Measuring, Monitoring, and Enforcing Temporary Water Transfers: Considerations, Case Examples, Innovations and Costs

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I. Introduction

Public and private organizations worldwide are experimenting with innovative water transfers to help match water supply and demand. Voluntary water transfers—water banking, short-term transfers, and permanent sales—can help communities balance competing needs like environmental use, food and fiber production, and energy generation.

Voluntary programs that pay farmers to reduce or cease irrigation are the focus of this report. In the western U.S., the most reliable or senior water rights[2] are largely held in agriculture. In dry periods junior water rights, often environmental, may face cutbacks leading to degraded habitat and newly threatened or endangered species. When governments or non-profits are willing and able to buy or lease water, there is potential for all water users to benefit—for example, when a city offers to pay more for water than what farmers could earn irrigating some of their least profitable fields.

Water transfers from agriculture have been controversial. Impacts to local businesses, microenvironments, and the character and culture of rural areas must be considered. Although water transfer agreements have had problems, they rival other supply options in terms of environmental impacts, energy efficiency, and financial cost. In many regions, infrastructure to convey water from sellers to buyers is already in place. An adequate legal framework for transferring the use of water also exists in many jurisdictions, though this framework can be improved. Grafton et al. (2010) compared water markets in Australia, Chile, China, South Africa, and the United States and found, "In all cases … further development of robust water rights and governance are possible, should policy makers wish to undertake the necessary reforms."

In this report we provide information to help development of temporary water transfer agreements by examining three topics that need to be addressed by such agreements: measuring transferred water, monitoring water sellers' transfer compliance, and enforcing transfer contracts.

The next section of this report describes measurement, monitoring, and enforcement (MME) methodologies and practices that can be used to (1) estimate or quantify the amount of water conserved through fallowing programs; (2) verify that specific crop fields and pastures enrolled in fallowing programs actually remain un-irrigated for the time periods specified; and (3) provide a clear structure of incentives for compliance in the form of penalties and other methods. This is based on a review of programs that seek to reduce consumptive use in crop production throughout arid regions of the world and other innovative water saving programs. The subsequent sections summarize ideas and innovations for improving MME, discuss the costs of MME strategies, and provide recommendations on improving MME.

Water conservation and transfer programs from California, Texas, Idaho, Oregon, the U.S. Department of Agriculture (USDA) and Australia are considered here. Fallowing programs in California, Oregon, and Idaho conserve water historically used to irrigate crops for transfer to other purposes. Recent iterations of these programs are examined. The Australian program

[2] First instances of terms defined in the Glossary (page 59) are highlighted.

discussed here is not a fallowing program but an attempt to cap diversions in the Murray-Darling Basin, which crosses several states. All the programs described originated in some form in the 1990s or early 2000s. Many of the programs are still operating and have been continually refined with passing years.

While many programs involve similar transfer types, water transfer terms vary. In this report the term "fallowing" refers to any transfer that conserves water by suspending irrigation on cropped land. The conserved water is often measured in terms of either historical water applications or historical crop consumption. We choose to focus on crop water consumption. Although it is more challenging to measure a change in water consumption, such changes are the objective of water acquisition programs that seek to free up irrigation water for other uses. We refer to water consumption in terms of evapotranspiration (ET). ET is the amount of water used by plants (transpiration) plus the water that evaporates from soil and plant surfaces (evaporation). Water that is applied but not consumed (such as drainage or recharge) is not part of ET.[3]

II. Measuring, Monitoring, and Enforcing: Issues and Case Examples

This section reviews implementation of measuring, monitoring, and enforcing in temporary water transfer programs. While MME is also important in permanent water transfers, it is even more so for temporary transfers because the net economic benefits of temporary transfers tend to be smaller. The aim of this section is to identify successful strategies to measure water consumption, monitor conservation, and enforce agreements. Failure to consider and address these issues could make temporary transfers infeasible, burdened by the weight of excessive measuring, monitoring, and enforcement costs.

In addition to supporting current transfer programs, advances in measuring, monitoring, and enforcement can make innovative transfers feasible. Deficit irrigation is one option. With deficit irrigation, crops are supplied water below their full transpiration potential. This is an attractive water transfer option because it allows farmers to grow their customary crops and conserve water at the same time. Yields decrease with deficit irrigation but profit losses can be offset by water conservation payments. Water savings per field might be small compared to fallowing, but deficit irrigation over large areas could add up to significant conservation. See Lindenmayer et al. (2011) or Geers and Raes (2009) for some advantages and disadvantages of deficit irrigation.

A. Measuring Water Savings

As demands on water intensify, the precise amount of water being consumed in competing uses is important both for conservation management and for potential water transfers. The transfer of water conserved by cropland fallowing gives rise to a complex measurement problem. If a specific area of cropland is not irrigated, how do buyers know how much water is "saved" and potentially available to transfer? Answering the question of how much water would have been used on a field had it been planted, irrigated and harvested can be knotty. The answer depends upon commingling influences including irrigation management practices; temperature and rainfall patterns; irrigation practices on neighboring farms; soil

[3] Traditional and innovative techniques to estimate evapotranspiration are described in greater detail in section VII. Appendix: Remote Sensing Techniques.

characteristics; economic incentives to plant competing crops; and return flow.

Return flow is an issue because decreases in return flow can damage other water users and habitats. Return flow is water that is applied to crops but not consumed. It includes drainage, recharge, and runoff. For example, a farmer applies 50 acre-feet of water to his fields each year, his crops consume 30 acre-feet, and the remaining 20 acre-feet is return flow. Downstream farmers rely on some of this return flow for use on their fields; it also supports habitat along drainage canals. If the farmer sold all 50 acre-feet, the downstream farmers and habitat would be injured by the sale. Likewise, fallowing savings measured in terms of applied water potentially exaggerate water savings and lead to insufficient water supply downstream. If the farmer is allowed to sell only his consumptive use (30 acre-feet), then the water that would have been return flow is left instream for other users. Not all fallowing programs address return flow accounting in their guidelines. Nevertheless, it is often an important issue that should be evaluated. Return flow that cannot be used for irrigation could still be valuable. If it drains into a saline sink, for example, it might have important recreation or habitat value.

Another issue not always considered in water programs is the reliability of conserved water measures and what effect this might have on program accountability. Without reliable records of historic water use, the ability to measure consumptive water use savings has traditionally been limited. Some early transfer programs, like Edwards Aquifer Authority (EAA) Irrigation Suspension Program, had no concrete way to gauge past water consumption in order to calculate conserved water. Water meters were uncommon, so the program aimed to reduce the amount of land in agricultural production instead of aiming to reduce water use by a specific amount. EAA selected land for the program based on the expected effects its temporary retirement would have on court-ordered flow levels for environmentally important springs. The land's location, past crops, and irrigation technology were used to rank its effect on springflow. Keplinger et al. (1998) later estimated the program's water savings based on weather patterns and irrigation estimates. However, as water becomes scarcer and transfers more expensive, buyers will likely demand more solid evidence of how much water their funds are conserving.

A method for estimating how much water will be saved through fallowing and made available for transfer should be agreed upon in advance if these types of arrangements are to succeed. As the Water Transfer Workgroup (2002) reported, based on California's experience, "The inability of interested parties to agree on the volume of transferable water associated with the short-term fallowing of agricultural lands has caused substantial controversy and delays in approving water transfer proposals." Methods used to quantify how much water is saved and transferrable vary across jurisdictions and transfer cases. Such agreements must be based on accepted methods for estimating water consumption, consider local complexities like return flow accounting, and be consistent with applicable laws.

Approaches for measuring the amount of water conserved from fallowing and other water conservation programs are summarized here. These examples are collected from several regions of the western U.S. and from Australia.

1. Case Example: Water Transfers Office, California Department of Water Resources and Resource Management Division, Bureau of Reclamation, Mid-Pacific Region

In 2009, the California Department of Water Resources Water Transfers Office (CDWR) and Bureau of Reclamation (BOR), or Project Agencies, released an updated technical report to facilitate water transfers in 2010. The report applied to water transfers from fallowing, crop shifting, or groundwater substitution involving State and Federal contractors, and Project Agencies' facilities. It was created to facilitate water transfer approvals by providing guidelines, not to regulate transfers (CDWR and BOR 2009). Additionally, the Project Agencies have reported on several common issues associated with central California water transfers. The reports provide additional background on the complexity of water transfer accounting.[4] The reports use the term cropland idling instead of fallowing to distinguish between fallowing done in normal crop rotations and fallowing done for water transfer purposes. (We prefer the term fallowing because most programs use it).

Sellers conserve water for transfer by fallowing and crop shifting, thereby reducing irrigation and on-farm water consumption (CDWR and BOR 2009). In order for transfers to occur, water sellers must demonstrate how fallowing or shifting will reduce consumptive water use. Sellers do this by providing five years of farming history data, maps, proof of water rights, and estimated past and current year evapotranspiration of applied water (ETAW). However, large water districts with consistent cropping patterns may not have to provide five years of crop history. The checklist of what is needed to validate water transfers is shown in Figure 1.

[4] "Water Transfer Office—Issues," CDWR, last modified April 21, 2011, http://www.water.ca.gov/watertransfers/issues/

Cropland Idling/Crop Shifting Transfers Technical Information – Proposal Checklist

- ☐ Submit past 5 years* data of:
  - ☐ Net crop acreages by crop (acres)
  - ☐ Fallowed Land (acres)
  - ☐ Dry Farmed Land (acres)
  - ☐ Total District Acreage (acres)
  - ☐ Total Farmable Acreage (acres)
- ☐ Maps showing:
  - ☐ District or Farm Operation Boundary
  - ☐ Current Fields Irrigated
  - ☐ Fields Routinely Irrigated or Not Irrigated
  - ☐ Fields to be Idled as Part of Water Transfer
- ☐ Basis of right to use surface water during the spring and summer in the year of the proposed water transfer
- ☐ ETAW
  - ☐ Base Year ETAW (Acre-feet)
  - ☐ Current Year ETAW (Acre-feet)

**With Project Agencies approval, 5 years of crop data may not be necessary for large water districts that can prove cropping patterns have changed very little from year to year.*

Figure 1 Project Agencies' Water Seller Checklist
(CDWR and BOR 2009)

The seller estimates the base year and current year consumptive water use (ETAW) to calculate how much water is being transferred. ETAW is calculated in four steps: (1) cropping patterns are established; (2) baseline ETAW is estimated based on cropping patterns; (3) current ETAW, after fallowing or crop shifting, is estimated; (4) current ETAW is subtracted from baseline ETAW. Step four shows the amount of water available for transfer. Each of these steps is described in more detail below. The Project Agencies also consider return flow when computing water transfer amounts. In their definition of ETAW they indicate that it does not include water lost to deep percolation or conveyance losses (CDWR and BOR 2009).

The cropping pattern is established using five years of crop history and maps. The maps must show district or farm boundaries, routinely irrigated fields, and fields in the proposed transfer. If an individual farmer wishes to transfer water, the farmer must submit crop history and maps for each proposed parcel. For individual farms or small water districts, crop histories will be used to find significant crop cycles. Where the cycles are apparent, either a repeating crop pattern or a five-year average will be used for the crop pattern.

If the seller is a large water district then the Project Agencies will use the previous year to establish the cropping pattern in most cases. The previous year will be used as long as the market for the crops in question has been stable, there has been a normal water supply, and acreage in the highest water using crops has been stable. Acreage stability is determined by comparing the previous year's acreage of the highest water using crops to their five-year average acreages. If the most recent year's acreage is within five percent of the five-year average acreage, then the district's cropping pattern is considered stable. If recent acreage is not within this limit, then the Project Agencies will use a more typical year or an average of years to establish a cropping pattern. Table 1 illustrates the hypothetical case of District A based on the rules described by the Project Agencies. District A's 2010 crop acreages of rice and sugar beets (their highest water using crops) are within five percent of their 2006-2010 average acreage. In this case, 2010 could be used to establish the cropping pattern (assuming the normal market and water year conditions were met). If a consensus on an appropriate cropping pattern can't be reached then the Project Agencies will not approve the transfer (CDWR and BOR 2009).

Table 1 District A Crop Patterns (hypothetical example)

Highest water use crops	Average acreage 2006-2010	5% of five-year average	2006-2010 acreage +/- 5%	Crop acreage 2010
Rice	10,000	500	9,500-10,500	10,250
Sugar beets	1,000	50	950-1,050	970

The cropping pattern is used to estimate baseline ETAW of irrigated fields. ETAW includes the amount of water used by the crop plus water evaporated from soil and plant surfaces, minus water supplied by rainfall or seepage.[5] The ETAW calculations assume crop water requirements under average rainfall and evaporation conditions. The amount of water considered transferrable by fallowing or crop shifting is the difference between the baseline and current ETAW for each field and specific crop fallowed. Table 2 shows example ETAW values. In a proposal to crop shift from sugar beets to melons on 100 acres, the baseline ETAW would be 250 acre-feet, the current ETAW would be 110 acre-feet, and the transferrable water would be 140 acre-feet.

Table 2 Estimated ET for Fallowing and Crop Shifting in 2010

Crop	ET (in acre-feet/acre)
Bean	1.5
Cotton	2.3
Melon	1.1
Rice	3.3
Sugar Beets	2.5
Sunflower	1.4
Tomato	1.8

Source: CDWR and BOR 2009

The ETAW values used in water transfers are provided by CDWR's Land and Water Use Office.[6] The Land and Water Use Office estimates ETAW annually for 20 crop categories.[7] ETAW is estimated using the Consumptive Use Program Plus (CUP+). CUP+ uses the daily Penman-Monteith and Hargreaves-Samani equations to estimate reference evapotranspiration

[5] "Models," California Department of Water Resources Land and Water Use, modified January 3, 2012, http://www.water.ca.gov/landwateruse/models.cfm
[6] Tom Filler, Chief, Water Transfer Section, Division of Integrated Regional Water Management, Department of Water Resources, email to Lana Jones, October 10, 2010.
[7] "Annual Land and Water Use Estimates," California Department of Water Resources Land and Water Use, modified January 20, 2010, http://www.water.ca.gov/landwateruse/anlwuest.cfm

(Orange et al. 2008). ET estimation and the Penman-Monteith equation are described in the Appendix: Remote Sensing Basics.

The Project Agencies prohibit certain crops for water transfers because of difficulties in measuring water savings: pasture, alfalfa in the Delta region, deciduous orchards, and vineyards. Certain other transfer proposals are also prohibited because of the difficulty of measuring or verifying water savings: removing permanent crops, enrolling groundwater-irrigated fields, fallowing on lands with shallow groundwater, and using water saved by fallowing or crop shifting to increase water use on other land controlled by the contracting party (CDWR and BOR 2012).

In addition to the Project Agencies' technical reports on water transfers, the CDWR has published 16 common problems on their website with recommendations for how to address them. Issue No. 8 discusses the problem of using normal condition baseline ETAW for transfers in years with reduced water deliveries. The paper recommends developing a new baseline for water sellers with reduced 2010 surface water allocations (CDWR 2009b).

If a seller will have a reduced allocation, the baseline estimate will depend on whether or not the seller will have to reduce ETAW. If the seller will *not* have to reduce ETAW then they must provide the Project Agencies with documentation showing how they will provide full ETAW with a reduced supply. The documentation could include water diversion history or conservation plans (CDWR 2009b). If the seller will have to reduce their ETAW then a baseline will be calculated based on district efficiency, which equals ETAW/diversions. Table 3 provides an example calculation of an adjusted baseline. The normal year used to compute district efficiency is 2009 and the reduced-supply year is 2010.

Table 3 Adjusted Baseline Calculations

District A	2009	2010
Maximum diversion (acre-feet)	100,000 (a)	80,000 (d)
ETAW (acre-feet)	70,000 (b)	TBD
Efficiency (b ÷ a)	70% (c)	-
Baseline (c * d)		56,000

Source: CDWR 2009b

In this example, District A's 2010 baseline would be 56,000 acre-feet. If the district reduced ETAW below 56,000 acre-feet, that amount could be transferred. From the perspective of diversions, the District would participate in a transfer in 2010 by diverting less than 80,000 acre-feet. Whatever diversion reduction made would create 70% of that amount for transfer. For example, if District A reduced diversions by 20,000, it would be able to transfer 14,000 acre-feet or 70% of the savings. If the district diverted no water, 56,000 acre-feet would be available for transfer. The baseline could be adjusted above 56,000 acre-feet, subject to the Project Agencies' approval, if the District showed that they would increase district efficiency in 2010. However, water transfer from crop substitution is capped at the difference between the 2010 allocation and actual diversions.

An additional issue addressed by CDWR is the use of ETAW to calculate the amount of water made available in fallowing and crop shifting programs. Resolving the ETAW problem is vital because of the growing popularity of water transfers based on fallowing and crop shifting. CDWR (2009a) noted the greater role of these transfers in meeting California's water needs but added, "there is considerable uncertainty over the amount of water that should be credited to the transferring party and how to monitor the idled fields." There are two potential problems with using current ETAW values. First, the values may be outdated, particularly for rice, and rice fallowing may play a major part in north to south water transfers. The reliability of outdated ETAW estimates is a concern because new crop varieties and refined water use measures have been introduced since the estimates were developed.

Second, water seeping from neighboring fields and weed growth may allow significant amounts of water to evaporate from fallowed fields (CDWR 2009a). Water conservation estimates are generally based on the assumption that fallowed fields use no water. The assumption that fallowed fields use no water is questioned due to evidence of significant evaporation from seepage or weeds. Hansen et al. (2010) confirmed this suspicion in Colorado with fallowed test fields. The fields averaged seven inches per year ET, only one inch less than fields planted with dryland crops.

The BOR is also concerned about ETAW in crop shifting if deep-rooted crops like safflower are switched to. Safflower has low ETAW but its roots may mine deeper water and dry the soil. River flows may suffer in following years if there isn't sufficient precipitation to make up for the drier soil (CDWR 2009a). The BOR recommends using the 2009 ETAW values for 2010 and undertaking additional research.

2. Case Example: Imperial Irrigation District, California

The Imperial Irrigation District (IID) 2010-2011 fallowing program contracted water for a transfer agreement with San Diego County Water Authority, for Salton Sea mitigation, to manage their annual Colorado River water use, to payback past year overuse, and to create water for storage (IID 2009a).

The 2010-2011 fallowing program was the eighth year of the program. The 2011-2012 program is currently underway.[8] The fallowing application and contract for participating fields has remained largely unchanged in recent years.

The fallowing application requires the basic details needed to establish historical water use on a field: the canal, gate, and account number for the field, the crops grown for the last three years, and the field acreage (IID 2009a). The water conserved by fallowing is estimated based on a "water use history formula adopted by the IID Board of Directors," that is adjusted for recent water use trends (IID 2010a). IID's water use history formula is based on water deliveries in eight of the last ten years. IID drops the high and low years and calculates a rolling average of the remaining eight years.[9] They then examine the trend over the last three years. Using the average and the trend, IID predicts what the next year's water usage would have been.[10] The calculation is also adjusted if the field was part of a previous fallowing

[8] "2011-2012 Fallowing Program," Imperial Irrigation District, accessed April 18, 2012, http://www.iid.com/index.aspx?page=396

[9] David Bradshaw, IID Assistant Water Manager, Agricultural Water Management, interview by Lana Jones, November 17, 2010

[10] David Bradshaw, IID Assistant Water Manager, email to Lana Jones, March 15, 2010.

program. Fields are allowed to participate up to two out of every four years.

IID pays farmers on a per acre-foot basis for up to six acre-feet per acre. So, the annual average water use is capped (for payment purposes) at six acre-feet per acre. The final result after the historical water use has been adjusted and capped is the field's Annual Baseline. IID then bases the payments made to farmers on the number of irrigable acres enrolled in the fallowing program multiplied by the Annual Baseline. Return flow is not accounted for in the Annual Baseline, although IID's Colorado River water allocation includes return flow (BOR 2011). IID return flows are tracked in Reclamation's Lower Colorado River Accounting System (BOR 2009).

3. Case Example: Edwards Aquifer Authority, Texas

The Edwards Aquifer Authority (EAA) 1997 Irrigation Suspension Program focused on increasing springflow and aquifer levels, and helping municipalities through critical droughts (Keplinger et al. 1998). Groundwater rights were not established at the time and most pumps were not metered. Consequently, it was impractical to target specific reductions in water use from individual wells. Instead, the program aimed to suspend irrigation on approximately 10,000 acres. Farmers' bids to participate in the program were scored based on farm location, crop, and irrigation technology. The characteristics expected to yield the largest impact on springflow received the highest scores. The scores were then divided into each farmer's offer price to select participating farmers (Keplinger et al. 1998).

Keplinger et al. (1998) estimated the program's impact on factors including irrigation pumping, springflow, and aquifer elevation. Irrigation pumping in the region is highly correlated with precipitation so impacts were estimated for wet, average, and dry years. Keplinger et al. analyzed 15 years of irrigation activity to find average pumping values for the five wettest, the five driest, and the five median years. They multiplied the averages for the three types of years by the actual number of acres enrolled in the 1997 program (9,669) to estimate the reduction in pumping associated with each type of year. The reduced pumping estimates ranged from about 7,700 to 23,000 acre-feet. 1997 turned out to be such a wet year that irrigation on fields not participating in the program was estimated to be only half as much as it would be in a typical wet year. As a result, Keplinger et al. (1998) estimated the actual reduction in pumping was 3,868 acre-feet.

An earlier Keplinger and McCarl (1995) study was used to estimate the effect of reduced pumping on springflow and aquifer elevation. The study used a regression-based model to explain springflow as a function of recharge and pumping in the eastern and western regions of the aquifer. Using the regression model, Keplinger et al. (1998) estimated that 28% of the 3,868 acre-foot pumping reduction directly benefited current springflow, resulting in an increase of 1,083 acre-feet. They estimated the other 72% (2,785 af) of reduced pumping went to aquifer elevation, springflow in later years, other springs, or other aquifers.

4. Case Example: Klamath Fallowing Programs, Oregon

In 2010, water conditions necessitated a fallowing program in the Klamath Water and Power Authority (KWAPA) service area. A March KWAPA notice said that deliveries from Upper Klamath Lake would not be sufficient to produce crops on land relying on surface water. The fallowing program was implemented to decrease water demand while providing "financial assistance" to irrigators agreeing to decrease irrigation with surface water on their land

(KWAPA 2010).

Irrigators wishing to participate in the program were asked to submit sealed bids containing a description of the land proposed for fallowing including a map, the number of acres to be fallowed, the crop irrigated in 2009, the crop that would have been irrigated in 2010, and the bidder's per acre financial assistance request. KWAPA said that they would base their selection of lands for the fallowing program on least cost per acre-foot of water saved. The determination of least cost is calculated by the KWAPA Executive Director based on crop, soil type, evapotranspiration, and other criteria. Specifics about the calculation are not provided but bidders may challenge the Director's decision (KWAPA 2010).

The Bureau of Reclamation (BOR) managed programs known as the Klamath Water Bank from 2001 to 2008.[11] A 2005 Government Accountability Office (GAO) report said that lack of reliable water measurement equipment and monitoring data in the Klamath Project made measuring the water saved by the bank a problem. The BOR responded to the measurement problem by setting up subsequent contracts with irrigators based on reducing their use of metered groundwater, instead of the acreage fallowed (GAO 2005). They introduced groundwater-pumping contracts, where groundwater is pumped into canals for others to use, in the third program year.

The BOR could not make a reliable estimate of water made available from fallowing based solely on the amount of acres irrigated each year in the Klamath Project. At the time of the GAO (2005) report, the BOR said, "the precise impact of the water bank cannot be determined because of year-to-year variation in irrigation demand and its determining factors such as temperature, precipitation, and crop types." The BOR originally assumed that five acre-feet were saved per acre fallowed and later revised the estimate to two acre-feet per acre. The BOR later consulted with the USGS for assistance in estimating the total amount of water saved by fallowing.

The USGS report concluded that although the water bank likely resulted in increased Klamath River flows, the precise amount of water saved was not measurable using streamflow data. The 100,000 acre-foot water bank requirement was small compared to the river's 1961-1999 average annual flow of over 1,500,000 acre-feet in the targeted stretch. The variability of streamflow also made the water bank's impact hard to detect. Despite being regulated by a dam, flow in the targeted river stretch had a standard deviation of 560,035 acre-feet due to climate variations. The increase in streamflow from the water bank was not measurable because it was likely within streamflow measurement error (USGS 2005).

The USGS said that net diversions—gross diversions less return flows—probably provide the best method to measure the benefits of the water bank despite potential problems with data accuracy. Using diversion and return data from 1961-99, the USGS regressed net diversions on net flows into Upper Klamath Lake. The net diversions from water banks years (2003 and 2004) were compared to the regression line and were lower than would be expected compared to years with similar inflows to Upper Klamath Lake (USGS 2005). The USGS cautioned that

[11] "2009 Water Supply Enhancement Study (formerly the Water Bank)," Bureau of Reclamation, last modified August 28, 2009, http://www.usbr.gov/mp/kbao/pilot_water_bank/index.html

this method must be used carefully because the water bank volumes and the diversion and return flow data error are near the same size.

In their conclusion, the USGS said that analysis of evapotranspiration rates in fallowed and irrigated fields would be required to obtain accurate estimates of water saved by fallowing.

5. Case Example: Murray-Darling Basin Cap, Australia

In 1995, the Murray-Darling Basin Ministerial Council decided to cap water use in the basin. The volume of the Cap was set at the level of 1993-94 water diversions. It was set in an effort to manage the Murray-Darling Basin in a way that would protect river environments and achieve sustainable consumptive use (Flett et al. 2009). The Independent Audit Group was established in 1996 to report on the implementation of the Cap (Cox and Baxter 1996). It has released a report each year since then.

The Cap, like some US programs, is focused on diversions. The capacity to measure compliance with the Cap varies by region and individual measurement systems. New South Wales, Victoria, South Australia, Queensland, and the Australian Capital Territory (ACT) have individual caps and are each evaluated separately. The Independent Audit Group bases their report on data provided by each state and the ACT (Flett et al. 2009).

Most Murray River water diverted in South Australia is metered. According to Flett et al. (2009), the state is “well placed to manage diversions within the respective Caps.” Queensland began a metering project in 2005 to get all unsupplemented diversions (i.e. diversions not taken from regulated public storage) across the state metered. In New South Wales, diversions from unregulated streams are generally not metered although these diversions represent less than 4% of the state’s long-term Diversion Cap. Unmetered use is estimated based on crop surveys and irrigation requirements (Flett et al. 2009).

B. Monitoring Compliance in Water Transfer Agreements

If accurate measuring is an important goal, then careful monitoring is also important to ensure that actual conservation aligns with planned, and often compensated, conservation. Depending on the program, monitoring may be coordinated by the party seeking water, the water district where the water originates, local government, or federal government agencies. Site visits are the most common form of monitoring in the programs surveyed.

Water buyers may be able to decrease the burden of monitoring with careful program structuring. For example, farmers enrolled in IID’s fallowing program agree to have their field headgates locked making irrigation impossible unless the headgate is tampered with. Programs administered by parties that have less control over water delivery can be trickier. Water transfer contracts should stipulate that farmers must not use water saved from an enrolled field to increase water use on a different field. Even with such contracts in place, fields beyond those enrolled in a program may need to be monitored to guarantee water savings.

1. Case Example: Water Transfer Office, California Department of Water Resources and Resource Management Division, Bureau of Reclamation, Mid-Pacific Region

The first step in monitoring outlined by the CDWR and BOR—or Project Agencies—is reporting. The seller is responsible for accurate reporting of the fallowing or crop shifting steps taken to make transfer water available (CDWR and BOR 2009).

Verification is the next step in monitoring. The Project Agencies or the seller, if approved by the Project Agencies, will verify the steps taken to make transfer water available. This part of the monitoring program must provide data that can be used to verify the amount of water made available for transfer. Data obtained to verify water savings will come from cropping data; maps showing participating fields; Project Agencies' staff field visits; past and current water diversions; and, in some cases, field test instruments.

Sellers must provide access to participating fields to the Project Agencies. Staff may check for water leaks, excess weed growth, changes in soil moisture, and shifts to specified crops. Areas with high groundwater or seepage may also be monitored with instruments to determine evaporation from soil and weeds, which reduce conserved water. The Project Agencies coordinate monitoring but water buyers and sellers must reimburse the Project Agencies for costs associated with monitoring activities.

2. Case Example: Imperial Irrigation District, California

In the IID 2010-2011 Program, as with past years' programs, when fallowing contracts are finalized on July 1, water delivery headgates for participating fields are locked (IID 2009b). IID then takes pictures of locked headgates with the fallow field behind them to monitor program participants, as shown in Figure 2. The Program Solicitation Announcement outlines the steps that must be taken for fields that share a gate or receive water from a gate that supplies other structures. For example, fields sharing a gate must have verifiable water use records to enroll in the fallowing program (IID 2009b). For the case of a gate that supplies other fields or structures not participating in fallowing, a farmer must submit a plan for the continued service of those structures with their program application (IID 2009a).

Figure 2 Locked Headgate and Fallow Field, IID Fallowing Program 2010

IID also puts other systems in place to make monitoring participating fields simpler. The crop code in IID's management system is revised so that water cannot be ordered for fields participating in the fallowing program. If water delivery gates cannot be locked then other physical blocks are installed on all enrolled fields. On the ground monitoring takes place as well. Fields are inspected or photo-verified quarterly by IID staff. The Bureau of Reclamation (BOR) additionally validates five percent of enrolled fields (IID 2008). The BOR visits annually and takes pictures of five percent of the enrolled fields in the validation process. The IID fallowing program is part of the Quantification Settlement Agreement (QSA), which requires the fallowing to be verified.[12]

3. Case Example: Edwards Aquifer Authority, Texas

The agreements, instructions, and contracts for the 1997 EAA Irrigation Suspension Program outline the ways that the EAA may monitor the program. In their Instructions to Offerors, EAA says that they may request additional maps or information about the acreage proposed for the program and inspect the property and irrigation system (Keplinger et al. 1998).

In the Irrigation Suspension Contract, they further state that the participant shall permit inspection of their enrolled acres and irrigation system by EAA representatives if given four-hour notice. The participant must grant the EAA representative access to their property for inspection (Keplinger et al. 1998).

In their more recent Edwards Aquifer Authority Rules (2010a), which governs groundwater within and withdrawn from the aquifer, the EAA reserves the right to enter a property to investigate rule violations. Any EAA agent may enter any property at any reasonable time for this purpose (EAA 2010a). Irrigators are required to submit an Agricultural Irrigation Assessment Form exhibiting their on-farm irrigation efficiency. Information submitted on this form is subject to EAA verification. Any irrigator with less than 60% irrigation efficiency is also required to submit a Groundwater Conservation Plan. The Groundwater Conservation Plan should outline what Best Management Practices the irrigators are going to implement to improve efficiency and an implementation schedule. EAA requires these irrigators to submit Groundwater Conservation Plan status reports every three years (EAA 2010b).

4. Case Example: Idaho Department of Water Resources

The Idaho Department of Water Resources (IDWR) began its Water Transactions Program (WTP) in 2003. The WTP is part of the Columbia Basin Water Transactions Program. The primary objective of the WTP is to increase instream flows and that is the focus of the monitoring protocols (IDWR 2006).

The IDWR WTP Monitoring and Evaluation Protocol lists seven monitoring methods ranked in order of complexity and cost. Method one uses stream miles. This method is based on the number of miles where additional habitat was created because the stream was reconnected. Method two uses photos of points of a stream segment and points above and below it. The points are monitored before and during the water transaction to show increased habitat. Method three uses site visits to verify satellite imagery and monitor contract compliance. Method four uses stream gauge measurement of flows during the water transaction period. A staff gauge, current metering, or continuous recorder is required with a cross section of readings. Method five uses satellite photos to show that irrigators leasing water are not irrigating fields. Method six uses the Physical Habitat Simulation model to evaluate the relationship between increased flow and habitat needs. This model relates stream data—e.g. water depth and velocity—to the needs of target species. Method seven uses Mike Basin models. These models predict the effect of irrigation changes on downstream flows (IDWR 2006).

[12] David Bradshaw, IID Assistant Water Manager, Agricultural Water Management, interview by Lana Jones, November 17, 2010

IDWR publishes a monitoring report on the Water Transactions Program's prior year transactions. The 2009 report describes monitoring on 21 transactions that increased flows and habitat on over 186 river miles (IDWR 2010). For example, an August 2009 site visit and Landsat images confirmed compliance on a five-year lease on Alturas Lake Creek for 2.66 cubic feet per second (cfs) of water from May through October. A stream gauge monitored flow in Alturas Lake Creek and a fish survey found 4 salmon in the creek below the original irrigation diversion point. The gauge measured flows of about 20 cfs to 500 cfs during the lease period (IDWR 2010).

5. Case Example: Klamath Water and Power Authority, Oregon

The KWAPA 2010 fallowing program contract stipulates that KWAPA and the water district where the land is located shall be granted access to the land contracted in the program (KWAPA 2010b). There is no other mention of monitoring in the 2010 contract or program documents.

6. Case Example: Murray-Darling Basin Cap, Australia

Monitoring in the Murray-Darling Basin is done on two scales (Garrick et al. 2009). The state government or irrigation companies monitor entitlement holders' water use. The Independent Audit Group (IAG) monitors states and territories and reports progress on implementation of the Cap to the Murray-Darling Basin Ministerial Council.

The most recently published audit by the IAG is from 2011. In order to audit progress on Cap implementation, the IAG gathered statistics on actual diversions in the 2010-11study period. They use these statistics to quantify total diversions and comment on Cap compliance. They also look at proposed diversion management rules and any problems with implementation of these rules. In the months before the audit was published, IAG met with state and ACT representatives to compare their water use to their caps and discuss progress (Cox et al. 2011).

7. Case Example: USDA Wetlands Reserve Program

The USDA's Wetlands Reserve Program (WRP) pays farmers, ranchers, and Indian Tribes to retire agricultural land in order to restore, protect, and enhance wetlands. Fiscal year 2010 had the highest single year enrollment in the program: 272,000 acres. As of November 2010, there were 2.3 million acres enrolled (USDA 2010). Landowners may participate in the program in three ways. The land may be enrolled with a permanent conservation easement and the USDA pays up to the full easement value and restoration costs. Alternatively, the land may be enrolled in a 30-year easement and the USDA pays up to 75% of both the easement value and restoration costs. Finally, the land may be enrolled in a restoration cost-share agreement with no easement and the USDA pays up to 75% of restoration costs (USDA 2008).

The WRP Manual says that state conservationists will develop processes to monitor easements and restoration agreements (USDA 2006). Restoration agreements are required to be monitored as restoration practices are being implemented and then at least once a year for the life of the agreement. For easements, annual site visits are required until conservation practices are established. Once established, sites may be monitored either annually by visit or annually by remote sensing with a site visit at least every three years. A monitoring checklist must be completed each year.

The monitoring checklist is a three-page form with questions about land ownership, conditions, and the status of easement compliance. Pictures are required from designated photo points for site-visit years. If easement conditions are not being met, there is space for descriptions of the violation and photos are required. Conservation goals are tracked with questions about habitat restoration, birds, vegetation, and restoration practices. Each question includes space for the reviewer to make comments about what changes are needed. A Practice and Cost Worksheet is provided at the end of the document to list what modifications are needed and to estimate their cost (USDA 2000).

C. Enforcing Water Transfer Agreements

Water transfer enforcement receives little attention in most fallowing program agreements. Program authorities may instead rely on existing state or district water permit enforcement procedures. The Edwards Aquifer Authority, for example, requires groundwater conservation plans from some irrigators but does not post enforcement procedures for the plans. However, they post the Edwards Aquifer Authority Rules, which describe enforcement procedures for all persons with Authority permits.

New water transfer programs could rely on local enforcement procedures or could choose to add enforcement language to transfer contracts. If a fallowing program wishes to include enforcement in transfer contracts, then drafters could look to other states or water districts for examples. Examples from a Texas groundwater district, Utah state, an Oregon water and power agency, and an Australian river basin are provided here.

1. Case Example: Edwards Aquifer Authority Rules, Texas

The Edwards Aquifer Authority Rules (2010a) detail how the Authority will manage water in the basin. The Rules include procedures for water applications, fees, groundwater withdrawals, water quality, and enforcement. The enforcement chapter of the Rules applies to any person who violates the Authority's rules or the terms or conditions of an Authority permit.

The Board of Directors of the Authority outlines six enforcement actions that it may take in the event of a violation. It may take these actions after giving the potential violator 10-day written notice and an opportunity to be heard at a Board meeting. The board may (1) suspend processing any pending applications; (2) suspend permits or other authorizations; (3) issue orders to cease and desist, and to take corrective action; (4) issue orders to plug, seal, or mark a well; (5) take any other action authorized by law including assessing penalties and filing civil suit; and (6) enter into a settlement agreement (EAA 2010a).

The Authority reserves the right to make a well physically inaccessible if the Rules are being violated. The Board may plug, seal, or mark a well if, for example, permit conditions are not being met. The sealing of a well would be undertaken to prevent unlawful groundwater withdrawals.

In the case of judicial action, the Authority would file a civil suit in the state district court. It may file suit for an injunction, civil penalties, attorney's fees and other costs associated with the suit. The civil penalties can range from $100 to $10,000 per violation per day plus attorney's fees and costs.

2. Case Example: Utah Division of Water Rights

The Utah Division of Water Rights provides a two-page brochure—Enforcement Procedures: A Brief Explanation (UDWR 2009)—outlining the actions they may take in the event of a water rights violation. If UDWR receives a referral of a violation, they will first investigate and evaluate. They will attempt to make sure the violator is aware of the investigation and if needed issue a Notice of Violation or Cease and Desist Order. A preliminary conference or hearing may then be held if requested, followed by a Final Order. Finally, they may investigate compliance.

UDWR offers different courses of action for violations depending on the water user's response. If the accused person disputes the violations he may request a hearing and file rebutting evidence. If the accused person recognizes that they may have committed a violation he may request a hearing to discuss a resolution and if an agreement is reached a Consent Order will be issued. The Consent Order is a settlement. It cannot be reconsidered or appealed. If the accused person does not respond, a Default Order will be issued (UDWR 2009).

UDWR may require violators to pay fines or replace water. Fines accrue on a daily basis from the first day of the violation and may continue until the violator is in compliance. UDWR calculates fines based on factors including the quantity of water taken, impact to others, and whether the violation was knowingly committed. Costs for enforcement, inspections, and replacement water may also be ordered. A violator may be required to replace water and submit a plan describing how it will be replaced. Owned or leased water may be used as replacement water.

In the event that violators don't comply with a Final Order or pay fines and enforcement costs, the fines and costs may continue to accrue. UDWR may then report the violator to a collection agency and take legal action to enforce the Final Order.

3. Case Example: Klamath Water and Power Authority, Oregon

Enforcement of the 2010 KWAPA fallowing program is limited to the termination of the contract. If the contracting irrigator breaks any of the terms of the contract, or doesn't allow KWAPA or the water district to access the land to monitor compliance, then the contract will be terminated. If the contract is terminated, the irrigator will not receive any contract payment (KWAPA 2010b).

4. Case Example: Murray-Darling Basin Cap, Australia

The Independent Audit Group (IAG) reported an area in New South Wales that exceeded their Cap in 2008-09: Baron/Upper Darling and Lower Darling Valley. The area exceeded their cap by an average of seven percent since 1997 and the IAG recommended a special audit. The IAG (Flett et al. 2009) said that mechanisms are needed to address the issue and that the excess water use "serves to undermine the Cap's effectiveness and its enforcement in the eyes of the wider community."

The groundwork for the first Murray-Darling Basin Authority (MDBA) Basin Plan was laid in the Water Act of 2007 (MDBA 2010). As part of the Basin Plan development process, the MDBA released an overview to the plan this year. The enforcement activities that the MDBA may undertake as prescribed by the Water Act of 2007 are summarized in the overview.

Actions that the MDBA is authorized to take to enforce the Basin Plan include: entering properties to gather evidence or monitor, applying to a court for an injunction or civil penalty, and issuing enforcement notices. The MDBA will be the enforcement agency of the Basin Plan but it will leave enforcement of individual entitlement holders to the states. The MDBA will also not use its enforcement powers as a first resort, preferring collaborative action (MDBA 2010).

D. Summary and Implications from Case Examples on Measuring, Monitoring, Enforcing

Significant resources have been spent in the U.S. and elsewhere to refine measuring water savings in voluntary programs to reduce agricultural use. Less attention has been paid to the monitoring and enforcement of programs. Monitoring may be comparatively straightforward in fallowing programs with the use of intermittent site visits and satellite imagery. Crop shifting programs would require more sophisticated monitoring techniques. However, with recent advances in remote sensing crop and ET mapping, monitoring crop shifting may be easier than it was in the past. Enforcement is only briefly mentioned in most program documents and is generally limited to the cancellation of payments.

Despite the unequal focus on measuring, monitoring, and enforcing water transfers, all three aspects could be improved. Innovative approaches are emerging in other water use contexts that may be useful in water transfer programs. Some of these emerging practices are examined in the following section.

III. Innovations: Options for Improving Measuring, Monitoring, and Enforcing

In this section we summarize ideas for improving MME protocols through use of GIS tools, remote sensing imagery, and other innovative ideas that have been either proposed or utilized in fallowing programs. We also look at strategies that may be adapted from other programs seeking to alter agricultural practices and measure or monitor those changes.

A. Why Are Innovations Needed?

Improving current measuring, monitoring, and enforcing of temporary water transfers will benefit water sellers as well as buyers. If employing innovative techniques reduces the costs of monitoring water transfers, those savings can be transferred to sellers in the form of larger payments, or to buyers to be used for additional conservation.

Water conservation programs lacking careful measuring, monitoring, and enforcement put themselves at risk of wasting money and water. In his 2010 report on the lessons learned from the Australian Water Reform Program, Young points out that although the Murray-Darling Basin Cap prevented states from issuing new water licenses, water use expanded considerably and water dependent ecosystems declined. Young (2010) attributes the over-allocation problem to the lack of on-farm monitoring of unmetered uses like tree plantings, and reduced return flows from irrigation efficiency improvements. He concludes, “it will be necessary to manage all forms of water use with greater precision.”

B. A Framework for Designing Monitoring Policy

Monitoring policies are examined in greater depth here. The underlying ideas relate to measuring policies as well. The USDA Economic Research Service (2005) breaks traditional monitoring down to two basic choices: intensive or minimal. Intensive monitoring requires visits to many farms by qualified staff. It is expensive and ties up staff time. Minimal monitoring may compensate for fewer visits with higher fines to encourage compliance. It may let problems slip by and the associated high fines may be unpopular with farmers (ERS 2005).

The ideal might then be intensive monitoring that didn't tie up staff but still avoided the use of heavy fines. Innovative systems using automated and remote technology could accomplish this goal. Alternately, refining the monitoring approach by targeting certain groups or offering compliance rewards may increase compliance without increasing monitoring and enforcement costs.

The problem of determining the efficient amount of compliance monitoring can be modeled by making assumptions about farmers' risk preferences and the monitoring agency's desired environmental outcomes. In the framework laid out by Choe and Fraser (1999), a farmer enrolled in an environmental protection scheme would prefer to do the least amount of conservation while getting the highest payment possible. The agency contracting for conservation may not be able to determine whether the farmer is conserving as agreed, introducing a moral hazard problem. In the water transfer case this would be equivalent to a farmer enrolling in a program but then using the water to continue growing crops, possibly bringing new fields under irrigation, despite being paid to conserve.

Monitoring is costly but a program that pays for water and gets none is more costly still. Programs with good monitoring practices will be more credible and therefore more likely to continue to be viable programs into the future. The water-buying agency must decide how much to monitor participating farmers. There is a trade-off between the amount of monitoring and the cost effectiveness of a program. At one extreme, complete monitoring could ensure total contract compliance by farmers but at a very high cost. The efficient level of monitoring will vary by program. Generally, efficient monitoring should encourage farmer compliance enough that the benefits of the transfer program are reasonably assured while monitoring costs are kept below an appropriate threshold. A threshold of one percent of total program costs (or less) might be used as a starting point. The costs section of this paper provides examples of the types and extent of monitoring costs.

In Choe and Fraser's (1999) model, the efficient level of monitoring depends on farmer and agency characteristics. The farmer is characterized by his costs, conservation efforts and risk preferences. The farmer is rewarded with a payment based on conservation effort. The payment may be negative, i.e. a fine, if the farmer conserves less than the agreed upon amount. The agency is characterized by its monitoring costs, monitoring effort, and choice of payments or fines.

The agency chooses their monitoring effort, payment and fine levels in an attempt to maximize conservation benefits less expected payment to the farmer and monitoring costs. The farmer chooses their level of actual conservation based on the agency's monitoring effort, the payment the farmer will receive for conservation, and the fine for cheating. The optimal model result, which varies with farmer risk aversion and monitoring costs, ranges from schemes with low monitoring and high payments (or fines) to schemes with intensive monitoring and a smaller range of payments and fines (Choe and Fraser 1999).

In the end, these models indicate that in all cases adopting better monitoring technology will benefit monitoring agencies in multiple ways. Choe and Fraser (1999) conclude that policy-makers should reduce monitoring costs by using advancing technologies, like satellite-based remote sensing. Remote sensing might also help reduce measuring costs.

C. Innovations in Measuring, Monitoring, and Enforcing

Measuring, monitoring, and enforcing innovations examined in this section range from those gaining acceptance in agricultural uses to those not yet tried or tested. Innovative techniques and technologies could increase measuring or monitoring accuracy and may not be expensive. However, the innovations need to be carefully matched to local needs and to appropriate uses. A technology useful for monitoring whether an enrolled field is being fallowed may be impractical for measuring the amount of water conserved by fallowing. Likewise, a technology suited to measuring water savings might be too complicated or expensive if all that's needed is verification that no irrigation has taken place on enrolled fields. New technology installation is required in some cases but existing technology or policy adjustment can also be used as a low-cost means to increase measuring, monitoring, and enforcing power.

1. Remote Sensing

Free remote sensing image archives, provided by NASA and the USGS, now span over three decades. This collection is an enormous, mostly untapped, resource for water managers. Although remote sensing is beginning to be used in official capacities, its full potential is not yet realized. The Bureau of Reclamation uses remote sensing data to map crops and riparian vegetation in the Lower Colorado River Basin (BOR 2009) and has also used remote images to monitor fallowing programs (DOI 2009). Researchers in the U.S. are estimating field-specific evapotranspiration (ET) using satellite images (Allen et al. 2007b; Elhaddad et al. 2011; Glenn et al. 2011; Piñón-Villarreal et al. 2010).

More and more conservation programs, including the USDA's Wetlands Reserve Program (USDA 2006) and the Idaho Department of Water Resources' Water Transfer Program (IDWR 2006), are using satellite images to monitor participants. Measuring water savings (based on changes in ET) with satellite images is a promising, though more complex, innovation. Samani et al. (2007) tout the use of remote sensing to calculate ET, "over a large scale for various crops, riparian vegetation and soil conditions without the complications associated with traditional methods of assessing ET."

Four uses of remote sensing to monitor and measure water use are examined here. The first two cases are primarily suited for monitoring participant compliance; the second two are suited for measuring water savings. In the first case, the Bureau of Reclamation's Lower Colorado River Accounting System (LCRAS) uses satellite imagery together with a GIS database to map vegetation annually. Once crops are mapped, the BOR estimates ET using classic crop-coefficient methods. In the second case, the National Agricultural Statistics Service's CropScape uses satellite images to produce crop cover maps for major crops all over the U.S. In the third case, surface energy balance methods combine thermal satellite images with ground-based weather data to estimate evapotranspiration. In the fourth case, vegetation index based methods combine indexes like the Normalized Difference Vegetation Index (NDVI) and traditional ET methods to estimate a relationship between local vegetative cover and ET.

For a detailed description of evapotranspiration (combined evaporation and transpiration) estimation and introduction to remote sensing and its use in water measuring and monitoring, please see the appendix: Remote Sensing Techniques.

a) Monitoring conservation

Programs wishing to adopt remote sensing could start by monitoring fields using satellite images. With 30 by 30 m pixels (.22 acres), Landsat images would be detailed enough to show fallowing on fields as small as a few acres. MODIS images, with a 250 by 250 m pixel size (15.44 acres), might be used to monitor large fields. The two examples below describe monitoring using remote sensing.

(1) Lower Colorado River Accounting System

The Bureau of Reclamation Lower Colorado Regional Office (BOR) reports diversions, return flows, and consumptive use of water diverted from the Colorado River below Lee Ferry in their annual Decree accounting reports.[13] These reports are produced to satisfy the U.S. Supreme Court's 1964 *Arizona v California* decree. The LCRAS was created to refine agricultural consumptive use estimates from Hoover Dam to Mexico using evapotranspiration.[14] The LCRAS reports have been produced in addition to the Decree reports since 1995.

LCRAS reports provide estimates of evapotranspiration (ET) for three ground covers: irrigated agriculture, riparian vegetation, and open water. The BOR uses remote sensing data from satellite images and GIS mapping to identify the different ground cover areas along the Colorado River, which are then stored in a GIS database. The satellite images come from Landsat 5, Landsat 7, and Terra satellites (BOR 2009). Ground surveys are also collected on about 12% of irrigated fields. Almost two thirds of the ground survey data is used to classify crop group images. The remaining ground surveys are used to check the accuracy of the classifications (BOR 2009).

[13] "Lower Colorado River Water Accounting," Bureau of Reclamation, modified January 2012, http://www.usbr.gov/lc/region/g4000/wtracct.html
[14] *Ibid.*

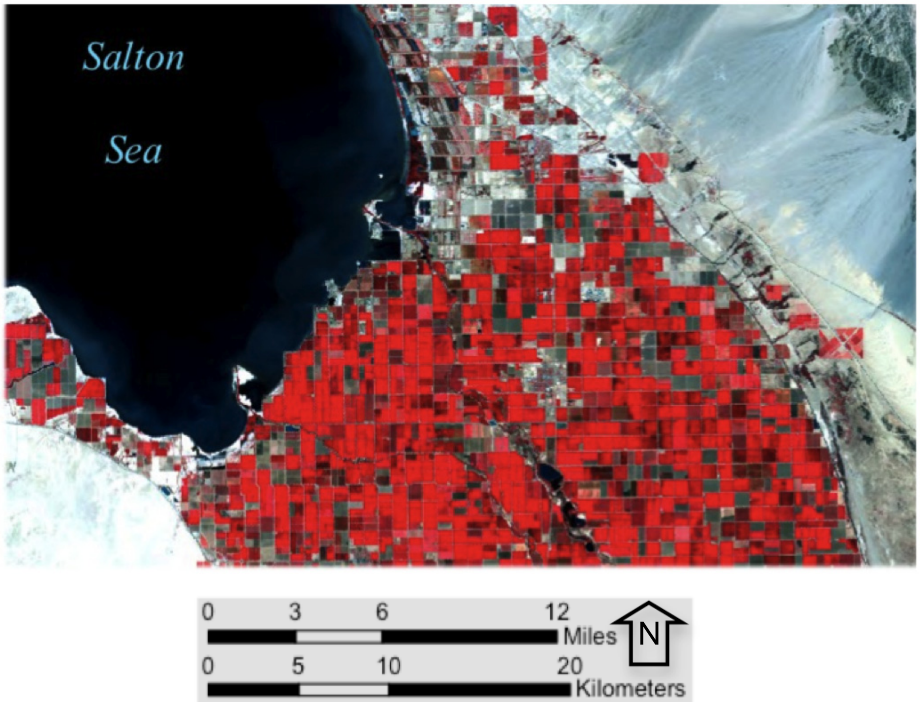

Figure 3 Imperial Irrigation District Landsat 5 TM Image, acquired May 1, 2008 (BOR 2009)

The spectral values obtained from the remote sensing images are used to differentiate ground covers. The BOR has analyzed the spectral values of ground reference sites to create spectral statistics for the different ground covers. They also created a spatial relational database containing all irrigated field borders. Using remotely-sensed spectral data and the spatial database, the BOR identifies the crop groups grown on each field each year (BOR 2009). In 2008, the BOR identified 28 crop groups. Crop groups included alfalfa, small grains, lettuce, idle, and fallow. The BOR calculates ET based on crop groups instead of calculating ET for each individual crop variety. Figure 3 shows a partial Landsat 5 image of the Salton Sea and Imperial Irrigation District from the LCRAS (BOR 2009). The image shows a color composite of bands 4, 3, and 2 from Landsat 5's TM instrument. It is false color, with band 4 (infrared) shown as red, band 3 as green, and band 2 as blue. This coloring makes vegetation stand out because green vegetation reflects infrared light. Vegetation shows up in shades of pink to dark red depending on type and growth stage.[15]

The BOR does not estimate ET for idle or fallow fields although they do identify them as crop groups. Although the BOR does not estimate ET values for fallow or idle fields in the LCRAS, this does not mean that these fields have zero water use. As noted by the California Department of Water Resources, water seeping from nearby fields and weed growth may allow significant amounts of water to evaporate from fallowed fields (CDWR 2009a).

A fallowing monitoring policy could be adapted from the BOR's method for identifying fields and ground cover. Their crop group mapping accuracy in 2008 was over 90% accurate (BOR 2009). Accuracy in the detection of fallow versus crop groups was not reported separately,

[15] "An Introductory Landsat Tutorial," NASA, last accessed June 5, 2012, http://zulu.ssc.nasa.gov/mrsid/tutorial/Landsat%20Tutorial-V1.html

although the difference between crops and fallow fields is probably easier to detect than differences between types of crops, particularly late in the growing season when crop vegetation is mature.

Accuracy depends in part on field size. Field size is not specified in the LCRAS, but fields in the basin tend to be large. Landsat TM pixels are 30 by 30 meters.[16] A one-hectare field, for example, would contain about 11 pixels. As a rough rule of thumb, monitoring fields larger than one hectare by remote sensing should be feasible depending on field shape. Monitoring smaller fields by Landsat could be possible but local images would need to be consulted. In Figure 3, a common field size is about 65 hectares (160 acres). Landsat TM resolution for fields of this size is over 700 pixels. In programs that wish to use Landsat as the primary monitoring method, minimum field size should be taken into account during enrollment.

Remote sensing data might also offer future potential for automated monitoring. Once fallowed fields were identified in a GIS database, satellite image retrieval and spectral comparison might be automated. If the spectral data for a fallowed field fell outside expected fallow parameters, the monitoring agency could verify on the ground.

(2) CropScape and the Cropland Data Layer

CropScape[17] is the online geospatial data and visualization service of the Cropland Data Layer produced by the National Agricultural Statistics Service (NASS). CropScape was unveiled in January 2011. The Cropland Data Layer (CDL) contains information about the type and location of over 100 major crops grown in the U.S. The CDL uses images from Deimos-1, UK-2, Waifs, and Landsat 5 satellites.[18] CropScape is the online portal for viewing the CDL. It doesn't require specialized software to view or download the spatial data. CropScape's uses include land cover monitoring and biodiversity assessment (NASS 2011).

CropScape imagery is produced at a sufficient scale to monitor individual fields—30 meters. However, at this time it is only useful for historic, not real time, monitoring. NASS does not release CDL data during the growing season because of its possible detrimental effect on the market and investors; and because it is unverified until the growing season is over (Mueller 2011). Early in the growing season it can also be difficult to distinguish fallowed fields from other fields, including rangeland (Mueller 2011). CropScape's release schedule limits its use as a real-time fallowing monitoring tool. However, it provides a detailed example of how GIS and satellite images can be combined for agricultural monitoring. Agencies might be able to develop a local real-time monitoring tool using CropScape as a guide.

For measuring actual reductions in water consumption, it could be used to establish past cropping patterns and estimate fallowed water savings. Its suitability will depend on the program location, whether the crops grown are among the over 100 crop types that CropScape supports, and the complexity of cropping patterns. Figure 4 shows an example of a partial CropScape, CDL image of Alamosa County, CO from 2011. Major crops in Alamosa include

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[16] "Land Cover Analysis," NOAA, last accessed April 20, 2012, http://www.csc.noaa.gov/crs/lca/faq_gen.html
[17] "CropScape – Cropland Data Cover," USDA NASS, last accessed April 20, 2012, http://nassgeodata.gmu.edu/CropScape/
[18] "About CDL," USDA NASS, last accessed April 25, 2012, http://www.nass.usda.gov/research/Cropland/SARS1a.htm

potatoes (rust), barley (hot pink), and spring wheat (light brown).

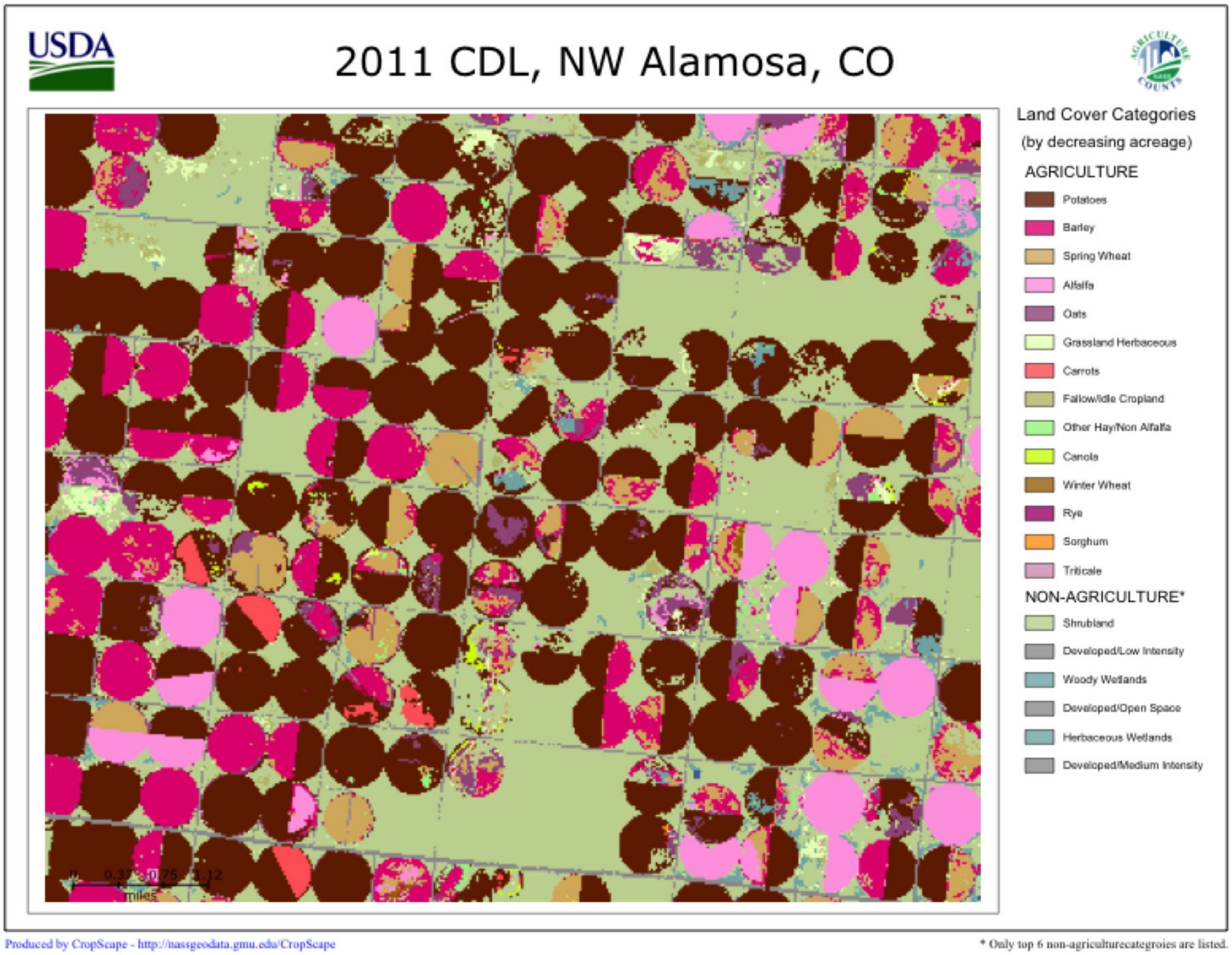


Figure 4 CropScape CDL Alamosa, CO 2011

b) Measuring conservation

A more advanced application of remote sensing involves using images to estimate actual farm field evapotranspiration. Remote sensing models to estimate ET have developed along two main lines: surface energy balance or vegetation index. Bastiaanssen and others have been refining the use of an energy-balance model coined SEBAL for over 15 years to estimate actual ET (for example, Bastiaanssen et al. 2005). Researchers in the Western U.S. have been working more recently to tailor these models to local climates and needs (Allen et al. (2007b) in Idaho; Piñón-Villarreal et al. (2010) in New Mexico; Taghvaeian (2011) in the Lower Colorado River Basin). ET models based on vegetation indexes have developed as an alternative and a complement to energy-balance models (Glenn et al. 2011; Hunsaker et al. 2007; Nagler et al. 2009).

The availability of historic as well as current remote sensing imagery gives users more options for measuring water conservation. Fallowing programs that estimate water savings using cropping pattern and crop coefficients could replace coefficients with remotely sensed ET.

Alternately, fallowing programs could estimate water savings by comparing remotely sensed ET on fallow fields and cropped fields in the same time period. In the first, or fixed-field option, ET would be estimated using remote sensing for the enrolled field over two time periods. The first period would be representative of historic cropping on that field. The second period would be the current fallow or crop shifting condition. Water conservation would be measured by taking the difference of ET over the two periods. In this case, the measurement would have to be adjusted to take differences in potential ET into account.[19] In the second, or cross-field option, measurement would be based on a comparison of ET on two fields during the same time period. The participating field would be engaged in crop shifting or fallowing. A matching field would be chosen based on its similarity to historic cropping on the participating field. Water conservation would be measured by taking the difference in estimated ET on the two fields.

Remote-sensing ET models are complex. To date, packaged software to run these models is not available. The investment required to implement them may not be justified in all programs. In areas with sufficiently large fields, remote sensing could be used to directly estimate ET changes on fields enrolled in conservation programs (size restriction based on spatial resolution of satellite images). If fields were not large enough for reliable remote ET estimation, water agencies might use remote sensing to update local crop ET coefficients instead of using traditional lysimeter and crop coefficient studies. A lysimeter measures actual evapotranspiration from crops by isolating the crops and tracking water going in and out of the lysimeter. Remote sensing offers a promising alternative for measuring water conservation in places where other measuring choices are either impractical or outdated.

(1) Surface energy balance

Surface energy balance (SEB) models use thermal satellite images to estimate ET. They are based on the principle that the energy arriving at and leaving a field surface must balance. As water evaporates and transpires it uses energy, so ET is a factor that can be estimated in the surface energy balance. Researchers have developed many SEB models. An example model, METRIC, is described here. Others include REEM (Samani et al. 2007), and ReSET (Elhaddad et al. 2011). ReSET is described in section VII. Appendix: Remote Sensing Techniques.

METRIC is an energy-balance method for mapping evapotranspiration at a moderate scale (limited by thermal image spatial and temporal resolution). The maps can be used for water rights conflicts, groundwater management, and determining actual ET at many scales (Allen 2005), although it is unsuitable for real-time irrigation scheduling. METRIC uses thermal images from Landsat satellites. Two Landsat (5 and 7) satellites follow overlapping 16-day imaging schedules with an offset of 8 days. However, Landsat 5 imaging was taken offline in November 2011 due to a rapidly degrading component. The USGS announced in May 2012 that Landsat 5 TM ceased regular acquisitions.[20] ET is interpolated between the satellite passes or possibly longer if images are not cloud free. Working with this schedule, METRIC offers a way to measure field water use at a seasonal scale. As farmers irrigate, their fields

[19] "Water Transfer Design and Verification," SEBAL North America, last accessed April 25, 2012, http://www.sebal.us/

[20] "Landsat 5 Thematic Mapper Ceases Routine Acquisitions - Update," USGS, May 8, 2012, http://landsat.usgs.gov/mission_headlines2012.php

become cooler because evapotranspiring water absorbs energy. This temperature difference is what the satellite images highlight. METRIC combines data from Landsat with ground-based reference ET to boost accuracy (Allen 2005). A video overview of how Landsat imagery can be used to estimate ET is available from NASA.[21]

METRIC offers a potentially cost effective, accurate way to measure water conservation using Landsat data. To date, six Landsat satellites have captured data going back over three decades,[22] so ET can be estimated for prior as well as current years. Landsat technology has changed over time however, and older data may be harder to work with. Most current applications, like METRIC, use Thematic Mapper (TM) imagery. TM was first introduced on Landsat 4, launched July 16, 1982.[23].

No major capital investments are required to implement METRIC although local weather stations are required. Allen (2005) lists three necessities for estimating ET using METRIC: high-resolution thermal satellite images, good quality weather data, and an "experienced, thinking human at the controls." Given that Landsat images remain free and that local weather station data is not hard to come by, the limiting factor for implementing these kinds of models is probably staff training.

The NASA/Goddard Space Flight Center Scientific Visualization Studio has created an animation showing visible, thermal, and METRIC ET images of an agricultural area in Idaho. Figure 5 shows Landsat's visual bands: 1, 2, and 3. Figure 6 shows Landsat's thermal band: 6. Figure 7 shows ET for the same area and day, calculated using METRIC.

Figure 5 Landsat Visual Image of Idaho Agriculture[24]

[21] Shoemaker, J. 2009, "Landsat: A Space Age Water Gauge," NASA, http://www.nasa.gov/topics/earth/features/landsat_water.html
[22] "From the Beginning," NASA, modified April 19, 2012, http://landsat.gsfc.nasa.gov/about/history.html
[23] "Landsat 4," NASA, modified April 19, 2012, http://landsat.gsfc.nasa.gov/about/landsat4.html
[24] "NASA/Goddard Space Flight Center Scientific Visualization Studio," NASA, last accessed April 20, 2012 http://svs.gsfc.nasa.gov/goto?3632

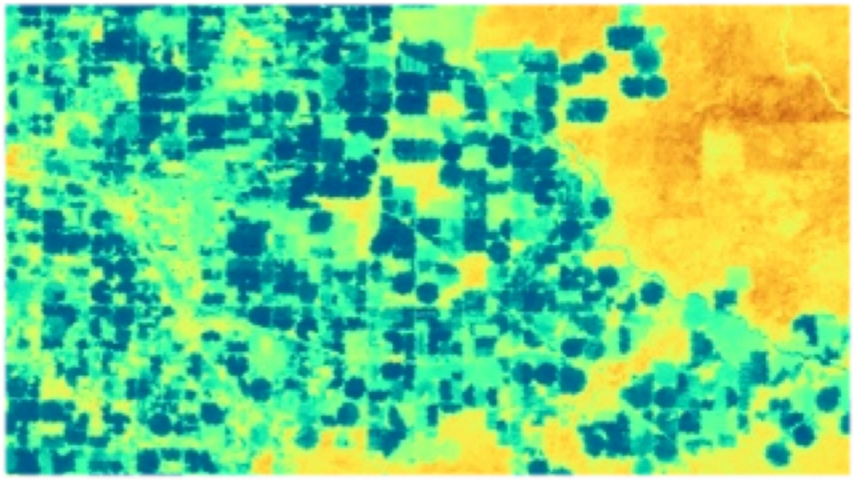
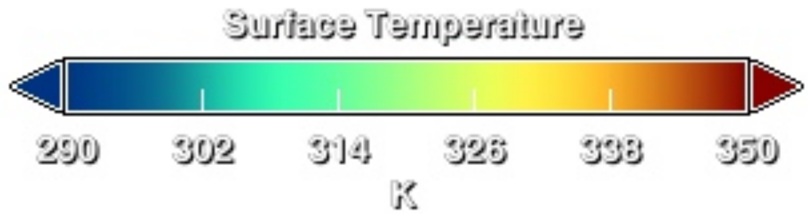


Figure 6 Landsat Thermal Image of Idaho Agriculture[25]



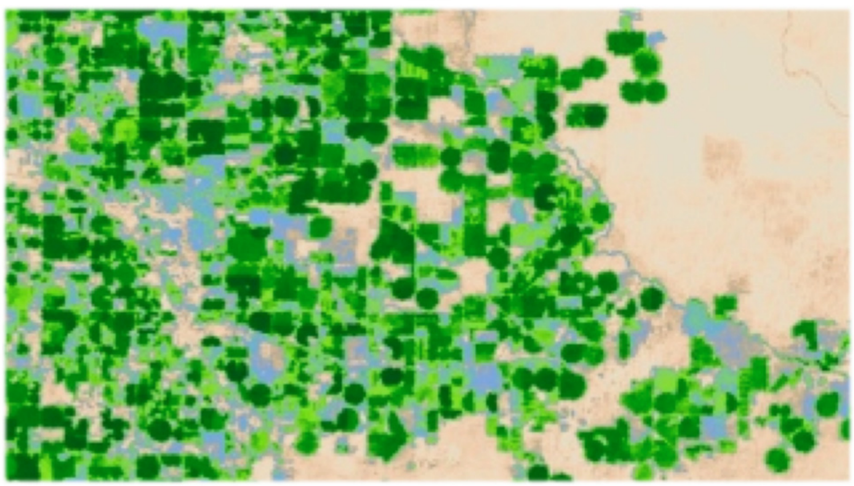
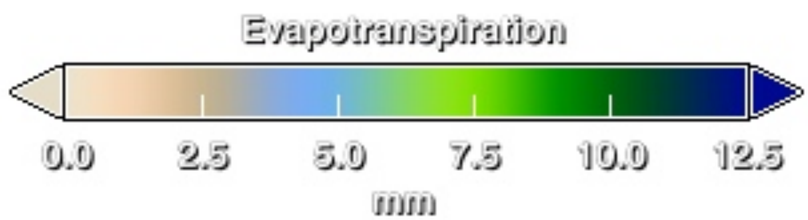


Figure 7 METRIC ET Map Created with Landsat Data of Idaho Agriculture[26]



(2) Vegetation index

Vegetation index (VI) methods are a less computationally intense way to estimate ET with remote sensing. Simplified versions of these methods might also be used to monitor

[25] "NASA/Goddard Space Flight Center Scientific Visualization Studio," NASA, last accessed April 20, 2012, http://svs.gsfc.nasa.gov/goto?3632
[26] *Ibid.*

conservation. Most vegetation index (VI) methods estimate the transpiration part of ET by comparing the amounts of red and near infrared light in an image. The Normalized Difference Vegetation Index (NDVI) is a commonly used VI. Its values range from -1 to 1. NDVI for barren areas is close to zero. It is moderate for shrub and grassland (0.2 to 0.3) and high for rainforests (0.6 to 0.8).[27]

Vegetation indexes are used in conjunction with ground-based reference ET (ET_0) to estimate ET. As part of their implementation, VIs must be calibrated by being regressed against ground ET measurements in the area where ET will be estimated. Empirical relationships are established between the VI, ET, and weather data to find the local correlation between vegetation cover and ET (Senay et al. 2011). VI methods cannot estimate evaporation like an SEB can, but plant transpiration is the larger part of ET and often the major unknown (Nagler et al. 2009). Once calibrated, VI methods can predict actual ET.

The main advantage of VI methods compared to SEB is ease of calculation. Rafn et al. (2008) say their NDVI method, "is relatively fast, easy, and requires little knowledge of evaporation physics and aerodynamics." Tang et al. (2009) compared the Landsat-based METRIC with a MODIS-based modified VI approach in the Upper Klamath River Basin in Oregon. Their comparison showed a tendency for the VI approach to underestimate seasonal ET and for METRIC to overestimate it, compared to surface flux observations. The primary disadvantage of vegetation index ET estimation is the focus on transpiration only.

2. <u>Precision Irrigation</u>

In the Flint River Basin, Georgia, a collaboration that began in 2004 to conserve water by making central pivot irrigation more efficient has since saved billions of gallons of water (TNC 2010). The Nature Conservancy, Flint River Soil and Water Conservation District, and the U.S. Department of Agriculture formed the Flint River Basin Partnership and have worked with farmers in the region to install the variable rate irrigation (VRI) systems responsible for the water savings. VRI systems are limited to use with sprinkler irrigation. They are also expensive, requiring regional and farm level infrastructure investments. Although the expense could be hard to justify solely for improved measuring or monitoring, VRI and other precision irrigation technologies could benefit farmers by improving yields, and lowering water use and associated input costs. This potential, combined with improved measuring and monitoring benefits for water transfer programs, could make them feasible in areas with multifaceted water conservation programs.

In a VRI system, a GPS is mounted on a central pivot or lateral move sprinkler irrigation system. A controller on the sprinkler uses soil moisture data collected from wireless monitors to manage water application rates. As the pivot moves around the field its position is tracked via GPS and valves on each sprinkler nozzle automatically open and close to provide precise irrigation (Watson and Scarborough 2010). Figure 8 illustrates how water application rates might vary across a field. The soil moisture monitors collect real-time data and send it via wireless broadband network to farmers. Farmers can then adjust irrigation schedules so water is applied only as needed (Watson and Scarborough 2010).

[27] J. Weier and D. Herring. "Measuring Vegetation (NDVI & EVI)," accessed February 20, 2012, http://earthobservatory.nasa.gov/Features/MeasuringVegetation/

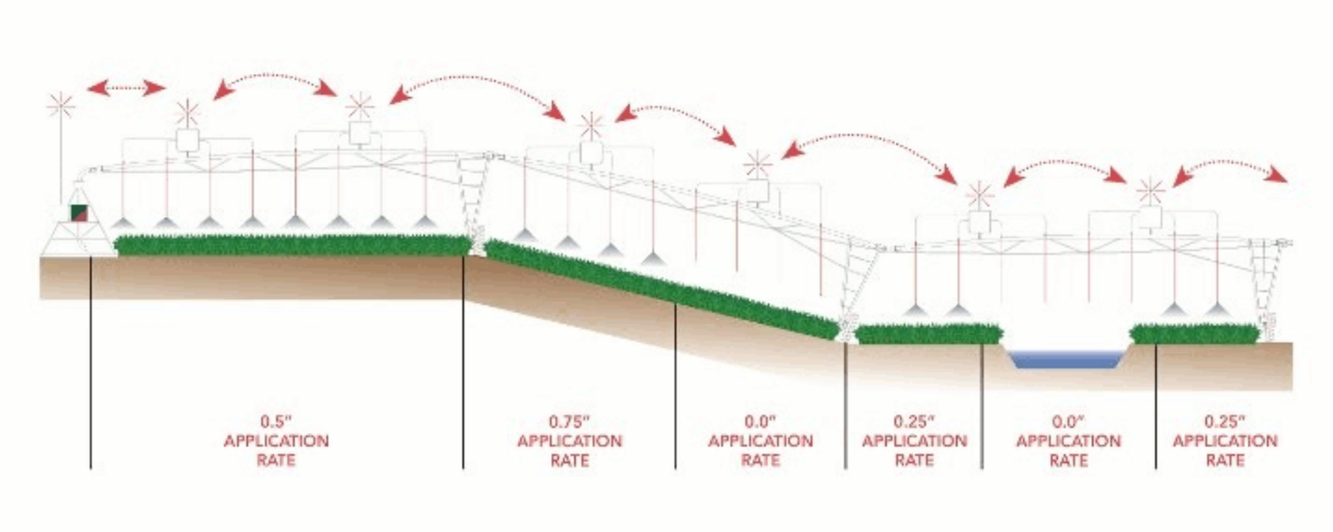


Figure 8 Variable Rate Irrigation System Illustration[28]

Regenesis Management Group, a Denver-based company founded in 2009, is testing a similar system in Colorado. The system, called SWIIM (Sustainable Water & Innovative Irrigation Management), feeds field-based water and crop data instantly to computers. Using the data, irrigation can be turned on and off when stream gauges or soil sensors measure the need to do so (CWI 2011). Regenesis hopes to be able to use the system to support water transfers. Precise water use measurements taken and stored by the system can be used to support farmers' transfer proposals, making water transfers easier to arrange.

Precision irrigation systems could support fallowing programs in two ways: measuring conserved water and monitoring contract compliance. A few seasons after such a system was installed, applied water records could be used in crop shifting or deficit irrigation programs. Water application records could be used to validate crop water savings when irrigators shift to lower water use crops. They could also provide evidence of reduced water application in deficit irrigation agreements.

The soil moisture monitors used in precision irrigation could be used to monitor fallowing programs. Where wireless broadband network was available or could be installed, remote soil moisture monitors could be placed in fallowed fields. Monitors with GPS units could transmit their position and soil moisture conditions to a central location. An automated system could be programmed to email a monitoring agency if the position of the monitor changed or if soil moisture benchmarks were exceeded. The system might also be programmed to check weather station data or compare data from multiple fields to reduce the likelihood of false positives. If the system detected unexpected moisture, a field visit would confirm if there was a sensor malfunction or if the field was being watered.

Remote soil moisture monitors save farmers significant time compared to driving from field to field to check soil (Watson and Scarborough 2010). Although farmers may prefer to check soil moisture by hand and use the monitors only for verification or additional information (Morris 2006). The potential time savings could be enjoyed by monitoring agencies if monitors

[28] "Precision Irrigation," accessed April 18, 2012, http://www.precisionirrigation.co.nz/

reduced the need to visit every farm engaged in fallowing.

3. Targeted Monitoring

Targeted monitoring has been proposed to alleviate the problem of moral hazard. Fraser (2004) developed a targeted monitoring model focused on conservation programs that provide payment for conservation with penalties for noncompliance. In these programs the problem of moral hazard, i.e. farmers taking payments without conserving, cannot be eliminated with traditional partial monitoring schemes. With targeted monitoring, a subset of participants is selected as the primary monitoring targets. The choice of what subset to target first may be random or based on participant characteristics.

Fraser examines three types of targeted monitoring: budget neutral, non-budget neutral, and adjusted budget neutral. In the budget neutral approach, an agency monitors the targeted group more and compensates for the extra cost by monitoring the non-targeted group less. In the non-budget neutral approach, an agency monitors the targeted group more while maintaining the same level of monitoring for the non-target group. In the adjusted budget neutral approach, an agency monitors the targeted group more while adjusting the level of monitoring and penalties in the non-targeted group to eliminate moral hazard. The division into targeted and non-targeted groups can made based on geography or other farmer or farm characteristics. If, for example, the program participants were divided equally into four groups, one group could be monitored during each monitoring period. The targeted group would rotate each period except that those found cheating in previous periods would continue to be in the targeted group (Fraser 2004).

Fraser rejects the budget neutral and non-budget neutral approaches because they do not stop everyone who was already cheating from doing so and they may induce cheating in the non-target group. He prefers the third approach because it has the potential to increase compliance in both the targeted and non-targeted group. With the third approach, the targeted group is monitored more while the non-targeted group is monitored less to maintain budget neutrality. To counteract the tendency for some in the non-targeted group to start cheating, the penalty for noncompliance was increased to the point that the risk of being caught cheating was too great for risk-averse participants to start cheating (Fraser 2004).

4. Compliance Rewards

Yano and Blandford (2009) show that the use of compliance rewards can increase compliance rates in agricultural conservation programs. A compliance reward is a payment made to a farmer if they are found to be complying with the terms of their conservation contract. The use of a compliance reward may be justified because models show it can increase farmer compliance without increasing monitoring cost in some situations. If it is assumed that the main goal of monitoring programs is to maximize contract compliance while minimizing monitoring cost, then compliance rewards could be useful. The authors do not suggest that compliance rewards should replace other monitoring efforts; only that compliance may be increased using rewards without increasing costs to the monitoring agency.

The authors first take a budget-neutral stance, assuming that monitoring agencies will not be able to increase their budgets in order to offer compliance rewards. To remain budget neutral, compliance awards can be funded either by reducing the amount of monitoring or by reducing the number of farmers enrolled in a program. If compliance rewards are funded by a reduction in monitoring effort then compliance will increase in some, but not all, situations. If monitoring effort is significantly reduced (inspection rate falls by more than 80%), some farmer's will be more likely to cheat despite the compliance reward.

Yano and Blandford (2009) show that high compliance rates are achievable using compliance rewards funded by a reduction in enrolled farmers. The problem with this approach however, is the potential of excluding the most effective farmers from the conservation program. If the water transfer buyer can rank farmers based on their anticipated benefit to a conservation program, this problem might be avoided. Although even if farmers can be ranked, the potential of not contracting with enough farmers to achieve targeted conservation is a problem with this funding method.

The authors also look at the choice between more compliance monitoring and compliance rewards assuming an increased budget. If more money is available, will compliance increase more if there is more monitoring or if there are more rewards? They show that the preferred choice depends on the monitoring and enforcement costs per farmer. For risk-neutral farmers, if monitoring costs are greater than the fine for noncompliance, compliance rewards work better than more monitoring. For risk-averse farmers, compliance rewards are more likely to work better than more monitoring as risk aversion rises. The authors point out that compliance rewards are preferred in cases where there is a limit on the noncompliance fine or monitoring costs are high or both.

5. <u>Other Innovations</u>

Innovations in energy monitoring might also be used to monitoring water conservation. For example, where smart electricity meters are available and used to measure power use associated with water pumping and conveyance, water use could be monitored in real time using electricity-monitoring programs like Google's PowerMeter. PowerMeter is a free tool that allows users to monitor electricity use online.

Audio or video monitoring with remote online access might also be employed to monitor well pumps or fallowed fields. Motion or sound activated recorders or cameras could be used. In the Kentucky Green River Conservation Reserve Program automated recording systems were installed to monitor bird and frog calls (Grubbs 2008). Sound recognition software was then used to automate the process of reviewing the sound files to catalog birdcalls. An automated system may be devised to detect sounds of pumps running or irrigation water flowing.

IV. Costs: Measuring, Monitoring, and Enforcing

In this section we provide cost estimates for the MME protocols described and descriptions of the specific tasks that need to be performed for effective application of these protocols. The cost estimates are based on prior studies, cost data released by public agencies, and personal communication with program agencies.

A. Balancing Costs and Accuracy

The first question that comes to mind in measuring, monitoring, or enforcing schemes might be—how accurate will they be? Accuracy is probably the most important determinant to the cost of measuring, monitoring, and enforcing voluntary water transfers. Very accurate measurements of applied water could be accomplished with, for example, variable rate irrigation systems that send hourly readings to centralized computers via wireless Internet. However, with installation costs estimated at $138 per acre,[29] this accuracy cannot be achieved without significant infrastructure investments.

Some level of infrastructure costs can be justified by the benefits of increased accuracy: increased buyer confidence that they are getting what they paid for, improved confidence in the water transfer program, and increased transfer participation. Federal funding may also be available to reduce the upfront cost of these kinds of investments, particularly from USDA programs such as EQIP.[30] In the southeastern U.S., average on-farm costs of variable rate irrigation systems dropped over $100 dollars to around $34 per acre after federal cost-share assistance.[31] However, the investment would only be worthwhile in areas where variable rate irrigation furthers other goals. The cost would be difficult to justify for increased water measuring or monitoring accuracy alone.

B. Estimating Costs of Measuring, Monitoring, and Enforcing

Limited data is available on the actual costs of measuring, monitoring, and enforcing water transfer programs. We provide cost estimates where available. Where cost estimates are not available we construct tables that could be used to summarize the major cost categories and aid in the comparison of different measuring, monitoring, and enforcing protocols.

1. <u>Traditional Measuring, Monitoring, and Enforcement Costs</u>

A common method for measuring fallowing program conservation is based on crop records. Programs managed by the California Department of Water Resources; Resource Management Division, Bureau of Reclamation, Mid-Pacific Region; Imperial Irrigation District; and Klamath Water and Power Authority use this method (CDWR and BOR 2009; IID 2010a; KWAPA 2010).

Traditional participant monitoring and enforcement tends to rely on field visits by the contracting agency. Imperial Irrigation District takes pictures of the locked headgates with fallow fields behind them (see Figure 2). Aerial photography is also used. Aerial photography is more expensive by IID estimates but is expected to take less staff time and have accuracy comparable to field visits. The increased availability of free satellite imagery will likely make aerial monitoring less expensive than field visits.

a) Water Transfers Office, California Department of Water Resources and Resource Management Division, Bureau of Reclamation, Mid-Pacific Region

The CDWR and BOR, collectively called the Project Agencies, accept water transfer proposals from individual farmers and water districts. The Project Agencies require sellers to send in crop records, maps, and proof of water rights (CDWR and BOR 2009).

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[29] "Introduction to Precision Agriculture," Clemson Cooperative Extension, last accessed April 20, 2012, http://www.clemson.edu/extension/rowcrops/precision agriculture.html
[30] "Environmental Quality Incentives Program," USDA, modified June 5, 2012, http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/eqip
[31] "Introduction to Precision Agriculture," Clemson Cooperative Extension, last accessed April 20, 2012, http://www.clemson.edu/extension/rowcrops/precision agriculture.html

The water seller calculates baseline consumptive water use for each field based on established crop patterns and the Project Agencies' estimates the evapotranspiration of applied water (ETAW). The amount of water considered transferrable is the difference between the baseline and current ETAW for each field and specific crop fallowed. The water seller must reimburse the Project Agencies for the costs to review and approve proposed water transfers (CDWR and BOR 2009).

The yearly costs for measuring in this case falls almost entirely on the water seller. The water seller must provide all documentation, calculate baseline and current ETAW, and reimburse the Project Agencies for any costs incurred in verifying and approving the transfer. The Project Agencies provide the ETAW values. In 2009, the CDWR reported potential problems with current ETAW values. First, the values may be outdated: new crop varieties and refined water use measures have been introduced since the crop consumptive use figures were developed. Second, water seeping from neighboring fields and weed growth may be allowing significant amounts of water to evaporate from fallowed fields. So, the assumption that fallowed fields use no water is questioned (CDWR 2009).

The major costs that the Project Agencies incur are associated with updating ETAW values. The CDWR outlines three action items to update ETAW: (1) holding a summit to discuss evapotranspiration of crops grown in the Sacramento Valley and to identify what is needed to monitor surface evaporation from idle fields; (2) developing a plan for ETAW research and establishing a timeline for updating ETAW; and (3) identifying cooperators and developing a financing plan for research and monitoring (CDWR 2009). The categories of costs incurred by the Project Agencies and water sellers are summarized in Table 4.

Table 4 Project Agencies and Water Seller Costs

Measuring Costs
Program Agencies' costs
Updating ETAW:
ETAW summit
Planning and timeline
Research and monitoring
Participant's costs
Review of:
crop records
maps
water rights
Establish crop pattern
Calculate baseline and current ETAW

The Agencies' year-to-year measuring costs associated with this approach are probably low although the costs to update ETAW could be significant. Lysimeter studies are the preferred method for finding or updating the crop coefficients used in ETAW calculations. Lysimeters measure actual evapotranspiration from crops and are generally custom made to suit local conditions. Lysimeter design variability makes their construction and installation costs difficult to predict. Table 5 lists the sizes and costs of some example lysimeters. The prices are inflation adjusted to 2011 dollars. Several of the studies reported costs for installing multiple lysimeters. We report cost per lysimeter for comparability.

Table 5 Lysimeter Construction and Installation Costs

	Source, Location	Size (l x w x h)	Cost/lysimeter ($2011)
I.	Marek et al. 1988, Bushland, TX	3 x 3 x 2.3 m	$125,013.41
II.	Schneider et al. 1993, Bushland, TX	.75 x 1 x 2.3 m	$6,350.20
III.	Jia et al. 2006, Citra, FL	1.52 x 1.52 x 1.37 m	$25,852.91
IV.	Payer and Irmak 2008, West Central NE	1.52 x 1.52 x 2.13 m	$14,872.80
V.	Event et al. 2009, Jordan Valley, Jordan	2.4 x 3 x 2.5 m	$70,963.89

The costs listed in Table 5 are for the design, fabrication, and installation of the lysimeters only. The studies do not include operation or maintenance costs. To find crop coefficients, only one crop can be studied at a time in each lysimeter and each crop must be cultivated for multiple seasons to obtain enough data.

If the Project Agencies chose a satellite-based method (like METRIC) for updating their ET values, the costs might be lower assuming multiple crops could be studied simultaneously. METRIC was estimated to cost over four times less than traditional means (based on electricity usage) in an Idaho proof-of-concept model of irrigation wells (Morse et al. 2008). METRIC's costs are discussed in more detail in the Innovative Measuring, Monitoring, and Enforcement Costs subsection, starting on page 39.

Up-to-date crop coefficients and traditional ET estimations approaches can provide accurate estimates of water savings in conservation programs. However, the accuracy of outdated crop coefficients, and ET estimates based on them, is uncertain. If crop coefficients are outdated or nonexistent, remote sensing could offer a cost-effective way to estimate water savings accurately.

b) Imperial Irrigation District fallowing program measuring

Imperial Irrigation District (IID) does not require farmers to send crop records with their fallowing program applications because it has water delivery records. Farmers are paid for fallowing based on water deliveries to enrolled fields on an adjusted rolling average of eight of the last ten years. The water yield from the program is also calculated based on reduced water deliveries. IID calculates two water yields: at-farm and at-river. The 2010-2011 Fallowing Program had 9,330.6 acres enrolled. The provisional at-farm water yield for the program was 50,266 acre-feet. The provisional at-river water yield for the program was 54,708 acre-feet (IID 2010b). That implies a per-acre yield of 5.38 acre-feet at-farm and 5.86 acre-feet at-river. The difference between the two yields is the combination of calculated seepage, evaporation, and other losses.[32]

IID's measurement approach is expected to be less costly than a crop ET based approach, like

[32] David Bradshaw, IID Assistant Water Manager, Agricultural Water Management, email to Lana Jones, March 15, 2011.

the one employed in the previous section, but it may be less accurate. Farmer's in the program are paid based on past water use history and trends. Water use history is based on the water delivered to the field, not the water consumed (ET). Presumably not all of the water applied to the field is consumed. Measurement based on historic deliveries could pay different rates for water conserved by fallowing different crops, depending on the ET of the crops and crop mix (double cropping of the same acres is common).

To illustrate the difference between measurement based on water deliveries and water consumption, consider the following example summarized in Table 6. In IID's program, alfalfa fallowing would pay farmers based on water history but limited to the 6 acre-foot program maximum (water application for alfalfa is estimated to average 8.5 acre-feet (Meister 2004a)). Cotton fallowing would pay farmers based on water history (estimated to average 5 acre-feet (Meister 2004b)). The 2010-11 payment of $75 per acre-foot (IID 2010a) would pay $450 per fallowed alfalfa acre and $375 per fallowed cotton acre. Alfalfa has higher estimated ET than cotton. If the ratio of applied water to ET between the two crops were the same, then payments based on water deliveries would be the same as payments based on consumptive use. Based on these per acre payments, IID is paying $134.33 per acre-foot for water conserved from alfalfa fallowing and $126.69 per acre-foot for water from cotton. As a result of this approach, farmers may have an incentive to fallow alfalfa acres before cotton acres. IID, however, would pay less for conserved water if farmers fallowed cotton. Payment is only one of the factors farmers base fallowing decisions on though. Additionally, if farmers pay more attention to payment per acre-foot of water applied instead of conserved, the incentive would work in the opposite direction.

Table 6 ET vs. Applied Water Payments

	ET[1]	Applied Water[2]	Total Payment per acre[3]	Effective Water Payment (payment/ET)
Alfalfa	3.35	8.5	$450[4]	$134.33
Cotton	2.96	5	$375	$126.69

[1] LCRAS 2009; [2] Meister 2004a, 2004b; [3] IID 2010a; [4] Based on 6 acre-foot maximum

However farmers make their fallowing decisions, the difference in payments for conserved water versus applied water could add up with a program of this scope. Consider the 2010-2011 Fallowing Program's total acreage of 9,330.6 (IID 2010b). If farmers offered only alfalfa acres in 2010-2011, IID would have paid $699,795 more than if farmers offered only cotton acres (9,330.6*(450-375)). Alfalfa fallowing would yield more water than cotton fallowing but at a higher cost per acre-foot conserved. The fairness of this approach and the potential for unintended consequences (concentrating fallowing in certain crop groups, changes in drainage) could be detrimental to the fallowing program, or regional economies and environments. These potential negatives could be viewed as a cost of the measurement approach used. IID's Fallowing Programs have been ongoing and successful for many years; updating their measurement procedure is probably not warranted. However, new programs may wish to take these costs differences into account when deciding on how to measure conserved water or pay farmers.

c) Imperial Irrigation District fallowing program monitoring

IID monitors fields participating in its fallowing program approximately four times per year: twice from the ground and twice from the air (usually satellite). IID staff drive to each field to take the ground photos. Satellite photos are purchased. Estimated annual monitoring costs incurred by IID are summarized in Table 7. IID is also looking into photos available from the Bureau of Reclamation (BOR) that are free. The free photos may have high enough resolution to monitor fallowed fields.[33] Five percent of fields fallowed in IID's program are also verified by the BOR to satisfy QSA requirements. The BOR drives out to the fields being verified with IID staff and takes additional photos. These costs are not included in IID's monitoring cost estimates. IID's estimated monitoring costs account for less than one percent of their overall program contracts expenses of $3,589,735 (IID 2010b).

Table 7 IID Fallowing Program Monitoring Costs

Ground photos	
Staff time: travel to fields; take, view, store photos	
Vehicle: fuel, maintenance & operation	
Camera: maintenance & operation, equipment	
Miscellaneous (computer hardware, storage, other)	
Total[1]	$2,000-3,000
Satellite photos	
Staff time: download, view, store photos	
Photos: purchase	
Miscellaneous (broadband Internet access, hardware, storage)	
Total[1]	$4,000-6,000
Annual Total (ground*2 + air*2)	$12,000-18,000
Per acre-foot water conserved (2010)[2]	$.22-.33

[1] Total estimates from David Bradshaw, IID, email Feb 2011; component categories are hypothetical

[2] 2010-2011 Fallowing Program provisional at-river water yield of 54,708.2 af (IID 2010b)

d) Bureau of Reclamation Klamath Project Water Bank

In the Government Accountability Office's 2005 report on the Bureau of Reclamation's operation of the Klamath Project Water Bank, three years of water bank expenditures are provided: 2002, 2003, and 2004. These costs are summarized in Table 8. Compliance monitoring costs are included in the "Other" category. Water quality analysis and a contract with the Oregon Water Resources Department are also included in the "Other" category (GAO 2005). Total "Other" costs represent 0.5%, 0.47%, and 2.5% of total water bank costs in 2002, 2003, and 2004.

Over the three years examined in the GAO report, the BOR reported that it modified its monitoring process. In 2003, the BOR monitored every water bank participant by visiting each field enrolled in fallowing at least once during the year. The BOR also relied on a kind of neighborhood watch: irrigators reporting on program participants in breach of contract. The 2003 compliance rate was estimated at 95%. In 2004, the BOR reduced monitoring efforts to

[33] David Bradshaw, IID Assistant Water Manager, Agricultural Water Management, email to Lana Jones, February, 2011.

reduce costs and only tested fields towards the end of the year. They relied more on neighborhood watch. No intentional violations were discovered in 2004 (GAO 2005). The BOR attributed the large increase in costs in 2004 to increased water requirements and introduction of groundwater pumping contracts (GAO 2005).

Table 8 BOR Water Bank Costs 2002-2004

Costs (2011$)	2002	2003	2004
Groundwater contracts	1,250,356	2,186,689	4,774,388
Klamath Project fallowing contracts	0	3,301,700	758,836
Off-project fallowing contracts	1,185,712	0	821,904
Administration	3,100	214,221	303,791
Other	12,772	27,155	172,408
Total	2,451,940	5,729,766	6,831,327

Source: GAO 2005 (dollar amounts inflation adjusted 2011$)

2. Innovative Measuring, Monitoring, and Enforcement Costs

Innovative measuring, monitoring, and enforcement methods may require significant upfront investments but are expected to be more accurate and less costly in the long run compared to traditional methods. Satellite technology would not require an upfront equipment investment but would require staff time to choose appropriate satellite based models, implement the models, and interpret their results.

a) Remote sensing

The Bureau of Reclamation uses satellite imagery to estimate total evapotranspiration (ET) in the Lower Colorado River Basin. Their models combine imagery taken from Landsat or SPOT satellites with a GIS database. Using spectral analysis, they identify the different types of ground cover in the basin. They use established ET crop coefficients for the ground cover types to calculate ET for the basin. Landsat images are available for free online from USGS.[34] SPOT images cost up to $10,000 per scene.[35]

Research is progressing on the use of satellite remote-sensing technology to estimate daily ET (Allen et al. 2007a and 2007b; French et al. 2010; Hunsaker et al. 2007). This research can be applied to create accurate estimates of actual consumptive water use history for individual fields, water districts, or basins. The cost to implement remote-sensing ET models could be substantial, however the results may be more accurate because the models make no assumptions about crop or field conditions. Proprietary options also exist.[36] Bastiaanssen et al. (2005), compared satellite-based ET to traditional methods: “Spatial coverage is available at the variety of scales needed: field, project, and basin. Temporal coverage is vastly superior at minimal cost to provide similar detail when compared to the field measurement of data.”

Courault et al. (2005) compare the advantages and disadvantages of several remote sensing ET estimation methods. They break the methods into five major categories: simplified, inference models, graphic, determinist, and 3D models. Of these, Courault et al. (2005) note

[34] http://glovis.usgs.gov/, http://earthexplorer.usgs.gov/
[35] Michael G. Baker, Remote Sensing and GIS Specialist, USDI Bureau of Reclamation, email to Lana Jones, February 2011.
[36] SEBAL North America, Inc. for example

the graphic method for being, “Operational, [and] low cost” compared to the other methods. Graphic and inference methods (i.e., vegetation index) are actively researched in the U.S. and have been the focus of remote sensing ET methods examined in this paper. One graphic method is the Surface Energy Balance Algorithm for Land (SEBAL). Bastiaanssen et al. (2005) describe SEBAL as, “a direct method to estimate ET without a priori knowledge on soil, crop, and management conditions… [It] is now an operational instrument for targeting, monitoring, and evaluating irrigation and drainage systems.”

The Idaho Department of Water Resources (IDWR) compared the costs of measuring groundwater well usage using a power consumption method to the University of Idaho’s graphic, satellite based METRIC method (Morse et al. 2008). The IDWR found the cost to measure all southern Idaho wells using METRIC was estimated at $154,450 or $25.97 per well (Morse et al. 2008). The main determinant of the cost was the number of Landsat images needed. The measuring location and time frame determine how many images are needed. For a single date, five Landsat images cover most of southern Idaho. Twelve dates were acquired, leading to a total of 60 images. Total processing costs on a per image basis were $2,574. Initial model programming and implementation costs are not included in this figure. These ramp-up costs could be significant (Morse et al. 2008).

The costs to use energy balance models like METRIC or SEBAL will depend on whether the user chooses to purchase commercial ET maps or implement a model in house. Morse et al. (2008) indicate that using METRIC “is a complex task, and good results will require considerable expertise, training, and experience.” Vegetation index (VI) methods are less complex and may lower implementation costs compared to SEB methods.

b) Remote soil moisture monitoring

A 2006 ATTRA (National Sustainable Agriculture Information Service)[37] study compared a range of soil moisture monitoring methods and included price estimates for each. The methods for measuring soil moisture vary in their cost and accuracy but the basic requirement of a monitoring program would be to detect the presence or absence of irrigation. In this case, a sensor that gives very accurate soil moisture levels would be unnecessary. Granular matrix sensors cost from $25 to $35 dollars and last from three to seven years (Morris 2006). These sensors must be connected to a data logger to retrieve soil moisture data. Data loggers cost from $60 to $500 not including the sensors and cables to connect sensors to the logger. Data loggers must still be visited periodically to collect the soil moisture data that has been logged. Remote sensing systems, like those used in variable rate irrigation systems, send soil moisture from buried sensors wirelessly to a central location computer. These systems start at $1000. The systems are expensive but they allow farmers to monitor soil moisture across multiple fields with one computer (Morris 2006).

A remote soil moisture sensing system would require an initial equipment investment plus time to install the system on all participating farms. However, because these systems could also benefit farmers in years when they are not participating in a fallowing program, cost-sharing arrangements could be explored. Morris (2006) quoted farmers who had instituted soil moisture monitoring on their land in a 2000-2004 National Center for Appropriate Technology

[37] “ATTRA homepage”, NCAT, last accessed June 6, 2012, https://attra.ncat.org/

(NCAT) project, saying that the monitors supported their irrigation decisions and that many saved water. One irrigator was able to delay watering two to three days after a late snowstorm and saved about $100 in electricity as a result. Figure 9 shows an example graphical output from a soil moisture data logger.

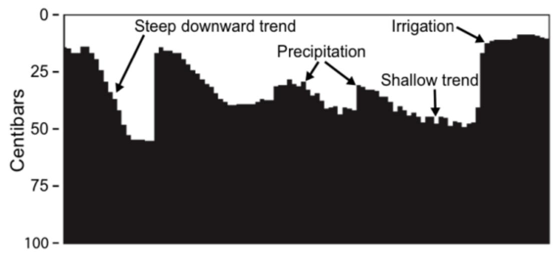

Figure 9 Soil Moisture Data Logger Display
(Morris 2006)

With this type of system, monitoring programs could achieve close to 100% compliance on fallowing contracts with minimal recurring costs. Some technological glitches and breakage would be expected, although they would likely cost less per year than the $15,000 IID monitoring bill. Enforcement would also be simplified with such a system because of the clear evidence the soil moisture monitor would provide. Precipitation would be identified by the height and slope of moisture readings. While these systems would not significantly increase compliance in a program that already had high compliance, it would provide evidence to water buyers that they are getting the water they paid for.

3. Comparing Costs

Table 9 groups common and innovative measuring, monitoring, and enforcement methods and summarizes their expected accuracy and costs to facilitate comparison among the methods. Recommendations based on the accuracy and costs of these methods are discussed in the next section.

Table 9 Cost Comparison Traditional & Innovative MME

Method	Accuracy	Upfront Cost	Ongoing Cost
Measuring			
Water delivery based	Will pay different water prices depending on the crops fallowed; accuracy of actual water savings will depend on strength of formulas used to convert applied water into consumed water	low	low
Traditional ET	Accurate when up to date but loses accuracy over time as crops and farming practices change	$6350-125,000 per installation[1] + O&M	depends on frequency of updates
Remote sensing ET	Accuracy comparable to traditional ET methods; once models are established, frequent updating of ET values to maintain accuracy possible	$30,890 per location + costs to set up model[2]	depends on frequency of updates
Monitoring & Enforcement			
Irrigator "neighborhood watch"	Method lacks verifiability; accuracy varies depending upon, among other considerations, relationships among program participants and water contracting agency	minimal	minimal
Site visits	Assuming site visits are unannounced and appropriately scheduled during the growing season, high accuracy possible	minimal	$4,000-6,000[3]
Satellite based	Assuming temporal and spatial scale available with minimal cloud cover, high accuracy possible	minimal	$8,000-12,000[3]
Remote soil moisture meters	Highly accurate method compared to other options; soil moisture data may have additional farmer and verification benefits; cost sharing with farmers or government agencies possible[4]	$1,000+ per installation[5]	low

[1] See Table 5; [2] Morse et al. 2008; [3] Ongoing costs on low end of range with free satellite imagery (David Bradshaw, pers. com. 2011); [4] http://www.clemson.edu/extension/rowcrops/precision agriculture.html; [5] Morris 2006

V. Recommendations for Effective Measuring, Monitoring, and Enforcing

In designing any irrigation fallowing program, it is essential to clearly articulate the overall goal of the program. Generally this will be to secure water at a reasonable price in order to transfer water to another use, whether it be environmental, in-stream, municipal, or another consumptive use. Other goals of a program could include securing water in a fair way with minimal disruption to local economies; and instilling confidence in water buyers while maintaining the goodwill of water sellers.

The task of ensuring that the water being purchased is actually conserved can be broken down into two main components: measuring conserved water, and monitoring and enforcing contracts. Defining and measuring conserved water is the more technically difficult part of the process. The expenses a program incurs in measuring conserved water will depend on the nature of the program, and perhaps, what the water will be used for. The final decision will be a balancing of costs and benefits. What are the benefits of having a very accurate measure of conserved water and what are the costs of that measurement? With new remote-sensing based methods of measuring ET, it may be possible to get accurate measurements at a lower cost than what was the norm in the past.

Acquisition programs need the goodwill of the irrigation community, including growers and district managers. Definitions of conserved water and MME protocols need to be developed with this goodwill component in mind. It is possible that a mutually agreed upon definition and set of MME protocols may represent a compromise between irrigation community acceptance and cutting edge technical understanding. Remote-soil moisture sensors, for example, would require significant involvement from irrigators to implement. The farming community may be willing to participate though, if the technology has been proven effective at both lowering costs and raising yields. Many of the innovative technologies discussed here have benefits to offer farmers, which should be emphasized when planning MME strategies. From a program point of view remotely sensed ET can provide accurate, reasonable-cost estimates of water savings. From a farmer point of view, it can provide real-time access to crop-water interactions and contribute to better irrigation scheduling.

Monitoring and enforcing contracts, while not necessarily technically difficult, can account for a significant portion of program costs. As with measuring though, innovative methods have emerged that could increase accuracy (and program compliance), while also decreasing costs compared to traditional methods.

In this section we suggest guidelines and make recommendations for developing and implementing effective measuring, monitoring, and enforcement of irrigation fallowing programs.

A. Measuring—Recommendations and Guidelines

Many of the technologies covered in this report can be used for either measuring reduced consumptive water use or monitoring compliance with fallowing program requirements. However, care should be taken to match the technology to its appropriate use. Monitoring fallowed fields using free Landsat images would require minimum staff training or time. Measuring the ET of fields before and after fallowing with remote sensing based models would require significantly greater investment. We explore three basic methods to measure water savings in this report: water delivery based, traditional ET, and satellite-assisted ET. The water delivery method is cost effective but is expected to be the least accurate of the methods. The traditional ET method is accurate and cost effective if up-to-date. However, if the ET crop coefficients used to calculate water savings are out-of-date, this method may be no more accurate than estimating water savings based on water deliveries. The optimal approach for measuring conserved water in a fallowing program depends on the crops, region, and availability of relevant ET crop coefficients. If crop types and practices have not changed significantly since crop coefficients were developed in a region, then we endorse their continued use. If, however, crop coefficients are outdated, we would recommend that fallowing programs consider updating ET values based on emerging satellite-assisted estimators. These estimators may be both more accurate and less costly than traditional ET estimators.

Tradeoffs between measurement costs and accuracy were discussed earlier in this report. The appropriate balance will differ across regions and time periods. Where water supplies have high economic and ecological value and there is intense competition for water, higher investments in accurate measurement may well be warranted. Figure 10 summarizes the questions program designers may ask when creating or updating a fallowing measurement scheme.

Fallowing Program Design—Measurement Questions

- ☐ Are region and crop specific ET coefficients available?
- ☐ How old are the ET crop coefficients?
- ☐ Have crop varieties or cropping practices changed since the coefficients were developed?
- ☐ Is there an estimate for ET on fallowed fields?
- ☐ What is the availability of remote-sensing data in the region?
- ☐ What is the cost of remote-sensing ET estimation and how does it compare to traditional ET estimation methods?
- ☐ What is the economic value per unit of water in the area, as indicated by market prices or other indicators?
- ☐ Are more accurate, and potentially costly, measurement approaches justified by high economic and ecological values associated with conserved water?

Figure 10 Measuring Design Questions

B. Monitoring and Enforcing—Recommendations and Guidelines

The monitoring and enforcement methods discussed in this report can be summarized in four basic categories: “neighborhood watch”, site visits, satellite based, and remote soil-moisture based. Of these, the “neighborhood watch” method of relying on neighboring irrigators to report contract breaches is the most cost effective but can be ruled out as a primary monitoring method in most cases because it does not provide hard evidence of compliance. Site visits are not as cost effective, but can be constructed to provide accurate records of fallowing compliance, particularly if photos are taken. Satellite-based monitoring is less cost effective if the images must be purchased. However, the availability of free images makes this option more attractive. If fields are large enough to discern on free Landsat images, remote sensing images are recommended for monitoring. As long as fields are monitored far enough into the growing season for the difference between weeds and crops to be apparent, this approach would be cost effective, require minimum staff time, and provide a history of fallowing compliance given that images are archived.

Monitoring and enforcement based on remote soil-moisture monitoring is the most expensive choice but it may be viable in some situations. Soil-moisture monitoring can improve on-farm water management and crop yield in addition to providing water savings for fallowing programs. These benefits plus the possibility of government or non-profit agency cost sharing could make this option feasible. Farmers may also be willing to invest in soil-moisture sensors that can save them time and money in the long run. If fallowing program agencies coordinate cost sharing agreements among farmers and federal agricultural programs, they may be able to procure a very accurate monitoring and enforcement tool at a reasonable cost.

A final recommendation in monitoring and enforcing fallowing programs is the option of targeted monitoring and compliance rewards. Both of these methods can increase compliance while keeping monitoring and enforcement costs stable. Targeted monitoring may be combined with any of the other methods. For example, if site visits were the main monitoring method, the fallowing program agency could divide participants into equal groups and alternate visits on a random schedule. Remote soil moisture monitors could also be randomly placed in select fields and rotated. Figure 11 summarizes the key questions program designers may ask when creating or updating a monitoring and enforcement scheme.

Fallowing Program Design—Monitoring & Enforcement Questions

- ☐ Is free Landsat imagery suitable to monitor fallowing? Sources: http://glovis.usgs.gov/ or http://earthexplorer.usgs.gov/
- ☐ Are fields large enough to be monitored by Landsat (roughly a hectare or more depending on shape)?
- ☐ Do regional water agencies purchase or use satellite imagery? Is it suitable to monitor fallowing? Is resource sharing possible?
- ☐ What is the cost of remote soil-moisture monitoring installation?
- ☐ Is government or non-profit funding available to support installation of remote soil-moisture monitoring systems?
- ☐ Are local irrigators interested in sharing in cost of remote soil-moisture monitoring systems?
- ☐ Can budget-neutral monitoring methods like targeted monitoring or compliance rewards support fallowing monitoring?

Figure 11 Monitoring and Enforcement Design Questions

VI. Conclusions

Water acquisition programs that rely upon cropland fallowing should consider in which specific arenas of MME the greatest gains can be made to more cost effectively achieve program goals. It is likely that an assessment across measuring, monitoring, and enforcing methods will provide ideas for overall cost savings and improvements in the amount of water acquired per unit cost. A mixture of MME strategies could provide increased program compliance while still remaining cost effective. A mixture of monitoring methods, for instance, might be advantageous in discouraging non-compliance, as program participants inclined toward non-compliance would have a harder time remaining undetected with multiple methods. A mixed approach could entail switching monitoring methods from year to year. Remote monitoring could be used every year with on-the-ground verification through field visits on a random schedule.

Emerging technology may enhance fallowing program measuring, monitoring, and enforcing accuracy while maintaining cost-efficiency. Satellite-based technology, in particular, is becoming available at the temporal and spatial scales necessary to be useful in fallowing programs. Furthermore, high-resolution imagery may be freely available. Moreover, greater numbers of water sector professionals are receiving training in working with remotely sensed imagery. Adoption of satellite-based monitoring could be the first step. If it proves worthwhile, satellite-based measuring, or ET estimation, might be explored. With better measuring, monitoring, and enforcement comes greater confidence in water conservation and transfer programs. Greater confidence can lead to more buyers and sellers entering the temporary water transfer market. As temporary water transfer agreements become more commonplace, the mechanisms for negotiating, approving, implementing and monitoring them become more refined and costs per unit of water acquired can decrease for everyone involved. Like the flow of water through timeworn channels, an efficient and mature transfer process can smooth the way for everyone involved.

VII. Appendix: Remote Sensing Techniques

An overview as applied to measuring and monitoring water use

keywords: remote sensing, evapotranspiration, vegetation index, VI, surface energy balance, SEB, water transfers

Images of Earth taken from outer space are revealing the planet's forms and fluxes. These remotely sensed images are giving researchers the ability to study planetary processes in near real time. Evapotranspiration has been a focus of remote sensing study because of its importance to the water balance and the difficulties measuring it using strictly ground-based methods. Researchers (Elhaddad et al. 2011, Glenn et al. 2011, for example) are refining techniques to analyze the consumption and movement of water using remote images. This guide provides a basic background on remote sensing and how it can be used to measure and monitor water use or evapotranspiration.

Remote sensing is gathering information from a distance. Energy reflected or emitted from the Earth is recorded and then processed, analyzed, and applied (White 1977). The information may be gathered from any distance. Remote sensing satellites gather information from low Earth orbit altitudes of up to 2000 km; cranes or airplanes enable remote sensing much closer to the ground. The primary remote-sensing inputs to estimate evapotranspiration as explored here are visible, infrared, or thermal images gathered from Earth observation satellites. The frequent collection and low cost of satellite images contribute to their popularity. However, the transformation of images into evapotranspiration estimates can be a lengthy process.

The ability to estimate evapotranspiration from satellite imagery depends on the purpose of the satellite and its imaging characteristics. The spatial, spectral, radiometric, and temporal resolution of images determine what applications they are best suited for. Spatial resolution in the digital realm refers to the actual area represented by each pixel in an image.[38] A 20-meter resolution will capture a 20 by 20 m surface square in each image pixel. Resolution affects the size of features that can be discerned in an image. For an area with fields smaller than 20 square meters, an image with a 20 m resolution may not be sufficient to accurately estimate ET. NASA's Landsat 7 has a spatial resolution of 15 to 60 m (depending on the sensor).[39] The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite has a spatial resolution of 250 m to 1 km.[40]

Spectral resolution[41] refers to the range of electromagnetic wavelengths that a sensor captures. Multi-spectral sensors record multiple separate wavelength ranges. For example, the Landsat 7 satellite's Enhanced Thematic Mapper Plus instrument has eight spectral bands ranging from 0.45 to 12.5 micrometers (μm). The spectral resolution of Landsat 7 includes visible and near infrared, short and long wave infrared (thermal), and panchromatic bands.[42]

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[38] "Landsat 7 Science Data Users Handbook 6.2 Spatial Characteristics," last modified March 11, 2011, http://landsathandbook.gsfc.nasa.gov/data_properties/prog_sect6_2.html
[39] "The Enhanced Thematic Mapper Plus," last modified January 11, 2012, http://landsat.gsfc.nasa.gov/about/etm+.html
[40] "Specifications," accessed February 6, 2012, http://modis.gsfc.nasa.gov/about/specifications.php
[41] Highlighted terms are defined in the Glossary, starting on page 59.
[42] "The Enhanced Thematic Mapper Plus," http://landsat.gsfc.nasa.gov/about/etm+.html

MODIS has 36 spectral bands ranging from 0.4 to 14.4 μm.[43]

Radiometric resolution refers to the sensors ability to distinguish between small brightness differences in a given spectrum. Radiometric resolution is measured in bits and tells the maximum range of values in the image. 8-bit sensors record 256 values (2^8=256). An image can be recorded as a series of values, with a corresponding value for each pixel. The image on the left in Figure 12 has 2-bit resolution compared to 8-bit resolution in the image on the right. The 2-bit figure has only 4 (2^2) values: black, white, and two shades of grey (compared to the 8-bit image's 256 shades). Landsat 7 has 8-bit resolution.[44] MODIS has 12-bit.

Figure 12 Radiometric Resolution: 2-bit vs. 8-bit[45]

For each instrument, choices must be made between spatial, spectral, and radiometric resolutions. Higher spatial resolution is attained through a smaller field of view, which limits the amount of energy reaching the instrument. Less energy means lower quality images. Decreasing spectral or radiometric resolution will increase the energy reaching the instrument and compensate for increased spatial resolution (Campbell 2002). Both need not be sacrificed though. Radiometric resolution can be maintained concurrent with high spatial resolution by widening the wavelength range of the sensor (decreasing spectral resolution).

Spectrum can also limit spatial resolution. For example, thermal radiation is longer wavelength and lower energy than visible radiation. To collect sufficient energy thermal sensors need to use a larger field of view, which limits spatial resolution. Thus thermal infrared images are generally lower resolution than what is possible in visible or near infrared images.[46] Figure 13

[43] "Specifications," http://modis.gsfc.nasa.gov/about/specifications.php
[44] "Landsat 7 Science Data Users Handbook 6.4," last modified March 11, 2011, http://landsathandbook.gsfc.nasa.gov/data_properties/prog_sect6_4.html
[45] "Radiometric Resolution," last modified January 29, 2008, http://www.nrcan.gc.ca/earth-sciences/geography-boundary/remote-sensing/fundamentals/2097
[46] "Thermal Imaging," last modified January 29, 2008, http://www.nrcan.gc.ca/earth-sciences/geography-

and Figure 14 show approximately the same region in the Yuma, AZ area. The Landsat 5 satellite took both the images on October 26, 2011. The images highlight Landsat's spatial resolutions at thermal versus visible spectrums. The thermal image has a resolution of 120 m compared to the visual image resolution of 30 m. The thermal image would have limited use for estimating ET of the smaller fields discernible in the upper right in the visible image. However, Landsat's thermal resolution currently is the best available for remote sensing ET estimation and is sufficient for many agricultural applications.

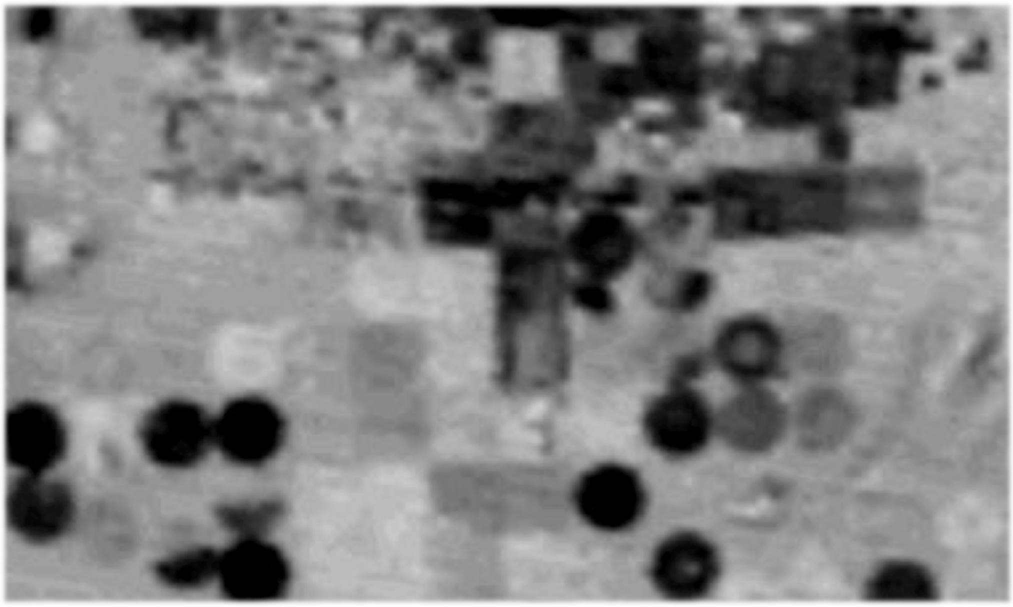

Figure 13 Landsat 5 Thermal Infrared Image, October 26, 2011, Yuma, AZ
120 m resolution, path 38, row 37[47]

Figure 14 Landsat 5 Visible Image, October 26, 2011, Yuma AZ
30 m resolution, path 38, row 37[48]

The final type of resolution affecting the usability of satellite imagery is temporal resolution. Temporal resolution refers to the time between passes over the same area by the same satellite. Landsat 7 has a temporal resolution of 16 days; MODIS has a temporal resolution of 1 to 2 days.

Landsat and MODIS products are well suited to estimating ET because of the balance of their resolutions (plus the images are easy to acquire and free). Landsat 7 offers high spatial

[47] "USGS Global Visualization Viewer," accessed February 10, 2012, http://glovis.usgs.gov/
[48] Ibid.

resolution, good spectral resolution, and fair temporal resolution. MODIS offers moderate spatial resolution, high spectral resolution, and high temporal resolution. Their relative strengths and weaknesses make each suited to different ET situations. Landsat's high spatial resolution makes it ideal for estimating ET at the farm field scale. However, its temporal resolution makes estimating ET between images complicated. MODIS' high temporal resolution makes it attractive for daily irrigation scheduling but its spatial resolution makes it impractical for medium or smaller fields. MODIS is well suited to larger scale ET estimation, like seasonal basin or catchment-wide ET.

A. Traditional Evapotranspiration Methods

Remote sensing of evapotranspiration (ET) is built upon traditional ET estimation methods. In order to show how remote sensing estimations of ET compare to traditional ET estimates, a brief overview of traditional ET estimation is presented here.

ET is a combined measure of the water vaporized by soil surface evaporation and plant transpiration (Allen et al. 1998). ET may be measured directly by probe or lysimeter. Lysimeters are the preferred method to measure crop ET but the costs to make, install, and operate them are prohibitive in most cases. So methods have evolved to estimate potential ET based on current meteorological conditions and some simplifying assumptions. Potential ET is a concept that was developed in the mid twentieth century to simplify ET estimation. Instead of estimating the entire ET equation for every type of crop, the calculation was split into two pieces: potential ET and crop coefficient. Potential ET is the amount of water transpired at the given climatic conditions by a short, uniform green crop that has plenty of water and is completely shading the ground (Penman 1956). Once potential ET is estimated, it is adjusted with a crop coefficient to estimate ET for a specific crop. Potential ET was later replaced with the more precise reference ET (ET_0), which specifically defines the reference crop as a large area of actively growing green grass 12 cm tall (Allen et al. 1998). Many methods for calculating reference ET have been developed that offer a range of complexities and accuracies. For example, the Blaney-Criddle method requires only one input, air temperature, to provide a rough estimate of monthly reference ET.[49] Compare this to the currently recommended Penman-Monteith method that estimates daily reference ET using four weather inputs: solar radiation, air temperature, humidity, and wind speed.

In the Blaney-Criddle, Penman-Monteith, and other similar methods the steps to estimate crop ET are roughly the same. Consider a farmer estimating last week's ET for a field of wheat using the traditional FAO Penman-Monteith method (see Allen et al. 1998 for a full description). She would calculate reference ET (ET_0: standardized potential ET) and multiply it by the crop coefficient (K_c) for her wheat. Using reference ET simplifies the computation of ET by removing crop specifics from the initial estimation. Reference ET is what ET would have been for a standardized grass crop given the previous week's meteorological conditions. The standardized grass crop is a freely transpiring, disease and weed free crop, with no stress from limited soil moisture (Allen et al. 1998).

The FAO Penman-Monteith method using reference ET is practical. Four weather inputs are needed: solar radiation, air temperature, humidity, and wind speed. In states with weather

[49] "Chapter 3: Crop Water Needs," FAO, last accessed May 4, 2012, http://www.fao.org/docrep/s2022e/s2022e07.htm#3.1

station networks, like California (CIMIS)[50] and Arizona (AZMET),[51] the weather inputs (and calculated reference ET in these cases) are available without any additional investment on the farmer's part. All the farmer has to do to estimate ET is retrieve reference ET from a website and multiply it by her specific crop coefficient. A downside of this method is the local nature of the measurements. Actual ET can vary even over small distances, especially where topology or soil characteristics are varied (Tang et al. 2009).

In addition to spatial variations, there is uncertainty inherent in the calculation of reference ET. Weather station quality and location affect reference ET. The ASCE-EWRI (2005) recommend using data from weather stations that are surrounded for 100 m in all directions by "nearly level expanses of uniform vegetation that are supplied with sufficient water through precipitation and/or irrigation to support ET near maximum levels." Weather station siting is important because the assumptions built into the reference ET equation are based on a uniform grass crop. Reference ET calculated from weather stations in fields that fail to meet ASCE-EWRI recommendations could be inaccurate depending on local conditions. Adjusting or estimating weather data may be necessary.

The reference ET equation is also a matter of choice. Different versions of the Penman-Monteith equation have been proposed, tested, and recommended. Some perform better than others depending on local conditions. Ventura et al. (1999) compared the precision of five Penman-Monteith equations to lysimeter-measured ET in California and Italy. The hourly lysimeter values for ET ranged from about 30 to 600 $W\ m^{-2}$. The root mean-square error (RMSE) of the Penman-Monteith computed reference ET values compared to measured ET was between 23 and 47 $W\ m^{-2}$. The larger errors tended to occur when the ET values were highest. The authors note that when measuring ET, RMSE of less than 50 $W\ m^{-2}$ is considered good.

Only one method is recommended for worldwide application: the FAO Penman-Monteith (Allen et al. 1998). In the US, a slightly modified version of the Penman-Monteith, the ASCE Standardized Reference Evaporation Equation, is recommended (ASCE-EWRI 2005). The methods are virtually identical. The ASCE method also allows for computation based on a standardized alfalfa crop that is used with alfalfa based crop coefficients.

The second part, the crop coefficient, makes this method easy to use but also brings in more ambiguity. The crop coefficient adjusts reference ET based on crop type and growth stage. To estimate actual crop ET, reference ET is multiplied by a crop coefficient. Crop coefficients are developed for crops grown in optimal conditions so they are only approximations of actual ET. Actual wheat ET will vary from its associated crop coefficient for reasons like plant variety differences, management choices, and soil salinity (Glenn et al. 2011). According to Glenn et al. (2011) these variations often lead to lower than expected water demand. For example, disease or limited soil moisture will lower ET. Using crop coefficients to schedule irrigation could lead to over-watering in these cases. They could also lead to under-watering in cases where, for example, a new crop variety has higher yields and ET.

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[50] "CIMIS Overview," accessed February 8, 2012, http://wwwcimis.water.ca.gov/cimis/infoGenCimisOverview.jsp
[51] "About AZMET," accessed February 8, 2012, http://ag.arizona.edu/azmet/az-about.htm

Figure 15 and Figure 16 show crop coefficients developed for two varieties of durum wheat grown in southwestern Arizona by Ottman (2004) and Sanchez and Brown (2009). Ottman used neuron probes to develop coefficients for durum wheat (Kofa variety). Sanchez and Brown used lysimeters to develop coefficients for durum wheat (Havasu variety). The methods used to determine the coefficients most certainly contribute to the differences of the studies' findings. Lysimeter are the preferred method for developing crop coefficients. The initial crop coefficients are not comparable because of differences in data reporting, however, Sanchez and Brown attribute the high initial value in their study to the irrigation required to initiate the crop. The 20-day coefficient in the Ottman study of Kofa wheat is 40 percent higher than the Sanchez and Brown study of Havasu wheat. However, the Havasu wheat crop coefficient peaks about 10 percent higher than Kofa. These two studies highlight the differences between similar crops grown in similar areas. ET estimation will be less certain when using crop coefficients that were not locally or recently developed for relevant crop varieties.

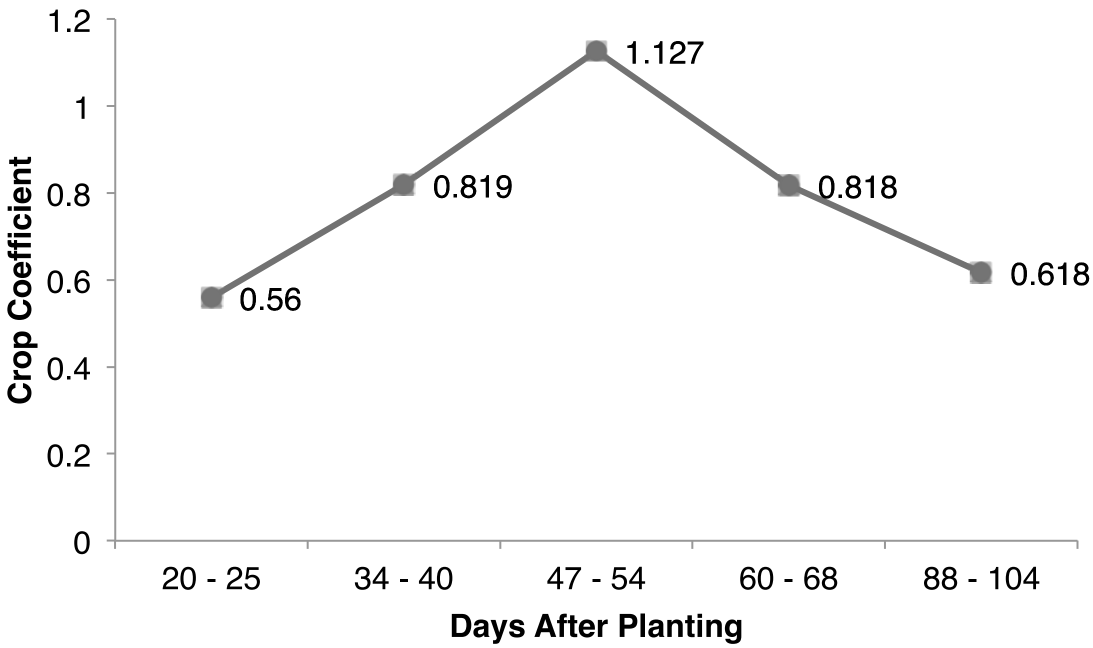

Figure 15 Crop Coefficients, Durum Wheat (Kofa variety) planted Feb. 13, 2004, Yuma, AZ (Adapted from Ottman 2004)

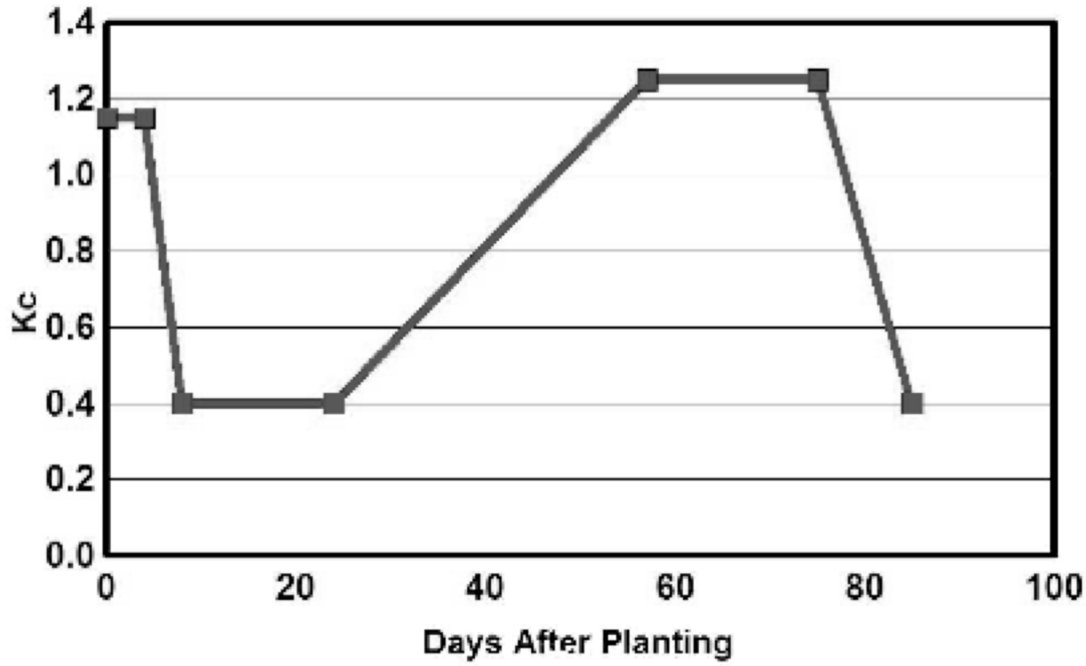

Figure 16 Crop Coefficients, Durum Wheat (Havasu variety) planted Feb. 3, 2009, southwestern AZ
(Sanchez and Brown 2009)

An additional problem with the use of crop coefficients is their availability. In his 2004 paper, Ottman said that Arizona crop coefficients were nonexistent. The alternatives at the time were coefficients from California or estimates based on outdated work done in Phoenix. Sanchez and Brown made the point again in 2009: "Appropriate crop coefficients for calculating ET from weather based ET_o estimates for irrigation scheduling are lacking." Besides lacking crop coefficients, the on the ground accuracy of the FAO Penman-Monteith/crop coefficient method has been repeated as a key motivation in developing ET methods based on or assisted by remote sensing (Tang et al. 2009, Glenn et al. 2011, Hunsaker et al. 2007). The costs and benefits of remotely sensed ET are explored in the next section.

B. Estimating Evapotranspiration Using Remote Sensing

Evapotranspiration (ET) models that rely on remote sensing fall into two main categories: surface energy balance or vegetation index. Both methods have been used to estimate ET in irrigated agriculture. Each has its strengths and weaknesses, which will be discussed after a general description of the methods. Local conditions and expertise can limit the appropriateness of either model. Remote sensing ET models are generally not completely reliant on remotely acquired data. Many still use ground data as inputs and for calibration.

1. Surface Energy Balance

Surface energy balance (SEB) methods estimate ET using thermal satellite imagery. Thermal images from Landsat are available free of charge.[52] ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) also takes thermal images, however they are not freely available to the public. SEB methods are based on the principle that the energy leaving a field surface has to equal the energy arriving there for a given time period. ET can

[52] "USGS Global Visualization Viewer," accessed February 10, 2012, http://glovis.usgs.gov/

be estimated based on a surface energy balance because as water evaporates and transpires, it uses energy. The energy consumed by ET is calculated as the latent energy after sensible heat flux and soil heat flux are subtracted from net radiation (Allen et al. 2007a). In practice, evaporative fraction is often reported in place of latent heat flux. Evaporative fraction is the ratio of latent heat to latent plus sensible heat (Shuttleworth et al. 1989). Evaporative fraction can then be converted into ET.

Researchers have developed many SEB models. They mainly differ in how they estimate sensible heat flux (Elhaddad et al. 2011). Some models estimate the energy balance of soil and vegetation separately. Others use contrasting wet and dry points in an image to define the thermal characteristics for extreme ET values. One commonality of the models is their reliance on data from at least one weather station within the satellite image (Elhaddad et al. 2011).

Researchers in the western U.S. have been working to tailor SEB models such as METRIC (Allen et al. 2007a), REEM (Samani et al. 2007), and ReSET (Elhaddad et al. 2011) to local conditions. These models work on similar principles; a recent application of ReSET will be explored here as an example. ReSET (Remote Sensing of ET) differs from the other models in its ability to use data from multiple weather stations. It can be calibrated with local maximum reference ET from weather stations like METRIC or used uncalibrated with no imposed maximum like SEBAL (Bastiaanssen et al. 2005, for example).

ReSET, like others, employs algorithms that use remotely sensed spectral data to calculate surface albedo, temperature and other components of the SEB (Elhaddad et al. 2011). Sensible heat flux for each pixel is modeled using the hottest and coldest pixels in the image as anchors. The hottest pixel is assumed to be dry or fallow soil with no ET. The coldest pixel is assumed to be a well-irrigated crop with maximum ET. An iterative process is used to calculate the parameters needed to estimate sensible heat flux for the rest of the image. After sensible heat flux is estimated for each pixel, latent heat and the evaporative fraction are calculated using the SEB equation. This procedure provides the evaporative fraction for each pixel at the time the satellite image was taken. ET is then calculated by multiplying evaporative fraction (EF) by the quotient of 24-hour net radiation minus 24-hour soil heat flux divided by latent heat of vaporization. It is converted to a daily value by assuming ET is constant all day and multiplying by 86,400 (converting seconds to a day).[53]

SEB methods have several advantages compared to other types of ET estimation. First, rather than potential, actual ET is computed (Allen et al. 2007a). In a 2011 comparison of water balance and remote sensing methods to estimate basin scale ET, Senay et al. state that SEB methods also do not require any assumptions about types of crops, or crop and soil conditions, and are better at handling stressed vegetation (e.g., diseased, water or nutrient stressed). Calibrated SEB methods like METRIC have an additional advantage in their ability to overcome possible accuracy and bias problems inherent when estimating net radiation and heat fluxes (Allen et al. 2007a).

The primary disadvantage of SEB methods is probably the sophistication required to

[53] ET_{24} = 86,400 x EF x (Net radiation_{24} - soil heat flux_{24})/latent heat of vaporization (see Equation (9), Elhaddad et al. 2011)

successfully implement them. Rafn et al. (2008) indicate that SEB methods are, "time consuming and require specialized software and knowledgeable personnel, making them potentially cost prohibitive for some applications." Factors like cloud cover, elevation, and latitude also affect SEB calculations and can produce spurious results (Senay et al. 2011). The necessity of picking wet and dry pixels can be a problem in some areas. In heterogeneous landscapes, wet seasons on one hand or dry conditions on the other can make locating pixels with zero ET or maximum ET close to impossible (Bouwer et al. 2008).

The future availability of thermal images could be a problem. Landsat 5 Thematic Mapper (TM) imaging was taken offline in November 2011 due to a rapidly degrading component. The USGS announced its intentions to suspend operations an additional 90 days on February 16, 2012 while a team investigates (Campbell 2012). On May 8, 2012, the USGS announced that Landsat 5 TM ceased regular acquisitions.[54] Landsat 7's Enhanced Thematic Mapper Plus is still operational although it experienced a Scan Line Corrector (SLC) failure in 2003. The failure leads to gaps in the image and data loss particularly at the edges.[55] The gaps can be filled using "nearest neighbor" techniques or information from other images close in time. NASA and USGS have partnered on the next Landsat spacecraft, the Landsat Data Continuity Mission (LDCM). It has expanded visible and infrared imaging capabilities as well as a 100 m thermal sensor. The LDCM is planned to launch in early 2013.[56]

2. Vegetation Index

Another common method for estimating ET using remote sensing employs vegetation indexes. Most vegetation index (VI) methods use a ratio of the values of red and near infrared light to estimate the transpiration part of ET. This method is based on the relationship between leaf density and transpiration and the observation that leaves absorb red light and scatter near infrared light (Glenn et al. 2008). The frequently used Normalized Difference Vegetation Index (NDVI) is calculated by subtracting red from near infrared values then dividing by red plus near infrared: NDVI = (NIR – Red)/(NIR + Red) (Glenn et al. 2010). Values range from -1 to 1. NDVI for water is negative and for barren areas it is close to zero. NDVI is moderate for shrub and grassland (0.2 to 0.3) and high for rainforests (0.6 to 0.8).[57]

Vegetation indexes are used in conjunction with reference ET (ET_0) to estimate ET, which leads to a refinement of the Penman-Monteith/crop coefficient (PM) method described earlier. However, the VI-based algorithms need to be regressed against ground ET measurements in the area where ET will be estimated. Empirical relationships are established between the VI, ET, and weather data to find the local correlation between vegetation cover and ET (Senay et al. 2011).

Nagler et al. (2009) indicate that while VI methods cannot estimate evaporation like SEB methods, plant transpiration is the larger part of ET and often the major unknown. The basic

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[54] "Landsat 5 Thematic Mapper Ceases Routine Acquisitions - Update," USGS, May 8, 2012, http://landsat.usgs.gov/mission_headlines2012.php
[55] "SLC-off Products: Background," modified December 30, 2010, http://landsat.usgs.gov/products_slcoffbackground.php
[56] "Landsat Data Continuity Mission," last modified March 22, 2012, http://ldcm.nasa.gov/
[57] J. Weier and D. Herring. "Measuring Vegetation (NDVI & EVI)," accessed February 20, 2012, http://earthobservatory.nasa.gov/Features/MeasuringVegetation/

VI-ET estimation approach calculates transpiration as a product of reference ET, empirical crop coefficient (k), and VI. In this equation, k is estimated by regressing transpiration and a VI over a crop cycle. The evaporative fraction can also be found using this equation by setting transpiration over reference ET equal to k times VI. The kVI term replaces the crop coefficient that would be used in the traditional PM method. This term reflects actual information about the current state of the crop (Nagler et al. 2009).

Once calibrated to local crops, a VI method can be used to predict actual ET. Hunsaker et al. (2007) compared an NDVI-based estimation with traditional PM-based ET for wheat in central Arizona. They tested the NDVI and PM methods and compared their estimates under normal, high and low planting densities; and high and low nitrogen treatments. They found NDVI to be robust for both optimum and sub-optimum conditions (Hunsaker et al. 2007). It performed particularly well compared to the PM in stands with low nitrogen.

The main advantage of VI methods compared to SEB is ease of calculation. Rafn et al. (2008) say their NDVI method, "is relatively fast, easy, and requires little knowledge of evaporation physics and aerodynamics." Additionally, the satellite imagery needed to calculate vegetation indexes are abundant compared to the thermal imagery needed for SEB methods. There are multiple satellites with visible and near infrared bands across a range of temporal and spatial resolutions (Glenn et al. 2010). MODIS, for example, has high temporal resolution (images taken every 1 to 2 days), and moderate spatial resolution (250 m). Tang et al. (2009) compared the Landsat-based SEB algorithm, METRIC with a MODIS-based modified VI approach in the Upper Klamath River Basin in Oregon. They noted the usual advantages of Landsat (high spatial resolution) and MODIS (high temporal resolution). Their comparison showed a tendency for the MODIS approach to underestimate seasonal ET and for METRIC to overestimate it, compared to surface flux observations.

The primary disadvantage of vegetation index ET estimation is the focus on transpiration only. In the desert southwest and similar areas, this may not be much of a drawback because soils are dry and soil evaporation is a small part of the water budget (Nagler et al. 2009). Vegetation indexes are also, "unable to detect early signs of water stress," unlike SEB methods (Nagler et al. 2009). The availability of images that are at sufficient spatial *and* temporal scale is also a consideration.

C. Conclusion

For those interested in using remote sensing methods to compute ET, the choice between methods comes down to two main criteria: the temporal and spatial scale of ET estimation and available expertise. SEB methods are more suited to well-defined basins than large areas (Senay et al. 2011). The computational cost and availability of thermal images may make SEB methods less attractive in some situations. Landsat thermal imagery is free, but until Landsat 5 is repaired or the next spacecraft (LDCM) is launched in 2013, there is only one operational thermal sensor, on Landsat 7. Landsat 7 images require an extra step to fill gaps because of the SLC failure. In locations with large fields (>25 hectare), the MODIS NDVI product may be the best bet to estimate ET. It has high temporal resolution and is faster, easier, and less expensive to process than SEB methods (Rafn et al. 2008). The Colorado River Basin districts have large fields, so MODIS-NDVI ET estimation is a possibility (Glenn et al. 2011). For medium or small agricultural fields, MODIS NDVI would be insufficient to estimate ET.

Future models might employ a combination of SEB and VI techniques. Glenn et al. (2008) recommend combining VI methods with land surface temperature (taken from thermal images) to provide enhanced estimates of ET and soil moisture. Nalger et al. (2009) recommend complementing VI methods with SEB methods. The VI would provide ET estimates but the SEB methods would be used as an auxiliary to detect plant stress.

Remote sensing is providing data that can complement traditional ET estimation methods. These methods can improve ET estimates and are a viable option compared to developing new lysimeter-based crop coefficients. ET estimates that are more timely and accurate can help irrigators track water use and align irrigation management with actual plant water needs. They may also help water managers develop a more complete picture of where water is going district or basin-wide.

VIII. Glossary

acre-foot	A unit of measure: approximately 325,850 gallons.
applied water	The amount of irrigation water applied to a field, typically over a season or year. This is not the amount of water consumed by the crop. Its main components include transpiration, evaporation, runoff, and recharge. It is typically greater than consumptive use in semi-arid zones.
baseline ET	Estimated historic evapotranspiration (ET) based on crop records and established crop ET rates. This can be used as the benchmark for computing water savings in fallowing or crop shifting programs when compared to estimated ET under conservation conditions.
benefit-cost analysis	A tool used in decision making that compares all the costs and benefits of a given action in present value monetary terms. Financial, environmental, social and other relevant costs and benefits may be included.
central pivot irrigation	A form of irrigation, where sprinkler heads are placed at intervals along pipes suspended above a field on wheeled supports. The pipe pivots from the center of the field, where the water source is, and traces a circle as it rotates.
crop coefficient (K_c)	The term that adjusts reference evapotranspiration when using the Penman-Monteith method. It is crop and growth stage specific. For example, to estimate the weekly evapotranspiration of a wheat field, the weekly reference evapotranspiration for the field would be multiplied by the crop coefficient for the variety and growth stage of the wheat.
crop consumptive use	The water expended in producing a crop, including transpiration and evaporation. Runoff and recharge are not a part of crop consumptive use. The term is used interchangeably with evapotranspiration (ET). It is equal to or less than applied water (in areas dependent on irrigation).
cropland idling	See fallowing.
cropping pattern	A field’s crop rotation history.
crop shifting	A change in cropping pattern, generally to crops with lower consumptive water use. The difference between historic and current consumptive water use may then be transferred to another use.
discount rate	The interest rate used to adjust future costs and benefits to make them comparable to current costs and benefits. Used when computing present value in a benefit-cost analysis.
electromagnetic	A length measurement used to describe electromagnetic radiation. The

wavelength	electromagnetic spectrum can be grouped by wavelength. For example, the visible spectrum ranges in wavelength from about 400 to 700 nanometers. Satellite sensors are designed to detect radiation in narrow wavelength ranges depending on the purpose of the sensor.
evaporation	The process by which water is vaporized to the atmosphere off a surface (e.g., water body or field).
evapotranspiration (ET)	The combined processes of evaporation and transpiration. In agriculture, the amount of water that is consumed in the process of growing crops. Also referred to as consumptive use.
fallowing	Forgoing crop production on a historically cropped field. In the context of this report, farmers are paid to fallow fields outside of their normal crop rotations in order to temporarily transfer water. Also called crop idling or forbearance.
forbearance	See fallowing.
headgate	The movable barrier between a canal and field that controls the flow of water.
infrared image	An image showing a band of electromagnetic information from the infrared range of the spectrum, between roughly 1 and 100 microns. Landsat 7's three infrared bands span less than 2 microns each. Infrared is split into groups: near, short, mid, long, and far. Long-wave infrared radiation is also called thermal radiation.
irrigation district	A body that has the legal authority to obtain and distribute irrigation water to a geographically defined group of irrigators. A district may collect fees and handle the governance, delivery, and legal rights of water.
junior water right	A water right with a relatively low priority compared to other water rights in the same system. If water supplies are limited, junior rights are more likely to have their supply reduced.
lateral move irrigation	A form of irrigation, where sprinkler heads are placed at intervals along pipes suspended above a field on wheeled supports. The pipe is rolled from one end of a field to the other and is supplied with water from one side.
lysimeter	A device for measuring actual evapotranspiration from crops. It is installed in an established field to resemble the surrounding conditions as closely as possible. The soil removed for its installation is replaced within the device and crops are planted. Its pan isolates the crops in the lysimeter from the surrounding field so that the water going in and out can be measured precisely.

moral hazard	When entering into an agreement, the potential for either party to behave contrary to the spirit of the agreement. For example, the seller in a water conservation agreement may consume water they agreed to conserve.
paper water	A documented water right that has not been recently or regularly used.
Penman-Monteith	The equation for estimating evapotranspiration (ET) based on a standardized grass crop under current meteorological conditions, i.e., reference ET. It is multiplied by a variety and growth stage specific crop coefficient to estimate actual ET.
permanent water transfer	The sale or transfer of a water *right*. Compare to a temporary sale or lease, where a specific volume of water is transferred but the seller retains the water right. Water leases greater than 50 or 100 years are considered permanent in some programs.
potential evapotranspiration	It is evapotranspiration (ET) of a short, uniform green crop that shades the ground completely and has plenty of water. It is a broad term. Penman-Monteith reference ET is a narrowly defined case of potential ET.
present value	The combined value of all current and future costs and benefits of a given outcome expressed in current monetary terms (by using a discount rate). It is used in benefit-cost analysis to compare outcomes with different timings of costs and benefits.
radiometric resolution	The ability of a sensor to differentiate intensity values within its spectrum range. It is measured in bits. The number of values a sensor can detect is found by raising two to its number of bits. For example, an 8-bit sensor can detect 2^8 or 256 values.
recharge	Water that percolates through the soil and reaches the groundwater table. This water might be extractable for future use.
reference evapotranspiration (ET_0)	The evapotranspiration of a freely transpiring standardized grass crop that has no weeds, disease, or lack of water.
remote sensing	Gathering information from a distance about energy reflected or emitted by the Earth.
seepage	Water that percolates through the soil. It may also be recharge.
senior water right	A water right with high priority compared to other water rights in the same system. If water supplies are limited, senior rights are least likely to have their supply reduced.
spatial resolution	In remote sensing, the ground area represented by one image pixel.

	For example, in an image with 60-meter resolution, each pixel would correspond to a 60 by 60 m area of ground.
spectral resolution	The range of electromagnetic wavelengths, or type of information, a sensor will detect. For example, band 6 on the Landsat 5 Thematic Mapper detects thermal radiation, with wavelengths from 10.4 to 12.5 microns.
surface energy balance (SEB)	A method for estimating evapotranspiration (ET) that uses thermal satellite images combined with ground weather station data.
temporal resolution	The length of time between subsequent satellite imaging of the same location. For example, Landsat 7 has a 16-day temporal resolution. The same location is imaged every 16 days.
temporary water transfer	The renting of a volume of water for a restricted period of time. The seller retains the permanent water right and sells only the use of the water under specified circumstances. Also called a water lease. Compare to permanent water transfer.
thermal image	An image showing electromagnetic information from the long-wave infrared range of the spectrum. Landsat 7's thermal band sensor has a range of 10.4 to 12.5 microns.
transpiration	The process where water taken up by the roots of plants is vaporized to the atmosphere from plant surfaces.
variable rate irrigation	A type of irrigation used with central-pivot or lateral-move sprinkler systems. The water application rate can vary at each sprinkler head. Rates are based on readings from soil moisture sensors in the field. The entire system can be automated and remotely accessed using specialized software and wireless networking. Also called precision irrigation.
visible spectrum	The portion of the electromagnetic spectrum that is visible to the naked eye. Wavelengths in the visible spectrum range from about 400 nanometers at the violet end of the spectrum to 700 nanometers at the red end of the spectrum.
water bank	A water storage and/or transfer entity. A storage bank allows members to store water in reservoirs or underground aquifers for future use or to benefit the water supply. A transfer bank buys and leases water or acts as an intermediary between water buyers and sellers.
water right	The legal right to use a quantity of water. It may be subject to limits including beneficial use, timing, total volume, and extraction rate. Rights generally have seniority based on the origination date. See paper water, junior water right, and senior water right.

W m^{-2}	Watts per meters squared; an alternate measure of evapotranspiration. To convert to mm per day (mm day^{-1}), multiply by 0.0353.

IX. Acronyms

ACT	Australian Capital Territory
ASCE	American Society of Civil Engineers
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATTRA	National Sustainable Agriculture Information Service
AZMET	Arizona Meteorological Network
BOR	U.S. Bureau of Reclamation
CDWR	California Department of Water Resources
CIMIS	California Irrigation Management Information System
EAA	Edwards Aquifer Authority
ERS	Economic Research Service
ET(AW)	evapotranspiration (of applied water)
EWRI	Environmental and Water Resources Institute
FAO	Food and Agriculture Organization of the United Nations
GAO	U.S. Government Accountability Office
GIS	geographic information system
GPS	global positioning system
IAG	Independent Audit Group
IDWR	Idaho Department of Water Resources
IID	Imperial Irrigation District
KWAPA	Klamath Water and Power Authority
LCRAS	Lower Colorado River Accounting System
LDCM	Landsat Data Continuity Mission
METRIC	Mapping Evapotranspiration at high Resolution with Internalized Calibration
MDBA	Murray-Darling Basin Authority
MME	measuring, monitoring, and enforcing
MODIS	Moderate Resolution Imaging Spectroradiometer
NASS	National Agricultural Statistics Service
NCAT	National Center for Appropriate Technology
NDVI	Normalized Difference Vegetation Index
PM	Penman-Monteith evapotranspiration equation
QSA	Quantification Settlement Agreement
ReSET	Remote Sensing of ET
SEB	surface energy balance
SEBAL	Surface Energy Balance Algorithm for Land
SLC	Scan Line Corrector
TM	Thematic Mapper
UDWR	Utah Division of Water Rights
USGS	U.S. Geological Survey
USDA	U.S. Department of Agriculture
VI	vegetation index
VRI	variable rate irrigation

WRP Wetlands Reserve Program
WTP Water Transaction Program

X. References

Abtew, W. 1996. “Evapotranspiration Measurements and Modeling for Three Wetland Systems in South Florida.” *Water Resources Bulletin* 32:465–473.

Allen, R.G. 2005. “METRIC: High Resolution Satellite Quantification of Evapotranspiration Overview.” http://www.kimberly.uidaho.edu/water/metric/FtCollins/Allen_Allen_METRIC_Overview_Moscow_2.pdf. University of Idaho.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. “Crop evapotranspiration Guidelines for computing crop water requirements FAO Irrigation and drainage paper 56.” Food and Agriculture Organization of the United Nations, http://www.fao.org/docrep/X0490E/x0490e00.htm#Contents.

Allen, R.G., M. Tasumi, A. Morse, R. Trezza, J.L. Wright, W. Bastiaanssen, W. Kramber, I. Lorite, and C.W. Robison. 2007a. “Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications.” *Journal of Irrigation and Drainage Engineering* 133:395–406.

Allen, R.G., M. Tasumi, and R. Trezza. 2007b. “Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)–Model.” *Journal of Irrigation and Drainage Engineering* 133:380–394.

ASCE-EWRI. 2005. The ASCE Standardized Reference Evapotranspiration Equation. Technical Committee report to the Environmental and Water Resources Institute of the American Society of Civil Engineers from the Task Committee on Standardization of Reference Evapotranspiration. ASCE-EWRI, 173 pp.

Bastiaanssen, W.G.M., E.J.M. Noordman, H. Pelgrum, G. Davids, B.P. Thoreson, and R.G. Allen. 2005. “SEBAL Model with Remotely Sensed Data to Improve Water-Resources Management under Actual Field Conditions.” *Journal of Irrigation and Drainage Engineering* 131:85–93.

BOR. 2009. “Lower Colorado River Accounting System Evapotranspiration and Evaporation Calculations Calendar Year 2008.” Report, Bureau of Reclamation Lower Colorado Region, September.

BOR. 2011. “Colorado River Accounting and Water Use Report Arizona, California, and Nevada.” Bureau of Reclamation Lower Colorado Region, May. http://www.usbr.gov/lc/region/g4000/wtracct.html.

Bouwer, L.M., T.W. Biggs, and J.C.J.H. Aerts. 2008. “Estimates of spatial variation in evaporation using satellite-derived surface temperature and a water balance model.”

Hydrological Processes 22:670–682.

Campbell, J. 2012. “Landsat 5 Suspension of Operations Extended.” USGS News Release, http://www.usgs.gov/newsroom/article.asp?ID=3109.

Campbell, J.B. 2002. Introduction to Remote Sensing, 3rd ed. New York: The Guilford Press.

CDWR. 2009a. “Issue No. 2 ETAW Values.” http://www.water.ca.gov/drought/transfers/issues.cfm.

CDWR. 2009b. “Issue No. 8 Establishing Baseline of Land and Water Use.” http://www.water.ca.gov/drought/transfers/issues.cfm.

CDWR and BOR. 2009. “DRAFT Technical Information for Water Transfers in 2010.” Technical report, Water Transfers Office, California Department of Water Resources and Resource Management Division Bureau of Reclamation, Mid-Pacific Region, November.

CDWR and BOR. 2012. “DRAFT Technical Information for Water Transfers in 2012.” Technical report, California Department of Water Resources and Resources Management Division Bureau of Reclamation, Mid-Pacific Region, February.

Choe, C., and I. Fraser. 1999. “Compliance Monitoring and Agri-Environmental Policy.” *Journal of Agricultural Economics* 50:468–487.

Courault, D., B. Seguin, and A. Olioso. 2005. “Review on estimation of evapotranspiration from remote sensing data: From empirical to numerical modeling approaches.” *Irrigation and Drainage Systems* 19:223–249.

Cox, W., and P. Baxter. 1996. “Setting the Cap Report of the Independent Audit Group.” Report, Murray-Darling Basin Ministerial Council, November.

Cox, W., C. Higgins, and T. Hillman. 2011. “Review of Cap Implementation 2010-11 Report of the Independent Audit Group.” Report No. 216/11, Murray-Darling Basin Authority, October.

DOI. 2009. “Department of the Interior Land Imaging Report.” Summary, Department of the Interior Remote Sensing Working Group, http://remotesensing.usgs.gov/FY09DOILandImagingReport.pdf.

EAA. 2010a. “Edwards Aquifer Authority Rules.” Edwards Aquifer Authority, http://amr.edwardsaquifer.org/display policies rules m.php?pg=rules, June 21 rev.

EAA. 2010b. “Groundwater conservation plan.” Edwards Aquifer Authority, http://www.edwardsaquifer.org/display document cat.php?cID=6, November.

Elhaddad, A., L.A. Garcia, and J.L. Chávez. 2011. “Using a Surface Energy Balance Model to Calculate Spatially Distributed Actual Evapotranspiration.” *Journal of Irrigation and Drainage Engineering* 137:17–26.

ERS. 2005. “Flexible Conservation Measures on Working Land.” Report No. 5, U.S. Department of Agriculture, Economic Research Service, June.

Evett, S., N. Mazahrih, M. Jitan, M. Sawalha, P. Colaizzi, and J. Ayars. 2009. “A Weighing Lysimeter for Crop Water Use Determination in the Jordan Valley, Jordan.” *Transactions of the ASABE* 52:155–169.

Exner-Kittridge, M.G., and M.C. Rains. 2010. “Case Study on the Accuracy and Cost/Effectiveness in Simulating Reference Evapotranspiration in West-Central Florida.” *Journal of Hydrologic Engineering* 15:696–703.

Flett, D., P. Baxter, and T. Hillman. 2009. “Review of Cap Implementation 2008-09 Report of the Independent Audit Group.” Report No. 45/09, Murray-Darling Basin Authority, November.

Fraser, R. 2004. “On the Use of Targeting to Reduce Moral Hazard in Agri-environmental Schemes.” *Journal of Agricultural Economics* 55:525–540.

French, A.N., D.J. Hunsaker, T.R. Clarke, G.J. Fitzgerald, and P.J. Pinter Jr. 2010. “Combining Remotely Sensed Data and Ground-Based Radiometers to Estimate Crop Cover and Surface Temperatures at Daily Time Steps.” *Journal of Irrigation and Drainage Engineering* 136:232–239.

GAO. 2005. “KLAMATH RIVER BASIN Reclamation Met Its Water Bank Obligations, but Information Provided to Water Bank Stakeholders Could Be Improved.” Reports to Congressional Requesters No. 05-283, Government Accountability Office, www.gao.gov/cgi-bin/getrpt?GAO-05-283, March.

Garrick, D., M. Siebentritt, B. Aylward, C. Bauer, and A. Purkey. 2009. “Water markets and freshwater ecosystem services: Policy reform and implementation in the Columbia and Murray-Darling Basins.” *Ecological Economics* 69:366–379.

Geerts, S., and D. Raes. 2009. “Deficit irrigation as on on-farm strategy to maximize crop water productivity in dry areas.” *Agricultural Water Management* 96:1275–1284.

Glenn, E.P., A.R. Huete, P.L. Nagler, and S.G. Nelson. 2008. “Relationship Between Remotely-sensed Vegetation Indices, Canopy Attributes and Plant Physiological Processes: What Vegetation Indices Can and Cannot Tell Us About the Landscape.” *Sensors* 8:2136–2160.

Glenn, E.P., P.L. Nagler, and A.R. Huete. 2010. “Vegetation Index Methods for Estimating Evapotranspiration by Remote Sensing.” *Surveys in Geophysics* 31:531–555.

Glenn, E.P., C.M.U. Neale, D.J. Hunsaker, and P.L. Nagler. 2011. “Vegetation index-based crop coefficients to estimate evapotranspiration by remote sensing in agricultural and natural ecosystems.” *Hydrological Processes* 25:4050–4062.

Grafton, R.Q., C. Landry, G.D. Libecap, S. McGlennon, and R. O'Brien. 2010. "An Integrated Assessment of Water Markets: Australia, Chile, China, South Africa and the USA." NBER Working Paper Series Working Paper 16203.

Grubbs, S. 2008. "Assessing changes across spatial and temporal scales due to conservation practices associated with the Kentucky Conservation Reserve Enhancement Program in the Upper Green River Basin." Annual report, National Resources Conservation Service.

Hansen, N., T. Holtzer, J. Pritchett, and B. Lytle. 2010. "Water-Conserving Cropping Systems: Lower South Platte Irrigation Research and Demonstration Project." *Colorado Water* 27:7–10.

Hunsaker, D.J., G.J. Fitzgerald, A.N. French, T.R. Clarke, M.J. Ottman, and P.J. Pinter Jr. 2007. "Wheat Irrigation Management Using Multispectral Crop Coefficients: I. Crop Evapotranspiration Prediction." *Transactions of the ASABE* 50:2017–2033.

IDWR. 2006. "Attachment B IDWR Water Transactions Program Monitoring and Evaluation Protocol." Idaho Water Resource Board, http://www.idwr.idaho.gov/waterboard/WaterPlanning/Water%20Transaction%20Program/PDFs/Monprotocol.pdf.

IDWR. 2010. "Idaho Water Transaction Program 2009 Monitoring and Evaluation Report." Idaho Water Resource Board, http://www.idwr.idaho.gov/waterboard/WaterPlanning/Water%20Transaction%20Program/PDFs/ME_Report2009.pdf.

IID. 2008. "Imperial Irrigation District Fallowing Program Status Report." http://www.iid.com/Media/Fallowing-Program-Summary-2003-2008-Presentation.pdf.

IID. 2009a. "2010-2011 Fallowing Program Field Application Form." Imperial Irrigation District, http://www.iid.com/Modules/ShowDocument.aspx?documentid=587.

IID. 2009b. "Imperial Irrigation District 2010-2011 Fallowing Program Solicitation Announcement." http://www.iid.com/Modules/ShowDocument.aspx?documentid=590.

IID. 2010a. "Agreement for Fallowing Land in the Imperial Irrigation District." Imperial Irrigation District, http://www.iid.com/Modules/ShowDocument.aspx?documentid=591.

IID. 2010b. "Imperial Irrigation District 2010-2011 Fallowing Program Participants July 1, 2010 - June 30, 2011." http://www.iid.com/Modules/ShowDocument.aspx?documentid=592.

Jia, X., M. Dukes, J. Jacobs, and S. Irmak. 2006. "Weighing Lysimeters for Evapotranspiration Research in a Humid Environment." *Transactions of the ASABE* 49.

Keplinger, K.O., and B.A. McCarl. 1995. "Regression Based Investigation of Pumping Limits and Springflow Within the Edwards Aquifer." Working paper, Department of Agricultural Economics, Texas A&M University, College Station, Texas, August.

Keplinger, K.O., B.A. McCarl, C.C. Chen, and R. Ward. 1998. "The 1997 Irrigation Suspension Program for the Edwards Aquifer: Evaluation and Alternatives." Working paper No. 178, Texas Water Resources Institute, February.

KWAPA. 2010a. "2010 Land Idling Program." Klamath Water and Power Agency, March 22.

KWAPA. 2010b. "Klamath Water and Power Agency 2010 Land Idling Program Contract." Klamath Water and Power Agency.

Lindenmayer, R.B., N.C. Hansen, J. Brummer, and J.G. Pritchett. 2011. "Deficit Irrigation of Alfalfa for Water-Savings in the Great Plains and Intermountain West: A Review and Analysis of the Literature." *Agronomy Journal* 103:45–50.

Marek, T., A. Schneider, T. Howell, and L. Ebeling. 1988. "Design and Construction of Large Weighing Monolithic Lysimeters." *Transactions of the ASAE* 31:477–484.

MDBA. 2010. "Guide to the proposed Basin Plan: overview." Report No. 60/10, Murray-Darling Basin Authority, Canberra.

Meister, H.S. 2004a. "U.C. Cooperative Extension Sample Cost to Establish and Produce Alfalfa Hay Flat Planted Hay Production Imperial County–2004." AF-IM-04-02.

Meister, H.S. 2004b. "U.C. Cooperative Extension Sample Cost to Establish and Produce Cotton Imperial County–2004." CT-IM-04.

Morris, M. 2006. "Soil Moisture Monitoring: Low-Cost Tools and Methods." Working paper No. IP277, ATTRA National Sustainable Agriculture Information Service, www.attra.ncat.org/attra-pub/PDF/soil moisture.pdf.

Morse, A., W.J. Kramber, and R.G. Allen. 2008. "Cost Comparison for Monitoring Irrigation Water Use: Landsat Thermal Data Versus Power Consumption Data." In *Pecora 17 The Future of Land Imaging...Going Operational*. Denver, Colorado: ASPRS.

Mueller, R. 2011. "Cropland Mapping with Satellite Data." In *Remote Sensing Applications for U.S. - Mexico Border Water Management*. San Diego, CA: Water Education Foundation.

Nagler, P.L., K. Morino, R.S. Murray, J. Osterberg, and E.P. Glenn. 2009. "An Empirical Algorithm for Estimating Agricultural and Riparian Evapotranspiration Using MODIS Enhanced Vegetation Index and Ground Measurements of ET. I. Description of Method." *Remote Sensing* 1:1273–1297.

NASS. 2011. "NASS Launches New CropScape Geospatial Data Service." News Release, http://www.nass.usda.gov/Newsroom/printable/01_10_11.pdf, January.

Orang, M.N., R.L. Snyder, and J.S. Matyac. 2008. User's Guide Consumptive Use Program Plus. California Land and Water Use, Department of Water Resources and Department of Air, Land and Water Resources, University of California, Davis, Version 1.0.

Ottman, M. 2004. “Crop Coefficients for Estimating Small Grain Water Use.” Final Report, Arizona Grain Research and Promotion Council, August.

Payero, J., and S. Irmak. 2008. “Construction, Installation, and Performance of Two Repacked Weighing Lysimeters.” *Irrigation Science* 26:191–202.

Penman, H.L. 1956. “Evaporation: An Introductory Survey.” *Netherlands Journal of Agricultural Science* 4:9–29.

Piñón-Villarreal, A.R., Z.A. Samani, A.S. Bawazir, M.P. Bleiweiss, R. Skaggs, and V.T. Tran. 2010. “Estimating Water Use Through Satellite Remote Sensing.” Technical Completion Report No. 357, WRRI, December.

Rafn, E.B., B. Contor, and D.P. Ames. 2008. “Evaluation of a Method for Estimating Irrigated Crop-Evapotranspiration Coefficients from Remotely Sensed Data in Idaho.” *Journal of Irrigation and Drainage Engineering* 134:722–729.

Samani, Z., A.S. Bawazir, R.K. Skaggs, M.P. Bleiweiss, A. Piñon, and V. Tran. 2007. “Water Use by Agricultural Crops and Riparian Vegetation: An Application of Remote Sensing Technology.” *Journal of Contemporary Water Research and Education* 137:8–13.

Sanchez, C.A., and P. Brown. 2009. “Determination of Evapotranspiration (ET) for Desert Durum Wheat using Weighing Lysimeters in the Lower Colorado River Region.” Final Report No. 09-03, Arizona Grain Research and Promotion Council.

Schneider, A., T. Howell, and J. Steiner. 1993. “An Evapotranspiration Research Facility Using Monolithic Lysimeters From Three Soils.” *Applied Engineering in Agriculture* 9:227–232.

Senay, G.B., S. Leake, P.L. Nagler, G. Artan, J. Dickinson, J.T. Cordova, and E.P. Glenn. 2011. “Estimating basin scale evapotranspiration (ET) by water balance and remote sensing methods.” *Hydrological Processes* 25:4037–4049.

Shuttleworth, W.J., R.J. Gurney, A.Y. Hsu, and J.P. Ormsby. 1989. “FIFE: The variation in energy partition at surface flux sites.” In Remote Sensing and Large-Scale Global Processes (Proceedings of the IAHS Third Int. Assembly, May 1989). Baltimore, MD: IAHS, 186.

Smith, J. 2011. “The Story of Regenesis Management Group: Balancing Water Use for Profit and Conservation.” *Colorado Water* 28:19–21.

Taghvaeian, S. 2011. “Water and Energy Balance of a Riparian and Agricultural Ecosystem Along the Lower Colorado River.”

Tang, Q., S. Peterson, R. Cuenca, Y. Hagimoto, and D. Lettenmaier. 2009. “Satellite-based near-real-time estimation of irrigated crop water consumption.” *Journal of Geophysical Research* 114, D05114.

TNC. 2010. “Our Woods, Our Waters, Our Way of Life Georgia Update.” www.nature.org/media/georgia/georgia_spring_2010_update.pdf, Spring.

UDWR. 2009. “Enforcement Procedures: A Brief Explanation.” Utah Division of Water Rights, http://www.waterrights.utah.gov/regulation/brochure.pdf.

USDA. 2000. “WRP Monitoring Checklist Title 440 Conservation Programs Manual.” Exhibit No. 514.89, Natural Resource Conservation Service, http://directives.sc.egov.usda.gov/23896.wba, October.

USDA. 2006. “Title 440 Programs Wetland Reserve Program Subpart G - Quality Control.” Part No. 514, Natural Resource Conservation Service, http://directives.sc.egov.usda.gov/, September.

USDA. 2008. “At a Glance: Wetlands Reserve Program.” U.S. Department of Agriculture, http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_008151.pdf, May.

USDA. 2010. “USDA Announces Unprecedented Enrollment in Voluntary Effort to Restore the Nation’s Wetlands.” Release No. 0603.10, November 12.

USGS. 2005. “Assessment of the Klamath Project Pilot Water Bank: A Review from a Hydrologic Perspective.” Report, U.S. Geological Survey Oregon Water Science Center, Portland, Oregon, May.

Ventura, F., D. Spano, P. Duce, and R.L. Snyder. 1999. “An evaluation of common evapotranspiration equations.” *Irrigation Science* 18:163–170.

Water Transfer Workgroup. 2002. “Water Transfer Issues in California.” Report, Final Report to the California State Water Resources Control Board, June.

Watson, R., and B. Scarborough. 2010. “Flint River Basin Irrigation: Wireless Water for Biodiversity.” PERC Case Study, Property and Environment Research Center, September.

White, L.P. 1977. Aerial photography and remote sensing for soil survey, P. H. T. Beckett, V. C. Robertson, and R. Webster, eds. Oxford: Clarendon Press.

Yano, Y., and D. Blandford. 2009. “Use of Compliance Rewards in Agri-environmental Schemes.” *Journal of Agricultural Economics* 60:530–545.

Young, M. 2010. “Environmental Effectiveness and Economic Efficiency of Water Use in Agriculture: The Experience of and Lessons from the Australian Water Reform Programme.” Report, OECD, www.oecd.org/water.