate what issues influenced the performances of these fields.
From an analysis of the aggregate data I identify numerous trends in urban and small farm water use including the effect of field area, method, crop type, uniformity, and scheduling on total water use. Small fields are more likely to have lower efficiencies than large fields due to economies of scale, lower levels of irrigation education, the less labor required to irrigate a small area than a larger area, and challenges with application uniformity of fields with a high perimeter to area ratio. Surface systems appear more likely to apply excessive irrigation depths than sprinkle systems, although if managed well they can outperform a poorly managed sprinkle system. Of the six crop types in my study orchards had both the highest area-weighted average gross irrigation depth and ET, and orchards and pastures had the lowest weighted average efficiencies. However, none of the crop types in my study had as high of irrigation depths as the average value for landscapes from the DWRe’s 2009 *Residential Water Use Study*. Additionally, gardens had a significantly lower average irrigation depth and a much higher efficiency than the landscapes in the study, indicating that promoting gardens as an alternative to conventional landscaping may have the potential to conserve M&I water in urbanized areas. All of the crop types had higher efficiencies than the 50% assumption currently used by the DWRe in its estimates for secondary water systems, indicating that the 50% efficiency assumption may not be valid. There also seems to be a relationship between application uniformity, field size, and gross irrigation depth, with larger fields generally having lower gross irrigation depths and higher uniformities than small fields. Lastly, scheduling also played a big role in efficiency with the fields that irrigated on a fixed interval schedule generally applying far more water than those fields that irrigated with a partially fixed, variable, or random interval. For all except one of the farms in my study the majority of the excess
applied water went directly to deep percolation return flows, the timing of which occurred either early season only or all season long, but not only late in the season as often is found with landscapes.

According to the 2015 legislative audit of the DWRe’s agricultural and M&I water estimation methods, numerous improvements are needed. The DWRe can use the data in this paper to better understand water use in the quickly growing sector of urban and small farm agriculture. This could help them in improving the M&I estimates of gpcd and to better calibrate their models of basin scale agricultural use. It will also aid them in designing more effective water conservation programs to address the real issues faced on the ground.

For the irrigators in my study I provide detailed field specific recommendations as to how they can better manage their irrigation systems to save on-farm water, energy, time, agricultural inputs, and potentially improve yield. The three main areas needing improvement are management related and include 1) measuring system flow rates, 2) proper irrigation scheduling, and 3) obtaining a decent application uniformity, and I provide suggestions for how to go about addressing these issues.

Lastly I provide recommendations to the USU Extension as to which technical and management areas of urban and small farm agricultural irrigation need further attention so they can improve educational programs and outreach efforts to better meet the needs of urban and small farmers. Of utmost importance is irrigator awareness of the economic or other benefits of having good irrigation practices, as they are unlikely to make any changes in their current irrigation operations if they are unaware of the benefits of doing so. Also, they may be under the impression that improving efficiency requires investment in new
technologies, thereby overlooking the role of good management, which requires little to no capital investment but rather some basic education and planning. Programs developed to reduce water use on urban and small farms should address teaching about low cost and easy flow measurement methods, how to use online irrigation scheduling tools, and how to improve sprinkle system uniformity with proper nozzle matching and maintenance.

**Further Work**

Most of the irrigators in my study were unaware of their efficiencies, and irrigated either by feel or based on a weekly schedule either set by them or on their irrigation turn as dictated by their canal company. Considering the growing number of urban and small farms within Utah, and the considerable depths of water that these farms often apply, there exists a great need for a “Farm Check Program”, similar in design to the USU’s Center for Water Efficient Landscapes (CWEL) “Water Check Program”. The “Water Check Program” conducts free irrigation system audits for residential landscapes in numerous counties in the state, and gives the landowners advice as to how to improve their irrigation system configuration and management. Based on the amount of time and effort spent on irrigation on urban and small farms, I believe that such a program would have great appeal to urban and small farmers, and would greatly help the state reach its water conservation goals.
REFERENCES


DiscoveryDV [Computer software]. DecisionVIS, State College, PA.


*MATLAB* version R2010b [Computer software]. Mathworks, Natick, MA


APPENDICES
Appendix A. Glossary of Terms and Notation
The following symbols and terminology is used in this paper:

- \( a \) = placeholder variable in water balance calculations;
- \( A \) = area (acre-feet);
- \( AW_{end} \) = available water at end of day (in);
- \( AW_{initial} \) = initial available water (in);
- \( AWC \) = available water capacity, from USDA’s WebSoilSurvey (in/ft);
- \( b \) = placeholder variable in water balance calculations;
- \( CI \) = confident interval (%);
- \( CU \) = christianson’s coefficient of uniformity (%);
- \( CV \) = coefficient of variation;
- \( d_{ave} \) = average catch can depth (in);
- \( D \) = inside pipe diameter (in);
- \( D_{end} \) = root zone depletion at end of day (in);
- \( D_{end, sub, initial} \) = sub Root zone initial depletion (in);
- \( D_{initial} \) = initial root zone depletion (in);
- \( D_{f, initial} \) = initial root zone depletion fraction;
- \( D_{f, sub} \) = sub root zone depletion fraction;
- \( D_{f, sub, initial} \) = sub root zone initial depletion fraction;
- \( D_{start} \) = root zone depletion at start of day (in);
- \( D_{start, sub} \) = sub root zone depletion at start of day (in);
- \( DU \) = distribution uniformity;
- \( \Delta EL \) = elevation gain down field (ft/length of tape);
- \( ET_{adj} \) = adjusted evapotranspiration (in);
- \( (ET_{adj}/ET_{potential})_{ave} \) = average ratio of adjusted ET to potential ET;
- \( ET_{crop} \) = crop evapotranspiration (in);
- \( ET_{irr} \) = evapotranspiration from irrigation (in);
- \( ET_{potential} \) = potential evapotranspiration (in);
- \( ET_{ref} \) = reference evapotranspiration, from USU Climate Center (in);
- \( EU \) = emission uniformity (%);
- \( F \) = reduction coefficient 0.36 for multiple outlet pipes with greater than 31 outlets, from Table 8.7 Keller and Bliesner (1990);
- \( gpcd \) = gallons per capita per day
- \( gpm \) = gallons per minute
- \( GID \) = gross irrigation depth (in);
- \( GRF \) = gross return flow (in);
- \( h_f \) = head loss through the tape (ft);
- \( H \) = drip tube datasheet head (ft);
- \( H_a \) = average head (ft);
- \( H_l \) = lateral inlet head (ft);
- \( H_n \) = head at end of pipe (ft);
- \( I \) = Irrigation (in);
- \( IE \) = field irrigation efficiency (%);
- \( I_{total} \) = total irrigation in season (in);
- \( J \) = friction loss gradient (ft/100ft);
\( K \) = unit conversion, 0.133 for English units;

\( K_c \) = crop coefficient;

\( K_{c, \text{max}} \) = maximum crop coefficient, Utah Consumptive Use document;

\( K_{c, \text{mid}} \) = mid-season crop coefficient at mature canopy;

\( K_{c, \text{min}} \) = minimum crop coefficient, Utah Consumptive Use document;

\( K_d \) = emitter constant of proportionality;

\( K_s \) = transpiration reduction factor;

\( K_y \) = seasonal yield response factor, from FAO 56 Table 24;

\( L \) = length of pipe (ft);

\( m \) = expected value;

\( MAD \) = management allowed depletion (%)

\( p \) = depletion fraction, from FAO 56 Table 22;

\( P \) = precipitation (in);

\( P_{\text{eff}} \) = effective precipitation (in);

\( P_{\text{total}} \) = total precipitation in season (in);

\( q \) = drip tube datasheet flow rate (gpm/100ft);

\( q_a \) = average emitter emission rate (gpm/emitter);

\( q_n \) = minimum emitter emission rate (gpm/emitter);

\( Q \) = tubing flow rate at a point along lateral (gpm);

\( Q_i \) = tubing flow rate at lateral inlet (gpm);

\( RAW \) = readily available water (in);

\( RF \) = return flow (in);

\( RF_{\text{irrig}} \) = irrigation return flow (in);

\( RF_{\text{total, irrig}} \) = total irrigation return flow (in);

\( RF_{\text{precip}} \) = precipitation return flow (in);

\( RF_{\text{total, precip}} \) = total precipitation return flow (in);

\( RZ_{\text{adj}} \) = root zone correction factor;

\( s \) = standard deviation;

\( s^2 \) = variance;

\( s12 \) = covariance;

\( \Delta s_{\text{irr}} \) = change in storage from irrigation (in);

\( S_e \) = emitter spacing (ft);

\( \Delta SM \) = change in soil moisture (in);

\( TAW \) = total available water (in);

\( TAW_{\text{max}} \) = maximum total available water (in);

\( v_s \) = emitter coefficient of manufacturing variation, mid-range value of 0.15 for average quality line-source tubing Table 20.1, Keller and Blienser (1990);

\( V \) = irrigation volume (acre-feet);

\( x \) = emitter discharge exponent;

\( X \) = location of minimum pressure (ft);

\( Y \) = arbitrary variable used in statistical equations;

\( Y_a/Y_m \) = theoretical reduction in yield from plant water stress;

\( z_j \) = catch can depth (in);

\( Z_r \) = root zone depth (ft);
\( Z_{r, \text{adj}} \) = adjusted root zone depth (ft);
\( Z_{r, \text{max}} \) = mature crop rooting depth, from FAO 56 Table 22 (ft); and
\( Z_{r, \text{min}} \) = root zone depth at transplanting (ft);
Appendix B. Water Balance Equations
Note: ** signifies to use this equation for the first time step only

The below calculations are based on the irrigation water balance equation B.1.

\[
\Delta SM = I + P - ET_{crop} - RF
\] (B.1)

\[
I_i = \frac{V_i}{A}
\] (B.2)

\[
P_{eff, i} = 0.8 \times P_i
\] (B.3)

\[
K_{c, i} = ??
\] (B.4)

\[
ET_{potential, i} = K_{c, i} \times ET_{ref, i}
\] (B.5)

Measure or estimate the initial root zone depletion \(D_{initial}\).

\[
D_{start, i} = D_{initial} \quad **
\] (B.6)

Calculations for established perennial crops.

\[
TAW = Z_{max, i} \times AWC
\] (B.7)

\[
RAW = TAW \times p
\] (B.8)

\[
K_s, i: \quad if \ D_{start, i} \leq TAW
\]

\[\text{then } K_s, i = 1\]

\[\text{else } K_s, i = \frac{TAW - D_{start, i}}{TAW - RAW}\]

\[
ET_{adj, i} = K_s, i \times K_c, i \times ET_{ref, i}
\] (B.10)

\[
D_{end, i}: \quad if \ D_{start, i} + ET_{adj, i} - I_i - P_i < 0
\]

\[\text{then } D_{end, i} = 0\]

\[\text{else } D_{end, i} = D_{start, i} + ET_{adj, i} - I_i - P_i\]

\[
AW_{end, i} = TAW - D_{end, i}
\] (B.12)

\[
RF_i: \quad if \ I_i + P_{eff, i} - ET_{adj, i} > D_{start, i}
\]

\[\text{then } RF_i = I_i + P_{eff, i} - ET_{adj, i} - D_{start, i}\]

\[
ET_{potential, i} = K_{c, i} \times ET_{ref, i}
\] (B.5)
Calculations for annual crops.

Calculations for annual crops must account for the changing root depth as the plant matures. My equations are based on my own approach at solving the mass balance assuming that as the rooting depth increases more of the stored available water (from off-season precipitation) becomes available, and that deep percolation return flows do not occur until all water has left the mature root zone. Therefore, excess water applied in the immature root zone first refills the soil to field capacity below within the mature rooting depth of the crop before deep percolating out of the control volume. This approach considers any irrigation that is stored within the entire soil profile a beneficial use. To simplify the explanations I call the zone that is within the mature root zone but still below the current root zone the “sub zone”.

\[ R_{Z_{\text{adj}},i} = \frac{K_{c,i} - K_{c_{\text{min}}}}{K_{c_{\text{mid}}} - K_{c_{\text{min}}}} \]  \hspace{1cm} \text{(B.14)}

Once \( R_{Z_{\text{adj}},i} \) reaches a maximum it stays at that value and the equation is no longer valid.

\[ Z_{r,i} = R_{Z_{\text{adj}},i} \left( Z_{r,\text{max}} - Z_{r,\text{min}} \right) + Z_{r,\text{min}} \]  \hspace{1cm} \text{(B.15)}

\[ TAW_i = Z_{r,i} \ast AWC \]  \hspace{1cm} \text{(B.16)}

\[ TAW_{i-1} = TAW_i \hspace{1cm} ** \]  \hspace{1cm} \text{(B.17)}

\[ TAW_{\text{max}} = Z_{r,\text{max}} \ast AWC \]  \hspace{1cm} \text{(B.18)}

\[ RAW_i = TAW_i \ast p \]  \hspace{1cm} \text{(B.19)}

Measure or estimate the mature root zone depletion fraction \( D_{f,\text{initial}} \).

\[ A_{W_{\text{initial}}} = TAW_i \ast (1 - D_{f,\text{initial}}) \]  \hspace{1cm} \text{(B.20)}

\[ A_{W_{i-1}} = A_{W_{\text{initial}}} \hspace{1cm} ** \]  \hspace{1cm} \text{(B.21)}
\[ D_{\text{start, } i} = TAW_i - AW_i \]  \hspace{1cm} (B.22)

\[ D_{\text{end, sub, initial}} = (TAW_{\text{max}} - TAW_i) \times D_f, \text{ initial} \]  \hspace{1cm} (B.23)

\[ D_f, \text{ sub, initial: if } D_{\text{end, sub, initial}} > 0 \]
then \[ D_f, \text{ sub, initial} = \frac{D_{\text{end, sub, initial}}}{(TAW_{\text{max}} - TAW_i)} \]
else \[ D_f, \text{ sub, initial} = 0 \]  \hspace{1cm} (B.24)

\[ D_{\text{f, sub, } i-1} = D_f, \text{ sub, initial} \]  \hspace{1cm} (B.25)

\[ K_s, i: \] if \[ D_{\text{start, } i} \leq TAW \]
then \[ K_s, i = 1 \]
else \[ K_s, i = \frac{TAW_i - D_{\text{start, } i}}{TAW_i - RAW_i} \]  \hspace{1cm} (B.26)

\[ ET_{\text{adj, } i} = K_s, i \times K_c, i \times ET_{\text{ref, } i} \]  \hspace{1cm} (B.27)

\[ a = AW_i - (TAW_i - TAW_{i-1}) \times (1 - D_f, \text{ sub, } i-1) + I_i + P_{\text{eff, } i} \]

\[ AW_i: \] if \[ a < 0 \]
then \[ AW_i = 0 \]
else if \[ a > TAW_i \]
then \[ AW_i = TAW_i \]
else \[ AW_i = a \]  \hspace{1cm} (B.28)

\[ b = a - AW_i \]  \hspace{1cm} (B.29)

\[ D_{\text{start, sub, } i} = (TAW_{\text{max}} - TAW_i) \times D_f, \text{ sub, } i-1 \]  \hspace{1cm} (B.30)

\[ RF_i: \] if \[ b - D_{\text{start, sub, } i} > 0 \]
then \[ RF_i = b - D_{\text{start, sub, } i} \]
else \[ RF_i = 0 \]  \hspace{1cm} (B.31)

Irrigation return flow and precipitation return flow for both perennial and annual
crops

RF_{irrig, \ i}: \ \text{if} \ \ i_i \neq 0 \ \text{and} \ P_{eff, \ i} \neq 0 \ \text{and} \ RF_i \neq 0

\text{then} \ RF_{irrig, \ i} = RF_i \left( \frac{l_i}{I_i + P_i} \right)

\text{else if} \ \ i_i \neq 0 \ \text{and} \ RF_i \neq 0

\text{then} \ RF_{irrig, \ i} = RF_i

\text{else} \ RF_{irrig, \ i} = 0

RF_{precip, \ i}: \ \text{if} \ \ i_i \neq 0 \ \text{and} \ P_{eff, \ i} \neq 0 \ \text{and} \ RF_i \neq 0

\text{then} \ RF_{precip, \ i} = RF_i \left( \frac{P_i}{I_i + P_i} \right)

\text{else if} \ \ P_i \neq 0 \ \text{and} \ RF_i \neq 0

\text{then} \ RF_{precip, \ i} = RF_i

\text{else} \ RF_{precip, \ i} = 0

\text{Theoretical reduction in yield from plant water stress}

\left( \frac{ET_{adj}}{ET_{potential}} \right)_{ave} = \frac{\sum_{i=1}^{n+1} \left( \frac{ET_{adj, \ i}}{ET_{potential, \ i}} \right)}{n}

\left( 1 - \frac{Y_a}{Y_m} \right) = K_y \left( 1 - \frac{ET_d}{ET_m} \right)

\text{Irrigation Efficiency}

ET_{irr} = \frac{l_{total} - RF_{total, \ irr}}{(l_{total} - RF_{total, \ irr}) + (P_{total} - RF_{total, \ precip})} \times ET_{total}

\Delta S_{irr} = \frac{l_{total} - RF_{total, \ irr}}{(l_{total} - RF_{total, \ irr}) + (P_{total} - RF_{total, \ precip})} \times \Delta S_{irr}

IE = \frac{\text{vol. irrig. water beneficially used}}{\text{vol. irrig. water applied} - \Delta \text{storage of irrig. water}} \times 100\%
\[ IE = \frac{ET_{irr}}{I_{total} - \Delta S_{irr}} \times 100\% \]
Appendix C. Accuracy Calculations and Results
To calculate the accuracies of the variables used in my water balance I used equations from *Accuracy of Irrigation Efficiency Estimates* by Clemmens and Burt (1997). A short list of the principal equations I used is included here. For a more detailed explanation of the statistical variables and equations see Clemmens and Burt (1997).

Standard statistical accuracy variables and relationships for a variable $y$ with 95% confidence interval.

$$CV = \frac{s}{m}$$  \hspace{1cm} (C.1)

$$m_y - 2s_y \leq y \leq m_y + 2s_y$$  \hspace{1cm} (C.2)

$$CI = \pm 2s = \pm 2CV$$  \hspace{1cm} (C.3)

**Combinations of variance equations**

**Addition:**

$$m_o = m_1 + m_2$$  \hspace{1cm} (C.4)

If $y_1$ and $y_2$ are independent,

$$CV_o^2 = \frac{m_1^2}{m_0^2} CV_1^2 + \frac{m_2^2}{m_0^2} CV_2^2$$  \hspace{1cm} (C.5)

**Multiplication:**

$$m_o = m_1 m_2 + s_{12}^2$$  \hspace{1cm} (C.6)

If $y_1$ and $y_2$ are independent,

$$CV_o^2 = CV_1^2 + CV_2^2 + CV_1^2 CV_2^2$$  \hspace{1cm} (C.7)
Division:

\[ m_o = \frac{m_1}{m_2} \left( 1 + \frac{s_{y_2}^2}{m_2^2} - \frac{s_{y_1}^2}{m_1 m_2} \right) \]  

(C.8)

If \( y_1 \) and \( y_2 \) are independent and the term \( s_{y_2}^2 / m_2^2 \) is small,

\[ CV_o^2 \approx CV_1^2 + CV_2^2 \]  

(C.9)

I used conservative estimates of independent variable accuracies for \( P \) and \( ET \) found in the Clemmens and Burt (1997)

\[ P = \pm 30\% \]  

(C.10)

\[ ET = \pm 10\% \]  

(C.11)

Table 5 shows the accuracies of each variable used in the water balance calculations along with the flow measurement device used on each field.
Table 5. Accuracy of Variables Used in Water Balance Calculations

<table>
<thead>
<tr>
<th>Field ID</th>
<th>Area - (I)</th>
<th>Flow Measurement Device</th>
<th>Volume - (D)</th>
<th>Depth - (D)</th>
<th>Deposition Initial - (I)</th>
<th>ET - (I)</th>
<th>Initial Depletion - (I)</th>
<th>Available Water Capacity - (I)</th>
<th>Root Zone Depth - (I)</th>
<th>Soil Moisture - (D)</th>
<th>Return Flows - (D)</th>
<th>RF from Irrigation Efficiency - (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accuracy (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>16%</td>
<td>1</td>
<td>1%</td>
<td>16%</td>
<td>30%</td>
<td>10%</td>
<td>25%</td>
<td>33%</td>
<td>2.16</td>
<td>10%</td>
<td>36%</td>
<td>31%</td>
</tr>
<tr>
<td>B</td>
<td>7%</td>
<td>8</td>
<td>2%</td>
<td>8%</td>
<td>30%</td>
<td>10%</td>
<td>25%</td>
<td>33%</td>
<td>2.16</td>
<td>10%</td>
<td>36%</td>
<td>31%</td>
</tr>
<tr>
<td>C</td>
<td>14%</td>
<td>8</td>
<td>2%</td>
<td>14%</td>
<td>30%</td>
<td>10%</td>
<td>25%</td>
<td>33%</td>
<td>2.16</td>
<td>10%</td>
<td>36%</td>
<td>41%</td>
</tr>
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<td>4</td>
<td>1%</td>
<td>20%</td>
<td>30%</td>
<td>10%</td>
<td>25%</td>
<td>33%</td>
<td>2.04</td>
<td>10%</td>
<td>24%</td>
<td>36%</td>
</tr>
<tr>
<td>E</td>
<td>7%</td>
<td>11</td>
<td>5%</td>
<td>9%</td>
<td>30%</td>
<td>10%</td>
<td>25%</td>
<td>33%</td>
<td>2.04</td>
<td>10%</td>
<td>36%</td>
<td>-</td>
</tr>
<tr>
<td>F</td>
<td>3%</td>
<td>11</td>
<td>5%</td>
<td>6%</td>
<td>30%</td>
<td>10%</td>
<td>25%</td>
<td>33%</td>
<td>2.09</td>
<td>10%</td>
<td>36%</td>
<td>-</td>
</tr>
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</table>

(I) Independent variable
(D) Dependent variable
-- when RF was zero, equations do not work because of a division by zero
1. Seametrics WMP electromagnetic flow meter
2. Seametrics AG2000 electromagnetic flow meter
3. McCrometer Mc Mag 3000 electromagnetic flow meter
4. Sensus iPERL electromagnetic flowmeter
5. Turbine flow meter
6. EKM 1” pulse output water meter
7. Culinary meter
8. Sharp crested weir
9. S&M flame
10. Broad crested weir
11. Volumetric method
Appendix D. Uniformity Calculations
Sprinkle irrigation application uniformity

Christianson’s coefficient of uniformity is defined in Merriam and Keller’s *Farm Irrigation System Evaluation: A Guide for Management* as

\[
CU = \left( 1 - \frac{\text{ave. dev. from the ave. catch}}{\text{ave. catch}} \right) \times 100\% \quad (D.1)
\]

or in statistical terms

\[
CU = \left( 1 - \frac{\sum_{j=1}^{n} \text{abs}(z_j - d_{ave})}{\sum_{j=1}^{n} z_j} \right) \times 100\% \quad (D.2)
\]

and the DU is

\[
DU = \frac{\text{ave. depth of low quarter}}{\text{average depth}} \quad (D.3)
\]

The *average depth of the low quarter* is the average of the 25% lowest catch can depths.

MATLAB Script:

The MATLAB script calculates the CU via the following algorithm.

1) Create an array using the *meshgrid* command to represent the field size in 10 foot increments oriented with the direction of the lateral runs corresponding to the array columns.

2) Insert the array of catch can data into the index in the field array where it was collected.

3) Add the catch data along the length of the column to simulate nozzle spacing along lateral.

4) Simulate the single nozzle arc on the field edges by taking catch values from the cans.
on one half of the grid closest to the radius of the sprinkler and sweeping them 180° using
the *meshgrid* command, creating an array mimicking a 180° arc of single nozzle coverage.

5) Add the single nozzle array to the top and bottom of the lateral column.

6) Simulate overlapping between laterals by adding the completed lateral array across the
field based on actual lateral spacing.

7) Create a 3D image using the *surf* command.

8) Calculate CU using depth matrix.

Note: Due to the irregularity of field shapes I encountered I simplified some fields with
irregular edges into rectangular shapes that most closely matched the actual field size.

```plaintext
%% MATLAB sprinkle system uniformity script

millilitertocubicinches = 0.061024;  % volume measurement
catchcanarea = 24.30132;  % sq inches
% IMPORT DATA SET FROM EXCEL - labeled "data" in the Workspace.
% ROTATE DATA AND CONVERT VOLUME TO DEPTH
% data % shows original volume matrix.
% rotates original data set so that sprinkler lateral is vertical
% NOTE: create if/else statement to make future replications more automated
data1 = rot90(data);
% data1 = data  % use this if original data set is taken along vertical
% sprinkler lateral.
% convert volumes to depths
depth = data1*millilitertocubicinches/catchcanarea;  % converting volume to
% depth, in
% RADIAL CANS
% extract values corresponding to radial cans
radialdistance = 0:10:40;  % distance from sprinkler, ft
radialcans = fliplr(depth(end,1:5));  % Extract 1-5 values from last row, and
% flips them left to right so that 0 distance corresponds with can adjacent
% to sprinkler
p = polyfit(radialdistance,radialcans,2);  % creates three value array with
% coefficients of a x^2 fit polynomial equation
% create meshgrid, which is a representation of area.
x = -40:10:40;  % radius perpendicular to the lateral with sprinkler in middle.
y = 0:10:40;  % DISTANCE FROM SPRINKLER ALONG LATERAL TO FIELD EDGE
```
\[ X, Y \] = meshgrid(x, y);
% create distance vector (i.e. the distance from each cell to the sprinkler)
d = sqrt(X.^2 + Y.^2);
% create swept radial matrix on SOUTH of field
southedge = nan*ones(size(d)); % create matrix size d with NaN
southedge(d>=50)=0; % when distance is >= 50, zero depth
southedge(d<50)=p(1)*d(d<50).^2+p(2)*d(d<50)+p(3); % % for radius within reach,
% use polynomial equation
% create swept radial matrix on NORTH of field
northedge = rot90(rot90(southedge));
% delete first row (outside of bounds)
northedge([1, :) = [];
% DEFINING FIELD DIMENSIONS
fieldlength = 150; % field length along lateral, ft
fieldwidth = 130; % field width along lateral, ft
field = zeros(fieldlength/10 + 1, fieldwidth/10 + 1); % create array of field
% area with dimensions in 10 ft increments
% specifying number of rows and columns in the field
[rowsField, columnsField] = size(field);
[rowsdepth, columnsdepth] = size(depth);
% PASTING A SMALL MATRIX WITHIN A LARGER ONE
% !!!DO THIS AS MANY TIMES AS THERE ARE CatchCan Data sets along lateral
% PASTING FIRST DEPTH MATRIX INTO FIELD
% Specify upper left row, column of where we'd like to paste the small matrix.
row1 = 9; %
column1 = 1;
% Determines lower right location.
row2 = row1 + rowsdepth - 1;
column2 = column1 + columnsdepth - 1;
% See if it will fit.
if row2 <= rowsField
% It will fit, so paste it.
field(row1:row2, column1:column2) = depth; % field array now includes
% first matrix
else
% It won't fit
warningMessage = sprintf('That will not fit',... row2, column2);
uiwait(warndlg(warningMessage));
end
% PASTING SECOND DEPTH MATRICES INTO FIELD
% Specify upper left row, column of where we'd like to paste the small matrix.
row1 = 5; %
column1 = 1;
% Determines lower right location.
row2 = row1 + rowsdepth - 1;
column2 = column1 + columnsdepth - 1;
% See if it will fit.
if row2 <= rowsField
    % It will fit, so paste it.
    field(row1:row2, column1:column2) = depth;
else
    % It won't fit
    warningMessage = sprintf('That will not fit',...
                            row2, column2);
    uiwait(warndlg(warningMessage));
end
% REPEAT PASTING OF DEPTH MATRICES UNTIL ENTIRE LENGHT OF LATERAL HAS % REPRESENTATIVE VALUES
% DELETE VALUES IN LAST ROW OF LATERAL DEPTH MATRIX
field([12],:) = [0];
% ADD SOUTHEdge WITH LATERAL VALUES
[rowssouthedge, columnssouthedge] = size(southedge);
% Specify upper left row, column of where we'd like to paste the small matrix.
row1 = 12; %
column1 = 1;
% Determines lower right location.
row2 = row1 + rowssouthedge - 1;
column2 = column1 + columnssouthedge - 1;
% See if it will fit.
if row2 <= rowsField
    % It will fit, so paste it.
    field(row1:row2, column1:column2) = southedge;
else
    % It won't fit
    warningMessage = sprintf('That will not fit',...
                            row2, column2);
    uiwait(warndlg(warningMessage));
end
% ADD NORTHEdge WITH LATERAL VALUES
[rowsnorthedge, columnsnorthedge] = size(northedge);
% Specify upper left row, column of where we'd like to paste the small matrix.
row1 = 1; %
column1 = 1;
% Determines lower right location.
row2 = row1 + rowsnorthedge - 1;
column2 = column1 + columnsnorthedge - 1;
% See if it will fit.
if row2 <= rowsField
% It will fit, so paste it.
field(row1:row2, column1:column2) = northedge;
else
% It won't fit
warningMessage = sprintf('That will not fit',...
row2, column2);
uiwait(warndlg(warningMessage));
end
% CIRCSHIFT(FIELD) - move lateral across field.
% The rectangular field area (not actual field shape) starts at column 3
FirstPipeDistance = 10; % distance from left edge of selected area to lateral
NoOfCansInRadial = 5; % number of cans in radial, including can at sprinkler
initialshift = -(NoOfCansInRadial-(FirstPipeDistance/10+1));
field1 = circshift(field, [0, initialshift]);
distancebetweenmoves = 60; % distance to apply circshift
field2 = circshift(field1, [0, distancebetweenmoves/10]);
field3 = circshift(field2, [0, distancebetweenmoves/10]);
% delete out-of-bound columns - I could automate this process, but it seems
% unnecessary as it only needs to be done to first and last move at most.
field1(:,[1,13,14]) = [0]; % deletes initial columns that fall outside area
field3(:,[1,2,3,4]) = [0]; % deleted final columns that fall outside of area
fieldfinal = field1 + field2 + field3;
figure
% CREATE 3D IMAGE OF FIELD DEPTHS
surf(flipud(fieldfinal)) % flips fieldfinal so that surface image is as
% appears from observer in field.
axis equal % sets aspect ratio of axis to equal
% CALCULATE CU
m = mean(fieldfinal(:));
abszm = abs(fieldfinal-m);
CU = 100*(1-sum(abszm(:))/sum(fieldfinal(:)));
% CALCULATE DU
a = 0.25*numel(fieldfinal); % number of elements in low quarter
b = sort(fieldfinal(:)); % sorts matrix elements in ascending order
lowqvalues = b(1:a); % Extract 1-5 values from last row, and flips them left
% to right so that 0 distance corresponds with can adjacent to sprinkler
DU = 100*mean(lowqvalues)/mean(fieldfinal(:));

Drip system uniformity
EU = (1 − 1.27v_s) \frac{q_n}{q_a} \times 100\% \tag{D.4}

The minimum emitter flow rate, \(q_n\), is initially assumed to be at the very downstream end of the drip tube. The \(q_a\) is calculated using an iterative guess and check method as follows:

1) Guess \(q_a\).

2) Calculate the friction loss gradient \(J\) in units of ft/100ft for small smooth plastic pipes.

\[ J = K \frac{Q^{1.75}}{D^{4.75}} \tag{D.5} \]

\(Q\) is the tubing flow rate in gallons per minute (gpm) and is estimated as the average emitter flow rate \(q_a\) times the number of emitters in the drip tape.

3) Calculate the head loss through the tape.

\[ h_f = JF \frac{L}{100} \tag{D.6} \]

4) Calculate the average head.

\[ H_a = H_t − 0.75h_f − 0.5\Delta EL \tag{D.7} \]

5) Calculate the emitter discharge exponent \(x\) using two data points of flow rate vs pressure plot obtained from the t-tape datasheet.

\[ x = \frac{\log\left(\frac{q_1}{q_2}\right)}{\log\left(\frac{H_1}{H_2}\right)} \tag{D.8} \]

6) Calculate the emitter constant of proportionality \(K_d\) using \(q_1\) and \(H_1\) values from step 5.
\[ K_d = \frac{q}{H^x} \]  

(D.9)

7) With \( K_d \), calculate \( q_a \) with equation D.9 using the value of \( H_a \) determined in step 4.

8) Adjust \( q_a \) from step 1 until it equals the \( q_a \) calculated in step 7.

To verify that the minimum pressure is indeed located at the end of the tubing, the location of minimum pressure is calculated as follows:

1) For multiple equally spaced outlets the flow rate at any location in the pipe can be described with equation D.10.

\[ Q = Q_l - \left( \frac{q_a}{S_e} \right) X \]  

(D.10)

The pressure in the pipe will be at a minimum when the friction loss gradient \( J \) is equal to the ground slope. Therefore, combining equations D.10 and D.5 and setting \( J \) equal to the field slope in \( \% \), the location of minimum pressure can be found with equation D.11.

\[ X = \frac{S_e}{q_a} \left[ Q - \left( \frac{J D^{4.75}}{K} \right)^{\frac{1}{3.75}} \right] \]  

(D.11)

If the location of minimum pressure \( x \) is approximately equal to the length of the tape, the minimum pressure \( q_n \) will also be at the end of the tape. Because the farmer surface irrigates a separate part of the same field, the field slope \( \Delta EL \) was given a conservative estimate of 0.001 ft/ft.

The minimum pressure is calculated as follows:

1) Calculate the pressure at the end of the pipe.
\[ H_n = H_l - h_f + \Delta EL \]  \hspace{1cm} (D.12)

2) Calculate \( q_n \) using equation D.9.

Calculate the EU with equation D.4.
Appendix E. Summary Statistics
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<th>Return Flow (in)</th>
<th>Return Flow from RRC (in)</th>
<th>ET from RRC (in)</th>
<th>Irrigation Efficiency (%)</th>
<th>CU EU (%)</th>
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</table>

**Table 6. Summary Table with Water Balance Variables and Performance Metrics**
The total area in each crop in my study is shown below in Table 7, which I used in the area-weighted average gross irrigation depth (GID) and irrigation efficiency (IE) by crop type calculations.

Table 7. Area of Each Crop Type in Study

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Total Area (acres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>36.30</td>
</tr>
<tr>
<td>Cereal</td>
<td>8.33</td>
</tr>
<tr>
<td>Garden</td>
<td>5.09</td>
</tr>
<tr>
<td>Orchard</td>
<td>3.22</td>
</tr>
<tr>
<td>Pasture</td>
<td>9.16</td>
</tr>
<tr>
<td>Vegetables-Mulch</td>
<td>2.51</td>
</tr>
</tbody>
</table>
Appendix F. Performance Summary and Recommendations by Field
To avoid repetition of terminology and data, the below field performance summaries are intended to be read in conjunction with the list of terms in Appendix A and the summary statistics in Appendix E.

**Field A – Periodic-move Hose-fed Sprinkle Irrigated Community Garden**

**Fig. 28. Field A - Time series water balance**

**Fig. 29. Field A - Cumulative seasonal water balance**
Field A - Performance Summary

**Application uniformity:** The coefficient of uniformity (CU) was lower than recommended for high value crops. Achieving a decent CU is difficult with mixed garden beds where tall crops intercept the spray, but the hose fed sprinkle system help as it allows sprinklers to be periodically moved, which should improve the CU.

**Schedule:** The irrigation frequency was good, but duration at the beginning of the season, when the annual crops rooting depth is still shallow, was longer than necessary. Irrigation run times could probably have decreased by 25% until mid-July.

**Configuration and operation:** The system configuration was decent but it is labor intensive moving hoses for the hose-fed sprinklers. There were no leaks and mostly matched nozzles with a range in flow rate of 2.7 gpm and up to 14 psi of pressure difference, which is quite high. For the long runs of hose I suggest buying a larger diameter hose (from 5/8” to 3/4”) to reduce the pressure loss to the farthest nozzles. If irrigator wished to reduce labor costs, they could consider installing a fixed sprinkler or drip system complete with inline valves so that certain sprinklers can be shut off in an area is left uncultivated.

**Crop water stress effect on yield:** The soil moisture very rarely dropped to the MAD, so a reduction in yield due to crop water stress was unlikely.

**Other:**

The flow rate at time of the field test was 42.7 gpm.
**Fields B & C – Surface Irrigated Grass Hay/Pasture and Apple Orchard**

**Fig. 30. Fields B & C - Time series water balance**

**Fig. 31. Fields B & C - Cumulative seasonal water balance**
Fields B & C - Performance Summary

Application uniformity: I made no observations of the uniformity for this field.

Schedule: The irrigation frequency was good, but the durations of second, third, and fourth irrigations were roughly 50% longer than needed (assuming a perfect uniformity). The irrigator could have done one more short irrigation once more in September to keep the soil moisture up above the maximum recommended depletion, although this late in the season the labor required to do so may not be worth the irrigator’s effort.

Configuration and operation: Achieving uniform application with surface irrigation is very difficult. Some good practices to improve efficiency include diking the end of the field to prevent tailwater runoff, and creating “berms and basins” down the length of the field to direct and control flooding, and achieve a faster advance of water across the field. Integrating these features into the field would probably be a good long term goal.

Crop water stress effect on yield: The soil moisture only dropped to the MAD at the very end of the season, so a reduction in yield due to crop water stress was unlikely.

Other: The system flow rates were 0.75, 1.32, 1.32, and 0.84 cfs for the four irrigations, which equates to 4.0, 7.5, 9.0, and 7.0 inches applied.
Field D – Fixed Sprinkler Irrigated Garden

The plots are included in Case Study 3.

Field D - Performance Summary

Application uniformity: The coefficient of uniformity (CU) was lower than recommended for high value crops. This was likely due to the many clogged and poorly rotating sprinklers that I observed. I recommend inspecting and repairing sprinkler nozzles at the beginning of every season, and checking them for proper arc and rotation occasionally during the season.

Schedule: The irrigation frequency was good, but the durations all season long were excessive. It is possible that the poor uniformity led to dry spots in the garden, which led to over-watering. Irrigation durations could likely be reduced to 50% of what they were all season long.

Configuration and operation: There was decent sprinkler spacing, but many nozzles were mismatched, clogged, poorly rotating, and leaking. I recommend replacing all nozzles to a single matching type with radius of throw matched to the garden width.

Crop water stress effect on yield: The soil moisture seldom dropped to the MAD, so a reduction in yield due to crop water stress was unlikely. However, if fertilizers or other soil amendments are used in this garden they are likely being leached out by the excessive irrigation.

Other:

The sprinkler system flow rate was 15 gpm.
Field E – Fixed Sprinkler Irrigated Grass Pasture

Fig. 32. Field E - Time series water balance

Fig. 33. Field E - Cumulative seasonal water balance
Field E - Performance Summary

**Application uniformity:** This field did not attempt to achieve uniformity, as some areas were left intentionally unirrigated to avoid moving pipe.

**Schedule:** The irrigation frequency could have been much less (easily 50% as frequent) with longer irrigation durations (i.e. run times) to minimize labor and take advantage of the capacity of the soil to store water. A single late summer long duration irrigation would have kept the soil moisture above the minimum recommended level into the fall.

**Configuration and operation:** The system configuration was rather poor because the irrigation pipe connected directly to tall risers had bent pipe over the years, which led to tilted sprinkler risers and poor uniformity (e.g. the spray from one sprinkler was on a 45° angled plane). The nozzles were slightly mismatched resulting in a 2 gpm flow rate variability throughout the pasture, and numerous were clogged. I recommend reducing the height of the risers before replacing any pipe in the future to avoid damaging more pipe, and as the irrigator replaces nozzles over time to use only a standard 3/16” nozzle.

**Crop water stress effect on yield:** The ET was higher than the GID (and IE of 100%) and the uniformity was poor, so portions of the field were likely under-irrigated.

**Other:**

The total flow rate of the bottom three laterals is 56 gpm and the total flow rate of the upper three laterals is 53 gpm.
**Field F – Periodic-move Side-roll and Hand-move Sprinkle Irrigated Alfalfa**

![Field F - Time Series Water Balance](image)

**Fig. 34. Field F - Time series water balance**

![Field F - Cumulative Seasonal Water Balance](image)

**Fig. 35. Field F - Cumulative seasonal water balance**
Fig. 36. Field F – 3D plot of sprinkle uniformity

Field F - Performance Summary

Application uniformity: The coefficient of uniformity (CU) was above the minimum recommended value for low value crops, so I do not recommend any improvements.

Schedule: The first irrigation could have occurred roughly two weeks earlier and stayed at the same frequency to avoid depleting the soil moisture below the management allowed deficit (MAD) right before the first two cuttings. If the irrigations began earlier in the season the durations would be close to ideal.

Configuration and operation: The system configuration was good with only a few small leaks but highly varying nozzle sizes. As nozzles are replaced over time try consider using only 13/64”.

Crop water stress effect on yield: The soil moisture reached the MAD before each of the first two cuttings, so a reduction in yield due to crop water stress was possible. This irrigator should consider irrigating at slightly longer durations.

Other: The flow rate for all four hand-lines and two wheel-lines is ~472 gpm.
Field G – Periodic-move Side-roll Sprinkle Irrigated Alfalfa

Fig. 37. Field G - Time series water balance

Fig. 38. Field G - Cumulative seasonal water balance
Field G - Performance Summary

**Application uniformity:** The coefficient of uniformity (CU) was above the minimum recommended value for low value crops, so I do not recommend any improvements.

**Schedule:** The first irrigation could have occurred roughly two weeks earlier and stayed at the same frequency to avoid depleting the soil moisture below the MAD right before each of the three cuttings. The field may have benefited from one more irrigation in early September. The irrigation duration was good, but could have been a few hours longer for the first two irrigations.

**Configuration and operation:** The configuration was good. There was one large gasket leak and some varying nozzle sizes. As nozzles are replaced over time try consider using only 3/16”.

**Crop water stress effect on yield:** The soil moisture reached the MAD before each of the three cuttings, so a reduction in yield due to crop water stress was possible. This irrigator should consider irrigating at slightly longer durations.

**Other:** The system flow rate is ~138 gpm.
Field H – Periodic-move Side-roll Sprinkle Irrigated Alfalfa

**Fig. 40. Field H - Time series water balance**

**Fig. 41. Field H - Cumulative seasonal water balance**
Fig. 42. Field H – 3D plot of sprinkle uniformity

Field H - Performance Summary

**Application uniformity:** The coefficient of uniformity (CU) was slightly below the minimum recommended value for low value crops. Improving it may not be practical based on the current system configuration and constraints.

**Schedule:** The first irrigation could have occurred roughly two weeks earlier and stayed at the same frequency. The field may have benefited from one more irrigation in late August. The irrigation duration was good for the first irrigation, but could have been much longer for the final two irrigations.

**Configuration and operation:** The system configuration was decent with no leaks but slightly varying nozzle sizes. As nozzles are replaced over time try consider using only 3/16”.

**Crop water stress effect on yield:** The soil moisture dropped below the MAD before each of the three cuttings, so a reduction in yield due to crop water stress was possible. This irrigator should consider irrigating at slightly longer durations.

**Other:** I did not collect a flow rate for this field because I used a totalizer meter.
**Field I – Periodic-move Hose-fed Sprinkle Irrigated Vegetables**

**Fig. 43. Field I - Time series water balance**

**Fig. 44. Field I - Cumulative seasonal water balance**
Field I - Performance Summary

Application uniformity: I did not observe the uniformity for this field, but the hose fed sprinkle system which allows sprinklers to be periodically moved should result in a good CU.

Schedule: The schedule frequency was good early in the season, but by mid-July the irrigation durations were not long enough to keep the soil moisture above the minimum recommended value. Irrigation run times could have begun to increase in mid-July until there were double the June duration in early August. With double the run times, the frequency could easily be reduced by 50%.

Configuration and operation: The system configuration was adequate. There were no leaks and good matching of nozzles.

Crop water stress effect on yield: The soil moisture dropped below the MAD in mid-July and stayed below the MAD until mid-September when it received a roughly two inch irrigation. Therefore, a reduction in yield due to crop water stress was possible.
Field J – Periodic-move Hand-move Sprinkle Irrigated Alfalfa

Fig. 45. Field J - Time series water balance

Fig. 46. Field J - Cumulative seasonal water balance
Field J - Performance Summary

**Application uniformity:** The coefficient of uniformity (CU) was slightly below the minimum recommended value for low value crops. Replacing the third nozzle from the inlet that has a double nozzle with a single 13/64” nozzle would improve the CU.

**Schedule:** The irrigation frequency was not nearly enough to prevent the soil moisture from depleting beyond the MAD. Additionally, the irrigation durations were not nearly enough to recharge the soil moisture to acceptable levels. It is possible that in this location capillary action from a high water table contributed some water to the crop, minimizing its need for irrigation and throwing off the water balance. The field should have been irrigated earlier in the season and for up to twice the duration all season that it was.

**Configuration and operation:** The system had a decent configuration with a couple of leaks and only one greatly mismatched nozzle.

**Crop water stress effect on yield:** The soil moisture dropped below the MAD in early June and stayed there almost all growing season. Therefore, a reduction in yield due to crop water stress was very likely. The ET was higher than the GID (and IE of 100%) and the uniformity was poor, so portions of the field were likely under-irrigated. This irrigator should consider irrigating at slightly longer durations.

**Other:** The flow rate for this system was 68 gpm.
Field K – Surface Irrigated Grass Pasture and Apple Orchard

The plots are included in Case Study 5.

Performance Summary

Application uniformity: I made no observations of the uniformity.

Schedule: The irrigation frequency was roughly twice what was necessary, resulting in unnecessary labor costs. Irrigation durations in the early season were much longer than necessary, probably due to the labor required to continually move the water to flood different areas of the field. The excessive duration resulted in high return flows to the canal, which therefore does not constitute a large loss of water to the canal company. If fertilizers and amendments were used on the pasture the high return flows may have resulted in unnecessary leaching. To decrease labor the irrigation frequency could decrease by approximately 50%.

Configuration and Performance: Achieving uniform application with surface irrigation is very difficult. Some good practices to improve efficiency include diking the end of the field to prevent tailwater runoff, and creating “berms and basins” down the length of the field to direct and control flooding, and achieve a faster advance of water across the field. Integrating these features into the field would probably be a good long term goal. The configuration was labor intensive, but very low tech and probably satisfactory to the irrigator.

Crop water stress effect on yield: The soil moisture never dropped below the MAD, so a reduction in yield due to crop water stress was unlikely.

Other: The flow rate for this field started the season at 3 cfs and gradually reduced to 0.31 cfs by early September.
Field L – Drip Tube Irrigated Vegetables

The plots are included in Case Study 2.

Field L - Performance Summary

Application uniformity: The drip system calculated emission uniformity (EU) for the 560 foot run was exactly at the recommended value. The calculated emission uniformity for the 950 foot run was significantly below the recommended value. For the 950 foot run the irrigator should either increase the drip tape from 5/8” to 7/8”, or change to a lower rated flow rate tape to reduce friction losses that lead to pressure variability at the emitters.

Schedule: The irrigation frequency was higher than needed. Labor could have been saved by decreasing the frequency of irrigations to rely more on stored soil moisture. If the irrigation frequency was reduced however, the irrigation duration should increase proportionately. Additionally, the field would have benefited from one long duration irrigation in late June to bring the soil moisture depletion farther away from the MAD.

Configuration and operation: The configuration was good aside from my recommendations on a different type of drip tape for the 950 foot run.

Crop water stress effect on yield: The soil moisture closely followed the MAD, so a reduction in yield due to crop water stress was possible. The ET was higher than the GID (and IE of 100%) and the uniformity was only decent, so portions of the field were likely under-irrigated. This irrigator should consider irrigating at slightly longer durations.
Field M – Periodic-move Hand-move Sprinkle Irrigated Vegetables

Fig. 48. Field M - Time series water balance

Fig. 49. Field M - Cumulative seasonal water balance
Field M - Performance Summary

Application uniformity: The coefficient of uniformity (CU) was significantly below the minimum recommended value for high value crops. To improve the CU, consider using uniform distances along the lateral between nozzles.

Schedule: The irrigation schedule could have been slightly more frequent to prevent the soil moisture from depleting beyond the MAD. The irrigation duration was much longer than necessary to recharge the soil moisture to acceptable levels, and therefore resulted in large irrigation return flows to deep percolation. The durations could probably reduce 50% without under-irrigating much of the field.

Configuration and operation: The system had a decent configuration but had uneven sprinkler spacing and mismatched nozzles

Crop water stress effect on yield: The soil moisture dropped below the MAD continually throughout the season, so a reduction in yield due to crop water stress was possible.
Field N – Fixed Sprinkler and Manually Irrigated Community Garden

The plots are included in *Case Study 4*.

Field N - Performance Summary

**Application uniformity:** The secondary system coefficient of uniformity (CU) was lower than recommended for high value crops. Achieving a decent CU is difficult with mixed garden beds where tall crops intercept the spray. The cultivated area was only 23% of the secondary system irrigated area, so many nozzles could be have been readjusted to only irrigate the garden space, which would allow the duration to be significantly reduced.

**Schedule:** The irrigation frequency was more or less continuous because of manual irrigation by the community gardeners. The irrigation depths applied by the gardeners was 90% of the total irrigation in July and August, and more than 95% in September, resulting in an irrigation efficiency (IE) of only 16%.

**Configuration and operation:** The secondary system had a decent configuration of sprinklers. Two of the five nozzles were mismatched but still had reasonably matching flow rates.

**Crop water stress effect on yield:** The soil moisture never dropped below the MAD, so a reduction in yield due to crop water stress was unlikely.

**Other:** The irrigation management of this garden should probably be restructured to avoid such excessive irrigating. See *Case Study 4* in the *Results* section for detailed recommendations as to alternative management strategies. Also, to compare to another community garden in Cache Valley, see the results for Field A, which is irrigated only by an irrigation manager (i.e. there is no water available for the gardeners to irrigate with).
Field O – Periodic-move Hand-move Sprinkle Irrigated Apple Orchard

**Fig. 51. Field O - Time series water balance**

**Fig. 52. Field O - Cumulative seasonal water balance**
Field O - Performance Summary

Application uniformity: The coefficient of uniformity (CU) was slightly lower than recommended for tree crops, but this may not be critically important because the tree roots will likely be concentrated in the areas receiving the most water.

Schedule: In June the irrigation frequency and duration were much higher than needed, resulting in lots of deep percolation and unnecessary labor. Come July however the irrigation depths never fully recharged the soil moisture, so irrigation durations could have been longer at longer intervals (i.e. less frequent), saving labor.

Configuration and operation: The system configuration was good with no leaks and all except one nozzle (7/64”) having identical size and flow rate.

Crop water stress effect on yield: In July the soil moisture dropped below the MAD for nearly a month, so a reduction in yield due to crop water stress was possible.

Other: The system flow rate was ~51 gpm.
**Field P – Fixed Sprinkler Irrigated Grass Pasture**

**Fig. 54. Field P - Time series water balance**

**Fig. 55. Field P - Cumulative seasonal water balance**
Field P - Performance Summary

Application uniformity: This field did not attempt to achieve uniformity in all areas, as some areas were beyond the sprinkler spray.

Schedule: The irrigation frequency could have been much less to minimize labor, with much longer durations to take advantage of the capacity of the soil to store water.

Configuration and operation: The system configuration was decent but there was one cracked nozzle and many clogged nozzles and leaking sprinkler threads. The nozzle flow rates varied greatly, so it is likely that the field coefficient of uniformity (CU) is very low and that portions of the field were under and over-irrigated. I recommend this irrigator clean and inspect all nozzles at the beginning of the season and replace broken ones.

Crop water stress effect on yield: The soil moisture never dropped below the MAD, so the reduction of yield due to crop water stress was unlikely.

Other: The flow rates of the four laterals from most northern to most southern are 25.4, 22.7, 36.4, and 23.4 gpm.
**Field Q – Fixed Sprinkler Irrigated Grass Pasture**

Fig. 56. Field Q - Time series water balance

Fig. 57. Field Q - Cumulative seasonal water balance
Field Q - Performance Summary

**Application uniformity:** The coefficient of uniformity (CU) in this field was much lower than the recommended value for low value crops. Because the sprinkler system is fixed, the benefits of improving the uniformity may not be worth the costs.

**Schedule:** By mid-June the irrigations were far more frequent than necessary, resulting in lots of return flow and a low irrigation efficiency. If the frequency were halved, the duration could have stayed close to the same, which would result in less labor and less deep percolation.

**Configuration and operation:** The system configuration was decent, but there was an area in the middle of the pasture that received significantly less water than the area along the laterals. Five of the seven nozzles were perfectly matched.

**Crop water stress effect on yield:** The soil moisture never dropped below the MAD, so a reduction in yield due to crop water stress was unlikely.

**Other:** The system flow rate was ~59 gpm.
**Field R – Periodic-move Hand-move Sprinkle Irrigated Orchard Grass/Alfalfa Hay**

![Field R - Time Series Water Balance](image1)

**Fig. 59. Field R - Time series water balance**

![Field R - Cumulative Seasonal Water Balance](image2)

**Fig. 60. Field R - Cumulative seasonal water balance**
Field R - Performance Summary

Application uniformity: The coefficient of uniformity (CU) in this field was higher than the recommended value for low value crops, partially because of the large area to perimeter ratio. The far end of the field had irregular nozzle spacing.

Schedule: Irrigation could have started in early June when the soil moisture depletion dropped far below the MAD. Once irrigation started the frequency was good but the durations were far more than necessary, with more than half of the depth deep percolating beyond the root zone. For example, the first irrigation applied 13 inches when 6 was enough to refill the root zone. It is also possible that this field had some of the crop water need met by a high water table, which would throw off the water balance.

Configuration and operation: The configuration was good with a majority of nozzles matching in size but nozzle flow rate varying up to 1.5 gpm. Sprinkler spacing varied widely, particularly at the north side of the field. There were two significant gasket leaks and one hole in the pipe with a flow rate of 3.7 gpm, which is half of a nozzle flow rate.

Crop water stress effect on yield: The soil moisture dropped far below the MAD in June, so a reduction in yield due to crop water stress for the first cutting was likely.

Other: The system flow rate is 122 gpm.
**Field S – Periodic-move Hand-move Sprinkle Irrigated Cereal Crop Research Field**

**Fig. 62. Field S - Time series water balance**

**Fig. 63. Field S - Cumulative seasonal water balance**
Field S - Performance Summary

Application uniformity: I made no observations of the uniformity for this field.

Schedule: The first irrigation in mid-June could have been twice the duration to prevent the soil moisture depletion from dropping below the MAD in late June, where it oscillated for the rest of the season. By July, the irrigation frequency could be halves and the duration doubled to save labor.

Configuration and operation: I made no observation of the system configuration.

Crop water stress effect on yield: The crop could have benefitted from one longer irrigation early season to bring the soil moisture above the MAD. A reduction in yield due to crop water stress was possible. The ET was higher than the GID (and IE of 100%) and the because of sprinkle system uniformity portions of the field were likely under irrigated.
**Field T – Fixed Sprinkler Irrigated Apple Orchard**

**Fig. 64. Field T - Time series water balance**

**Fig. 65. Field T - Cumulative seasonal water balance**
Field T - Performance Summary

Application uniformity: The coefficient of uniformity (CU) was much lower than recommended for tree crops, but this is may not be critically important because the tree roots are likely concentrated in the areas receiving the most water.

Schedule: The irrigation frequency was almost perfect, fully utilizing the water storage capacity of the soil. The first two irrigation could have been half the duration, but by July the durations were pretty close to matching the crop ET with reasonably low return flows. These irrigations could probably be reduced by an hour or so.

Configuration and operation: The system had a poor configuration resulting in many dry spots from lack of sprinkler head to head coverage and tree interception of sprinkler spray. The nozzles were fairly closely matched, but a couple of them clogged. There were numerous leaking nozzle threads and gaskets.

Crop water stress effect on yield: The soil moisture dropped below the MAD only briefly a couple of times, so a reduction in yield due to crop water stress was unlikely.

Other: In summary the irrigation configuration and maintenance of this orchard was poor but the scheduling very good. The system flow rate was 65.4 gpm.
Field U – Periodic-move Hand-move Sprinkle Irrigated Mixed Vegetable Crop

Research Field

**Fig. 66. Field U - Time series water balance**

**Fig. 67. Field U - Cumulative seasonal water balance**
Field U - Performance Summary

**Application uniformity:** I made no observations of the uniformity for this field.

**Schedule:** The irrigation frequency was far higher than necessary. To reduce labor, the frequency could have been significantly less with a proportionate increase in duration.

**Configuration and operation:** I made no observations of the system configuration.

**Crop water stress effect on yield:** The soil moisture for this field was managed very well, never resulting in return flows nor dropping below the MAD. A reduction in yield due to crop water stress was unlikely. The ET was only slightly less than the GID (an IE of 94%) and the because of sprinkle system uniformity portions of the field were likely under irrigated.
Field V – Surface Irrigated Garden

The plots are included in Case Study 6.

Field V - Performance Summary

Application uniformity: I made no observations of the uniformity for this field.

Schedule: The schedule frequency in early summer was good, but the applied depths so high that the vast majority of the water went to deep percolation. Later in the season the frequency could have been reduced by up to 50%. Assuming that the water can advance to the end of the garden in a reasonable amount of time, the durations could have been reduced substantially. The irrigation efficiency was only 6%. I recommend to consider sprinkle irrigating at the beginning of the season during crop germination and when the roots are shallow, which would save considerable volumes of water and potentially labor.

Configuration and operation: Note that with these conditions of sandy soils and shallow-rooted annual crops, efficient surface irrigation is very challenging. Some practices to improve efficiency include diking the end of the area to prevent tailwater runoff, and creating “berms and basins” down the length of the field to direct and control flooding and achieve a faster advance of water across the garden. The irrigator was making a good first attempt at having a functional distribution network and lining the primary ditches with plastic to decrease deep percolation losses. I recommend continuing to make improvements in ditch lining and more distribution mains.

Crop water stress effect on yield: The soil moisture seldom dropped to the MAD, so a reduction in yield due to crop water stress was unlikely.

Other: The system flow rate started the season at 1.1 cfs and decreased to 0.75 cfs by mid-July.
Field W – Periodic-move Hand-move Sprinkle Irrigated Mixed Grass Hay/Pasture

The plots are included in Case Study 1.

Field W - Performance Summary

Application uniformity: The coefficient of uniformity (CU) was slightly below the minimum recommended value for low value crops, and the southern field edge received significantly less water than the middle. However, the benefits of increasing the CU for this field may not be worth the effort because the performance is already pretty good.

Schedule: The irrigation frequency and durations were adequate. To save labor, the frequency in June could have been less (e.g. halved) and the durations increased accordingly (e.g. doubled) to apply the same total amount of water.

Configuration and operation: The configuration was very good with only one leaking gasket and only one mismatched nozzle. The nozzle flow rates were closely matched.

Crop water stress effect on yield: The soil moisture never dropped to the MAD, so a reduction in yield due to crop water stress was unlikely. Additionally, the ET was a few inches less than the GID, so it is unlikely that much of the field was significantly under or over-irrigated.

Other: See Case Study 1 in the Results section for a more detailed discussion. The system flow rate was 69 gpm.
Field X – Periodic-move Hand-move Sprinkle Irrigated Mixed Grass Hay/Pasture

Fig. 68. Field X - Time series water balance

Fig. 69. Field X - Cumulative seasonal water balance
Fig. 70. Field X – 3D plot of sprinkle uniformity

Field X - Performance Summary

Application uniformity: The coefficient of uniformity (CU) was slightly below the minimum recommended value for low value crops. This was likely because the western field edge received significantly less water than the rest of the field.

Schedule: The irrigation frequency and durations were adequate. To save labor the irrigation frequency could have been reduced by up to a week, with no change or only a slight increase in duration. At the current schedule the duration was roughly 25% longer than necessary in July, and over 50% longer than necessary in August, which led to an efficiency of only 51%.

Configuration and operation: The system configuration was good with no significant leaks and perfectly matched nozzle sizes and flow rates.

Crop water stress effect on yield: The soil moisture never dropped below the MAD, so a reduction in yield due to crop water stress was unlikely.

Other: The system flow rate was 31 gpm.