Research Report:

Spatial Analysis of Application Efficiencies in Irrigation for the State of California

Prepared for:
United States Geological Survey
and
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ABSTRACT

Analyzing who is using the water, where, but most importantly, how efficiently, is important to identify enhancements already achieved and potential areas where further improvements can be made. *Application Efficiency* (*AE*) is a performance criterion that expresses how well an irrigation system performs when is operated to deliver a specific amount of water, for instance, the water requirements of a crop. *AE* is defined as the ratio of the average water depth applied and the target water depth during an irrigation event. The *average water depth* is the average height of water applied in a field during an irrigation event. The *target water depth* is the desired water to be supplied in a field during an irrigation event. The target water depth considered in this research is the *low quarter depth*, which is the average of the depths in the sections of the field that receive less water than the rest of the field (percentile < 0.25). Five irrigation surveys have been conducted in California: 1972, 1980, 1991, 2001 and 2010. These surveys have improved our understanding of the irrigations methods used on the various crops grown in California. The two primary goals of this project are: (1) estimate the spatial *AE* for different crops and hydrologic regions by using the irrigation surveys from 2001 and 2010 combined with theoretical AE values, and (2) create a geographic information system called California Irrigation Information System (CALIIS) to store and display this analysis. The primary target audience for the *AE* estimated in this report is regional/state water planners as well as large-scale water resource modelers. An extensive literature analysis was done to understand the relationship between *AE* and Distribution Uniformity (*DU*). A set of theoretical *AE* values were adopted considering the following assumptions: (a) irrigation surveys are representative samples of the population, (b) every farmer knew their irrigation system's *DU* and water requirements for their crops, (c) all farmers supplied exclusively the low quartile depth as the target water depth, and (d) water losses from the irrigation system were not considered. These assumptions allowed the use of *AE* values for hydrologic regions. Results show that averaged over all crops *AE* improved 3.0% statewide from 2001 to 2010. *AE* improved in all hydrologic regions of California, except in North Lahontan with a slight decrease of 0.1 % region wide. Sacramento River, South Coast and San Francisco Bay, are the hydrologic regions with highest increase in *AE*, 4.8%, 4.3% and 3.9% respectively. Similarly, the *AE* improved for all crops from 2001 to 2010, with highest *AE* values occurring in vineyards, subtropical trees, pistachio and almond and tomato. At least 14 crops improved their *AE* by 2% or more from 2001 to 2010: cotton, other field crops, cucurbit, onion and garlic, tomato (fresh and process, other truck crops, almond and pistachio, other deciduous, subtropical trees, turf grass and

landscape, and vineyards. Further refinement in AE values is needed to reduce and address the uncertainty in the results presented.

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TABLE OF CONTENTS

1. BACKGROUND

1.1. INTRODUCTION

Analyzing who is using the water, where, but most importantly, how efficiently, it is of substantial importance in order to identify potential places where improvements can be made. *Application Efficiency* (*AE*) as the ratio of the average water depth applied and the target water depth during an irrigation event. The *average water depth* is the average height of water applied in a field during an irrigation event. The average water depth depends on the crop and the irrigation method used, i.e. sub-surface, surface, sprinkler and drip. The target water depth is the desired water to be supplied in a field during an irrigation event. It is a common practice to use the *low quartile depth*, as the target depth. The low quartile depth is the average of the depths in the sections of the field that receives less water than the rest of the field (percentile < 0.25).

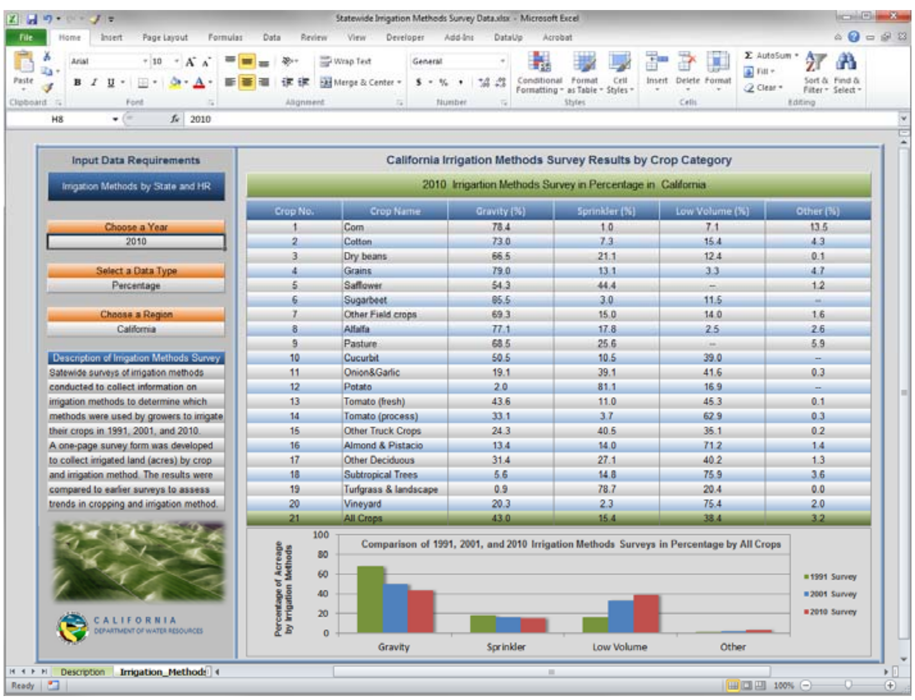


Figure 1: Statewide Irrigation Methods Survey Data.
(Source: Department of Water Resources. http://www.water.ca.gov/landwateruse/surveys.cfm)

Understanding the trends of how application efficiency has changed in time and varied in space is relevant because it helps to quantify how efficient water is applied, for which crops and where. Five irrigation surveys have been conducted in California: 1972 (Stewart 1975), 1980 (Hagan and Wagner 1983), 1991 (Snyder et al. 1996), 2001 (Orang et al 2008) and 2010 (Tindula et al. 2013). These surveys have improved the understanding and trends of the irrigations methods used and the types of crops grown in California. Before this study, the survey's results were displayed in a tabular format (Figure 1), but without a geographic component; thus it is difficult to relate the data and its geographical location if a person is not familiar with California hydrologic regions (DWR 2009a).

1.2. GOAL

The goal of this research is to provide a set of application efficiency values for the 10 California hydrologic regions (Figure 2) based on: (a) theoretical application efficiencies of different irrigation methods reported in literature and (b) data collected in the last two irrigation surveys (2001 and 2010). The application efficiency values have been stored in the California Irrigation Information System (CALIIS); which improves the visualization of results.

1.3. OBJECTIVES

Two are the main objectives of this research:

1) Introduce the irrigation system survey data into a Geographic Information System (GIS), called CALIIS, to provide easier access, use, and visualization of trends in irrigation system usage by region.

A geodatabase was built to store and display the irrigation survey data. The irrigation surveys contain data for 20 crops and 4 irrigation methods divided in 16 sub-methods. Data is displayed by hydrologic region. The geodatabase will store the time series for each crop and irrigation method.

2) Analyze spatially and temporally the application efficiency values for each irrigation method and crop.

A literature has been developed to review empirical and theoretical values for application efficiencies for each irrigation method and sub-method included in the 2010 irrigation survey.

1.4. TARGET AUDIENCE

The target audience for the application efficiency estimates presented in this report is regional/state water planners as well as large scale water resources modelers. Please read the section of Discussion (4.2.3) and Limitations (6.2), where limitations of the application efficiency values are explained.

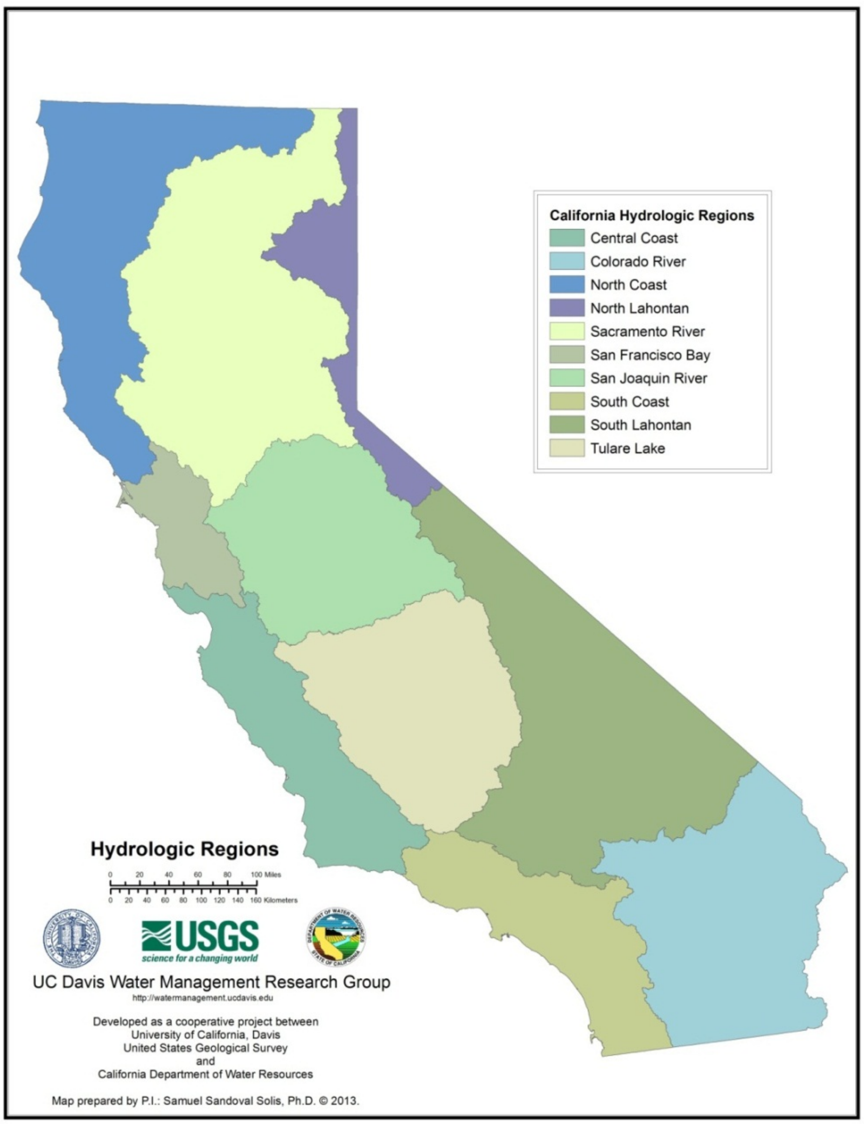


Figure 2: California Hydrologic Regions

- 3 -

2. LITERATURE REVIEW

2.1. INTRODUCTION

Agriculture first opened the door to the evolution of our civilization and society. The production of farming surpluses supported a sector of non-farmers, allowing for a society of politicians, priests, merchants, academics, artist, warriors, and room for creative thought. Improvements to agricultural systems assured more reliable food supplies for more people. This has changed nowadays with a booming global population who demands food and products obtained from natural resources. The feasibility of matching food production to population growth seems overwhelming in the light of today's trends. The United Nations estimated that by 2050 the world and United States (US) population are expected to be 8.9 billion and 408 million people, respectively; 29% and 32% more people than today's population (UN 2004). Current estimates indicate less than five percent of the population to be engaged and connected to agriculture (Ponting 2007). Demand is destined to overtax supplies if natural resources consumption is not curbed, specifically our appetite for water. This is not a problem caused by a single sector (e.g. agriculture), stretching water across a larger population is a burden to be shared among agricultural, economic, political and social sectors. A new attitude toward resource consumption and population demographics is essential to sustain harmony between human population growth and environmental stewardship. The efficient use of water is a key strategy, among others, to achieve a balance between water demand and supply.

2.2. CALIFORNIA

California is an important region to narrow the gap between water input and food output due the state's significant agricultural output, enormous crop diversity and the vulnerability of California's water supplies. California leads the nation in food production, outranking the second most productive state, Iowa, by nearly three times its export value (Henton et al. 2006). California is also essential for food diversity with a large range of specialty crops. In the 1940's, an agriculture census documented that only 6 percent of the state was dedicated to general crops, with the remaining 94 percent dedicated to specialized crop production (Hutchinson 1946). In 1945, the University of California estimated 118 distinct farming areas in California, with the second most diverse farming region of the time being Pennsylvania, with 25 different crop varieties (Johnston 2003). Kuminoff et al. (2000) reported California to be the exclusive US producer (over 99%) of 12 crops (almonds, artichokes, dates, figs, kiwifruit, olives, clingstone peaches, persimmons, pistachios, prunes, raisins and walnuts), and is responsible for 70% to 99% of 11 other specialty crops (wine grapes, table grapes, lettuce, strawberry, broccoli, carrots, avocados, lemons, plums, celery and cauliflower) (also in Finney and Symonds 2003). Despite the richness and abundance that California agriculture provides, food production faces future challenges due to finite water resources.

There are political and economic motivations to maintain and improve agro-production with less water. In 2009, California passed a wide-ranging legislative bills, referred as SBX7, encompassing a variety of water problems in California, such as: Delta governance and management (SBX7-1) (Simitian and Steinberg 2009), water bond measures (SBX7-2) (Codgill et al. 2009), groundwater monitoring (SBX7-6) (Steinberg and Pavley2009), water conservation (SBX7-7) (Steinberg 2009a) and water rights enforcement (SBX7-8) (Steinberg 2009b). In particular, SBX7-7 requires agricultural water suppliers to implement efficient water management practices by July 2012. Furthermore, the bill mandates preparation of agricultural water management plans by December 2012 (Steinberg 2009a).

Economic motivations to maintain and improve agro-production with less water are: (1) the reduction in the fixed cost to pay for water, such as energy cost, capital cost of new water supply projects, operation and maintenance; (2) the increase in crop yield by optimizing the minimum amount of water that can produce the maximum crop production; and (3) and the conservation of water resources for future production. Yet, capital cost is the dominant barrier to installing a new irrigation system. Caswell and Zilberman (2001) discuss the economic drivers of irrigation methods and the influences of a farm's region, crop and water source. They found groundwater dependent farmers, especially those in Kern County or growing almond and pistachio nuts, are more likely to install water efficient systems (e.g. drip and sprinkler). The high value cash crops and limited water available creates an adequate environment to become more economically efficient by using less water. At the irrigation district scale, Griffin (2006) analyzed pricing models for inter-seasonal and regional water efficiency, he identified pricing mechanisms to reduce water demand allowing for water surpluses among irrigation districts, and potential models to actively trade water and earmark water rights. Economic motivations are intertwined with political legislation of state water management, trickling down to enforce individual farm-scale decisions.

Efficient irrigation systems and management ameliorate urban water use competition, mitigate food prices and promote high quality of life standards in California. Although global irrigated land has expanded from 124 to roughly 660 million acres over the past century (Gleick 2000), California irrigated cropland has been at a constant decline. Loss of state farmland to urbanization, environmental restoration and projected snowpack reductions constrains farmable land and irrigation supplies. Approximately 40,000 agricultural acres are consumed by urbanization each year (Thompson 2009). Thus, a serious need for advanced water use efficiency is expressed through state political and economic actions. As public attitude, management decisions and hydraulic technologies influence the future of our water supplies and food production, we focus on the agricultural sector of irrigation water use.

2.2.1. Water in California

Although the global market is influenced by California food productivity, state irrigation depends on vulnerable and limited water supplies. Water users rely on groundwater from aquifers, surface water mostly from the Sierra Nevada snowpack or both. Groundwater and surface water sources are threatened by groundwater overdraft and declining snowpack levels accompanying rising annual temperatures. Sierra Nevada snowpack has been decreasing since the 1950s in response to climate change, threatening a major surface water source and storage for the state (Hanak et al. 2011). Upon limited snowpack, state and federal water projects are at risk to reduce the water allocation for irrigation, leaving those fortunate enough to overly groundwater to rely on such secondary supplies. However, recurring droughts and consistent groundwater pumping has led to groundwater overdraft, subsidence of ground elevation levels and seawater intrusion along the state coastline, leaving little water stored for future years of low snowpack and surface water (DWR 2003).

In addition to threatened water supplies, agriculture competes for water with other sectors, such as industrial, municipal and environmental water users. This competition requires the cooperation across all water-dependent sectors to maximize the benefits obtained from the use of water, sometimes tradeoffs must be made among stakeholders giving the finite nature of water resources. One of the strategies to minimize the tradeoffs is the efficient irrigation management. Irrigation Efficiency (IE) is not the single solution to all water problems; it is just one management strategy (among several strategies) to couple with increasing water scarcity, competing water uses, climate change, increasing water demand due to growing population, among other challenges

(DWR 2009b). Combining IE with improved crop selections, appropriate irrigation timing and other farm management actions will help sustain irrigated food crops demanded by a growing world population with finite land and water resources.

2.3. The Concept of Efficiency in Water Resources

The conceptual interpretation of efficiency is misunderstood occasionally throughout the literature, but often in societal and political usage of the term. The Merriam-Webster (2013) dictionary defines "Efficiency" as the ability to produce a desired result without wasting materials, time, or energy. In this paper the authors refers to efficiency as the capacity to produce a product (e.g. a commodity) at a predetermined or optimum rate of production (e.g. predetermined crop yield) using the least inputs possible (e.g. water, financial investment, fertilizer, etc.). The authors avoid on purpose the use of wasting material, in this case wasting water, because it has a pejorative meaning, it is assumed that water users do not waste resources on purpose.

Similarly to the conceptual definition of efficiency, there is frequent confusion within the literature when discussing and determining water use efficiency (WUE), irrigation efficiency (IE) and application efficiency (AE). Although there are clear definitions of these terms provided by the American Society of Agricultural and Biological Engineers (ASABE) and the American Society of Civil Engineers (ASCE 1978), both of them consistent with definitions provided by the US Department of Agriculture (USDA) and FAO (Hillel 1997), there is still confusion; these terms are used interchangeably or incorrectly. In this paper the authors adhere to the definitions of ASABE, ASCE and USDA.

3. Efficiency Criteria in Irrigation Systems

3.1. Introduction

Efficiency for irrigation can be catalogued from three points of view. :

1) Irrigation system performance,
2) Uniformity of water application, and
3) Crop response to irrigation

These measures are interrelated and vary on a spatial and temporal scale. The spatial may vary from a single field up to whole irrigation district, watershed or hydrologic region. The temporal scale can vary from a single irrigation event, up to a growing season or a period of years.

3.2. Key Definitions

Evaporation (E) is the conversion of water in liquid state to vapor. For the purposes of this report, it is only considered evaporation from free surfaces of water in transit, from plant surfaces intercepting irrigation water and from the soil surface interface between the wetted soil and the atmosphere above. (Burt et al. 1997). Evaporation can be modified by changing irrigation frequency, irrigation method, mulching, shading, and other techniques. *Transpiration* (T) is the volume of water that has passed through plant stomata and into the atmosphere as vapor.

Evapotranspiration (ET) is a generic term for the combined process of transpiration from plants and evaporation from soil and wet plant tissue. *Crop Evapotranspiration* (ET_C) is the amount of water for evaporation and transpiration that can be associated to determined crop within a field or cropped area.

Applied Irrigation Water (AW_t), or simply *Applied Water*, is the volume of water dedicated for irrigation purposes, it is the total volume of water that passes at the farm diversion point. A farm diversion point is a place where the water coming from the water source is or can be accounted, these points can be: the outlet of a groundwater well, river or canal intake and spillways.

Consumptive uses is the portion of the applied irrigation water that ends up in the atmosphere, plus water that is harvested in the crop and plant tissue, plus water considered irrecoverable, thus it is consumed. *Non consumptive uses* is any other portion of the applied irrigation water that abandons the field or root zone system, and that can be recovered or re-applied elsewhere. Examples of non consumptive uses are runoff, deep percolation, canal spills, among other

Beneficial uses of water is the amount of water required for an adequate grow of a crop in addition to crop evapotranspiration (ET_C). These water uses include: removal of salts (leaching for salinity control), microclimate control (evaporative cooling during extreme heat or frost protection), seedbed preparation, germination of seeds, softening of a soil crust for seedling emergence, and ET from plants beneficial to the crop (windbreaks or cover crops) (Burt et al. 1997, Imak et al. 2011). *Non-beneficial uses* are those uses intrinsic of the operation of irrigation systems, that cannot be avoided, such as reservoir evaporation, sprinkler evaporation, water needed for maintaining water quality standards in drains or wetlands, among others.

Reasonable uses are all beneficial plus certain non-beneficial uses of water. Unreasonable uses are volumes of water applied in excess or unnecessary for the adequate grow of a crop. Examples of non-beneficial uses are: uncollected tailwater (unrecirculated in the field), deep percolation in excess for salt removal, unnecessary ET outside the cropped area, among other.

Table 1 -Reasonable, unreasonable, beneficial and non-beneficial uses of water. Adopted from Burt et al. 1997

Reasonable Uses	*Beneficial Uses*	
	Crop evapotranspiration (ET_C)	
	Water harvested in the crop	
	Salt removal	
	Microclimate Control	
	Seed or weed germination	
	ET of beneficial crop plants	
	Non-Beneficial Uses	Non-Beneficial Uses
	Reservoir evaporation	
	Soil Evaporation	
	Sprinkler Evaporation	
	Water needed to maintain water quality standards	
	Some deep percolation due to non-uniformity	
	Unreasonable Uses	
	Excessive deep percolation	
	Excessive tailwater	

- 9 -

3.3. Irrigation System's Performance

This section describes criteria to evaluate the effectiveness of the physical system and operating decisions to deliver water from the water source(s) to crops. Often, the time span for criteria described in this subsection is growing season (S) but these criteria can also be calculated during an irrigation event (t).

3.3.1. *Conveyance Efficiency (CE)*

Water for irrigation is normally transported from the water source(s) to a diversion point where water is diverted into the farm field(s). Conveyance facilities include rivers, canals (earthen or lined), pipelines, and/or a combination of all of these. These facilities have conveyance losses, meaning that water reaching the farm diversion point is usually less that the water extracted from the water source(s). Conveyance losses include: canal seepage and spills, evaporation losses and leaks in pipelines. The conveyance efficiency (CE) is defined as the ratio between the water that reaches a farm or a control point (AW_t) and the diverted water from the water source (V_t^{Total}) fore the season (S)(Howell 2003), expressed as:

$$CE_S = \frac{AW_S}{V_S^{Total}} * 100 \qquad [1]$$

Where CE is the conveyance efficiency, AW_S is the volume of water that reaches the farm diversion point at a season S, and V_S^{Total} is the volume of water diverted from the water source. Conveyance losses include any canal seepage, and spills, reservoir seepage and evaporation. Typically conveyance losses are lower for closed conduits or pipelines than for unlined canals or natural riverbeds.

3.3.2. *Irrigation Efficiency (IE)*

Sometimes, water for irrigation may be applied for other uses than to meet the crop evapotranspiration needs. Irrigation Efficiency (IE) focuses on the actual hydraulic efficiency more than crop-water efficiency. IE is the ratio of water used *beneficially* to irrigation water applied, expressed by the ASCE (1978) as:

$$IE_S = \frac{V_S^{Beneficial}}{AW_S - \Delta(Storage)_S} \times 100 \qquad [2]$$

- 10 -

where $V_S^{Beneficial}$ is the water beneficially used (acre-feet, m^3) for a period of time S, and AW_S represents total water delivered to the farm diversion point (acre-feet, m^3), and $\Delta(Storage)_t$ is the change of water stored as soils moisture expressed as $Storage_t$-$Storage_{t-1}$ (acre-feet, m^3). *Beneficial* uses of applied water (Equation 3) include crop evaporation, leaching for salinity control, frost protection, and irrigation for field preparation (Equation 4). The water beneficially used

$$V_S^{Beneficial} = V_S^{Crop} + V_S^{Other} \quad [3]$$

Where other beneficial uses (V_S^{Other}) is:

$$V_S^{Other} = V_S^{Salt\ Removal} + V_S^{Microclimate} + V_S^{Seedbed} + V_S^{Beneficial\ Plants} + V_S^{Soil\ Crust} \quad [4]$$

Equation 2 has been simplified in Equation 5 by considering that there is no change in water stored $\Delta(Storage)_S$ from one season to the other. This assumption is discussed in more detail by Howell (2003).

$$IE_S = \frac{V_S^{Beneficial}}{AW_S} \times 100 \quad [5]$$

In equation 5, it is possible to replace the units of volume in numerator ($V_S^{Beneficial}$) and denominator (AW_S) by depth (feet, meters, etc.), with the understanding that this is a representative depth of water applied over a unit area (acre, hectare, square-foot, square meter).

The $V_S^{Beneficial}$ term in Equation 5 is sometimes subjective because *beneficial* water use is not a fixed term. As mentioned before, beneficial use may include crop evapotranspiration (ET_c) plus pre-irrigation water consumption (e.g. water used for leaching of root zone salts and/or for field preparation) plus water to protect the crop (water for frost protection or during extreme heat). Water losses that occur as result of excessive deep percolation, runoff, wind drift and spray droplet evaporation are normally not considered as beneficial use, and thus, decrease the *IE*. Runoff and deep percolation losses can be significant if tailwater is not reused or deep percolation water not recovered from groundwater. In the case where water is recovered, the beneficial water volume ($V_S^{Beneficial}$) (Eq. 3) should be adjusted to account for the net recovered tailwater and/or deep percolation water ($V_S^{Recovered}$), as shown in Eq. 6.

$$V_S^{Beneficial} = V_S^{Crop} + V_S^{Other} - V_S^{Recovered} \quad [6]$$

IE has also been called *Seasonal Irrigation Efficiency* (Howell 2003) to highlight the period of time considered during the calculations is a growing season. Sometimes, confusion amongst users appears when in instructive reports or peer-reviewed articles new definitions of *IE* and Water Use Efficiency (WUE) are created under the same namesake. For example, a recent report quantifying *WUE* for the California Department of Water Resources (Guivechi et al. 2012) re-defines *WUE* as a fraction of water outputs ($V_S^{Beneficial}$) to water inputs (AW_S). Adhering to the terminology explained in this report, Guivechi et al. (2012) is referring to *IE* and not to *WUE*.

3.3.3. *Irrigation Consumptive Use Coefficient (ICUC)*

The Irrigation Consumptive Coefficient Coefficient (*ICUC*) (Jensen 1993) is the ratio consumptive water uses ($V_S^{Consumptive}$) to the applied irrigation water (AW_S) during a period of time *S*,

$$ICUC_S = \frac{V_S^{Consumptive}}{AW_S} \times 100 \qquad [7]$$

where $V_S^{Consumptive}$ is the consumptive use of water of the crop during a season *S*, and AW_S represents the volume of water applied. Table 2 shows the relationship and differences between *ICUC* and *IE*.

Table 2 –Relationship and difference between *ICUC* and *IE* based on consumptive, non-consumptive, beneficial and non-beneficial use. Adopted from Burt et al. 1997

Crop ET_C Microclimate control Evap.	Deep percolation for salt removal	Beneficial Uses	IE(%)	100%
Sprinkler Evaporation Reservoir Evaporation Soil Evaporation	Excessive deep Excessive tailwater Unrecoverable spills	Non-beneficial Uses	100-IE	
-------Consumptive Use -----	-Non-consump. Use-			
--------------ICUC--------------	--------100-ICUC------			
------------------------------100%-------------------------				

3.3.4. *Irrigation Sagacity (IS)*

Irrigation sagacity evaluates the reasonable uses of water compared to applied water, as shown in Equation 8.

- 12 -

$$IS_S = \frac{V_S^{Reasonable}}{AW_S - \Delta(Storage)_S} \times 100 \qquad [8]$$

Similarly to irrigation efficiency, if there is no change in water stored $\Delta(S)_t$ from one season to the other, this equation can be simplified as follows:

$$IS_S = \frac{V_S^{Reasonable}}{AW_S} \times 100 \qquad [9]$$

Both, irrigation sagacity (*IS*) and irrigation efficiency (*IE*) consider applied water (AW_S) as the denominator, in equations 8 and 5 respectively. The main difference between *IS* and *IE* is in the numerator; *IS* considers the *reasonable water uses* ($V_S^{Reasonable}$) (Eq. 8) which can be *beneficial* and *non-beneficial*, while *IE* only considers the *beneficial water uses* ($V_S^{Beneficial}$) (Eq. 5). Table 3 relates and compares both efficiency performance criteria.

Table 3 –Relation between Irrigation Efficiency (IE) and Irrigation sagacity (IS) according to reasonable, unreasonable, beneficial and non-beneficial uses of water. Adopted from Burt et al. 1997.

Irr. Efficiency (IE)			Irr. Sagacity (IS)	
100%	IE (%)	*Beneficial Uses*	IS(%)	100%
		Crop evapotranspiration (ET_C)		
		Water harvested in the crop		
		Salt removal		
		Microclimate Control		
		Seed or weed germination		
		ET of beneficial crop plants		
	100-IE	*Non-Beneficial Uses*		
		Reasonable Uses		
		Reservoir evaporation		
		Soil Evaporation		
		Sprinkler Evaporation		
		Water needed to maintain water quality standards		
		Some deep percolation due to non-uniformity		
		Unreasonable Uses	100-IS	
		Excessive deep percolation		
		Excessive tailwater		

3.3.5. *Overall Irrigation Efficiency (CE)*

The overall irrigation efficiency (*OIE*) represents the efficiency of the entire physical system and operating decisions in delivering water from the source of water to its beneficial use. *OIE* is calculated by multiplying the Conveyance Efficiency (*CE*) and Irrigation Efficiency (*IE*):

$$OIE_S = \left[\frac{IE_S}{100} \times \frac{CE_S}{100}\right] \times 100 \qquad [10]$$

3.3.6. *Effective Irrigation Efficiency (CE)*

Re-use of runoff water decreases the amount of water pumped from a water source and can improve the overall irrigation efficiency (*OIE*). The Effective Irrigation Efficiency (EIE_S) is the overall irrigation efficiency corrected for runoff and deep percolation that is recovered, reused and/or restored to the water source without reduction in water quality (Irmak et al. 2011). EIE is expressed as:

$$EIE_S = \left[OIE_S + \left(FR_S \times \left(1 - \frac{OIE_t}{100}\right)\right)\right] \times 100 \qquad [11]$$

where FR_t is the fraction of the runoff, seepage and/or deep percolation that is recovered.

3.4. Uniformity of Water Application Performance

An important component improving the efficiency of irrigation systems is the uniform distribution of water. Often, the time span for criteria described in this subsection is an irrigation event (*t*) but some of these criteria can also be valid for the whole growing season (*S*).

3.4.1. *Distribution Uniformity (DU)*

Distribution Uniformity (DU) measures how well irrigation water is distributed to different areas in the field, called elements (Burt et al. 1997). An element, is the smallest unit area in the field that requires water, but big enough to assume that the variation of the distributed water within the element is not important. The low-quarter distribution uniformity (DU_t^{lq}) is used to characterize the applied irrigation water distribution over surface irrigation systems, but it also can be applied to micro and sprinkler irrigation systems. The places (elements) where less water is applied have traditionally been chosen to express uniformity because in these areas water stress can affect crop growth. The low-quarter distribution uniformity (DU_t^{lq}) is a proven and practical method to evaluate the *DU*.

The average distribution uniformity (d_t^{Avg}) in a field is calculated as the volume per unit area (*d*) for each element (*i*), from *i*=1 to *i*=*I*, weighted by the element's fraction of the total area (a_i).

$$d_t^{Avg} = \frac{\sum_{i=1}^{i=I} d_i * a_i}{\sum_{i=1}^{i=I} a_i} \qquad [12]$$

Special attention is given to the volumes per unit area of the low quartile (percentile < 0.25) of the sample ($i \in$ p<0.25). The volumes per unit area can also be expressed depth per unit area. The average low-quarter depth (d_t^{lq}) is:

$$d_t^{lq} = \frac{\sum_{i=1 \, for \, i \in p<0.25}^{i=I} d_i * a_i}{\sum_{i=1 \, for \, i \in p<0.25}^{i=I} a_i} \qquad [13]$$

The *low-quarter distribution uniformity* (DU_t^{lq}) is defined as:

$$DU_t^{lq} = \frac{d_t^{lq}}{d_t^{Avg}} \qquad [14]$$

where d_t^{lq} is the average low-quarter depth and d_t^{Avg} is the average depth of the water accumulated in all the elements. DU_t^{lq} represents the fraction of the lower quartile depth with respect to the average depth of all elements during a time *t*. *DU* is not an efficient term, thus, it has been recommended to present *DU* as a fraction number and not as a percentage, to underscore this distinction (Burt et al. 1997). DU_t^{lq} vary from 0 to 1, a DU_t^{lq} of 1 means that all element areas receive equal amounts of water per unit area; while a DU_t^{lq} of 0.8 means that the average depth of the low-quartile sample only received 80% of the average depth of the whole field.

3.4.2. Application Efficiency (AE)

Application efficiency (*AE*) is an efficiency criterion that expresses how well an irrigation system performs when is operated to deliver a specific amount of water. *AE* provides an estimation of how well a target irrigation depth is met in an irrigation event. . *AE* is defined as the ratio of the average water depth applied (d_t^{Avg}) and the depth of water required (d_t^{Req}) during an irrigation event. The *average water depth* is the average height of water applied in a field during an irrigation event. The *required water depth* (also known as *target water depth*) is the desired water to be supplied in a field during an irrigation event. *AE* evaluates what happens during a single irrigation event (t), even though the water has not yet been used, for example, for ET_C. (Burt et al. 1997)

$$AE_t = \frac{d_t^{Avg}}{d_t^{Req}} \times 100 \quad [15]$$

One of the assumptions of *AE* is that the target depth is considered uniform over the subject area. *AE* do not consider change in soils water storage $\Delta(Storage)_S$ because it refers to a single irrigation event (t).

3.4.3. Potential Application Efficiency (PAE)

The potential application efficiency (*PAE*) considers that the average depth of water applied (d_t^{Avg}) in a particular irrigation event *t,* should be the average of the depths in the low-quarter (d_t^{lq}):

$$PAE_t^{lq} = \frac{d_t^{Avg}}{d_t^{lq}} \times 100 \quad [16]$$

Furthermore, this consideration implies that losses due to deep percolation are minimized, and the *AE* will be at maximum with a slightly minimum area on the field underirrigated. For practical purposes, *PAE* can help to determine the amount of water to be applied:

$$d_t^{Avg} = d_t^{Req} \times \left(\frac{100}{PAE_t^{lq}}\right) \quad [17]$$

If the average depth of water applied is equal to the low-quarter depth ($d_t^{Avg} = d_t^{lq}$) in equation 16, then PAE_t^{lq} will be equal to 100%. Substituting a value of PAE of 100% in Eq. 17 represents that the depth of water required in the field (d_t^{Req}) is equal to the average of the depths in the low-quarter (d_t^{lq}) which is also equal to the average depth of water in the field (d_t^{Avg}) as shown in Equation 18.

$$d_t^{Req} = d_t^{Avg} = d_t^{lq} \; if \; PAE_t^{lq} = 100 \quad [18]$$

By definition *PAE* and *DU* are different, *DU* considers the water infiltration depths plus the depth of water intercepted (and evaporated) by the canopy and the water evaporated in the irrigation systems; e.g., water evaporated in sprinklers systems. On the contrary, *PAE* only considers infiltration depths. The PAE_t^{lq} can be calculated as function of *DU* if the surface losses are known or already estimated as follows:

$$PAE_t^{lq} \approx DU_t^{lq} \times (100 - Losses_t) \quad [19]$$

where $Losses_t$ (units: %) are surface water losses due to evaporation during spray drift, evaporation in the canopy and not reused runoff (Burt et al. 1997). Rogers et al. (1997) estimated a list of losses for different irrigation systems.

3.4.4. Low-Quarter Adequacy (AD)

The Low-Quarter Adequacy (*AD*) is a complementary criterion of *AE* that evaluates how much a required or target depth is met. The AD is expressed as:

$$AD_t^{lq} = \frac{d_t^{lq}}{d_t^{Req}} \quad [20]$$

where d_t^{lq} is the average low-quarter depth, d_t^{Req} is the depth required a determined irrigation event *t*. An *AD* value of less than 1 (*AD*<1) will indicate there is under irrigation in the field, an *AD* equal to 1 (*AD*=1) will indicate a proper irrigation, and a value higher than 1 (*AD*>1) will indicate overirrigation (See Table 4). Similarly than *DU*, *AD* is not an efficiency term; thus, it is recommended to be expressed as a fraction number and not as a percentage, to underscore this distinction.

Table 4 –Low-Quarter Adecuacy Values. Adopted from Burt et al. 1997

Value	*Irrigation*	*Comment*
AD > 1	Overirrigation	The difference between *AD* and 1 is the degree of overirrigation
AD = 1	Proper Irrigation	Application Efficiency equal to Potential Application Efficiency (*AE* = *PAE*)
AD < 1	Underirrigation	The difference between 1 and *AD* is the degree of underirrigation

- 17 -

3.5. Response of Crop to Irrigation Performance

3.5.1. *Water Use Efficiency (WUE)*

Water use efficiency (WUE) expresses the amount of water invested to produce a certain commodity amount; it is used to evaluate the resource and economic savings associated with a given crop. The output factor (numerator) ranges from biomass accumulation, total crop biomass or crop yield. The water input (denominator) is represented by total water put into system, transpiration or evapotranspiration (ET). Sinclair et al. (1984) discusses this confusion in detail, along with methods to improve WUE estimations; here WUE was defined as a ratio of biomass accumulated (e.g. crop yield) to water consumed (eg., evapotranspiration, total water input, transpiration). Equation 21 shows the determination of WUE commonly expressed as a ratio of crop output to water input:

$$WUE_t = \frac{Y_C}{ET_C} \qquad [21]$$

Where Y_C is the crop output or yield (units: pounds/acre or tons/hectare) and ET_C is the actual evapotranspiration of the crop (units: acre-feet/acre or m^3/hectare). If the crop output Y_C unit is pounds/acre and the water input ET_C unit is acre-feet/acre, the WUE units are pounds/acre-feet expressing the crop output (pounds) per unit of water input (acre-feet). WUE values must not be understood as the more units of water input, the more production to be harvested; instead, WUE should be understood as a parameter to compare in which regions the soil and climatologic conditions allows to obtain more (or less) crop biomass for unit of water. WUE is not to be confused with, or used interchangeable for irrigation efficiency (IE).

4. CALIIS – CALIFORNIA IRRIGATION INFORMATION SYSTEM

4.1. PROJECT FRAMEWORK

The main objective of this project is to integrate the irrigation systems' survey with an analysis of application efficiencies for each irrigation system, in order to create a California Irrigation Information System (CALIIS). Figure 3 shows the framework of CALIIS.

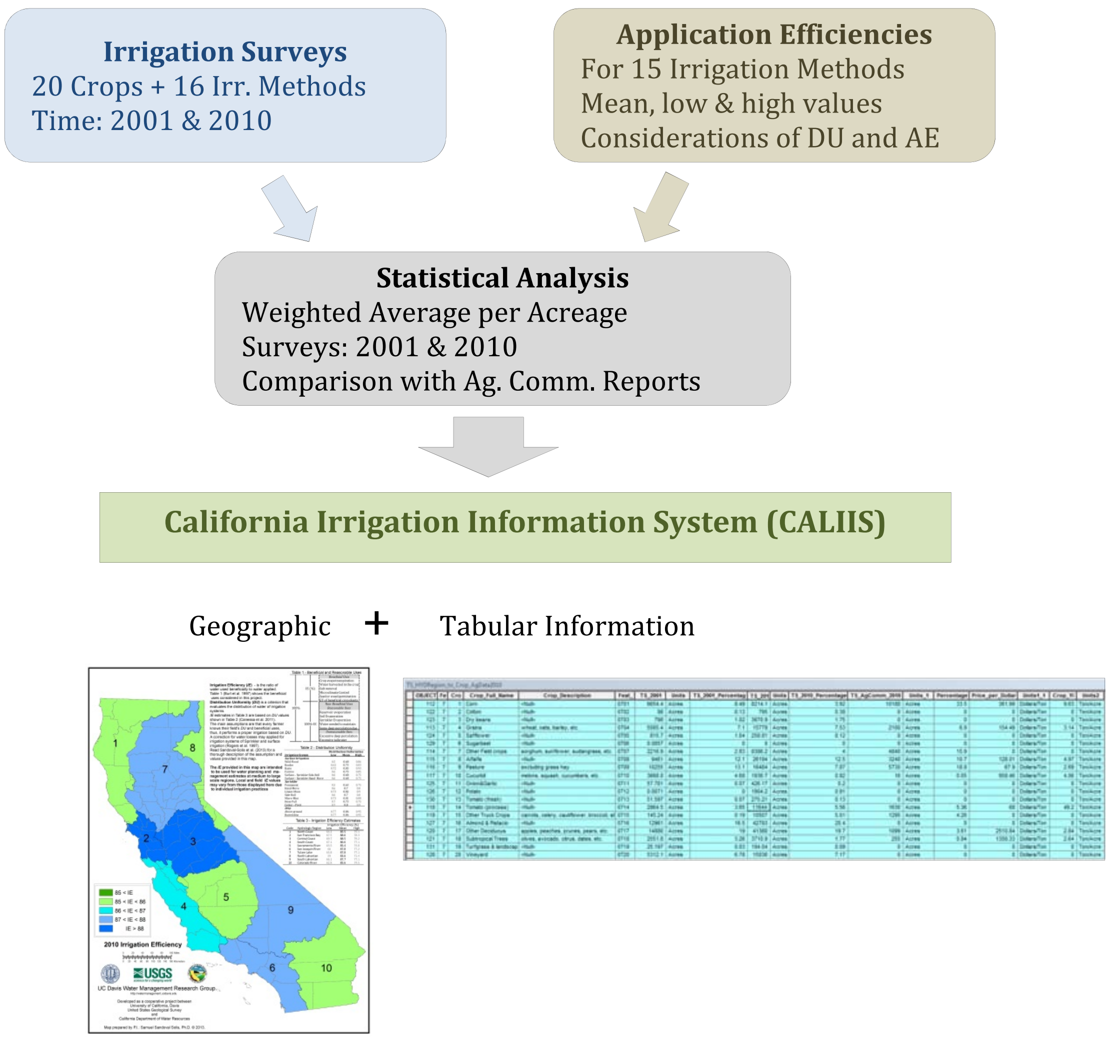


Figure 3: Framework to integrate irrigation surveys and application efficiencies into the California Irrigation Information System (CALIIS)

Two are the main sources of information for CALIIS: irrigation surveys of 2001 (Orang et al. 2008), 2010 (Tindula et al. 2013) and the *DU* values for several irrigation systems (Canessa et al. 2011). The following section explains the *DU* and *AE* values used in CALIIS. Then a brief description of the surveys and the construction and data framework of CALIIS are presented. Finally, the statistical analysis performed to couple the irrigation surveys with the *AE* values is explained in the last section of this chapter.

4.2. APPLICATION EFFICIENCIES

4.2.1. APPLICATION EFFICIENCY VALUES CONSIDERED FOR THE STATE OF CALIFORNIA

Table 5 shows the Application Efficiencies (*AE*) used in this study.

Table 5 –Application Efficiencies

	Application Efficiencies (%)		
Irrigation System	**Low**	**Mean**	**High**
Surface Irrigation			
Wild Flood	50	68	86
Border	62	73	83
Basin	72	83	93
Furrow	60	73	85
Surface – Sprinkler Side-Roll	60	68	75
Surface – Sprinkler Hand- Move	60	68	75
Sprinkler			
Permanent	70	78	85
Hand-Move	60	70	80
Linear-Move	73	82	90
Side-Roll	60	70	80
Micro-Mini	73	81	88
Hose-Pull	70	73	75
Center –Pivot	70	80	90
Drip			
Above ground	77	86	95
Buried drip	77	86	95

AE values for Table 5 come from Canessa et al. (2011), Charles M. Burt (personal communication, February 7, 2013), Tanji and Hanson (1990), Morris and Lynne (2006), Roger et al. 1997, Howell (2003), Hanson et al. (1999), and Irmak et al. (2011).

4.2.2. CONSIDERATIONS FOR APPLICATION EFFICIENCIES

For this study, the DU values presented in Table 5 are assumed to be the Application Efficiencies (AE) considering the following:

a) Most of the farmers know their *DU* in their field(s), this assumption allows to scale up field values into hydrologic regions.

b) There is a *proper irrigation* (see Table 4) in each irrigation event (t), meaning that every farmer supplied the low-quarter depth (d_t^{lq}) as the target depth (d_t^{Req}) in each irrigation event (t).

This assumption represent that the Lower Quartile Adequacy (AD_t^{lq}) (Eq. 20) is equal to 1, thus:

$$\text{if } AD_t^{lq} = \frac{d_t^{lq}}{d_t^{Req}} = 1; \text{ then: } d_t^{lq} = d_t^{Req} \qquad [22]$$

c) Each irrigation event was planned to deliver water for the low-quarter depth (d_t^{lq}) for all irrigation events (t) that correspond to the growing season ($t \in S$). Every farmer took into account their *DU* to plan for their average depth (d_t^{Avg}) during every irrigation event (t). Based on Eq. 14:

$$d_t^{Avg} = \frac{d_t^{lq}}{DU_t^{lq}}; \qquad [23]$$

d) The *DU* value remained constant for the whole irrigation season (S) in every irrigation event (t). This mean that for every irrigation event (t) the ratio d_t^{lq}/d_t^{Avg} is constant:

$$DU_S^{lq} = \frac{d_t^{lq}}{d_t^{Avg}} = \frac{d_1^{lq}}{d_1^{Avg}} = \frac{d_2^{lq}}{d_2^{Avg}} = \cdots = \frac{d_T^{lq}}{d_T^{Avg}} = Constant \qquad [24]$$

e) No irrigation water losses were considered. Infiltration losses and return flows were not considered as losses due to water can be stored in aquifers or reused downstream. Water losses due to evaporation during spray drift were neglected.

f) The Application Efficiency (AE) is the ratio of the average water depth applied (d_t^{Avg}) and the depth of water required (d_t^{Req}) during an irrigation event (t):

$$AE_t = \frac{d_t^{Avg}}{d_t^{Req}} \times 100 \qquad [25]$$

g) Application Efficiency can be approximated using the Distribution Uniformity. Considering equations 16, 22 and 25:

$$AE_t = \frac{d_t^{Avg}}{d_t^{Req}} \times 100 = PAE_t^{lq} = \frac{d_t^{Avg}}{d_t^{lq}} \times 100 \qquad [26]$$

- 21 -

Given that (Eq. 19):

$$PAE_t^{lq} \approx DU_t^{lq} \times (100 - Losses_t) \quad [27]$$

And that no water losses have been considered, then:

$$AE_t = PAE_t^{lq} \approx DU_t^{lq} \quad [28]$$

thus:

$$\boldsymbol{AE_t \approx DU_t^{lq}} \quad \textbf{[29]}$$

4.2.3. *Discussion*

The previous considerations make possible the use of Distribution Uniformity as an approximation for Application Efficiency. It is very unlikely that all farmers know the DU for every field; nevertheless, this assumption was made to extrapolate results of field *DU* to hydrologic regions. Also, most of the farmers tend to optimize their water use, trying to use only the required target depth on each irrigation event, thus the assumption of proper irrigation is very likely to be reasonable; thereof the lower-quartile adequacy is 1 (AD_t^{lq}=1). If these assumptions are reasonably true, then, the Application Efficiency (*AE*) and Potential Application Efficiency (*PAE*) also tend to 1 (*AE*=*PAE*=1). Equation 19 (also shown below) explains the relationship between *PAE* and *DU*,

$$AE_t = PAE_t^{lq} \approx DU_S^{lq} \times (100 - Losses)$$

The surface water losses (*Losses*) is the term that induces uncertainty in the analysis provided in this report. Examples of water losses are: water lost due to evaporation during spray drift, evaporation in the canopy and not reused runoff. In general, the *AE* (and also P*AE*) tends to be equal to *DU* if the surface water losses are negligible, such as low volume irrigation systems (Burt et al. 1997). *AE* tends to be slightly smaller than *DU* if the surface water losses are small, such as in sprinkler irrigation systems. *AE* tends to be smaller than *DU* if the surface water losses are significant, such as gravity irrigation systems (Burt et al. 1997). Thus, it is likely that some of the *AE* values provided in this report may overestimate the actual *AE* in a particular hydrologic region. On the contrary, in regions where underirrigation, also known as drought irrigation, is performed, the *AE* values provided in this report may underestimate the actual *AE*. Rogers et al. (1997) provide values for surface water $Losses_S$ for different irrigation systems.

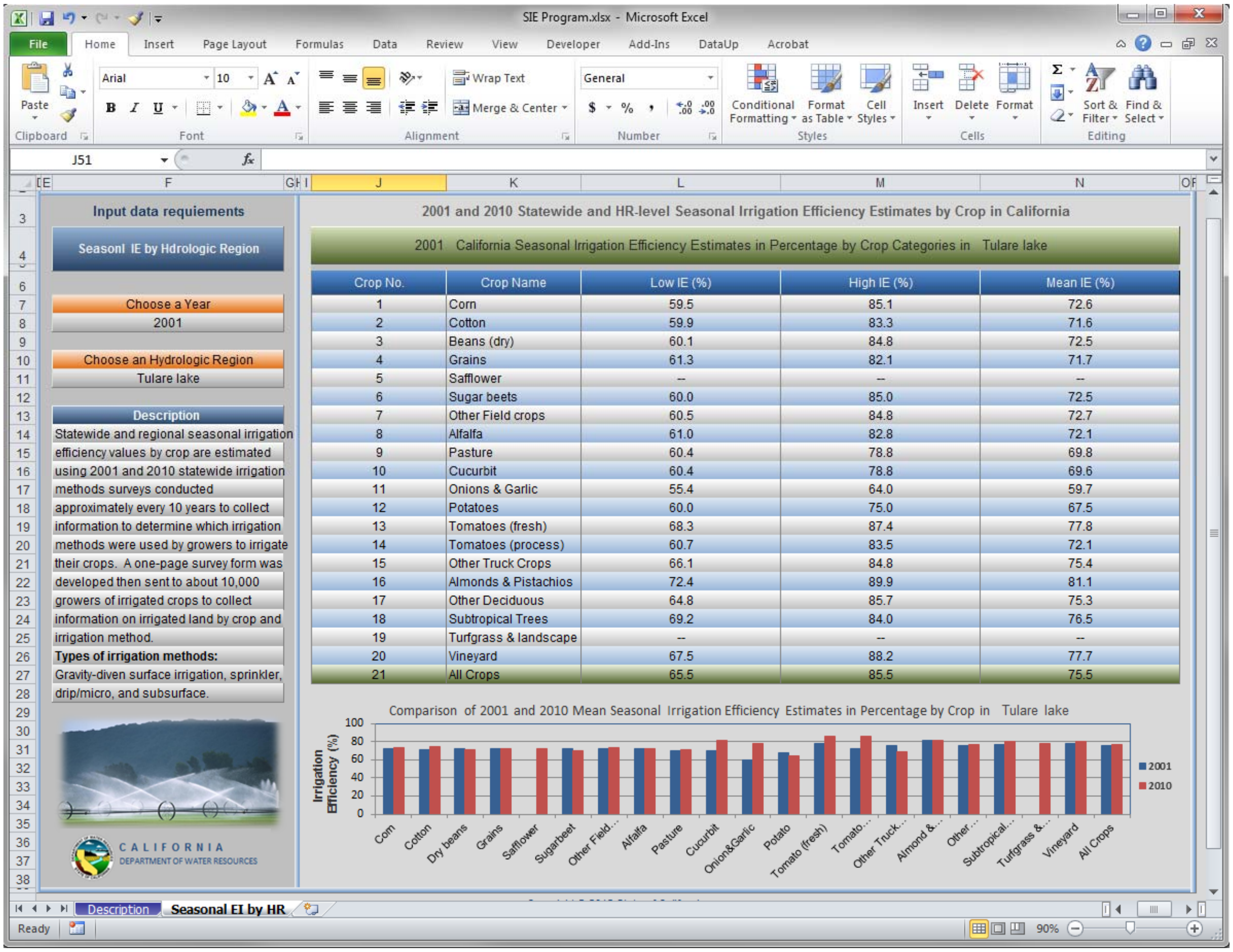
The authors fully acknowledge that some of these considerations cannot be valid for many crops and hydrologic regions. However, the main purpose of this approach is to estimate a rough approximation of application efficiencies for the state of California, for hydrologic regions water plans, as well for planning models. Also, the intention is that this report starts the discussion about application efficiency at the state level. The analysis and numbers provided in this report can be refined and modified according to the characteristics of every hydrologic region and subregion, when data becomes available.

4.3. GEODATABASE CONSTRUCTION

4.3.1. IRRIGATION SURVEYS: 2001 AND 2010

One of the main objectives of the project are to introduce the Irrigation Survey data from 2001 and 2010 (Figure 1), use the new Seasonal Application Efficiency program (Figure 4) developed by DWR (explained in Section 4.4) to an irrigation information system (IIS) format and perform a temporal and spatial analysis of application efficiency for each crop and irrigation method. This will help to determine the variability and uncertainty of how efficiently water is been used in agriculture, using application efficiency (AE) as performance criterion. Irrigation survey data was collected by county for 20 crops, 4 irrigation types, and 16 irrigation methods. Composing the data into an IIS format provides easier access, use, and visualization of irrigation trends for each of the ten hydrologic regions in California.

This section explains the data management, considerations and framework used to create the hydrologic regions database. A tutorial, located in Appendix A, shows the methods and procedures to manipulate data in the geodatabase from selecting by location and feature attributes, exporting selected data, construction of new feature classes, and construction of relationship classes.



Crop No.	Crop Name	Low IE (%)	High IE (%)	Mean IE (%)
1	Corn	59.5	85.1	72.6
2	Cotton	59.9	83.3	71.6
3	Beans (dry)	60.1	84.8	72.5
4	Grains	61.3	82.1	71.7
5	Safflower	--	--	--
6	Sugar beets	60.0	85.0	72.5
7	Other Field crops	60.5	84.8	72.7
8	Alfalfa	61.0	82.8	72.1
9	Pasture	60.4	78.8	69.8
10	Cucurbit	60.4	78.8	69.6
11	Onions & Garlic	55.4	64.0	59.7
12	Potatoes	60.0	75.0	67.5
13	Tomatoes (fresh)	68.3	87.4	77.8
14	Tomatoes (process)	60.7	83.5	72.1
15	Other Truck Crops	66.1	84.8	75.4
16	Almonds & Pistachios	72.4	89.9	81.1
17	Other Deciduous	64.8	85.7	75.3
18	Subtropical Trees	69.2	84.0	76.5
19	Turfgrass & landscape	--	--	--
20	Vineyard	67.5	88.2	77.7
21	All Crops	65.5	85.5	75.5

Figure 4: Seasonal Application Efficiency Program.
(Source: Department of Water Resources.)

4.3.2. *DATA FRAMEWORK*

The data framework for the geodatabase follows the structure shown in Figure 5. Starting from ten hydrologic regions it is subdived into twenty crops. From twenty crops it is possible to find the water source (ground, surface, both) or continue to four irrigation type. From irrigation type we can then specify the irrigation method and lastly the water sources for each method present. Note that the Figure 5 has the number of possible categories in parenthesis after the field name description as well as the key fields that relates the tables with the geographic files (shapefiles). This is to indicate that there are multiple values associated with each box in the schema. Table 6 lists the names for each subgroup in the geodatabase.

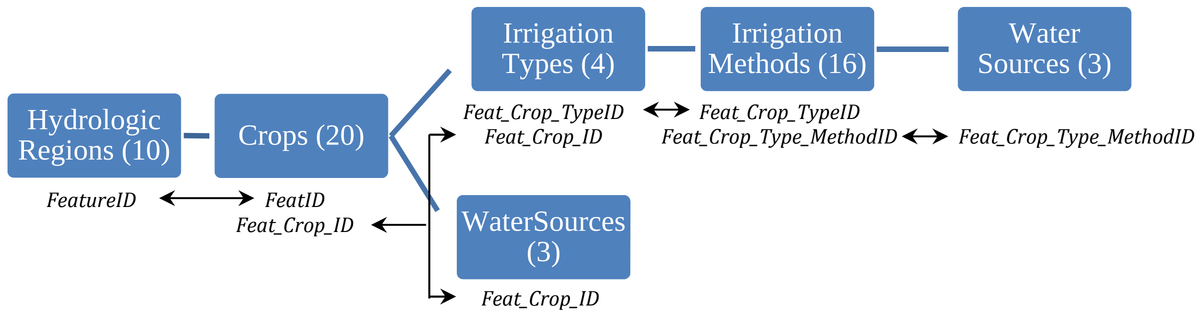


Figure 5: Data Framework of the Geodatabase.

Table 6 –Listed names for each subgroup in the Geodatabase

Hydrologic Regions	
1	North Coast
2	San Francisco Bay
3	San Joaquin River
4	Central Coast
5	Tulare Lake
6	South Coast
7	Sacramento River
8	North Lahontan
9	South Lahontan
10	Colorado River

Irrigation Types	
1	Gravity
2	Sprinkler
3	Low Volume
4	Other

Irrigation Methods	
1	Subsurface-Subsurface
2	Surface-Wildflood
3	Surface-Border
4	Surface-Basin
5	Surface-Furrow
6	Surface-Sprinkler-SideRoll
7	Surface-Sprinkler-Handmove
8	Sprinkler-Permanent
9	Sprinkler-Handmove
10	Sprinkler-Linearmove
11	Sprinkler-SideRoll
12	Sprinkler-MicroMini
13	Sprinkler-HosePull
14	Sprinkler-CenterPivot
15	Drip-AboveGround
16	Drip-Buried

Crops	
1	Corn
2	Cotton
3	Dry Beans
4	Grains (wheat, oats, barley, etc.)
5	Safflower
6	Sugarbeet
7	Other Field Crops (sorghum, sunflower, sudangrass, etc.)
8	Alfalfa
9	Pasture
10	Cucurbit (melons, squash, cucumber, etc.)
11	Onions and Garlic
12	Potato
13	Tomato (Fresh)
14	Tomato (Process)
15	Other Truck Crops (carrots, celery, cauliflower, broccoli strawberries, asparagus, etc.)
16	Almond and Pistachio
17	Other Deciduous (apples, peaches, prunes, pears, etc.)
18	Subtropical Trees (olives, avocado, citrus, dates, etc.)
19	Turfgrass and Landscape
20	Vineyard

Water Source	
1	Surface
2	Groundwater
3	Both

4.3.3. Data Sources

The data used to form the database was compiled from statewide irrigation surveys from 2001 (Orang et al 2008) and 2010 (Tindula et al. 2013). These data were compiled by county and surveys were sent to 10,000 randomized farmers from various counties within the state. Regional data was composed by the summation of county data within each region. Where regional and county boundaries overlapped, a distribution of the crops was composed based off of data from the DWR Land & Water Use Survey for various years. For these counties a percentage of crop values were added to each appropriate region. The limited sample size of returned surveys makes these data a sample set prone to skewed or inaccurate representations of crop and irrigation methods.

Data from the Agriculture Commissioner report for 2010 was delineated by county and distributed into regions similar as to that described above. This report covers a more comprehensive population based value that will be compared to the Irrigation Survey data within our analysis.

4.4. INTEGRATING APPLICATION EFFICIENCIES AND IRRIGATION SYSTEMS SURVEY

The irrigation survey contains acreage data ($Acreage_{i,j}$) for every crop (i) and irrigation system (j from j=1 to j=15) for all hydrologic regions (HR from HR=1 to HR=10). The statistical analysis was performed with three AE (k, from k=1 to k=3) performances (Table 5): low, mean and high.

Application efficiencies ($AE_{i,k}$) were estimated for every crop (i) and performance (k) that depends on the irrigation system (j) for each hydrologic region ($Acreage_{i,j} \in HR$) using a weighted average shown in the following equation:

$$AE_{i,k} = \frac{\sum_{j=1}^{j=15}[Acreage_{i,j} \times AE_{j,k}]}{\sum_{j=1}^{j=15} Acreage_{i,j}} \text{ where } Acreage_{i,j} \in HR \qquad [30]$$

For instance the mean AE of Corn ($AE_{\text{Corn,Mean}}$) in San Joaquin hydrologic region is:

$$AE_{Corn.\ mean} = \frac{\sum_{j=1}^{j=16}[Acreage_{Corn,j} \times AE_{j,mean}]}{\sum_{j=1}^{j=16} Acreage_{Corn,j}} \text{ where } Acreage_{Corn,j} \in San\ Joaquin \qquad [31]$$

where $Acreage$ and AE values will vary according to the 15 irrigation system (j) surveyed. Eq. 30 was used to estimate the IAE values representative of hydrologic regions, by substituting the total acreage ($Acreage_{Total,j}$) where a particular irrigation system is used instead of just for an individual crop ($Acreage_{i,j}$). This is possible because in this report is considered that the application efficiency depends on the irrigation system and not in the type of crop.

5. RESULTS

5.1. HYDROLOGIC REGION

Figure 6 shows the AE for the 2010 survey for the 10 Hydrologic regions of State of California.

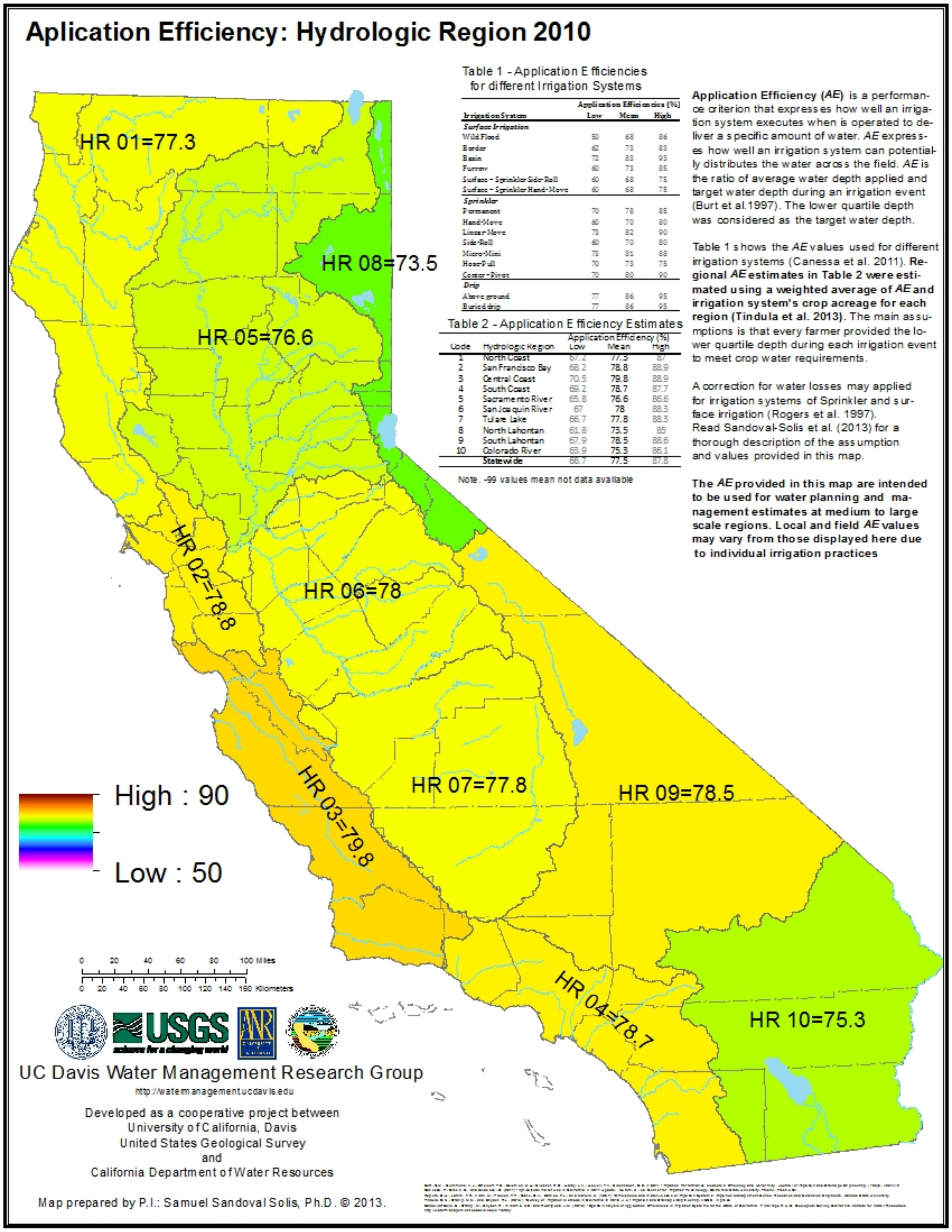


Table 1 - Application Efficiencies for different Irrigation Systems

Irrigation System	Application Efficiencies (%) Low	Mean	High
Surface Irrigation			
Wild Flood	50	68	86
Border	62	73	83
Basin	72	83	93
Furrow	60	73	85
Surface - Sprinkler Side-Roll	60	68	75
Surface - Sprinkler Hand-Move	60	68	75
Sprinkler			
Permanent	70	78	85
Hand-Move	60	70	80
Linear-Move	73	82	90
Side-Roll	60	70	80
Micro-Mini	73	81	88
Hose-Pull	70	73	75
Center - Pivot	70	80	90
Drip			
Above ground	77	86	95
Buried drip	77	86	95

Table 2 - Application Efficiency Estimates

Code	Hydrologic Region	Application Efficiency (%) Low	Mean	High
1	North Coast	67.2	77.3	87
2	San Francisco Bay	68.2	78.8	88.9
3	Central Coast	70.5	79.8	88.9
4	South Coast	69.2	78.7	87.7
5	Sacramento River	65.8	76.6	86.6
6	San Joaquin River	67	78	88.3
7	Tulare Lake	66.7	77.8	88.3
8	North Lahontan	61.8	73.5	85
9	South Lahontan	67.9	78.5	88.6
10	Colorado River	63.9	75.3	86.1
	Statewide	66.7	77.5	87.8

Note. -99 values mean not data available

Figure 6: Application Efficiency for Hydrologic Regions, ***Survey 2010***.

Figure 7 shows the AE for the 2001 survey for the 10 Hydrologic regions of State of California.

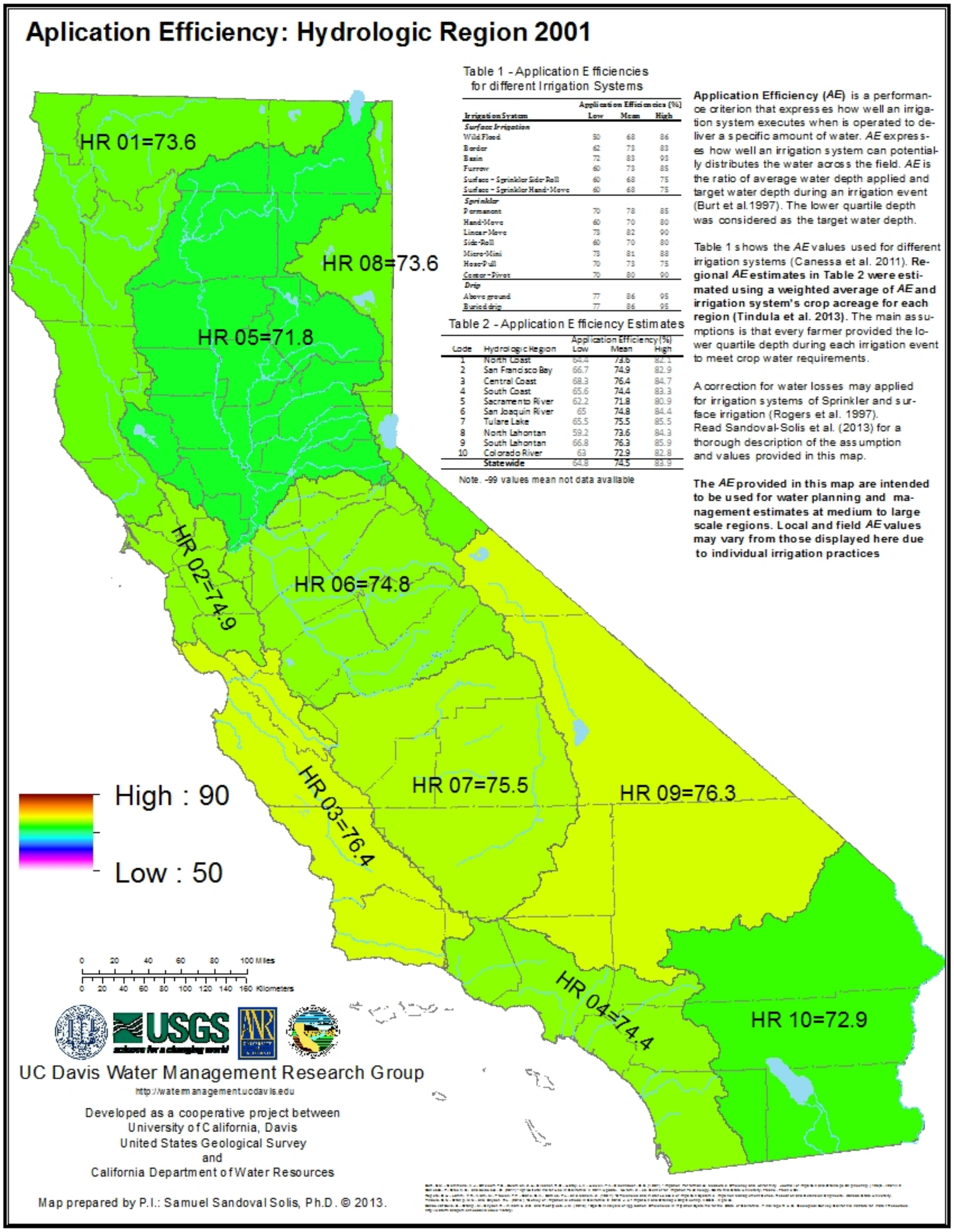


Figure 7: Application Efficiency for Hydrologic Regions, ***Survey 2001***.

5.2. For Crop

5.2.1. *Corn*

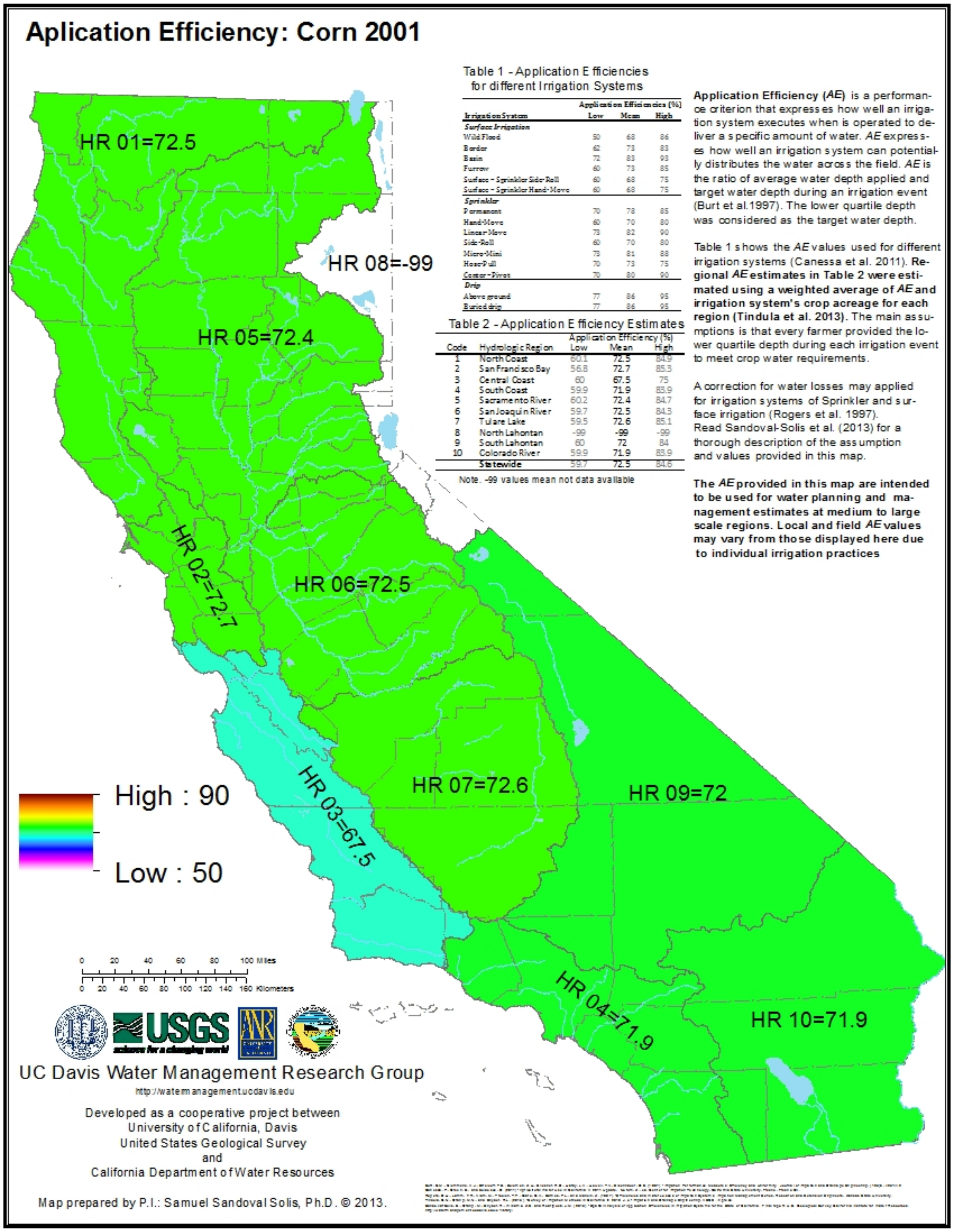


Figure 8: Application Efficiency for Corn, ***Survey 2001***.

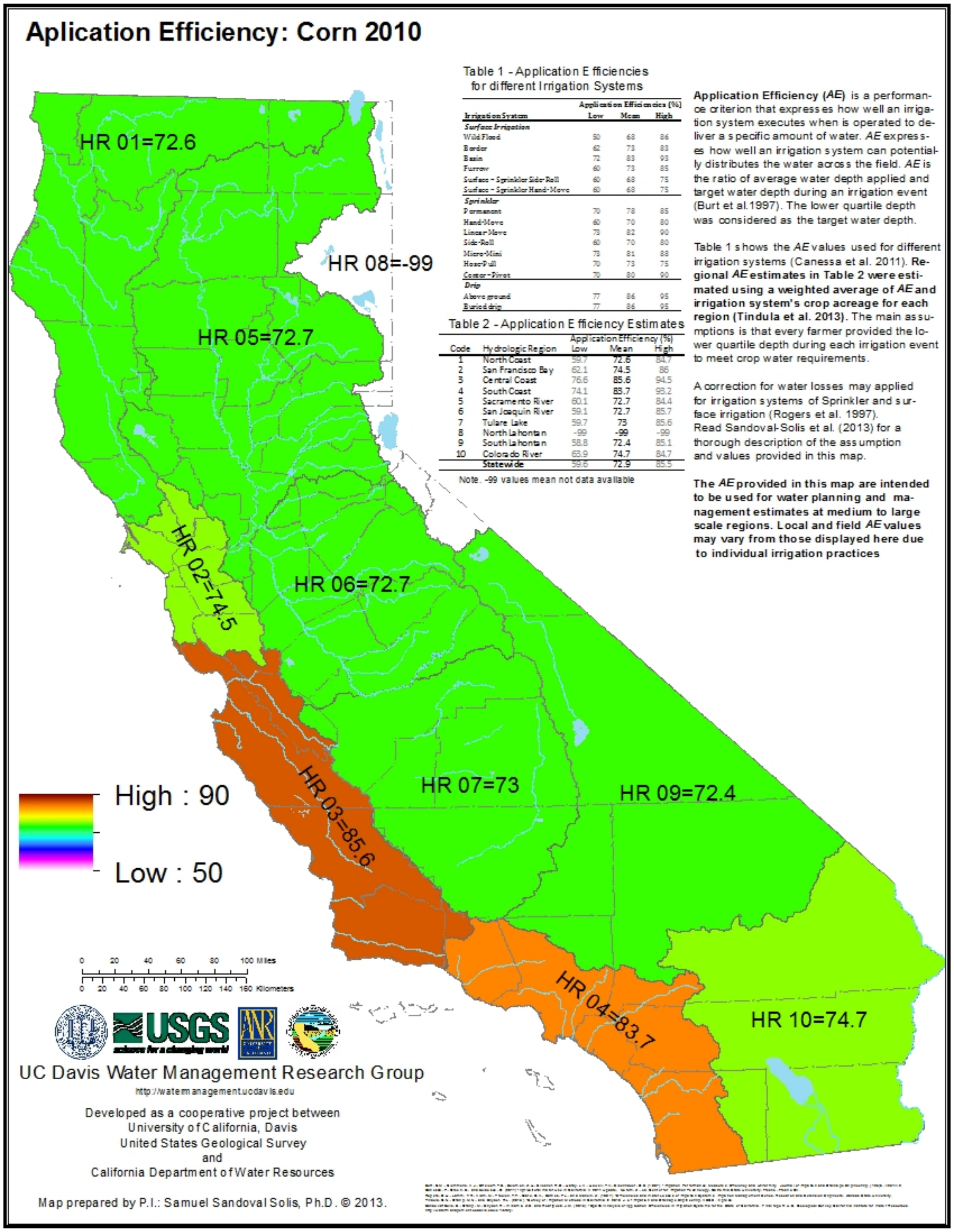


Figure 9: Application Efficiency for Corn, ***Survey 2010***.

5.2.2. *Cotton*

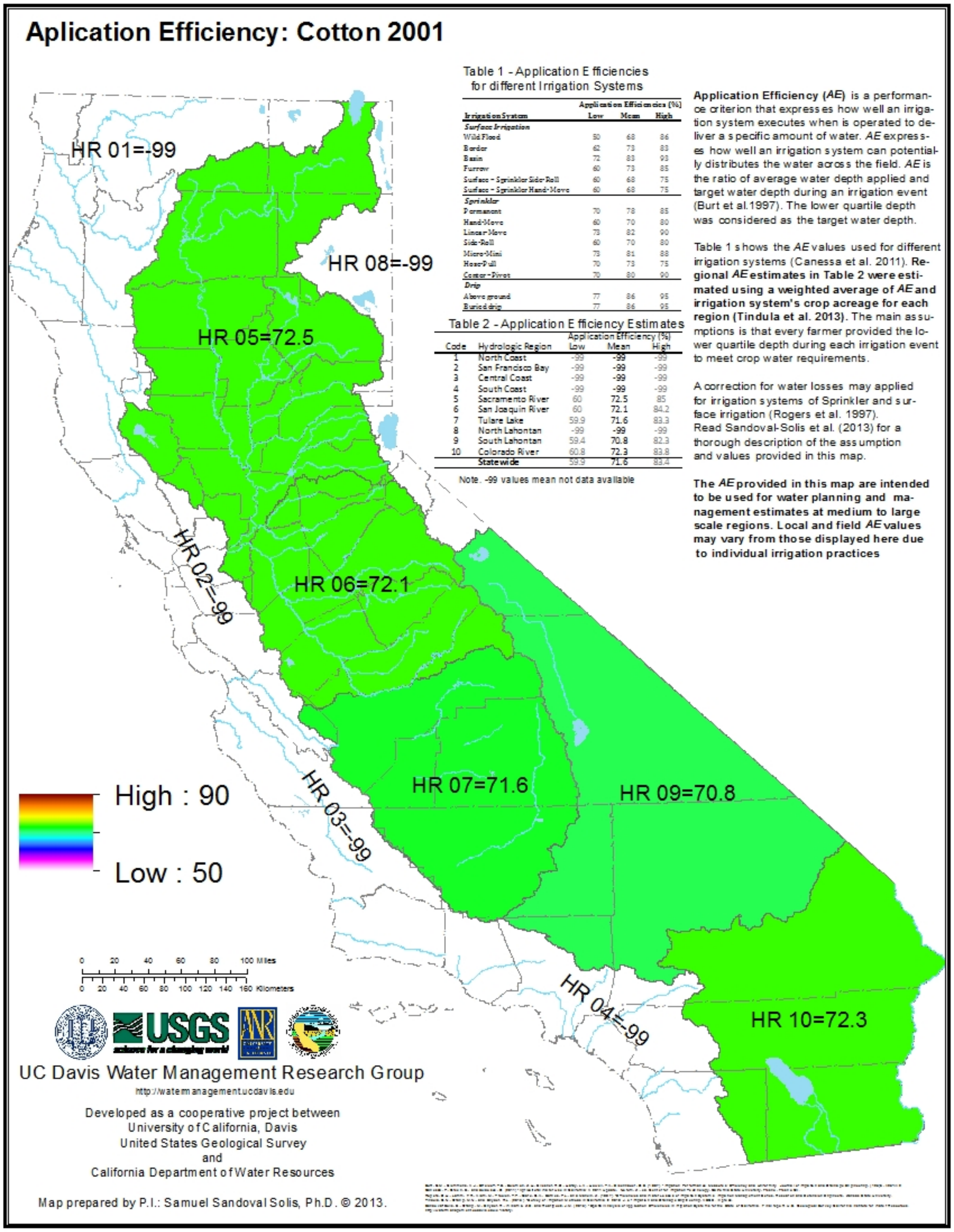


Figure 10: Application Efficiency for Cotton, ***Survey 2001***.

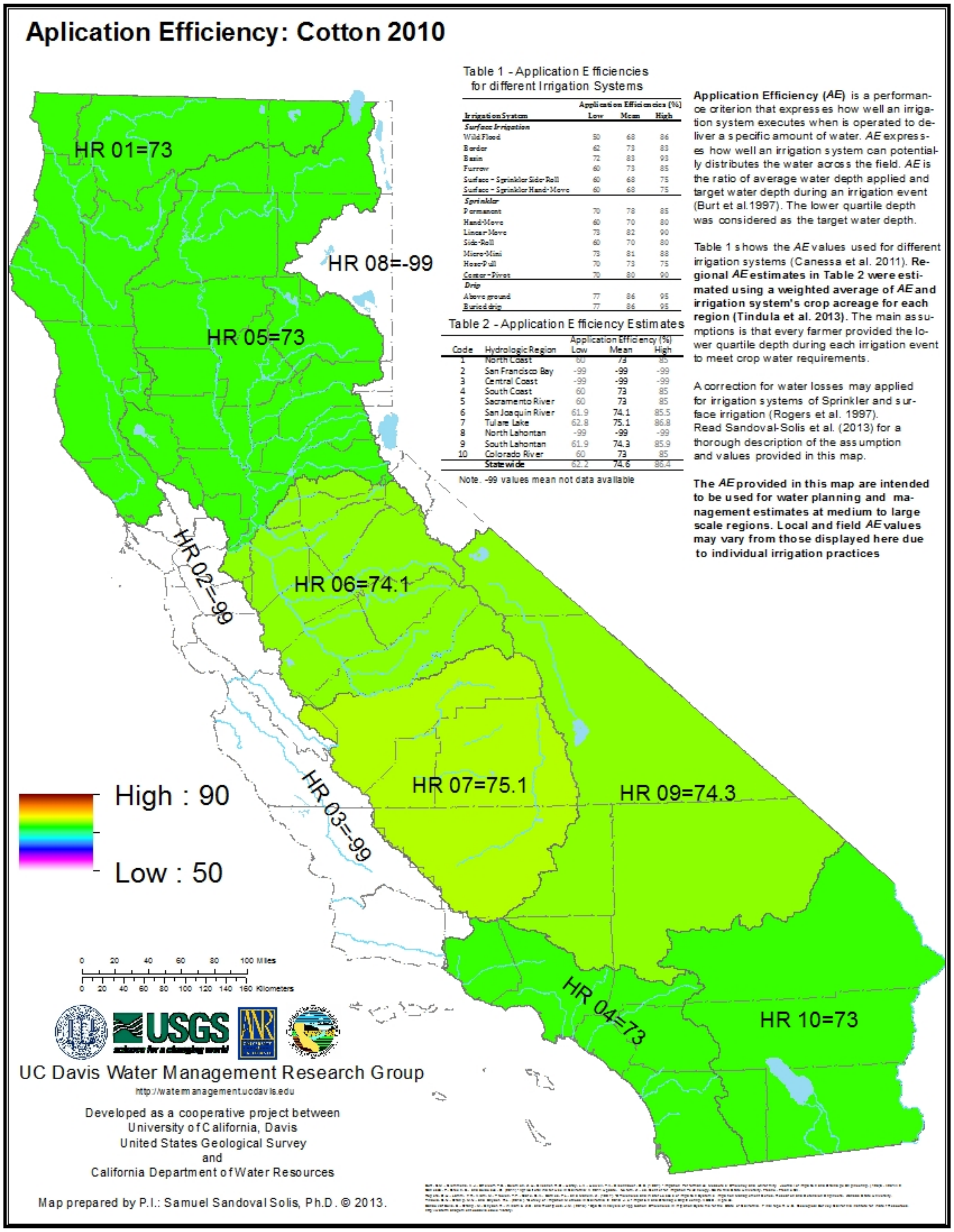


Figure 11: Application Efficiency for Cotton, ***Survey 2010***.

5.2.3. DRY BEANS

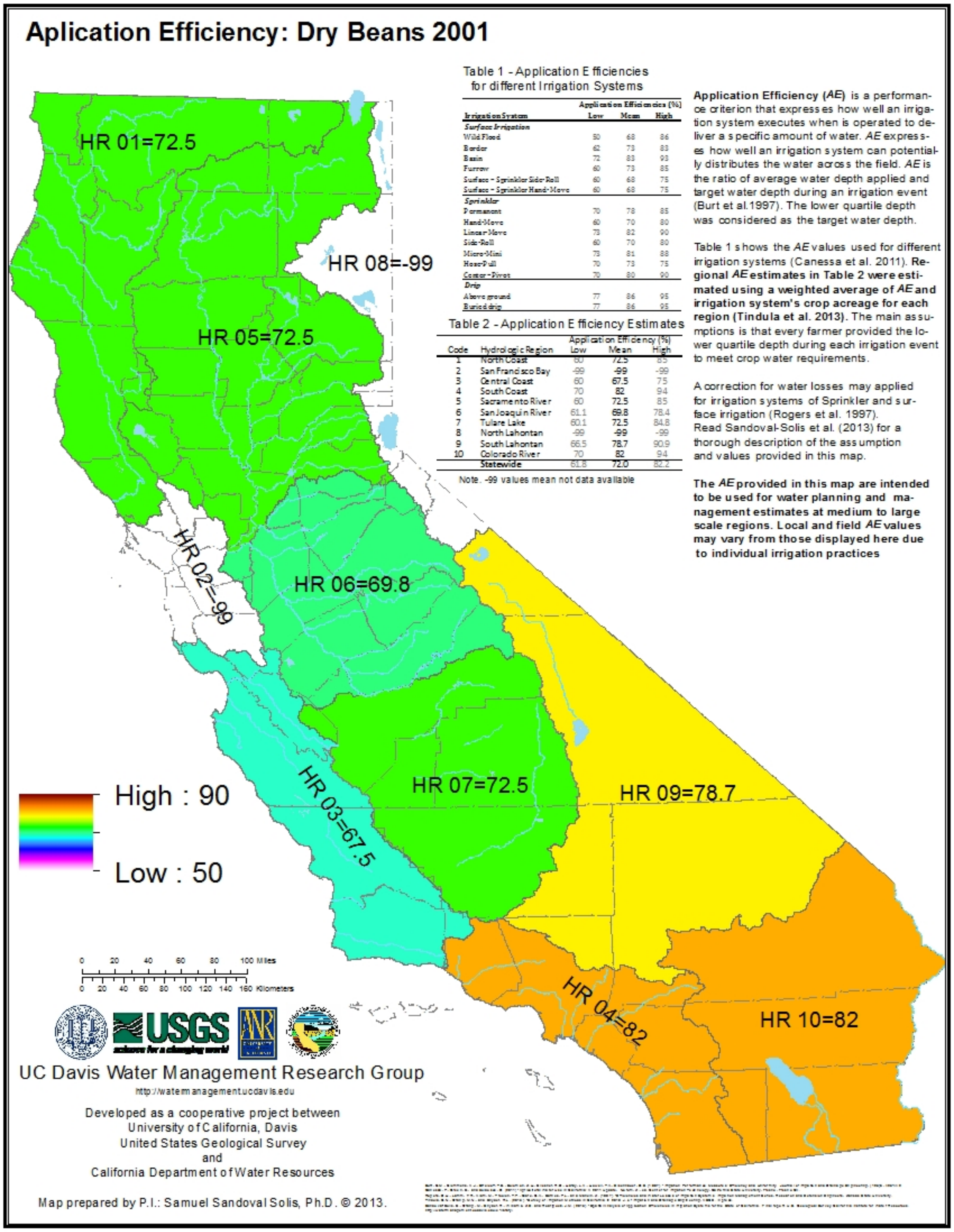


Figure 12: Application Efficiency for Dry Beans, ***Survey 2001***.

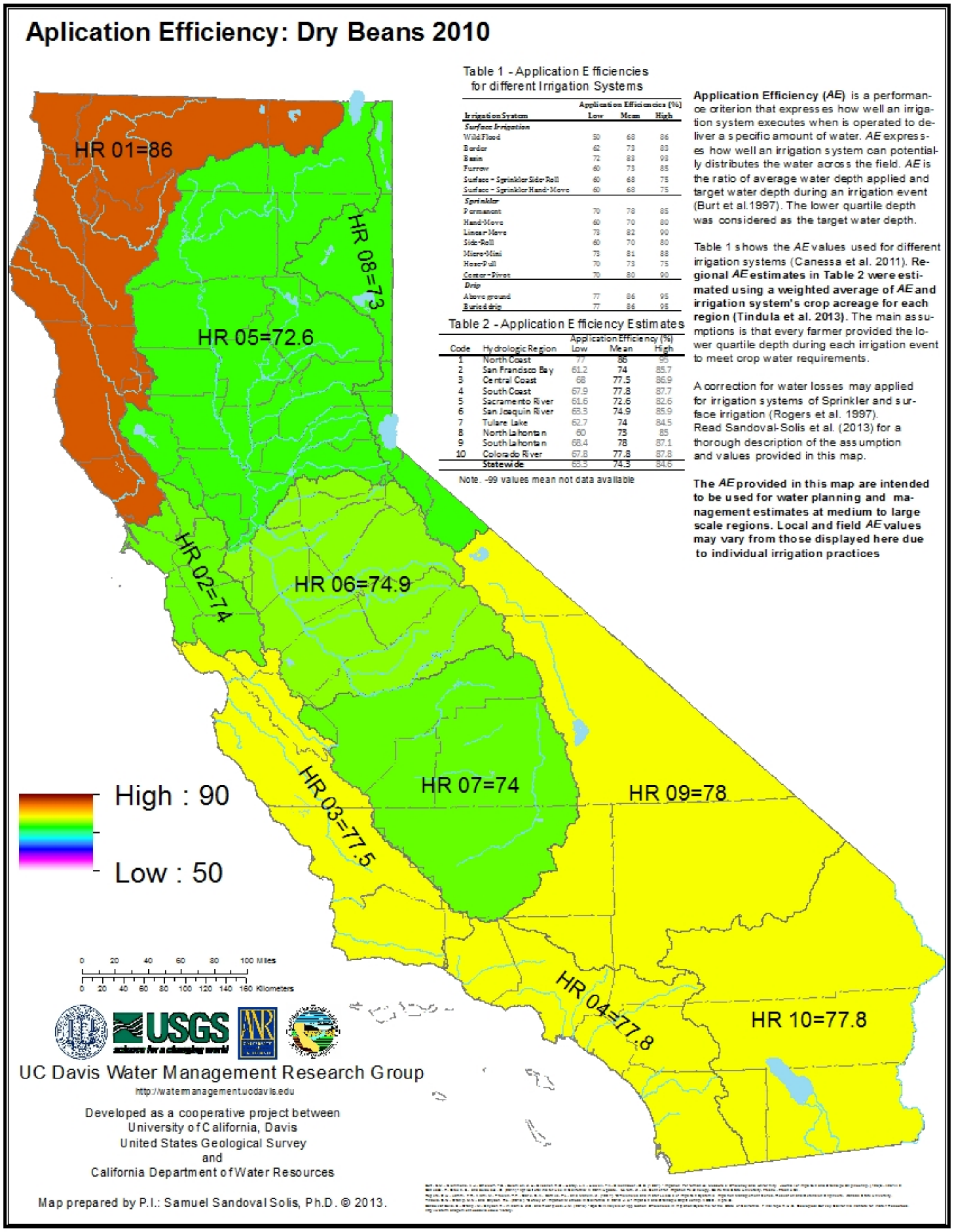


Figure 13: Application Efficiency for Dry Beans, ***Survey 2010***.

5.2.4. *GRAINS*

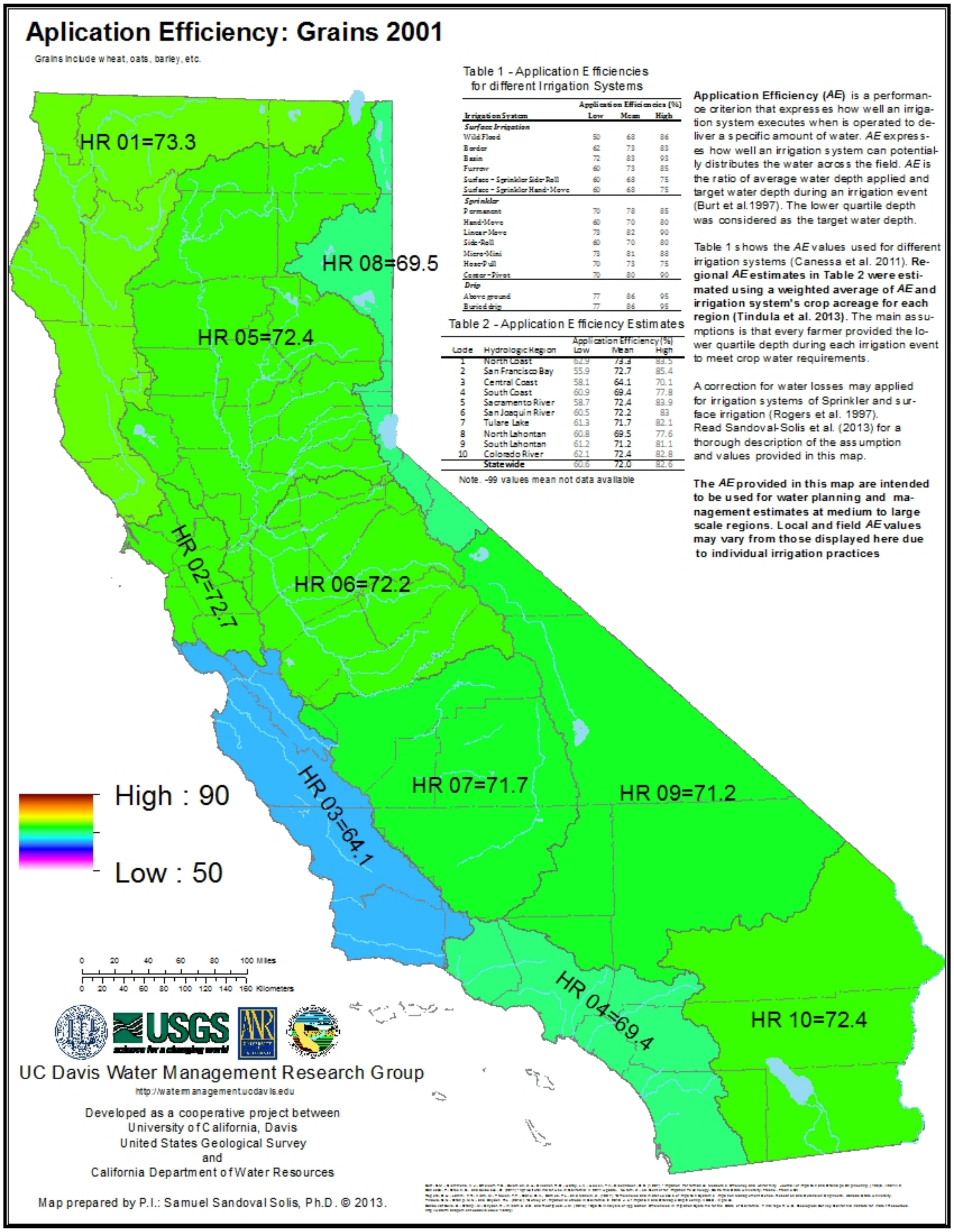


Figure 14: Application Efficiency for Grains, ***Survey 2001***.

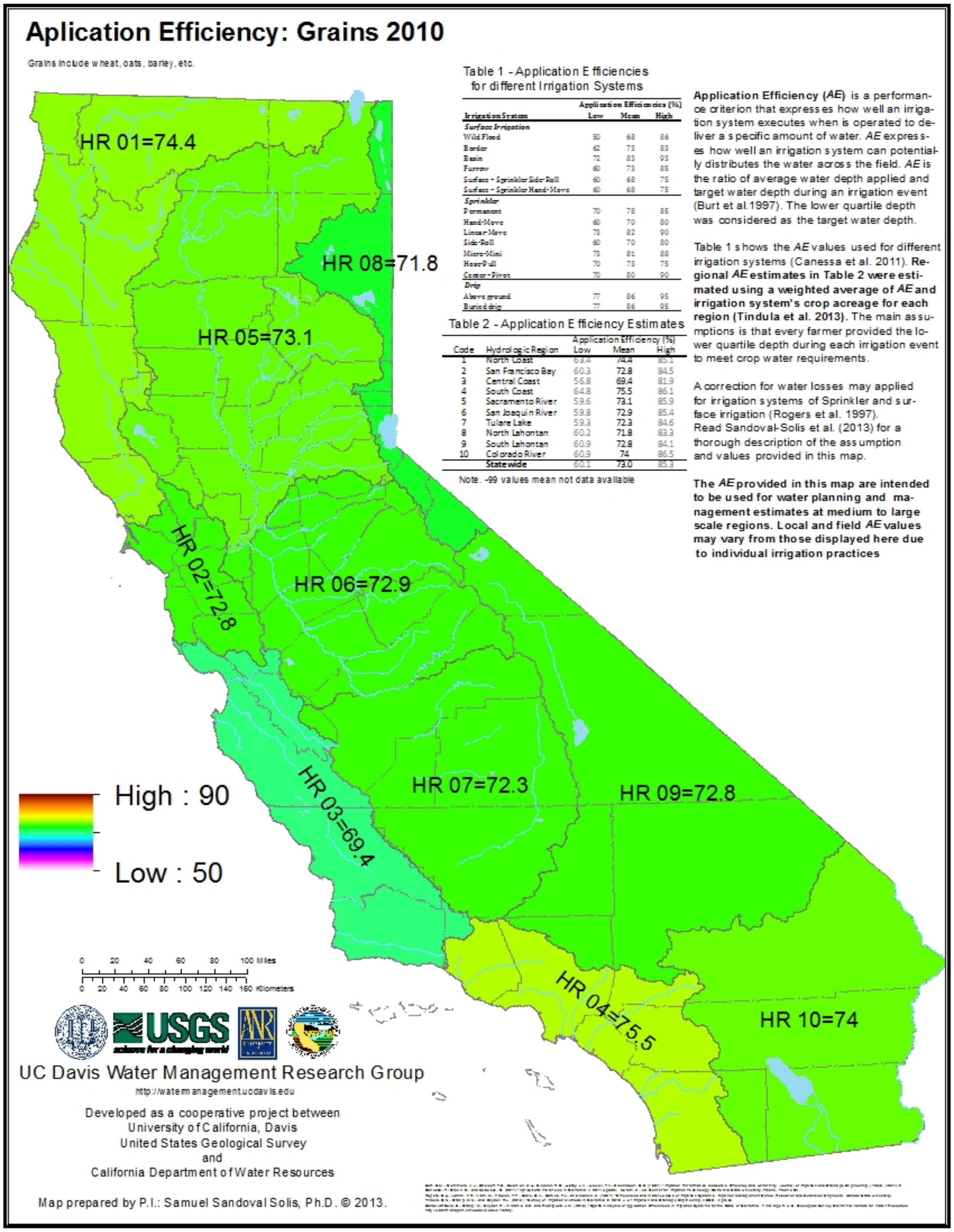


Figure 15: Application Efficiency for Grains, ***Survey 2010***.

5.2.5. *SAFFLOWER*

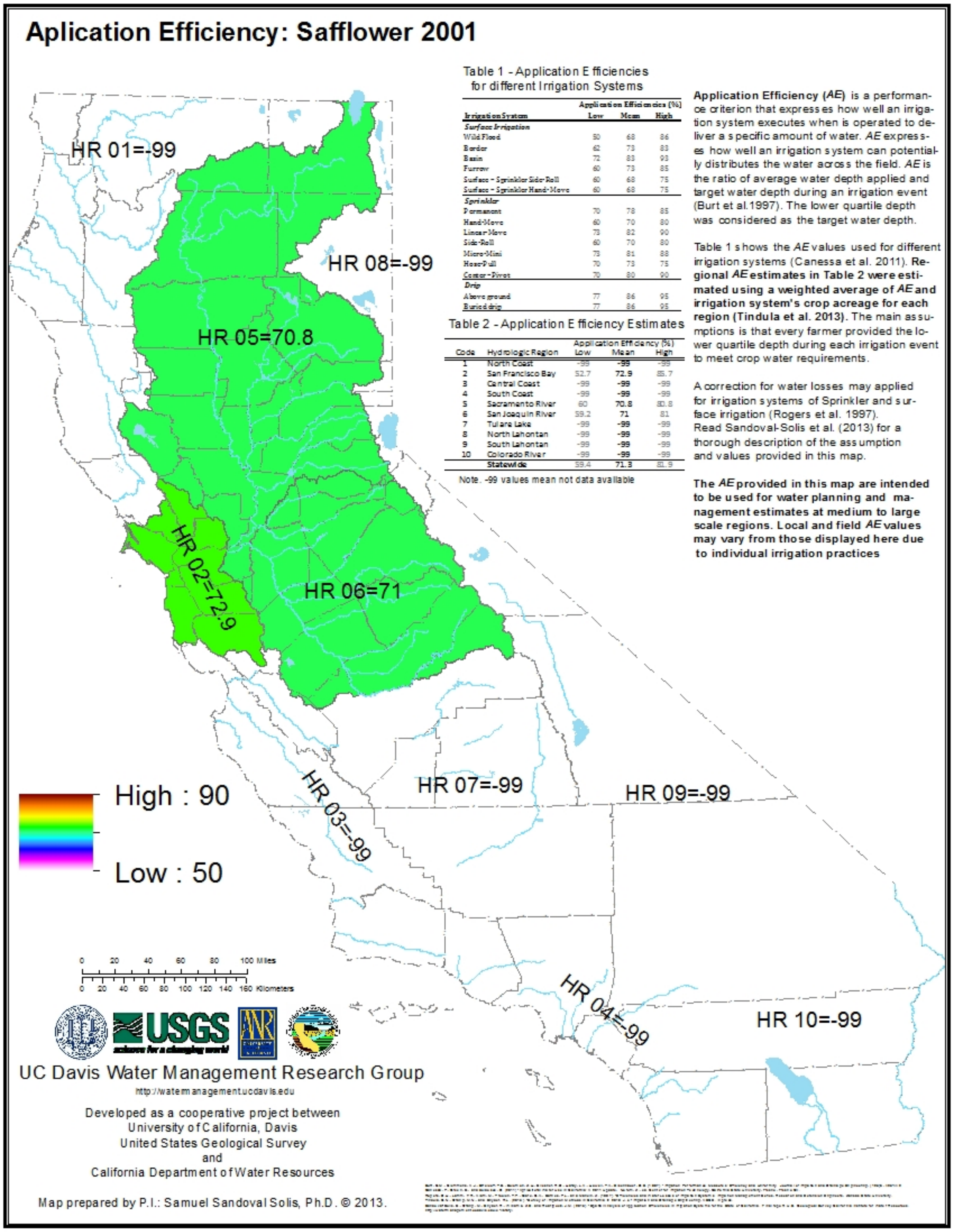


Figure 16: Application Efficiency for Safflower, ***Survey 2001***.

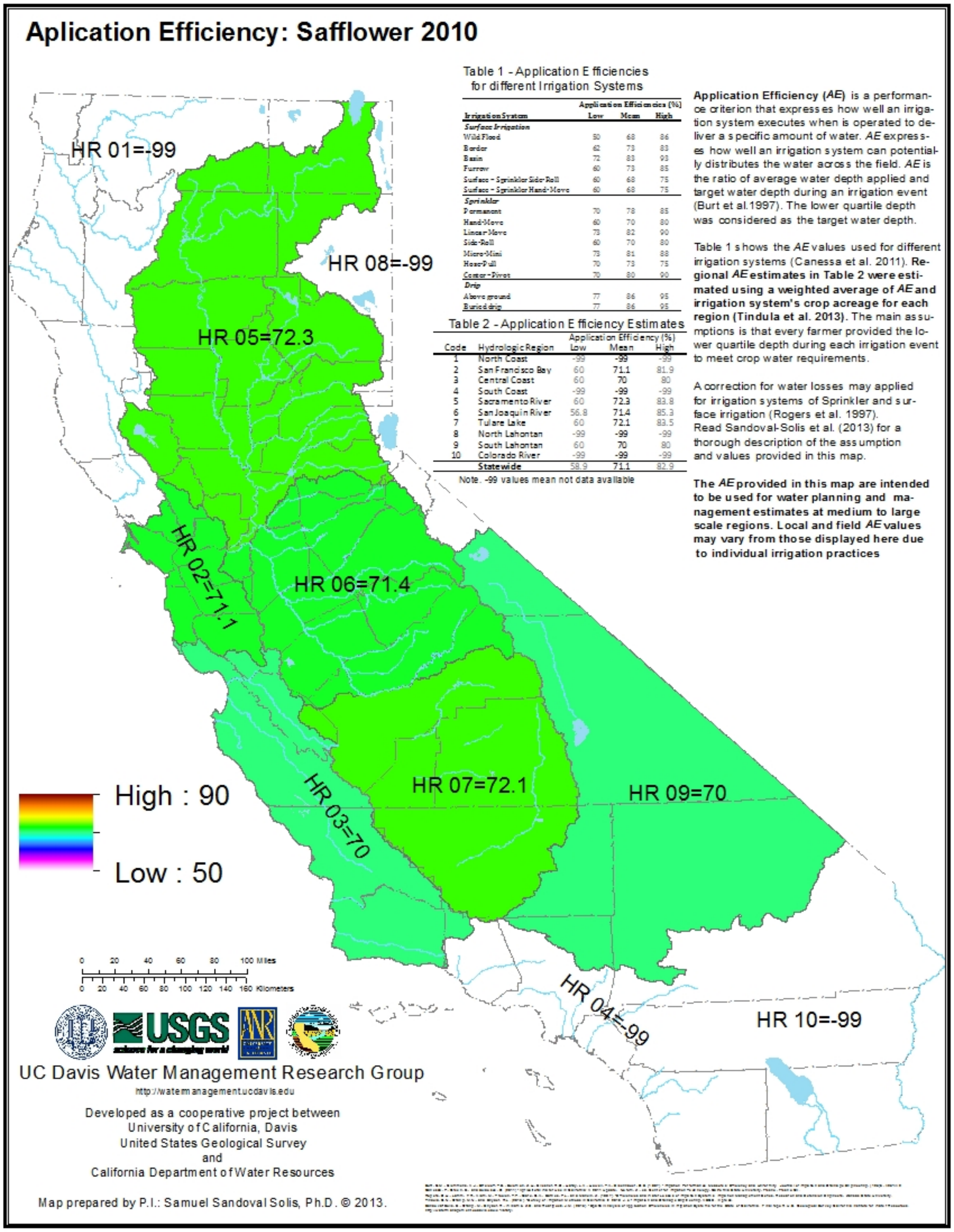


Figure 17: Application Efficiency for Safflower, ***Survey 2010***.

5.2.6. SUGARBEET

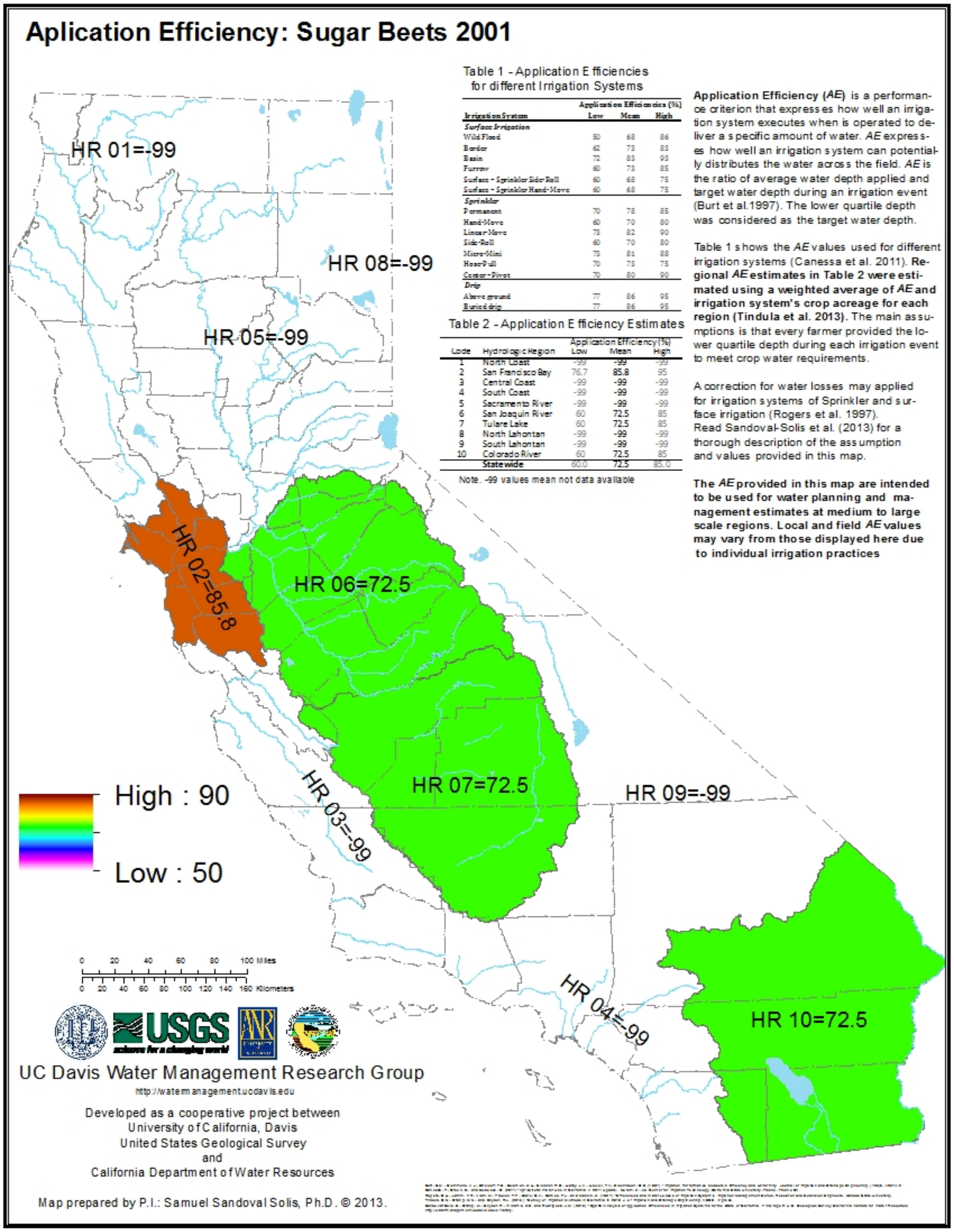


Figure 18: Application Efficiency for Sugarbeet, ***Survey 2001***.

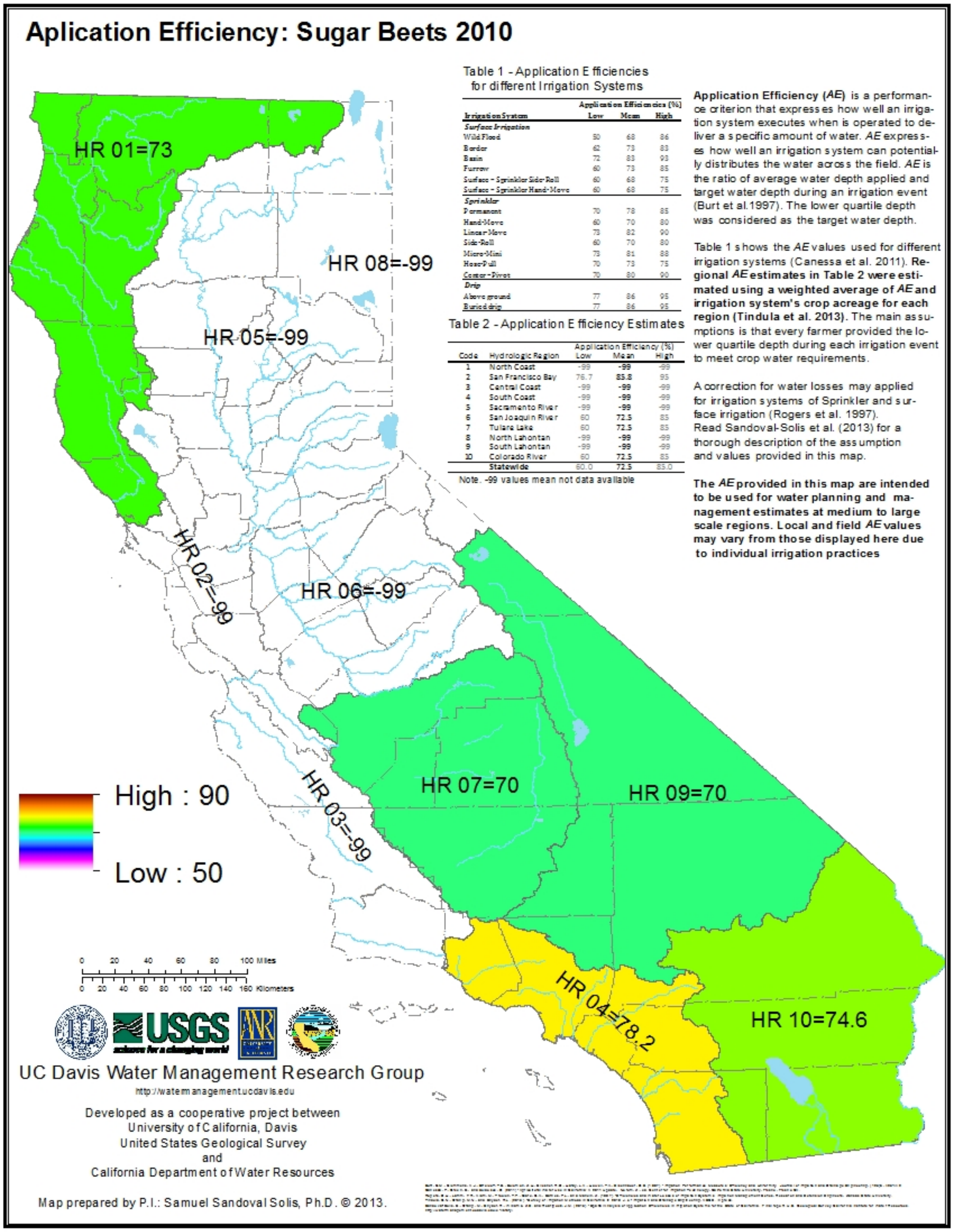


Figure 19: Application Efficiency for Sugarbeet, ***Survey 2010***.

- 41 -

5.2.7. OTHER FIELD CROPS

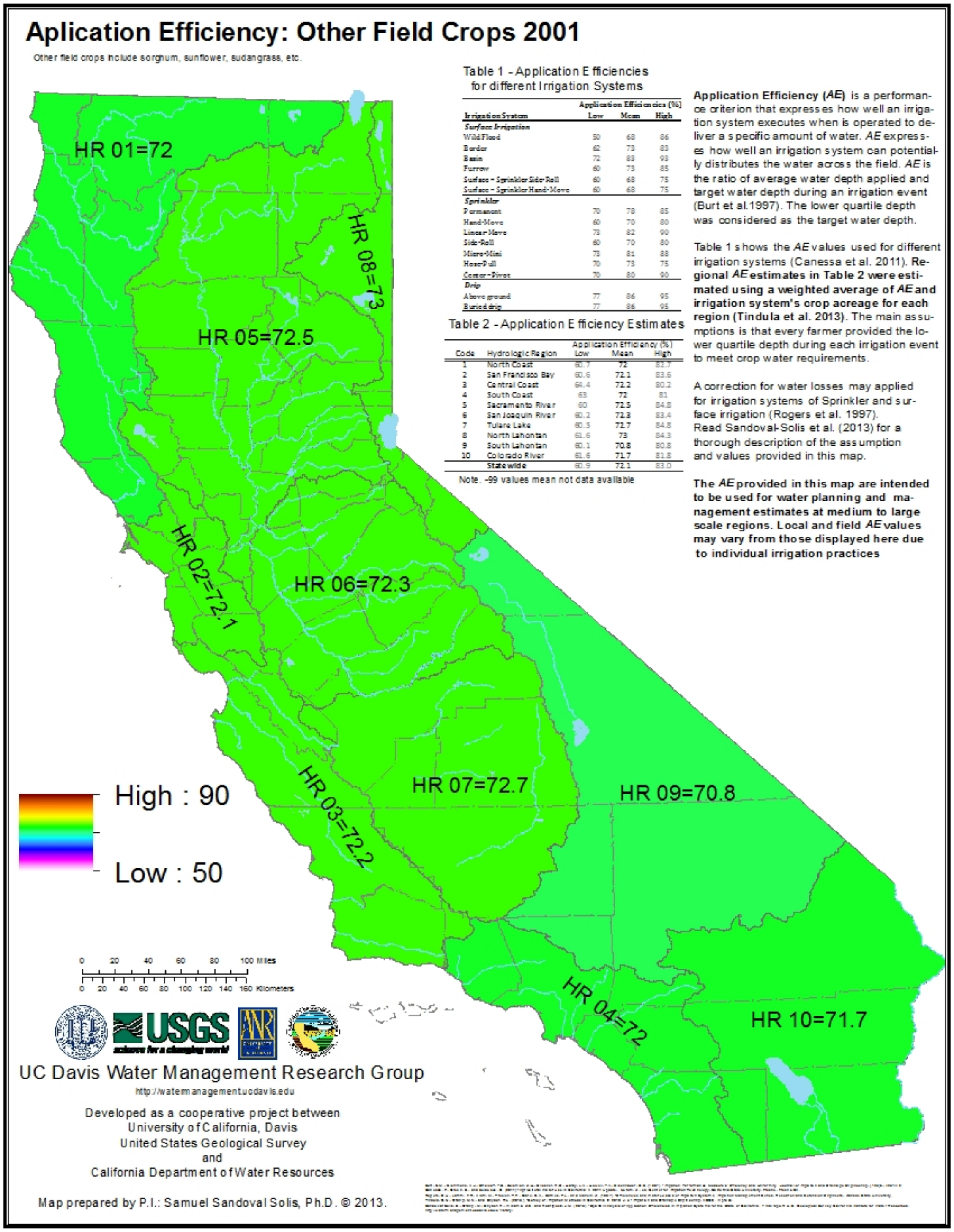


Figure 20: Application Efficiency for Other Field Crops, ***Survey 2001***.

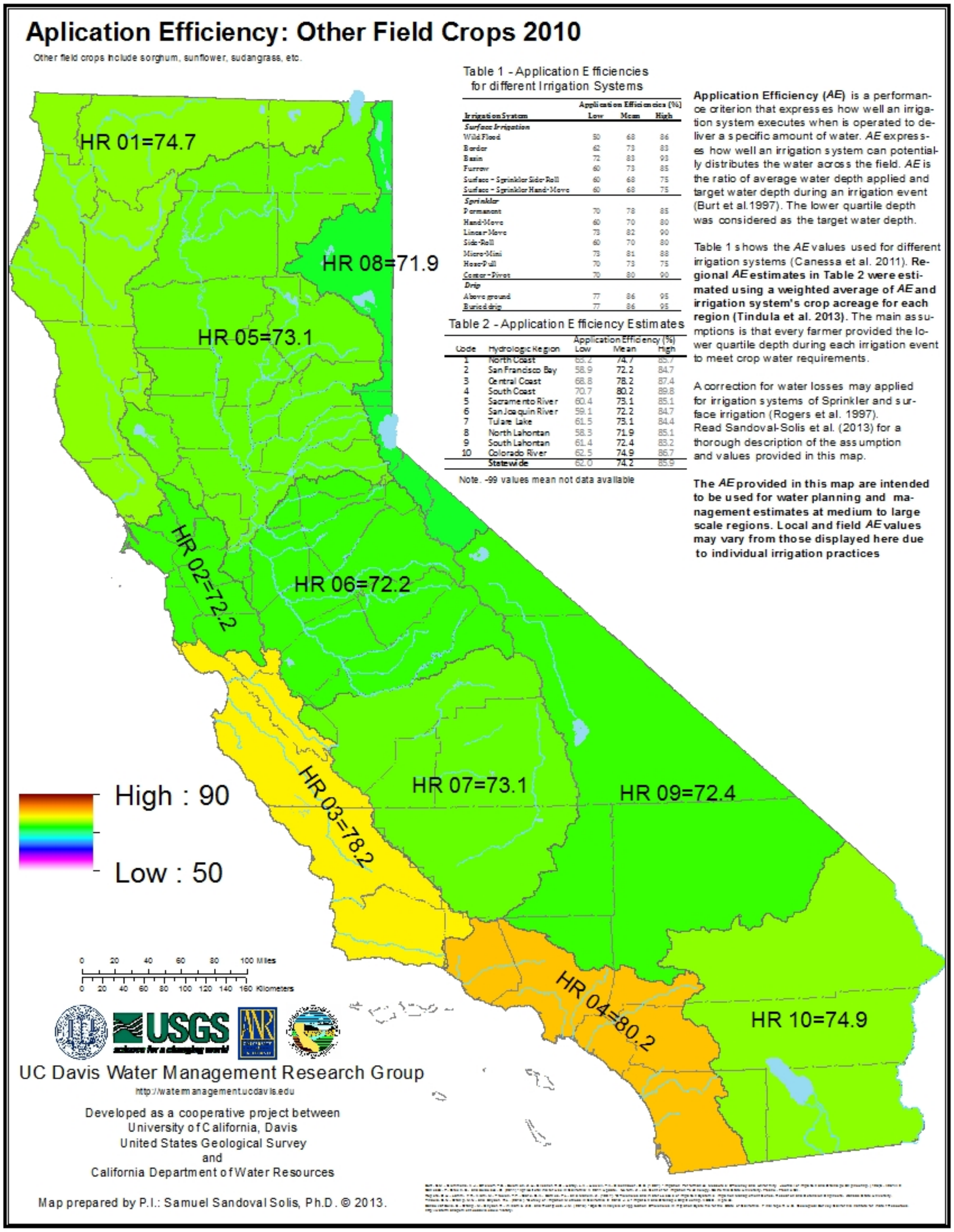


Figure 21: Application Efficiency for Other Field Crops, ***Survey 2010***.

5.2.8. ALFALFA

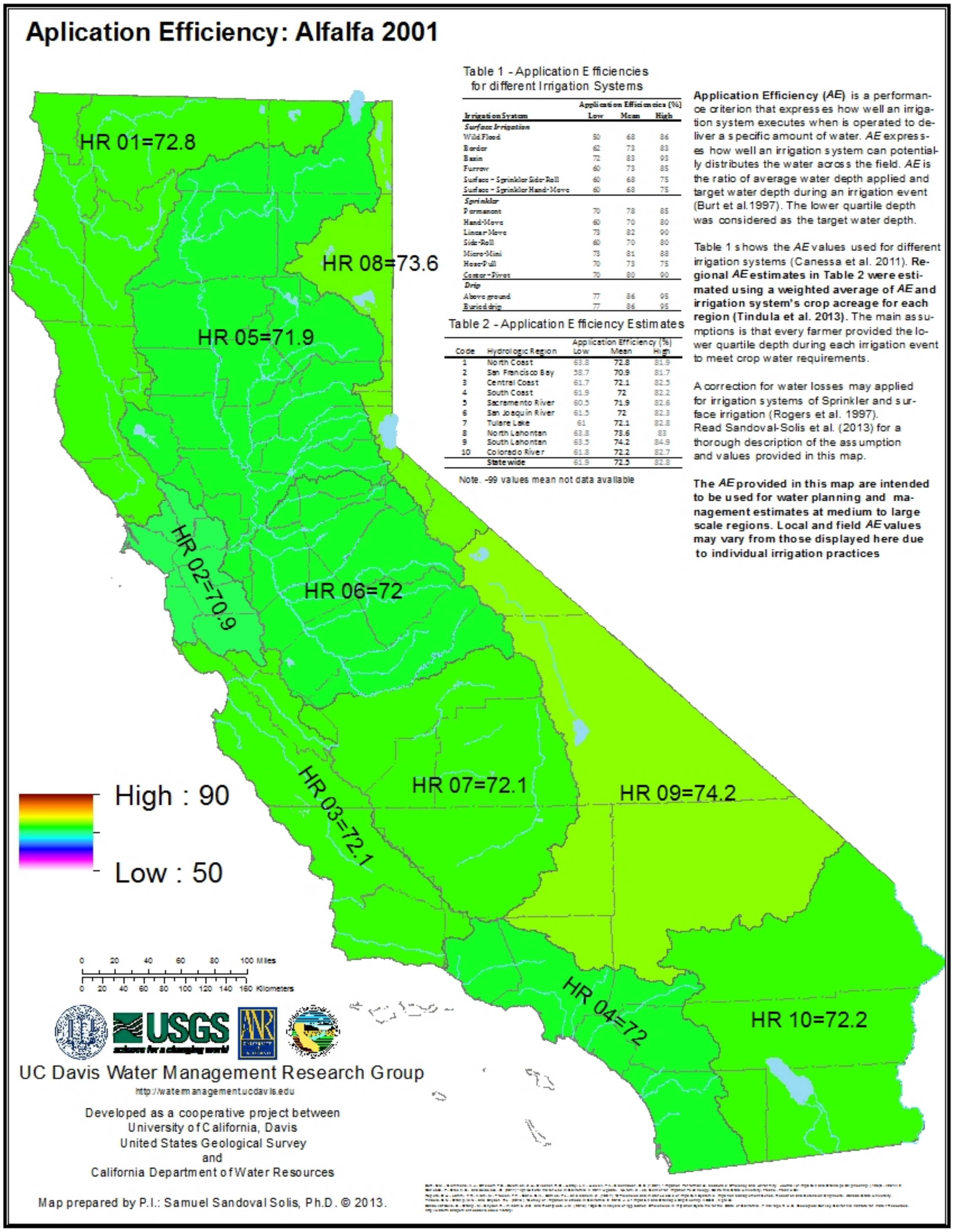


Figure 22: Application Efficiency for Alfalfa, ***Survey 2001***.

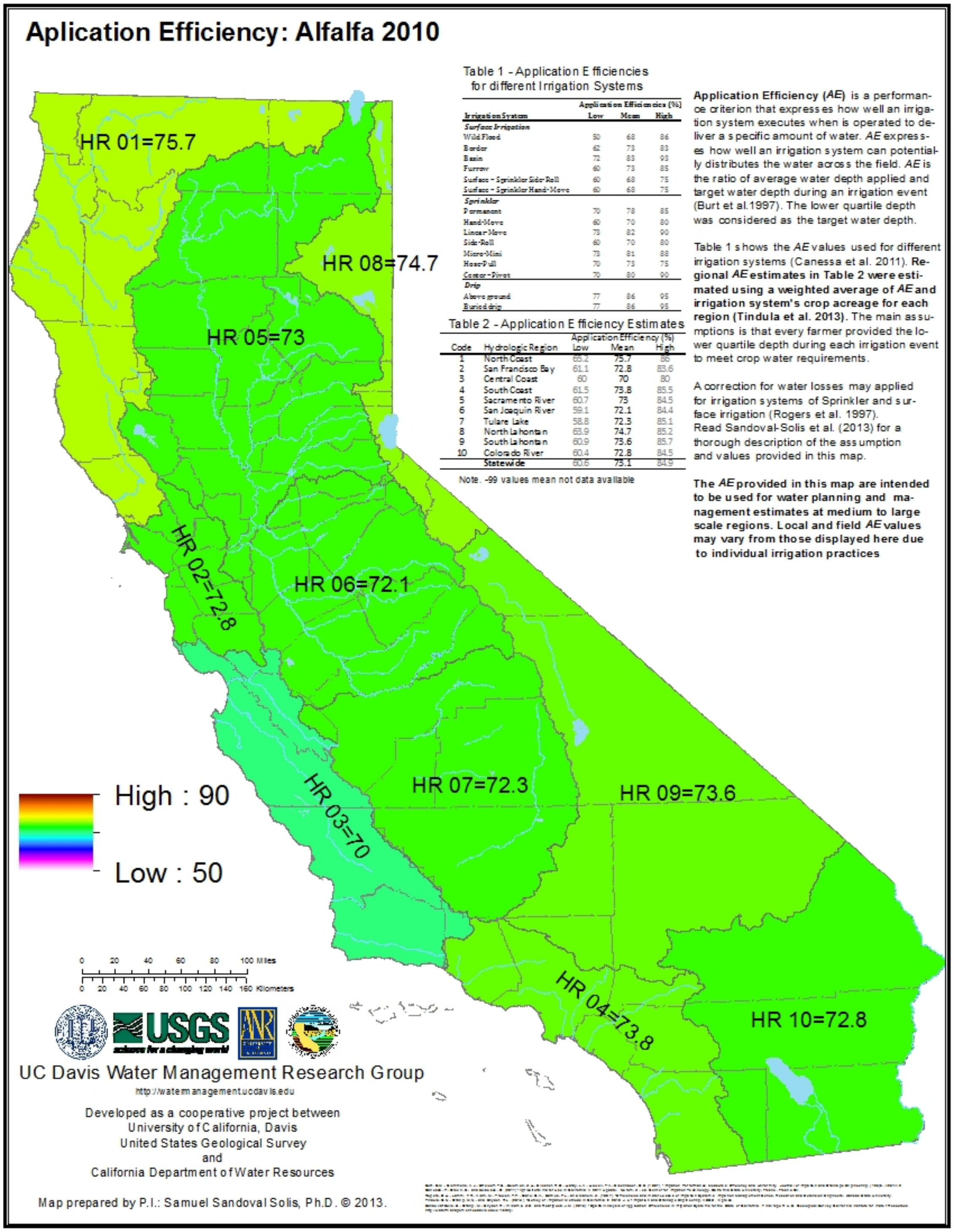


Figure 23: Application Efficiency for Alfalfa, ***Survey 2010***.

5.2.9. *Pasture*

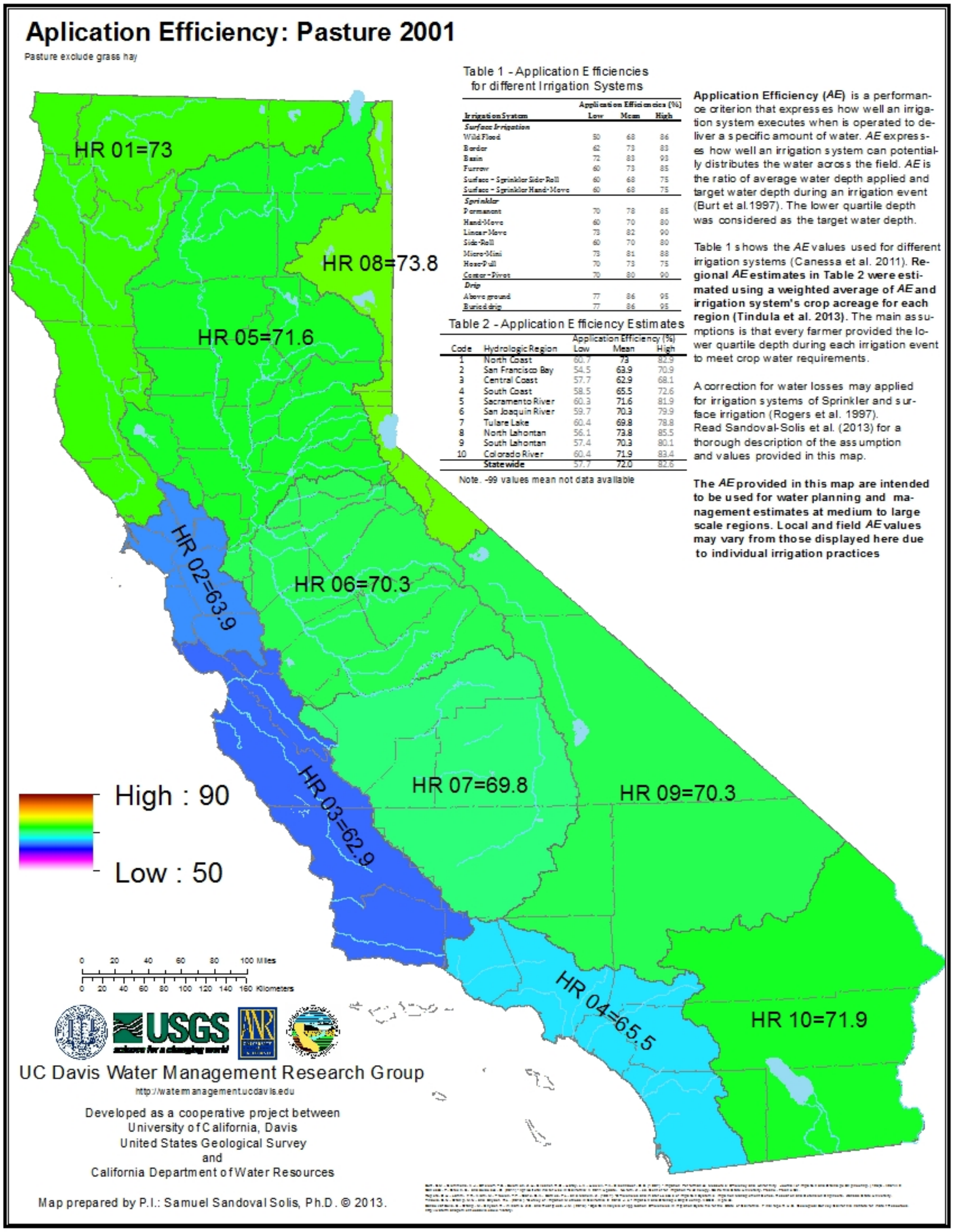


Figure 24: Application Efficiency for Pasture, ***Survey 2001***.

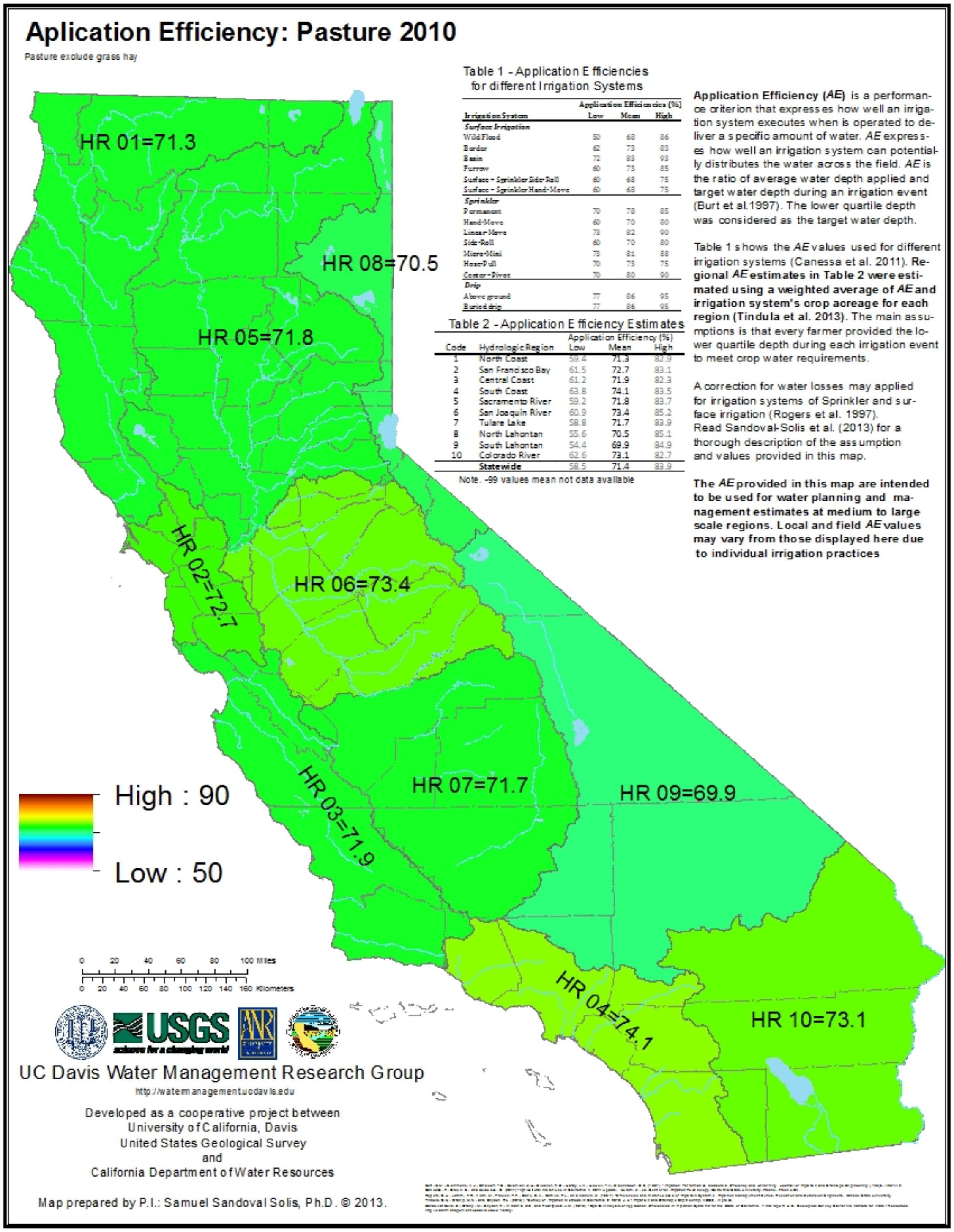


Figure 25: Application Efficiency for Pasture, ***Survey 2010***.

5.2.10. CUCURBIT

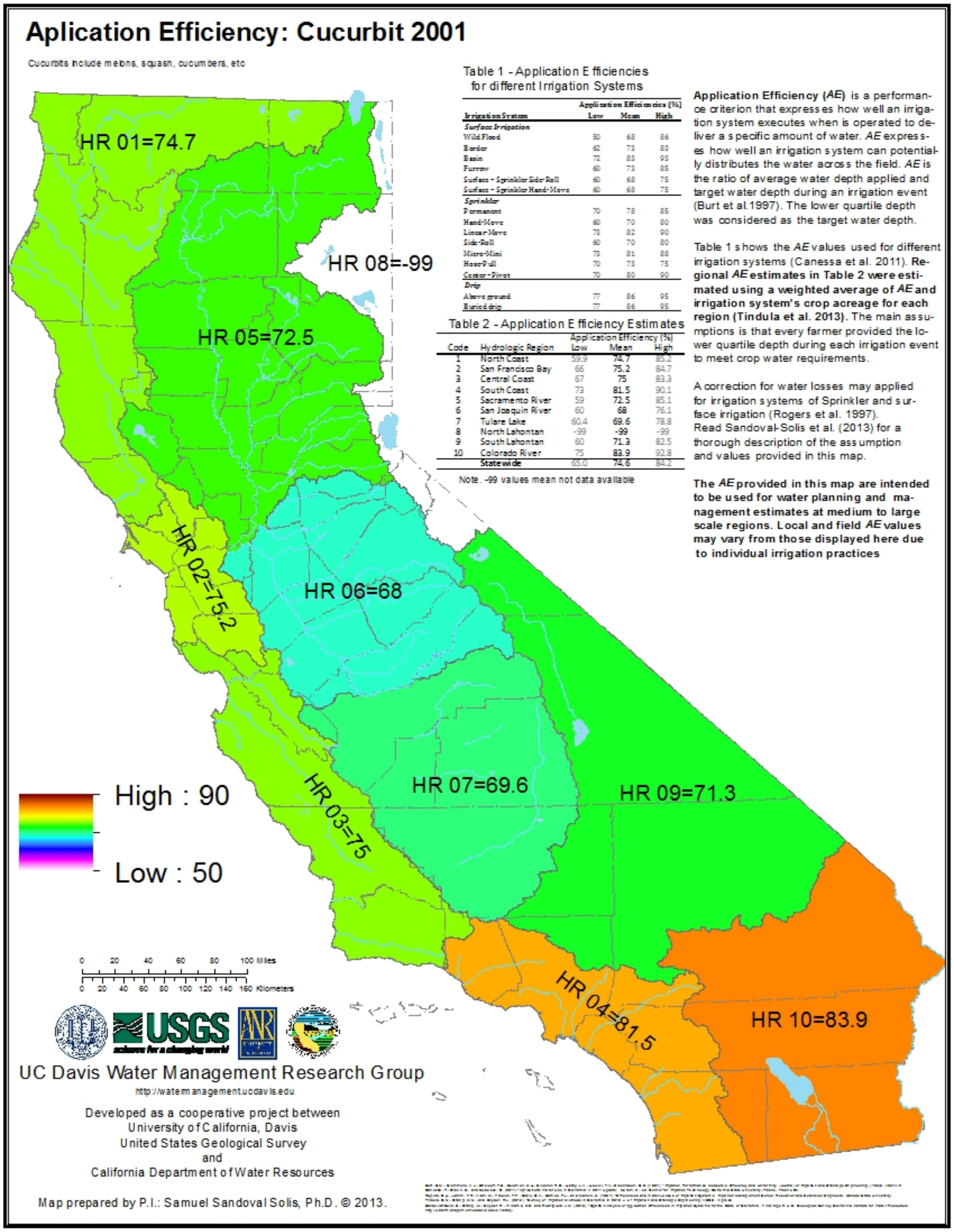


Figure 26: Application Efficiency for Cucurbit, ***Survey 2001***.

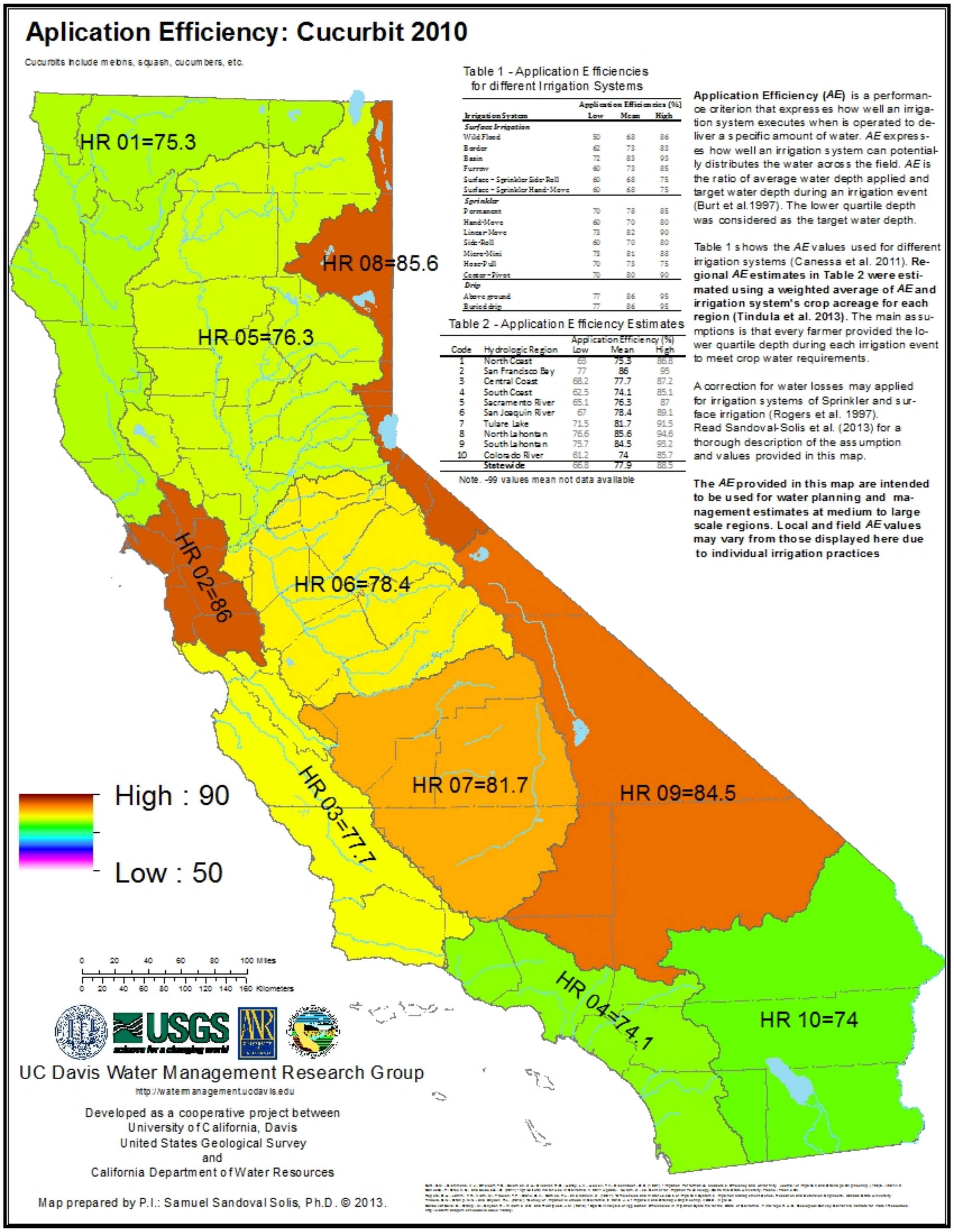


Figure 27: Application Efficiency for Cucurbit, ***Survey 2010***.

5.2.11. *ONION AND GARLIC*

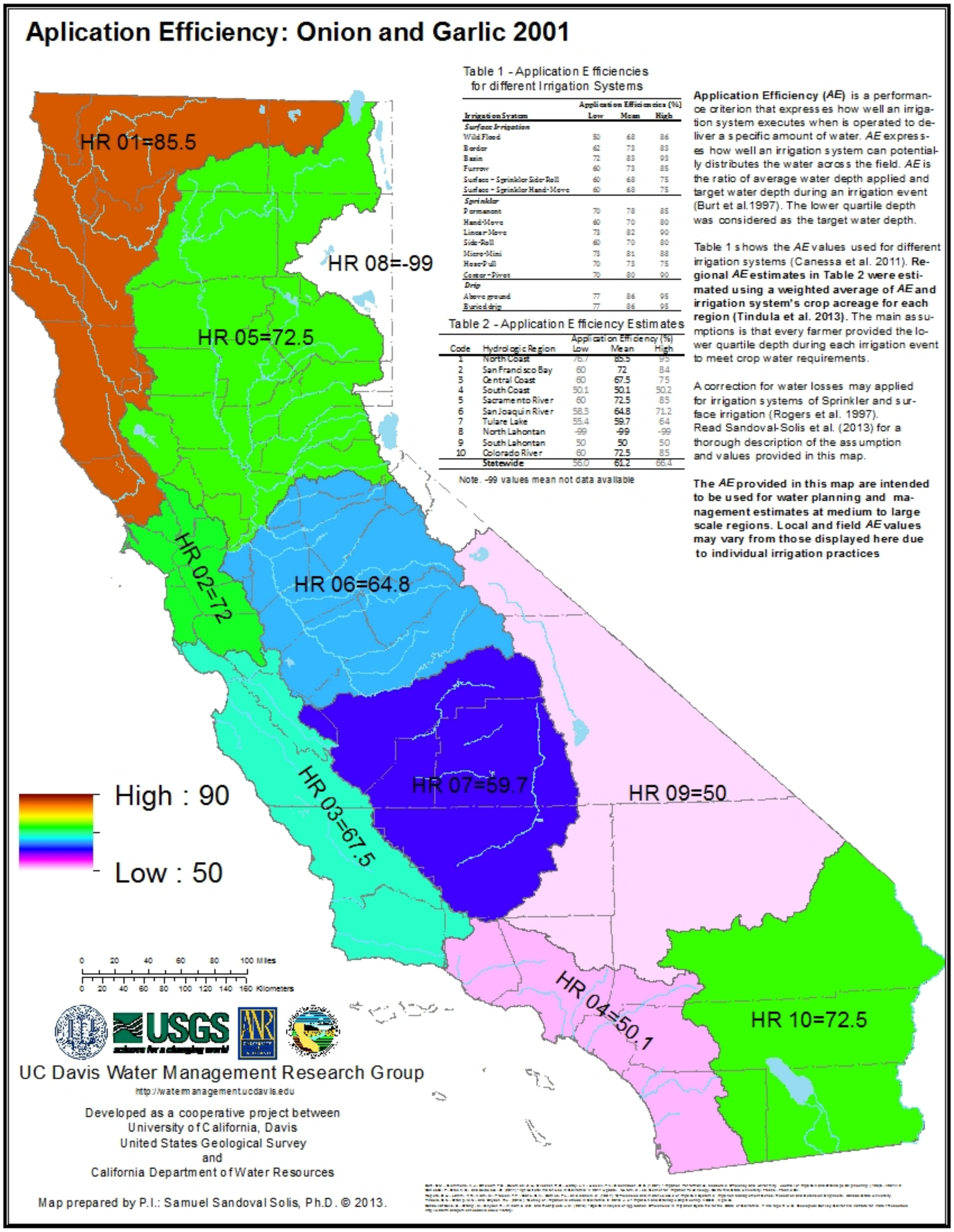


Figure 28: Application Efficiency for Onion and Garlic, ***Survey 2001***.

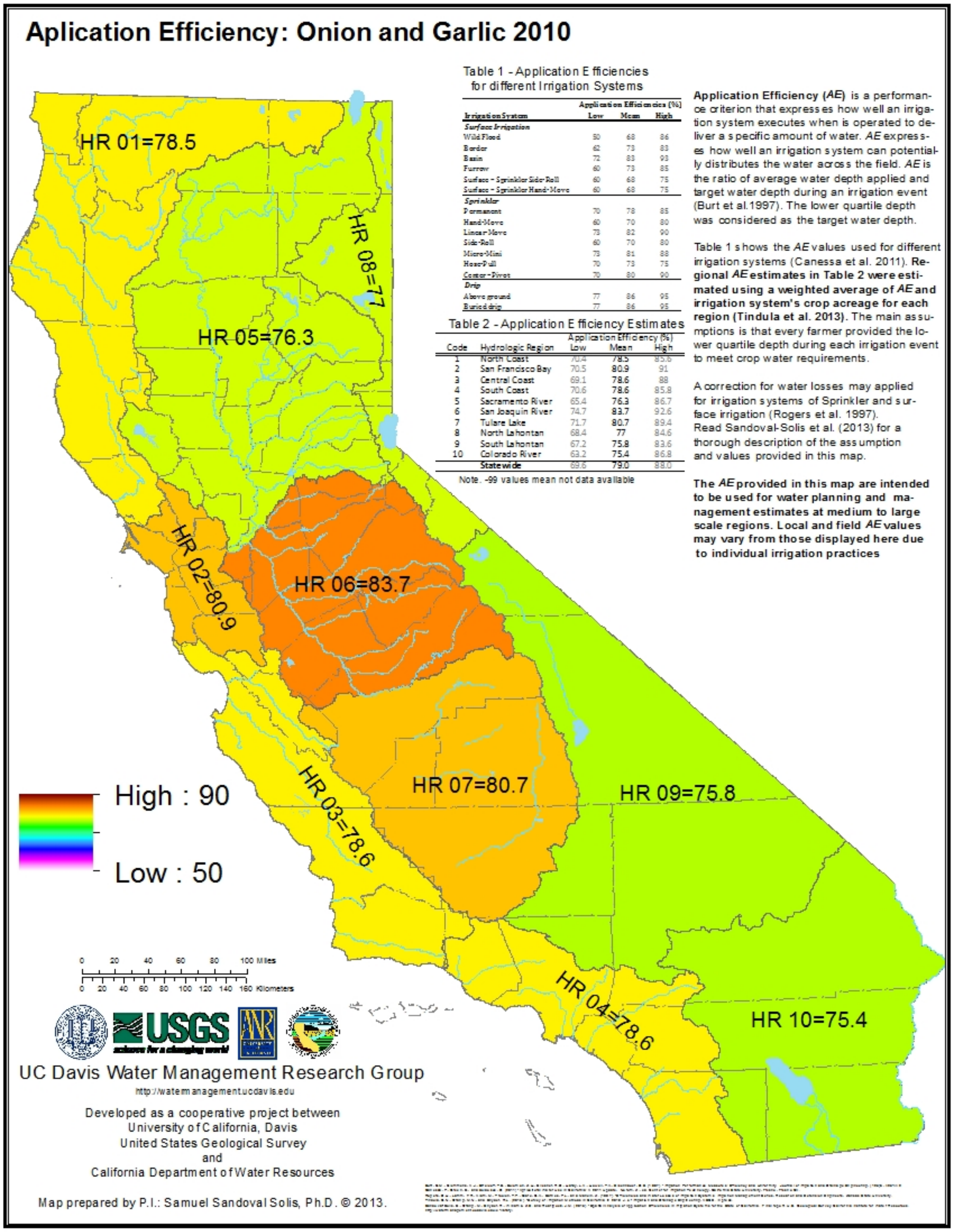


Figure 29: Application Efficiency for Onion and Garlic, ***Survey 2010***.

5.2.12. *POTATO*

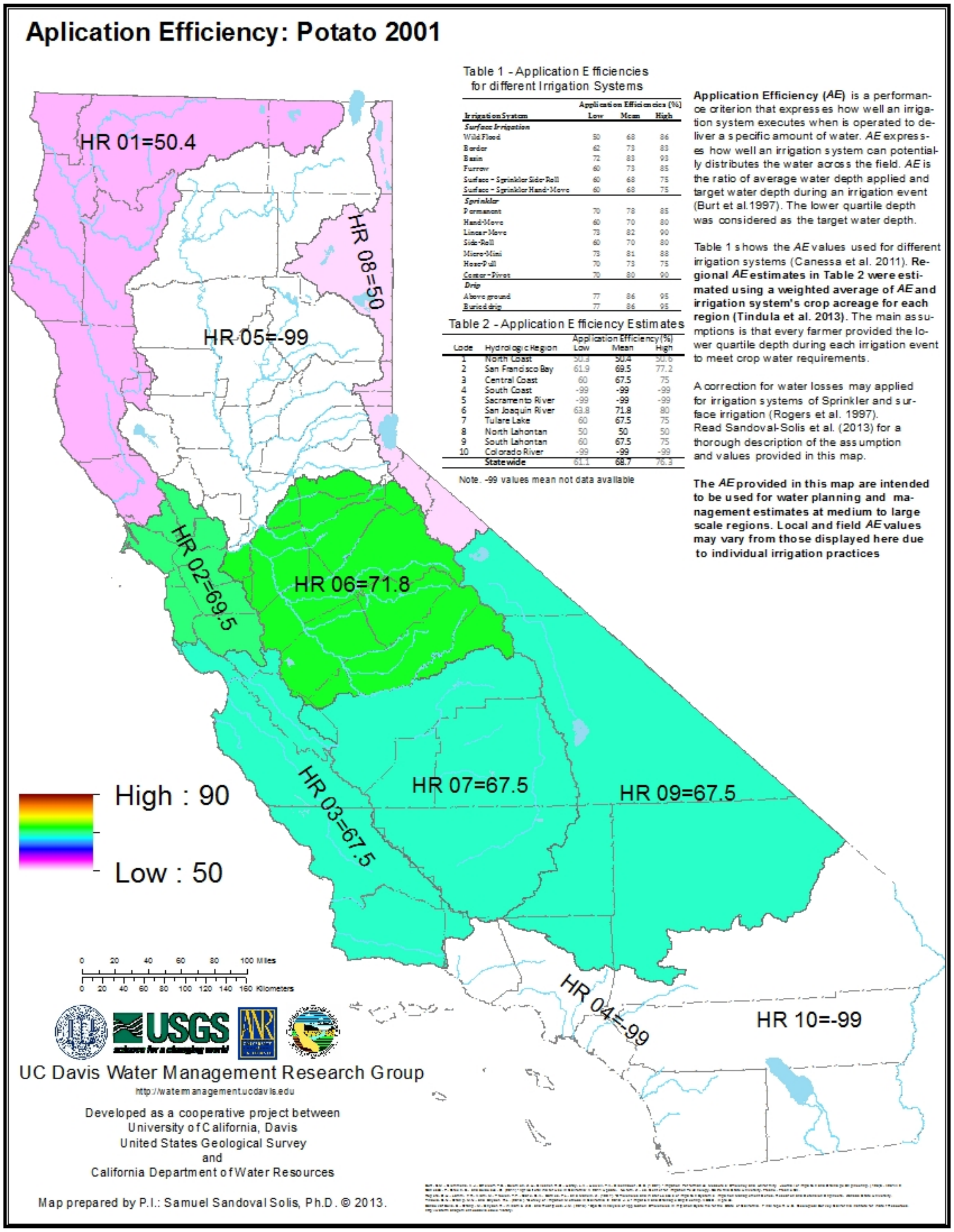


Figure 30: Application Efficiency for Potato, ***Survey 2001***.

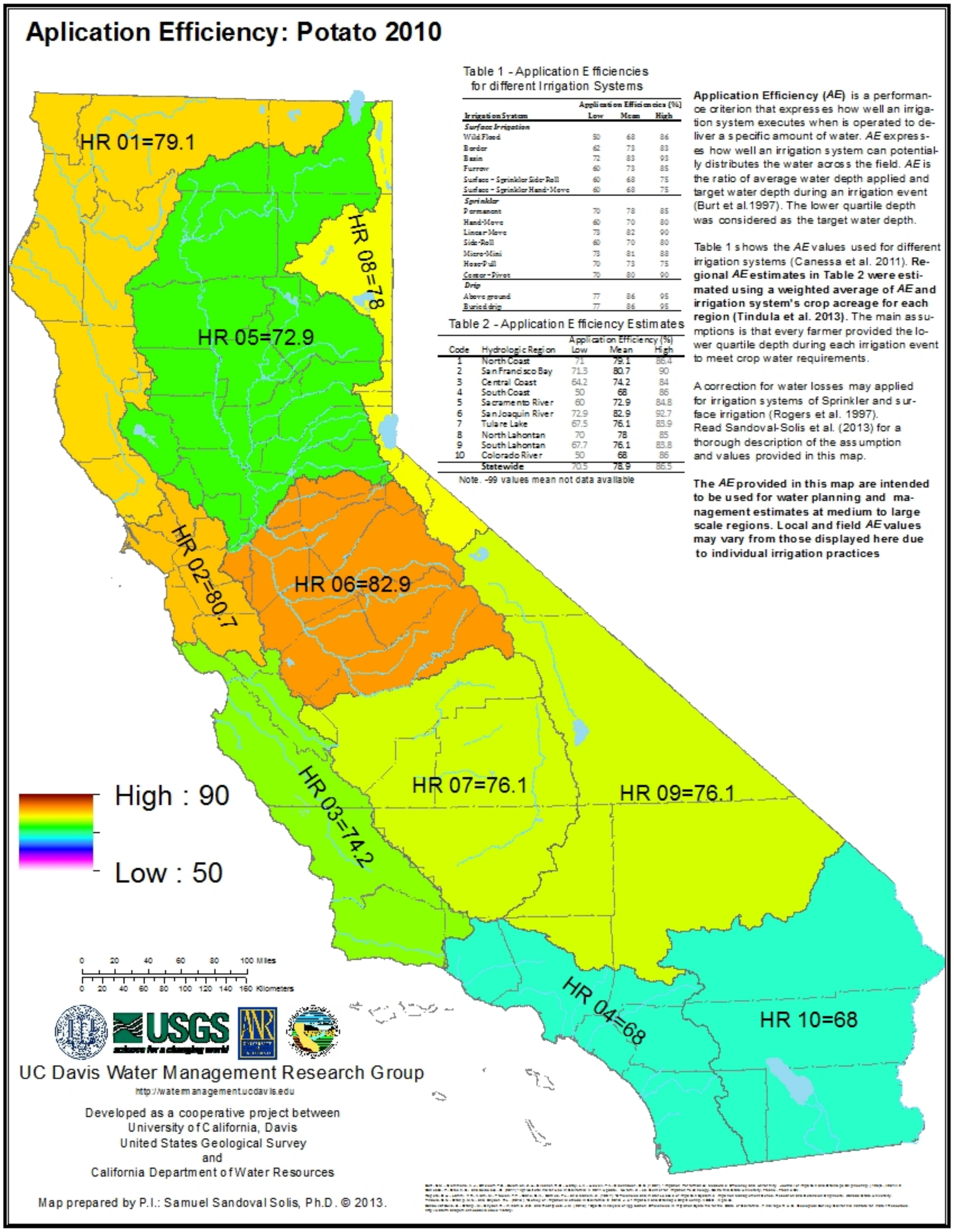


Figure 31: Application Efficiency for Potato, ***Survey 2010***.

5.2.13. *TOMATO - FRESH*

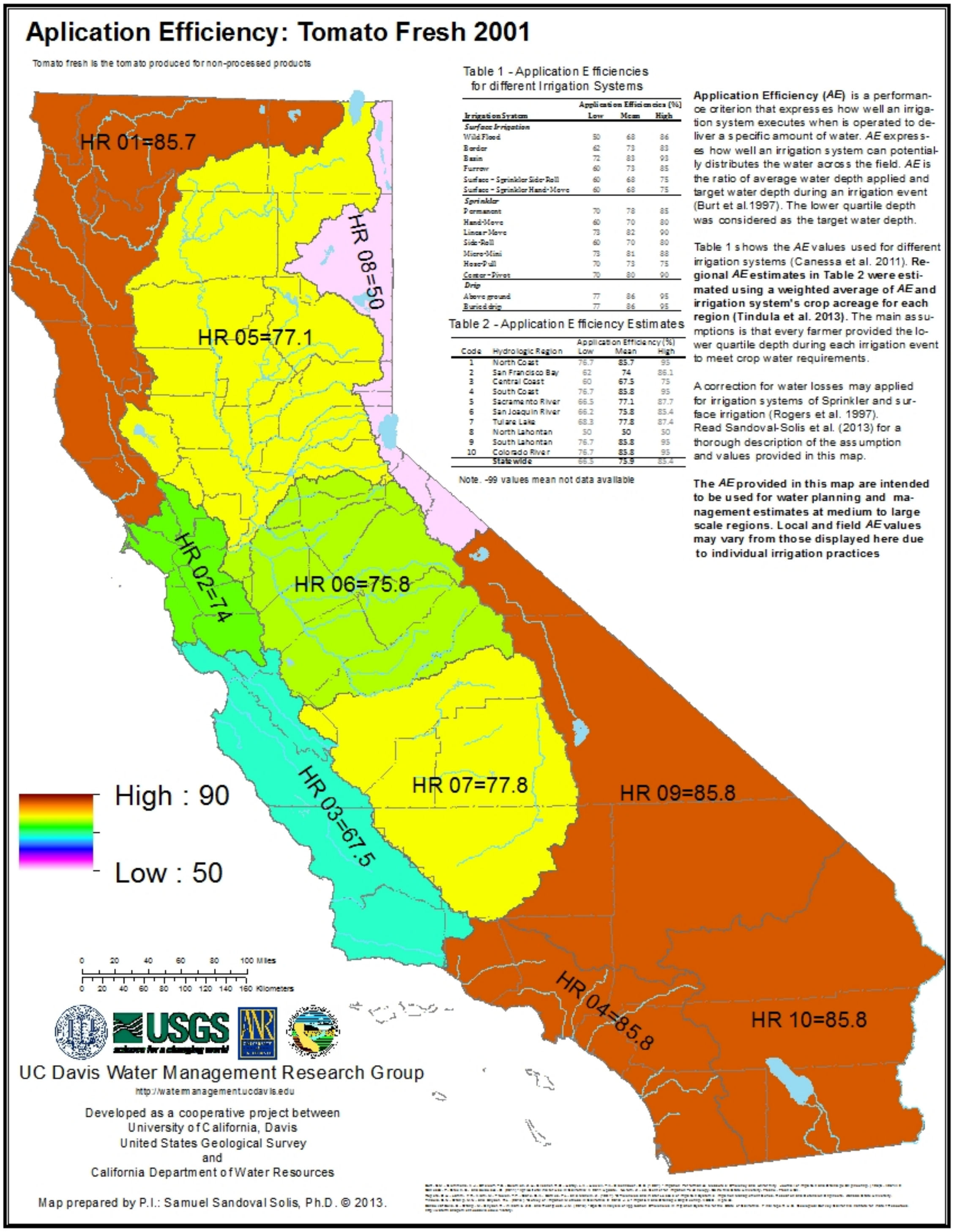


Figure 32: Application Efficiency for Tomato - Fresh, ***Survey 2001***.

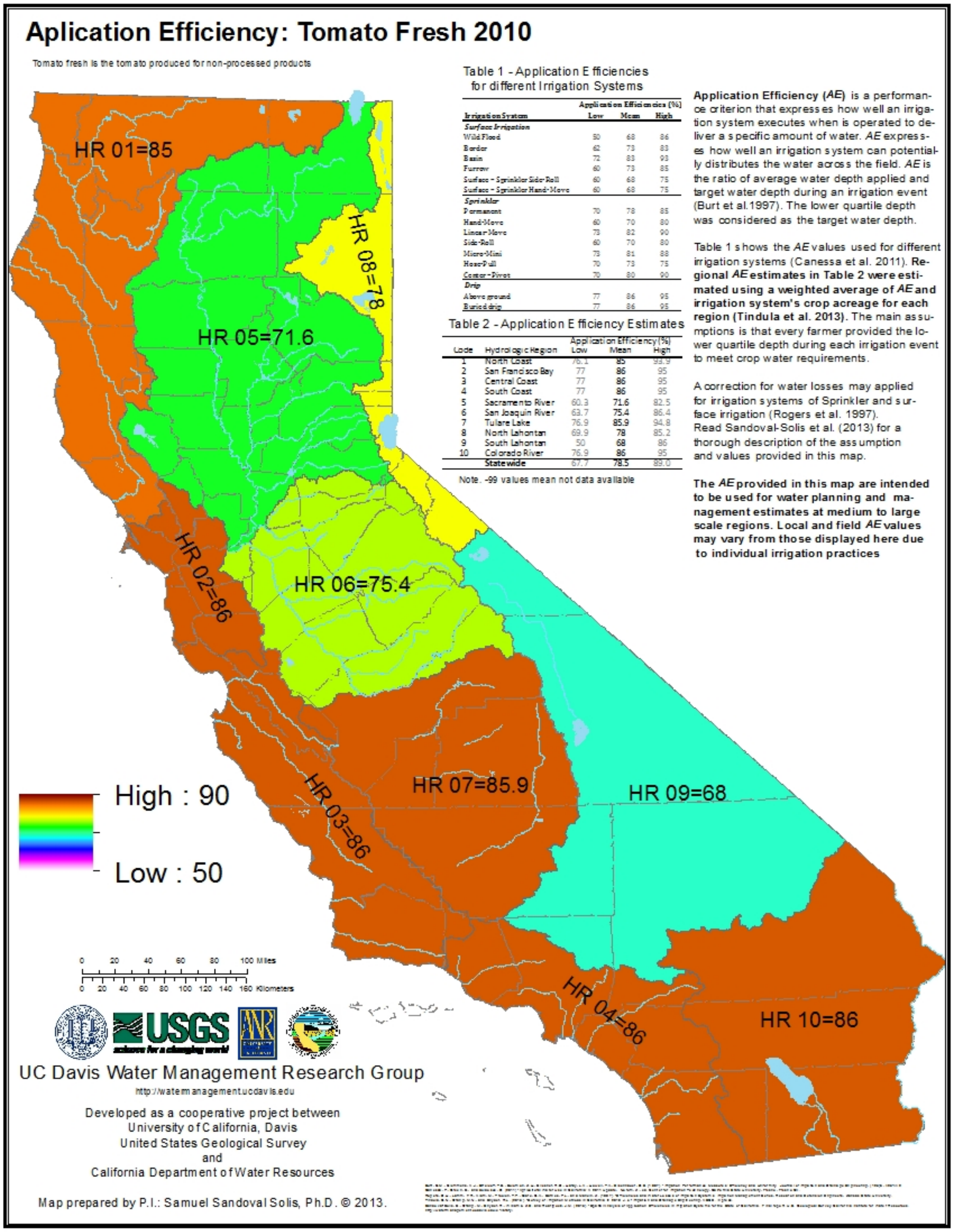


Figure 33: Application Efficiency for Tomato - Fresh, ***Survey 2010***.

5.2.14. TOMATO - PROCESS

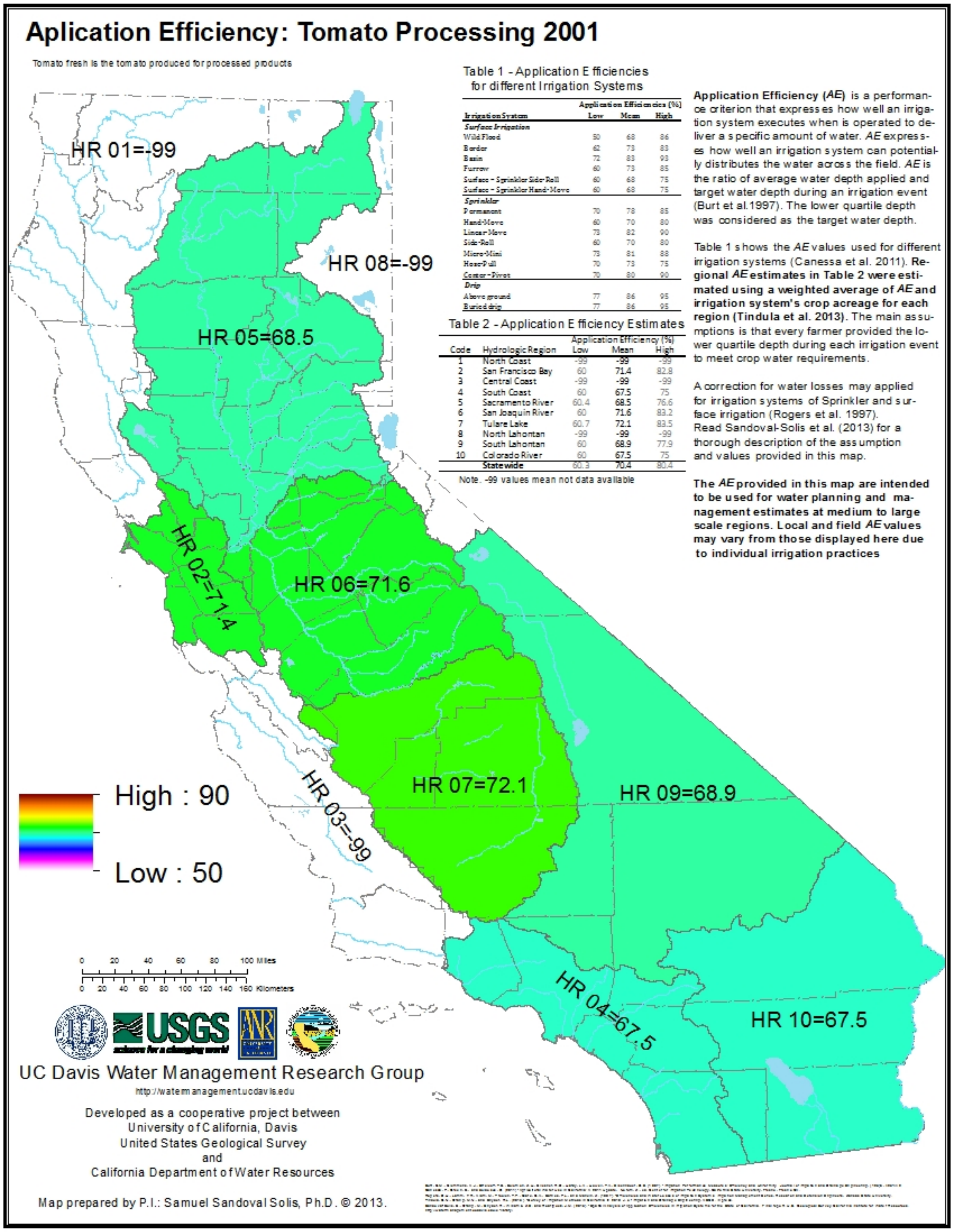


Figure 34: Application Efficiency for Tomato Process, ***Survey 2001***.

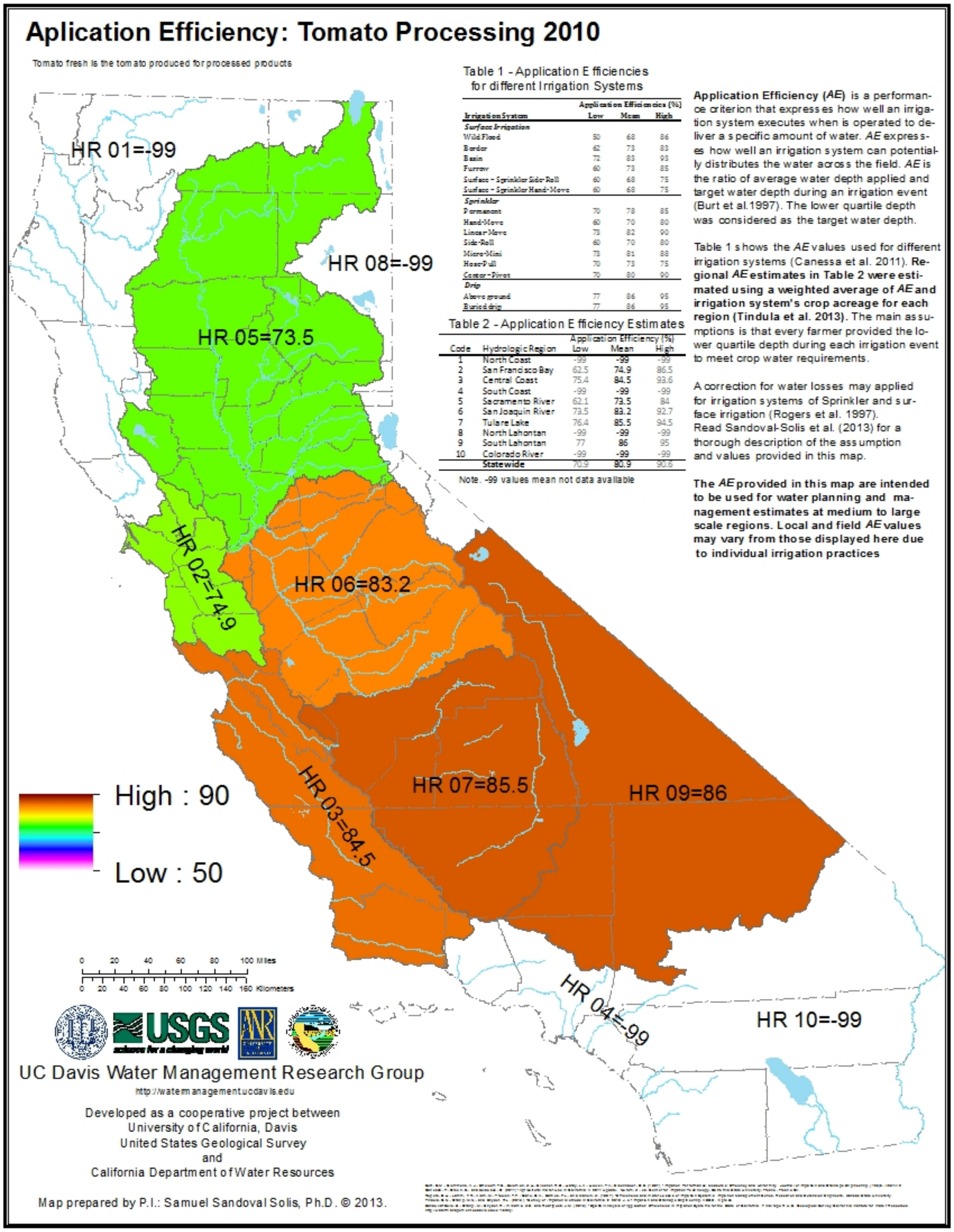


Figure 35: Application Efficiency for Tomato - Process, ***Survey 2010***.

5.2.15. *Other Truck Crops*

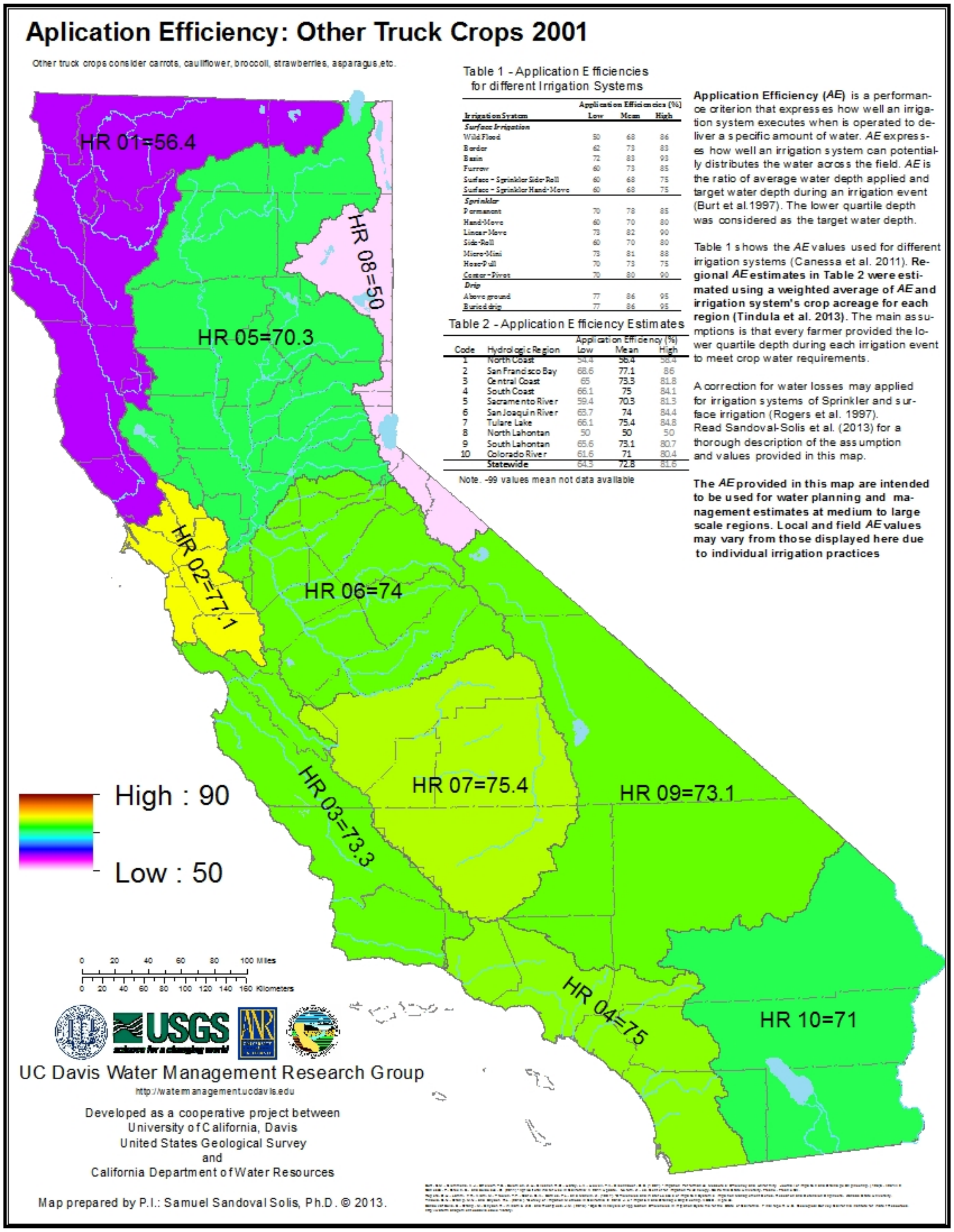


Figure 36: Application Efficiency for Other truck Crops, ***Survey 2001***.

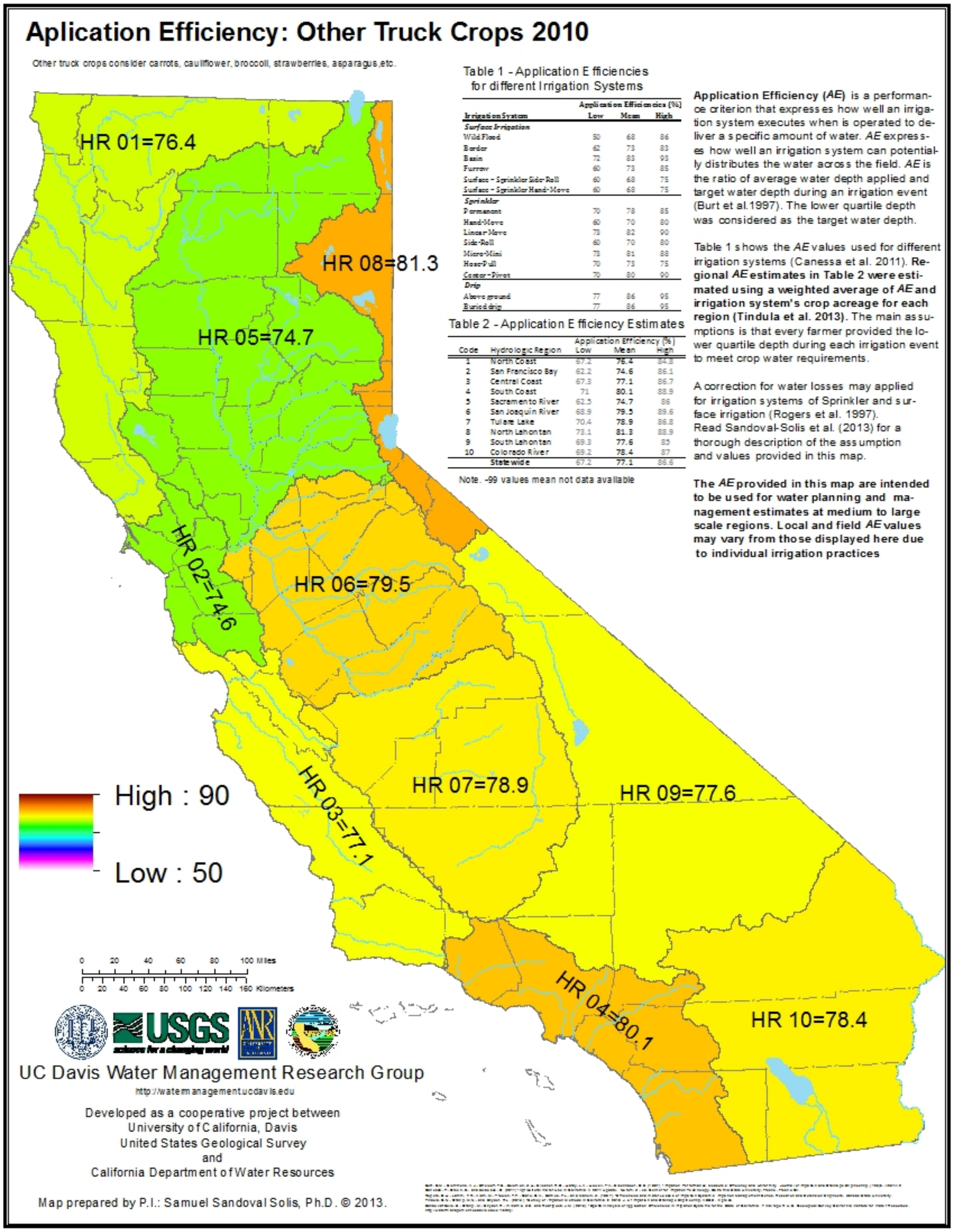


Figure 37: Application Efficiency for Other Truck Crops, ***Survey 2010***.

5.2.16. *ALMOND AND PISTACHIO*

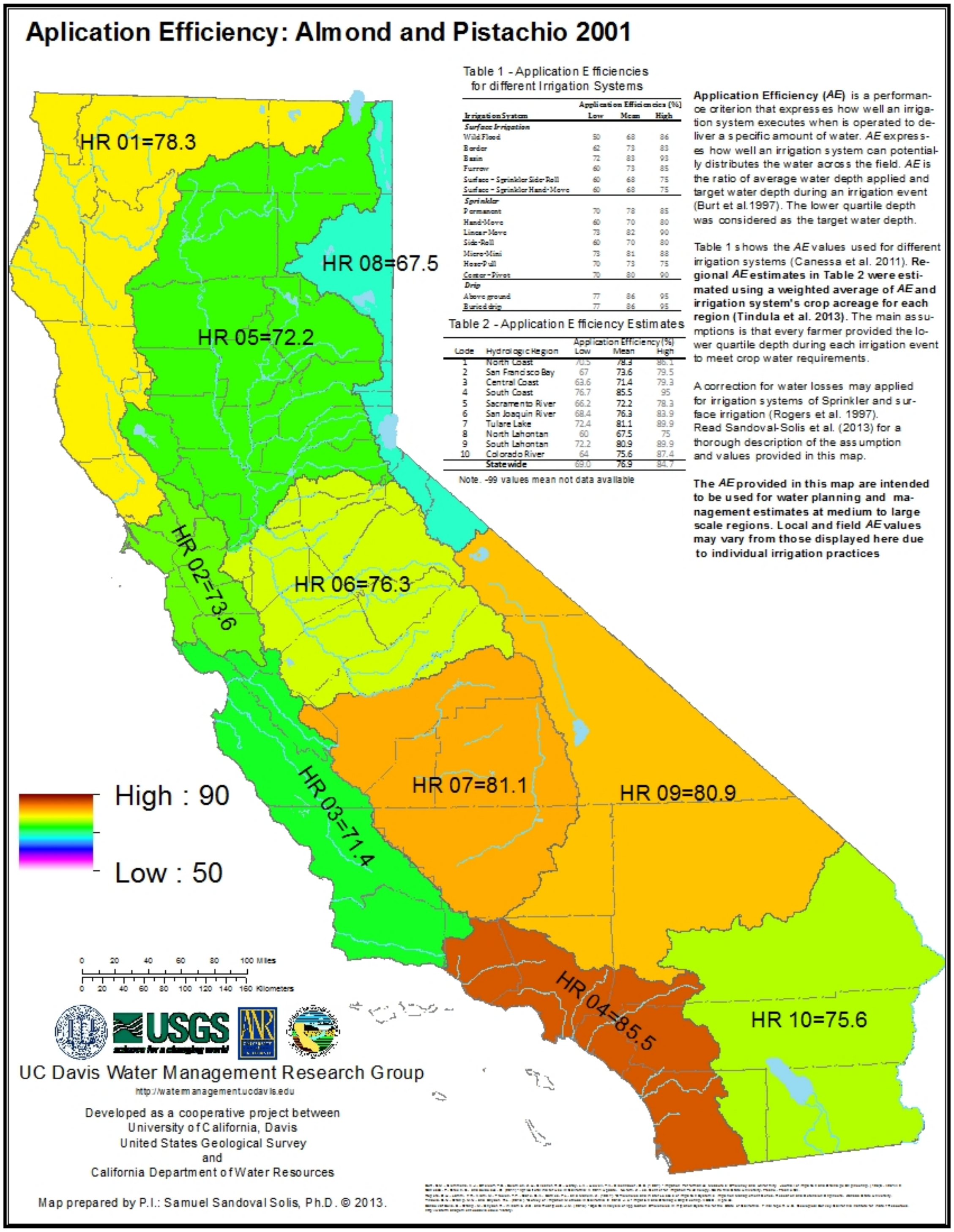


Figure 38: Application Efficiency for Almond and Pistachio, ***Survey 2001***.

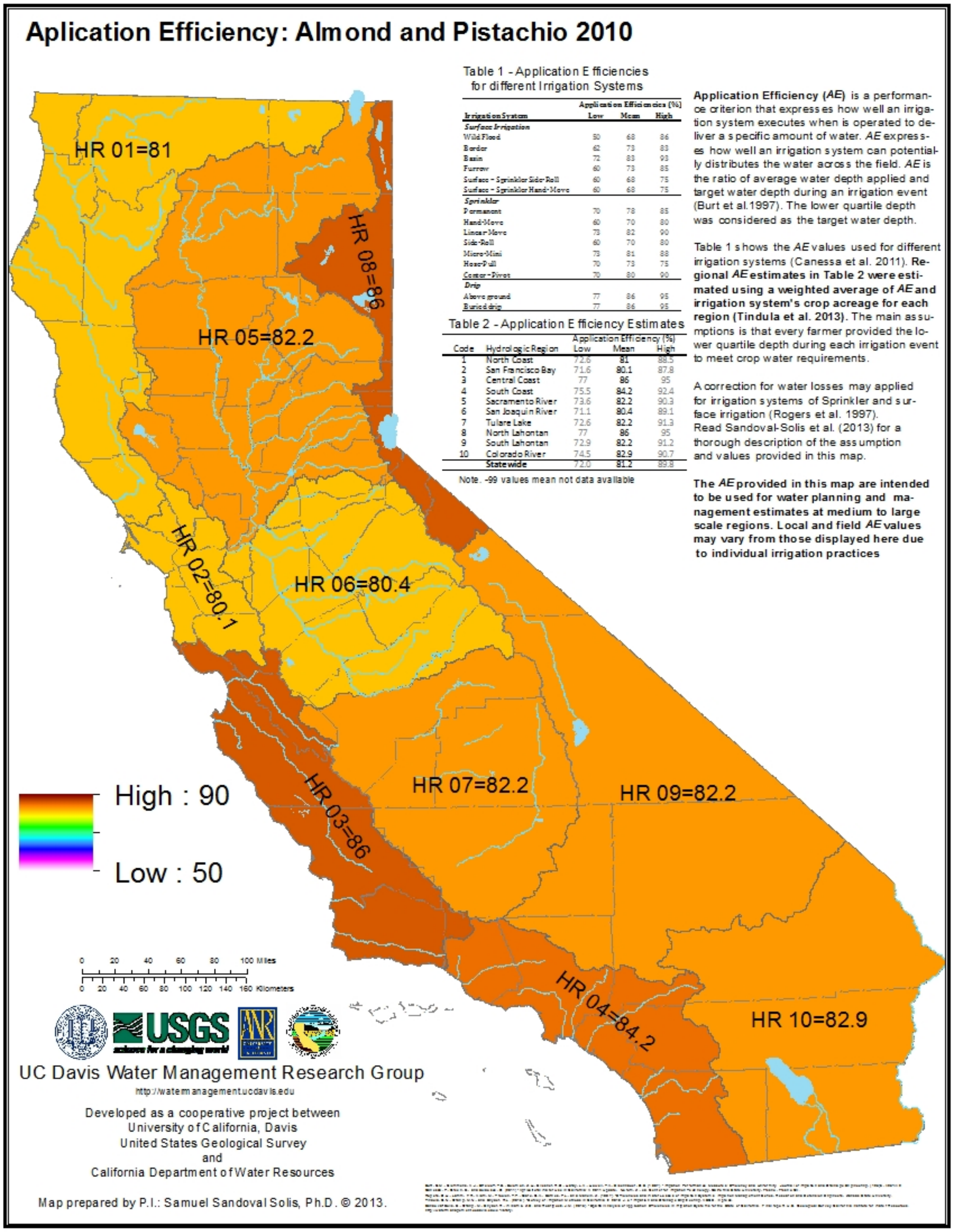


Figure 39: Irrigation Efficiency for Almond and Pistachio, ***Survey 2010***.

5.2.17. *OTHER DECIDUOUS*

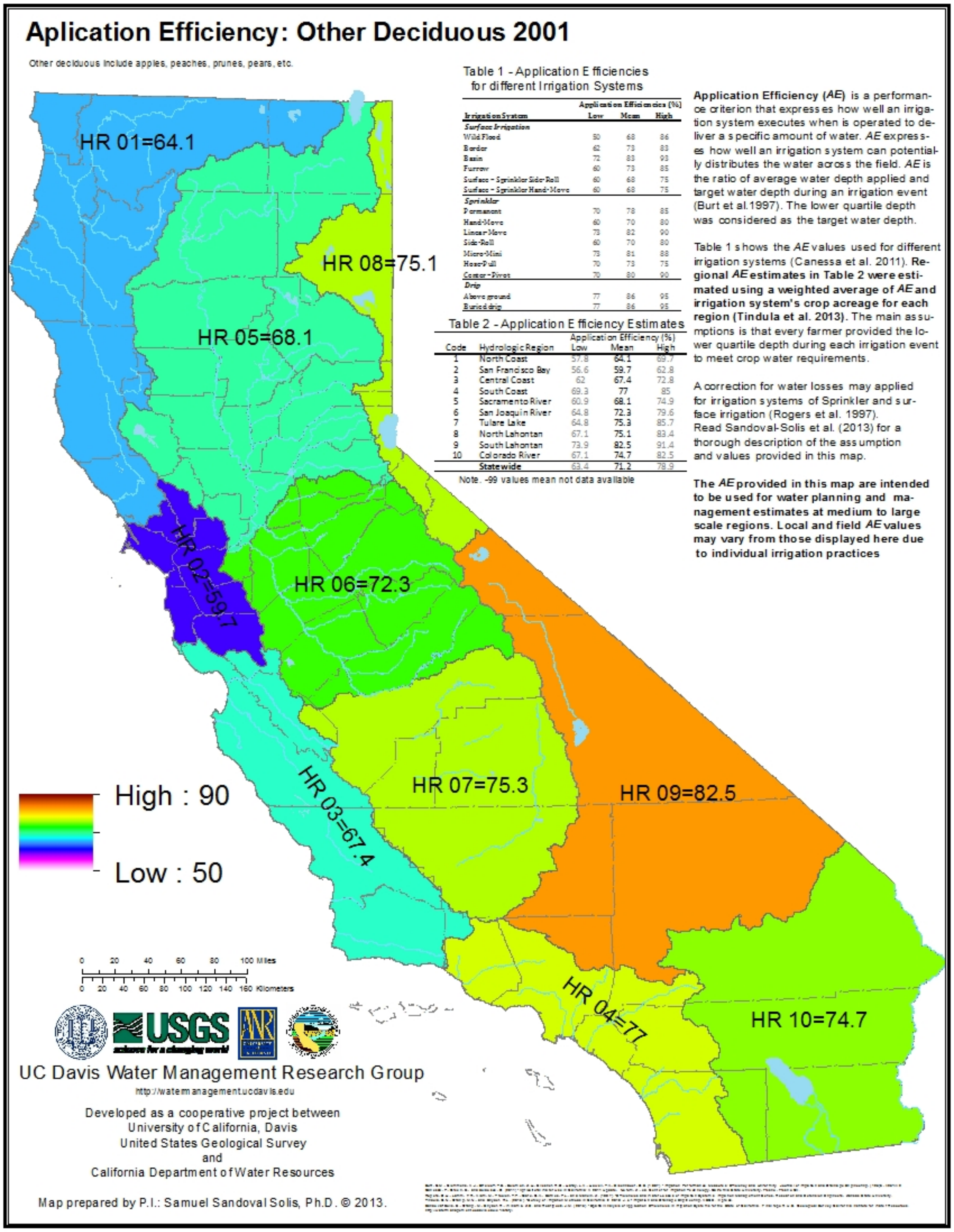


Table 1 - Application Efficiencies for different Irrigation Systems

Irrigation System	Application Efficiencies (%) Low	Mean	High
Surface Irrigation			
Wild Flood	50	68	86
Border	62	73	83
Basin	72	83	93
Furrow	60	73	85
Surface - Sprinkler Side-Roll	60	68	75
Surface - Sprinkler Hand-Move	60	68	75
Sprinkler			
Permanent	70	78	85
Hand-Move	60	70	80
Linear-Move	73	82	90
Side-Roll	60	70	80
Micro-Mini	73	81	88
Hose-Pull	70	73	75
Center-Pivot	70	80	90
Drip			
Above ground	77	86	95
Buried drip	77	86	95

Table 2 - Application Efficiency Estimates

Code	Hydrologic Region	Application Efficiency (%) Low	Mean	High
1	North Coast	57.8	64.1	69.7
2	San Francisco Bay	56.6	59.7	62.8
3	Central Coast	62	67.4	72.8
4	South Coast	69.3	77	85
5	Sacramento River	60.9	68.1	74.9
6	San Joaquin River	64.8	72.3	79.6
7	Tulare Lake	64.8	75.3	85.7
8	North Lahontan	67.1	75.1	83.4
9	South Lahontan	73.9	82.5	91.4
10	Colorado River	67.1	74.7	82.5
	Statewide	63.4	71.2	78.9

Note. -99 values mean not data available

Figure 40: Application Efficiency for Other Deciduous, ***Survey 2001***.

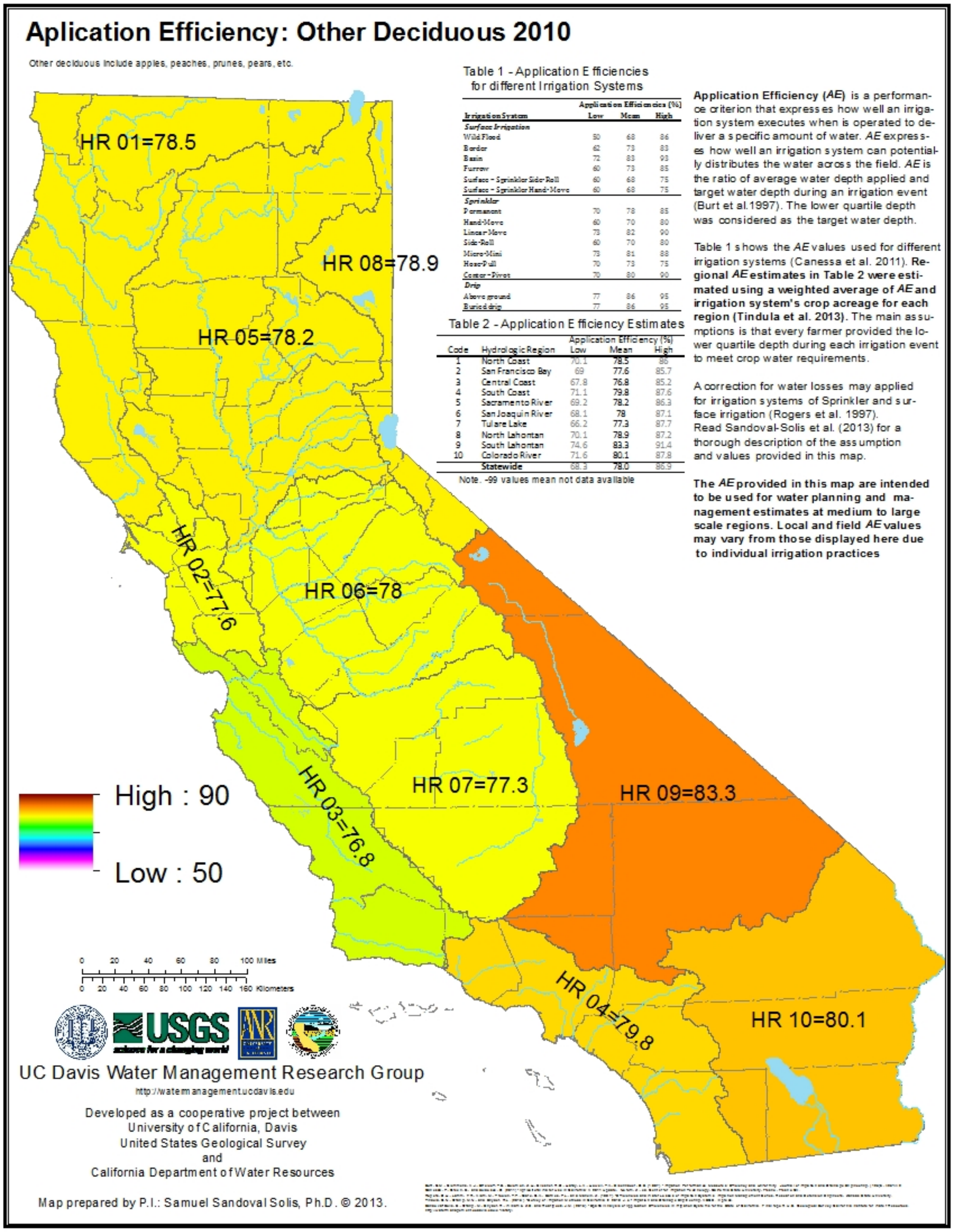


Figure 41: Application Efficiency for Other Deciduous, ***Survey 2010***.

5.2.18. *SUBTROPICAL TREES*

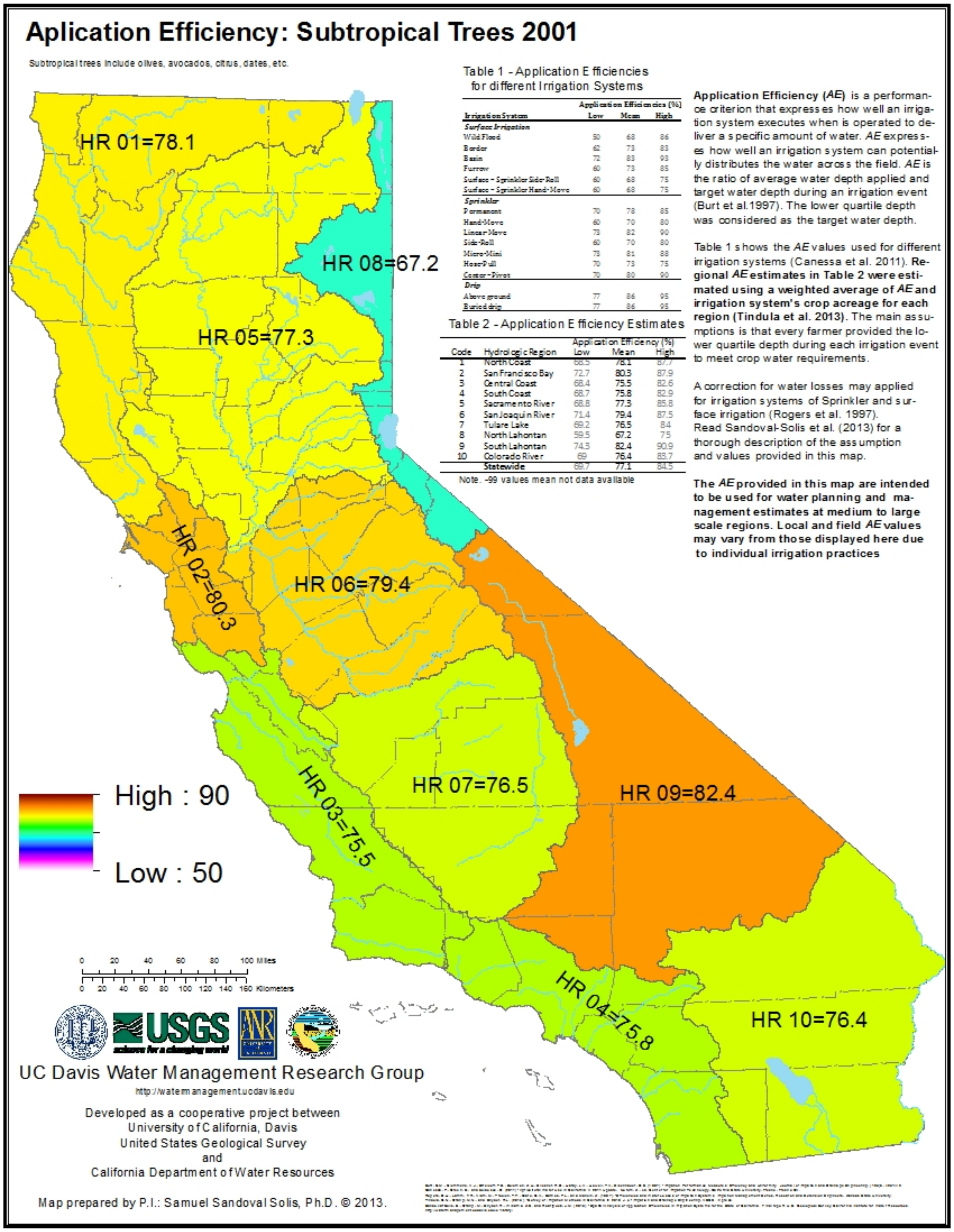


Figure 42: Application Efficiency for Subtropical Trees, ***Survey 2001***.

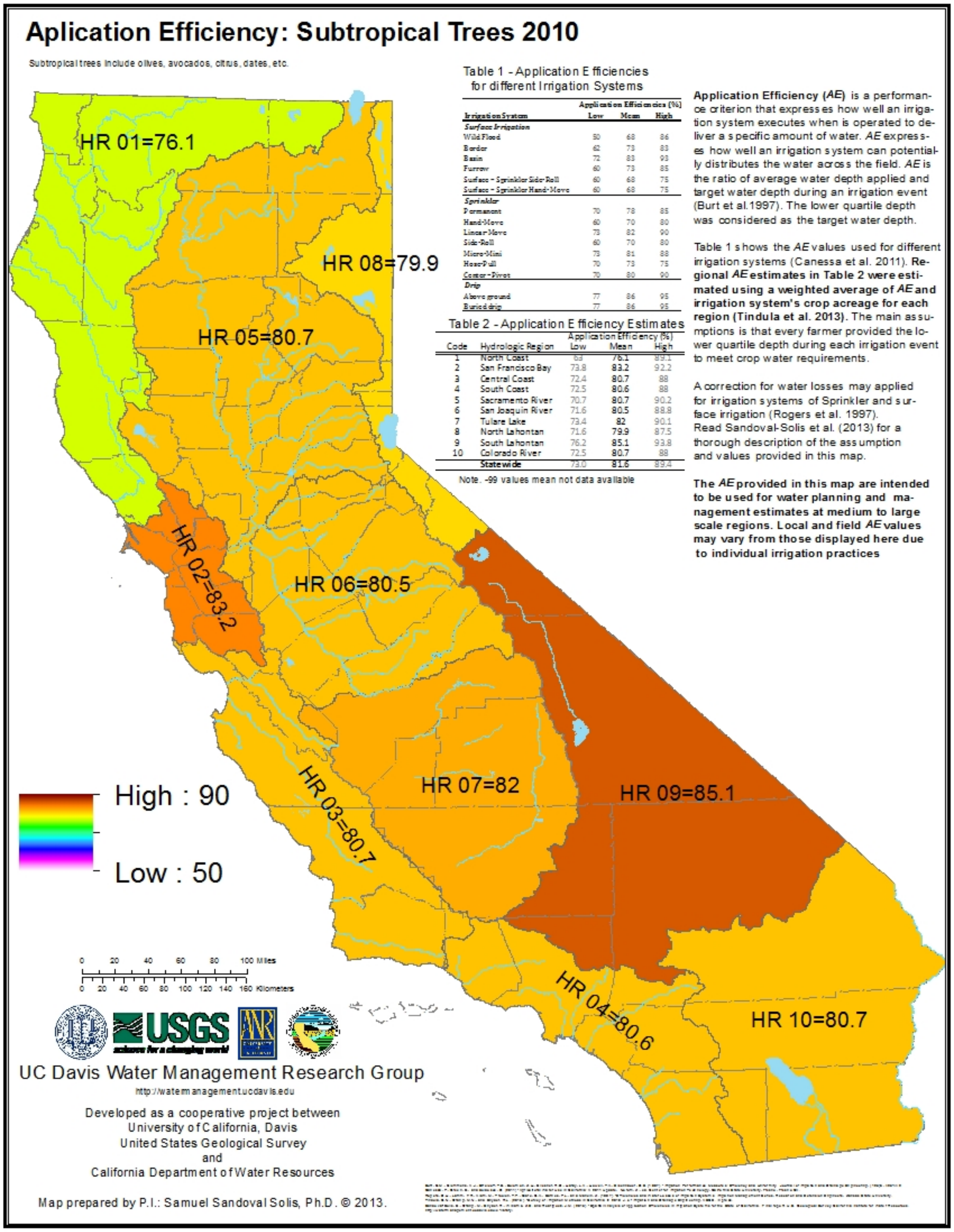


Figure 43: Application Efficiency for Subtropical trees, ***Survey 2010***.

5.2.19. *TURFGRASS AND LANDSCAPE*

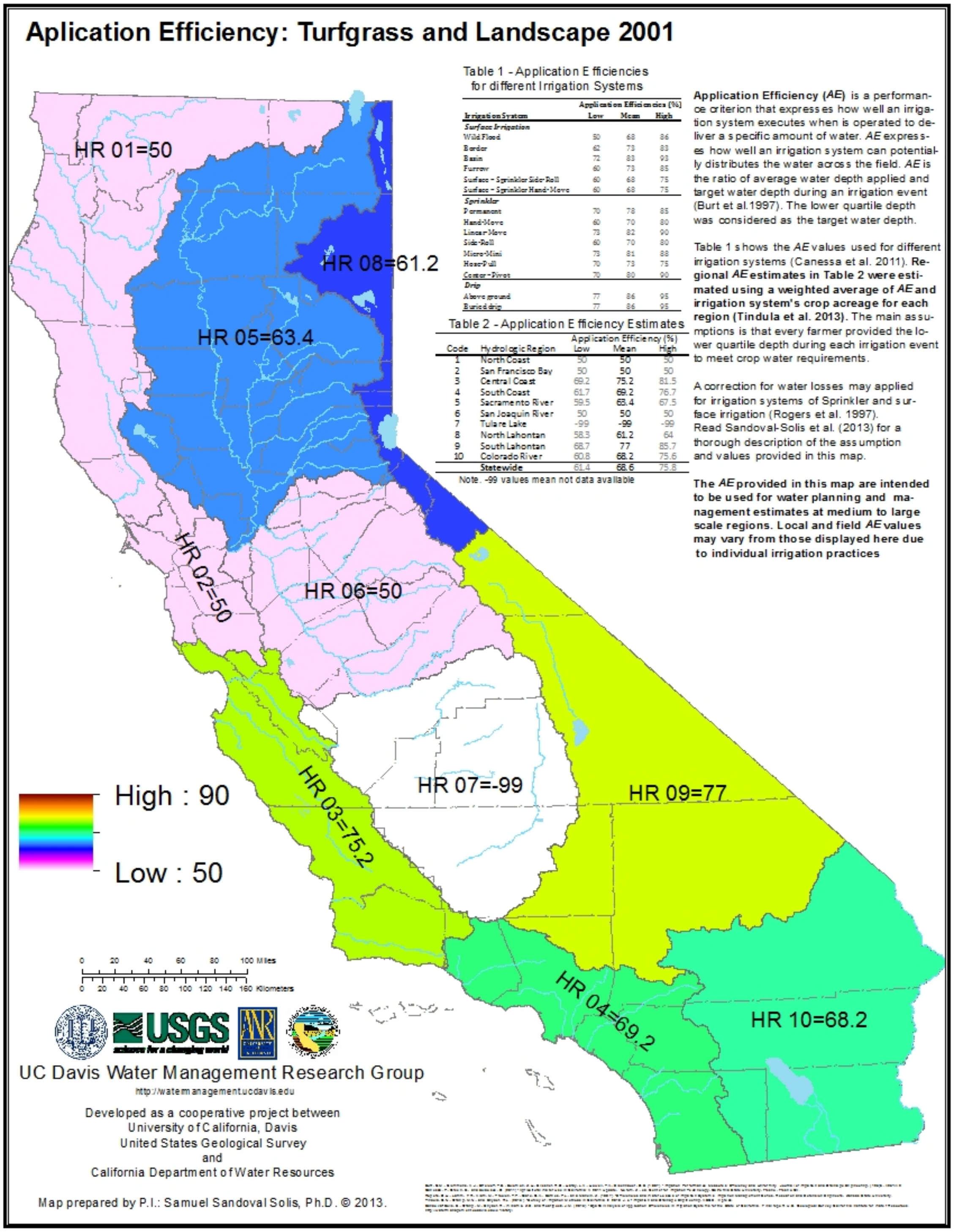


Figure 44: Application Efficiency for Turfgrass and Landscape, ***Survey 2001***.

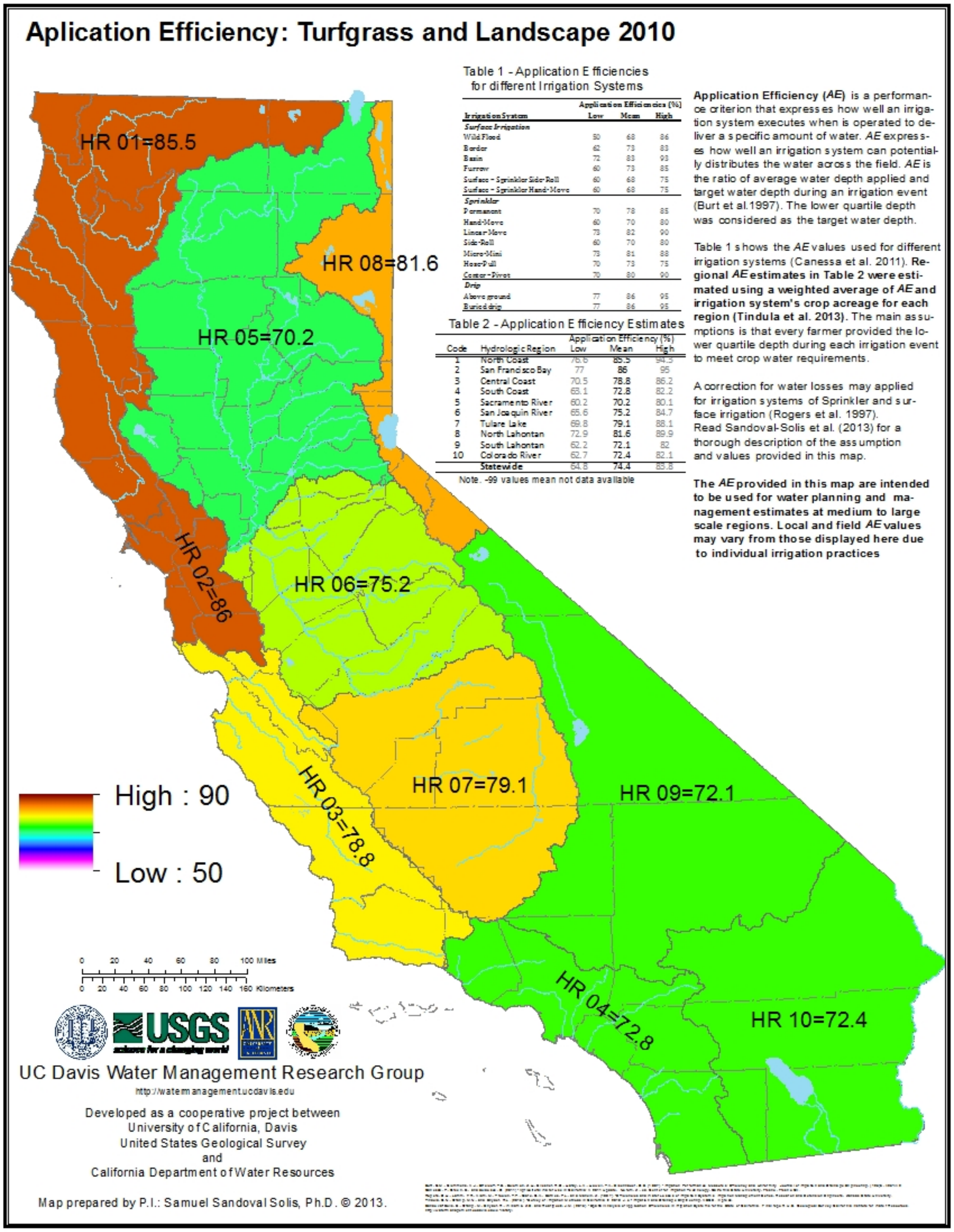


Figure 45: Application Efficiency for Turfgrass and Landscape, ***Survey 2010***.

5.2.20. VINEYARD

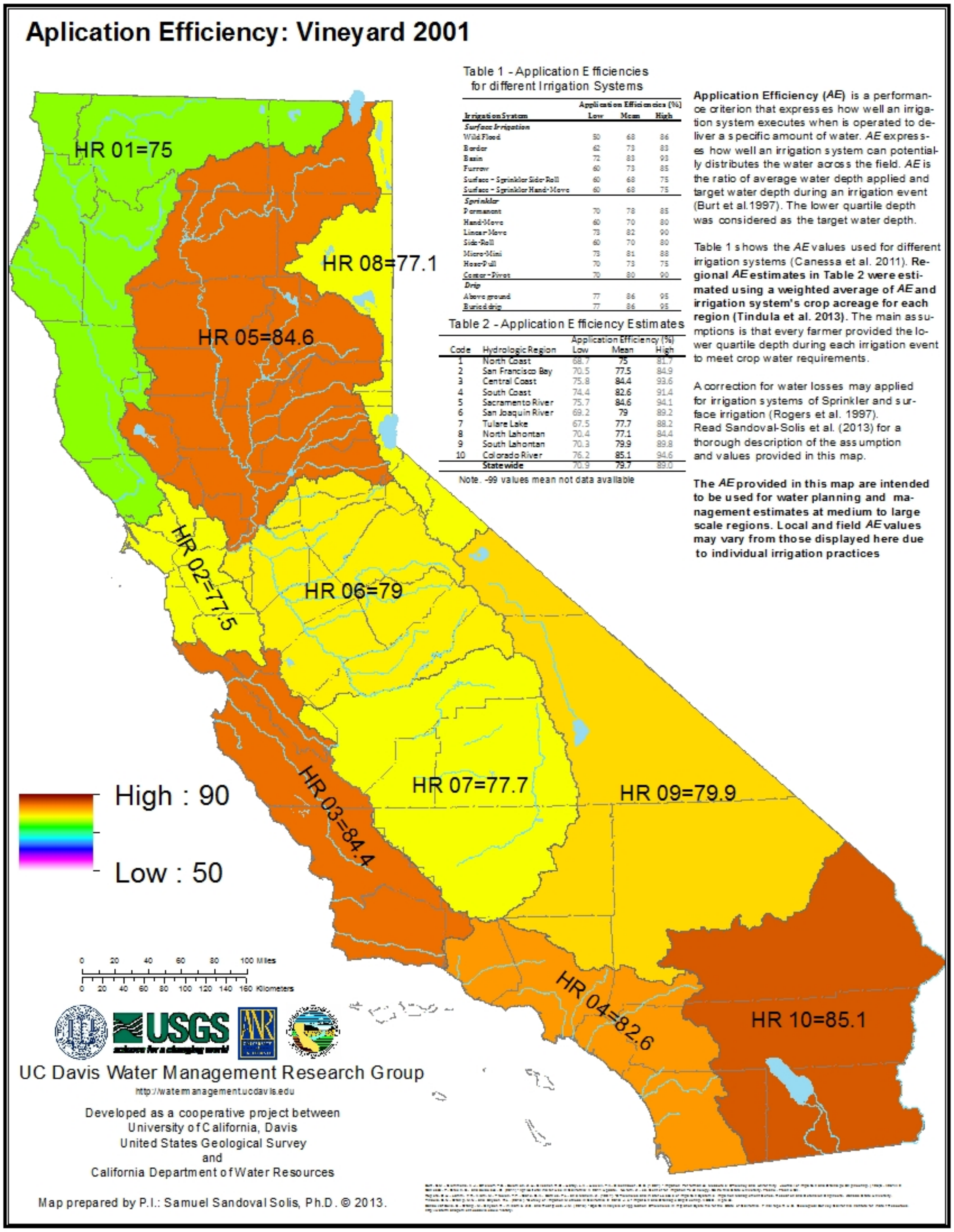


Figure 46: Application Efficiency for Vineyard, ***Survey 2001***.

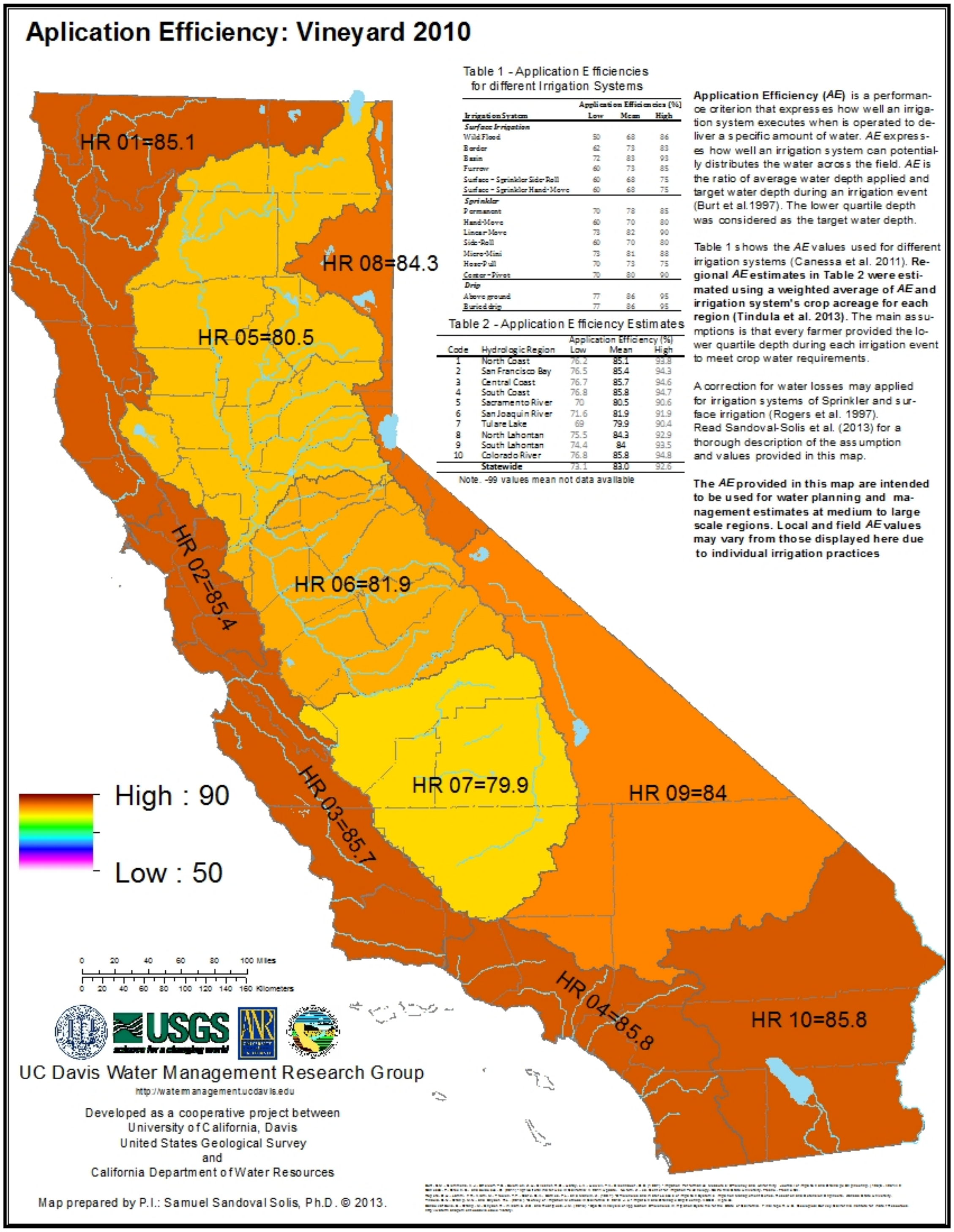


Figure 47: Application Efficiency for Vineyard, ***Survey 2010***.

- 69 -

6. CONCLUSION

6.1. CONCLUSIONS

Based on the analysis done, combining the irrigation surveys with theoretical application efficiencies, it was possible to estimate overall application efficiencies for 20 crops and by hydrologic region for two years, 2001 and 2010. **Table 7** shows the application efficiency for each hydrologic region and statewide. For the whole state of California, it is estimated that the mean *AE* has increased 3.1% from 74.5% to 77.5%. All hydrologic regions improved their *AE* (Δ*AE*), except North Lahontan, where a minimal -0.1% decrease in *AE* has been estimated. The three regions with highest increase in *AE* are: Sacramento River (4.8%) and South Coast (4.3%) and San Francisco Bay (3.9%).

Table 7 –Application Efficiencies for California Hydrologic Regions

	2001 Survey			2010 Survey			
Hydrologic Region	Low (%)	Mean (%)	High (%)	Low (%)	Mean (%)	High (%)	Δ*IE*
North Coast	64.4	73.6	82.1	67.2	77.3	87.0	3.7
San Francisco Bay	66.7	74.9	82.9	68.2	78.8	88.9	3.9
Central Coast	68.3	76.4	84.7	70.5	79.8	88.9	3.4
South Coast	65.6	74.4	83.3	69.2	78.7	87.7	4.3
Sacramento River	62.2	71.8	80.9	65.8	76.6	86.6	4.8
San Joaquin River	65.0	74.8	84.4	67.0	78.0	88.3	3.2
Tulare Lake	65.5	75.5	85.5	66.7	77.8	88.3	2.3
North Lahontan	59.2	73.6	84.3	61.8	73.5	85.0	-0.1
South Lahontan	66.8	76.3	85.9	67.9	78.5	88.6	2.2
Colorado River	63.0	72.9	82.8	63.9	75.3	86.1	2.4
Statewide	64.8	74.5	83.9	66.7	77.5	87.8	3.1

Similarly, the *AE* by crop has increased for most of the crops, as shown in Table 8. The crops with highest *AE* in 2010 are vineyards, followed by subtropical trees, almonds and pistachio, tomato (process), and onion and garlic (Column of 2010 Survey - Mean). The 2010 AE values for almost every crop increased [column Δ(AE)] compared to estimated AE in 2001, except for safflower and pasture. The largest increases in AE from 2001 to 2012 [column Δ(AE)] occurred in onion and garlic, tomato (process), potato, other deciduous (apples, peaches, prunes, pears, etc.), and turfgrass and landscape. At least 14 crops improved their AE by 2% or more (cotton, other field crops, cucurbit, onion and garlic, tomato-fresh. tomato process, other truck crops, almond and pistachio, other deciduous, subtropical trees, turf grass and landscape, and vineyards).

Table 8 –Application Efficiencies by Crop

Crop	2001 Survey Low (%)	2001 Survey Mean (%)	2001 Survey High (%)	2010 Survey Low (%)	2010 Survey Mean (%)	2010 Survey High (%)	Δ*IE*
Corn	59.7	72.5	84.6	59.6	72.9	85.5	0.4
Cotton	59.9	71.6	83.4	62.2	74.6	86.4	3.0
Dry beans	61.8	72.0	82.2	63.3	74.3	84.6	2.3
Grains	60.6	72.0	82.6	60.1	73.0	85.3	1.0
Safflower	59.4	71.3	81.9	58.9	71.1	82.9	-0.3
Sugarbeet	60.0	72.5	85.0	62.0	74.4	86.0	1.9
Other Field crops	60.9	72.1	83.0	62.0	74.2	85.9	2.1
Alfalfa	61.9	72.5	82.8	60.6	73.1	84.9	0.6
Pasture	57.7	72.0	82.6	58.5	71.4	83.9	-0.5
Cucurbit	65.0	74.6	84.2	66.8	77.9	88.5	3.3
Onion and Garlic	56.0	61.2	66.4	69.6	79.0	88.0	17.9
Potato	61.1	68.7	76.3	70.5	78.9	86.5	10.2
Tomato (fresh)	66.5	75.9	85.4	67.7	78.5	89.0	2.6
Tomato (process)	60.3	70.4	80.4	70.9	80.9	90.6	10.6
Other Truck Crops	64.3	72.8	81.6	67.2	77.1	86.6	4.3
Almond & Pistachio	69.0	76.9	84.7	72.0	81.2	89.8	4.3
Other Deciduous	63.4	71.2	78.9	68.3	78.0	86.9	6.7
Subtropical Trees	69.7	77.1	84.5	73.0	81.6	89.4	4.5
Turfgrass & landscape	61.4	68.6	75.8	64.8	74.4	83.8	5.8
Vineyard	70.9	79.7	89.0	73.1	83.0	92.6	3.3

6.2. LIMITATIONS

The objective of this analysis is to obtain a rough estimation of on farm *AE* across different hydrologic regions and crops across California. This was possible by considering several assumptions that may not be valid. The main assumptions are: (1) the irrigation survey is a representative sample of the population, (2) every farmer knew their irrigation system *DU* and their crops target depth, (3) the target depth was obtained considering the low quartile depth and the distribution uniformity, and (4) water losses from the irrigation system were not considered. For the first assumption, further statistical analysis is needed to test if the irrigation survey is representative of the population. For the second assumption, it is very unlikely that every farmer knows the DU of their irrigation system, or their target depth, nonetheless, this assumption was considered to make equal the DU and AE values. The third assumption considers that farmers do not waste water and only apply the required amount of water in every irrigation event, however this is not always true, lacking of knowledge of their *DU*, crop water requirement and target depth can provoke to use more water than needed. Finally, for the fourth assumption, the authors recognize that there are water losses in irrigation systems and that these must be considered when data is available.

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Appendix A. APPLICATION EFFICIENCIES TUTORIAL

California Application Efficiencies: ArcGIS Tutorial for Hydrologic Regions Geo-database

Project: Spatial Analysis of Irrigation Efficiencies for the State of California
Institution: United States Geological Survey

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Tutorial Prepared by: Kaylee Williams

Table of Contents

INTRODUCTION

Analyzing who is using the water, where, but most importantly, how efficiently, it is of substantial importance in order to identify potential places where improvements can be made. Application efficiency is defined as the ratio of beneficial water use for a determined crop and the applied water to that particular crop. The beneficial water use is the amount water beneficially transpired by plants, retained in the plant tissue and evaporated from adjacent soil surfaces, water for removal of salts or climate control, during a specific period of time. This value is highly dependent on the crop type. The applied water is the quantity of water applied to a specific crop per unit area, which depends on the irrigation method.

Understanding how irrigation methods and land use have changed over a time period is relevant to understanding what crops are being grown and how they are supplied with water throughout the state. Five irrigation surveys have been conducted in California (1972, 1980, 1991, 2001, and 2010); however they are compiled in an Excel format that has made the data less accessible for further water use analysis.

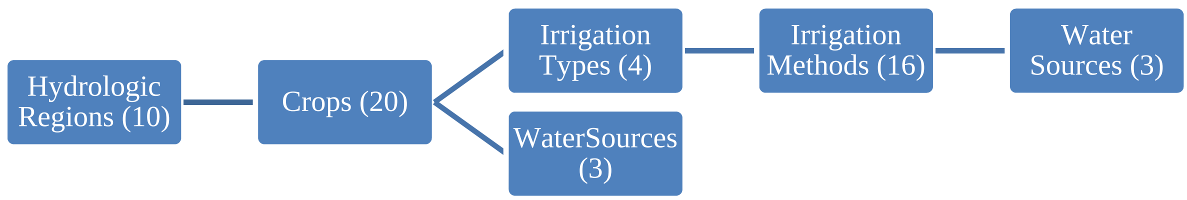
OBJECTIVES

The main objectives of the project are to introduce the Irrigation Survey data from 2001 and 2010 to a geographical information system (GIS) format called *California Irrigation Information System (CALIIS)*and perform a temporal and spatial analysis of water use efficiency for each crop and irrigation method. This will help to determine the variability and uncertainty of water use efficiency calculations. Irrigation survey data was collected by county for 20 crops, 4 irrigation types, and 16 irrigation methods. Composing the data into a GIS format provides easier access, use, and visualization of irrigation trends for each of the ten hydrologic regions in California.

This tutorial explains the data compilation and framework that was used in the creation of the database created for the hydrologic regions. It also will show how to manipulate data in the database from selecting by location and feature attributes. A in depth analysis discussion includes topics such as exporting selected data, construction of new feature classes, and construction of relationship classes.

DATA FRAMEWORK FOR GEODATABASE

The data framework for the geodatabase follows the pattern displayed below. Starting from ten hydrologic regions it is subdived into twenty crops. From twenty crops it is possible to find the water source (ground, surface, both) or continue to four irrigation type. From irrigation type we can then specify the irrigation method and lastly the water sources for each method present. Note that the figure below has the number of possible cateogories in parenthesis after the field name description. This is to indicate that there are multiple values associated with each box in the schema.



Below are the listed names for each subgroup for reference:

Hydrologic Regions:

1. North Coast
2. San Francisco Bay
3. San Joaquin River
4. Central Coast
5. Tulare Lake
6. South Coast
7. Sacramento River
8. North Lahontan
9. South Lahontan
10. Colorado River

Crops:

1. Corn
2. Cotton
3. Dry Beans
4. Grains (wheat, oats, barley, etc.)
5. Safflower
6. Sugarbeet
7. Other Field Crops (sorghum, sunflower, sudangrass, etc.)
8. Alfalfa
9. Pasture
10. Cucurbit (melons, squash, cucumber, etc.)
11. Onions and Garlic
12. Potato
13. Tomato (Fresh)
14. Tomato (Process)
15. Other Truck Crops (carrots, celery, cauliflower, broccoli strawberries, asparagus, etc.)
16. Almond and Pistachio
17. Other Deciduous (apples, peaches, prunes, pears, etc.)
18. Subtropical Trees (olives, avocado, citrus, dates, etc.)
19. Turfgrass and Landscape
20. Vineyard

Irrigation Types:

1. Gravity
2. Sprinkler
3. Low Volume
4. Other

Irrigation Methods:

1. Subsurface-Subsurface
2. Surface-Wildflood
3. Surface-Border
4. Surface-Basin
5. Surface-Furrow
6. Surface-Sprinkler-SideRoll
7. Surface-Sprinkler-Handmove
8. Sprinkler-Permanent
9. Sprinkler-Handmove
10. Sprinkler-Linearmove
11. Sprinkler-SideRoll
12. Sprinkler-MicroMini
13. Sprinkler-HosePull
14. Sprinkler-CenterPivot
15. Drip-AboveGround
16. Drip-Buried

Water Sources:

A) Surface
B) Groundwater
C) Both

DATA SOURCES

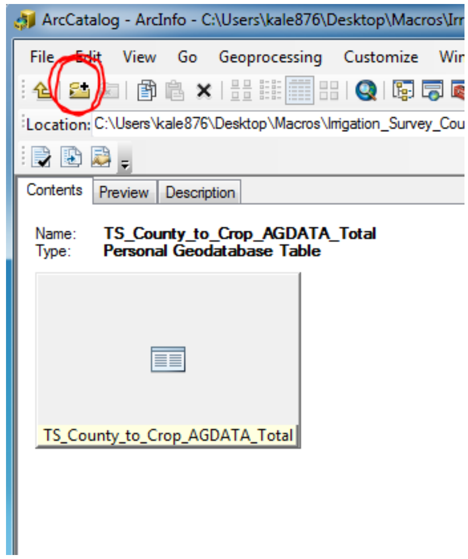
The data used to form the database was compiled from statewide irrigation surveys from 2001 (Orang et al 2008) and 2010 (DWR 2011). These data were compiled by county and surveys were sent to 10,000 randomized farmers from various counties within the state. Regional data was composed by the summation of county data within each region. Where regional and county boundaries overlapped, a distribution of the crops was composed based off of data from the DWR Land & Water Use Survey for various years. For these counties a percentage of crop values were added to each appropriate region. The limited sample size of returned surveys makes these data a sample set prone to skewed or inaccurate representations of crop and irrigation methods.

Data from the Agriculture Commissioner report for 2010 was delineated by county and distributed into regions similar as to that described above. This report covers a more comprehensive population based value that will be compared to the Irrigation Survey data within our analysis.

CONNECTING TO DATABASE

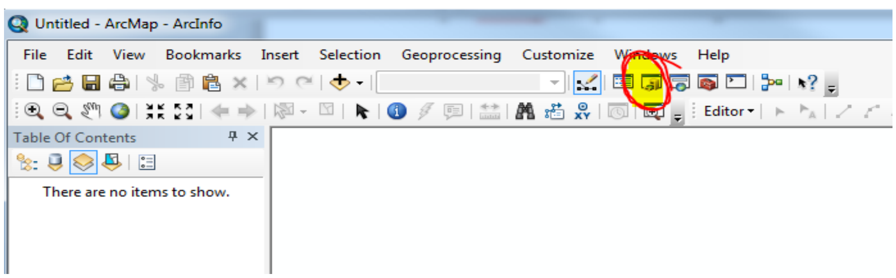
In order to connect to the database first download the database file from the website. If needed, unzip the file and save in an easily navigable folder on your computer.

Next, open ArcCatalog and select the ‘connect to folder’ in the second to upper toolbar. Navigate to the geo-database folder and Select.



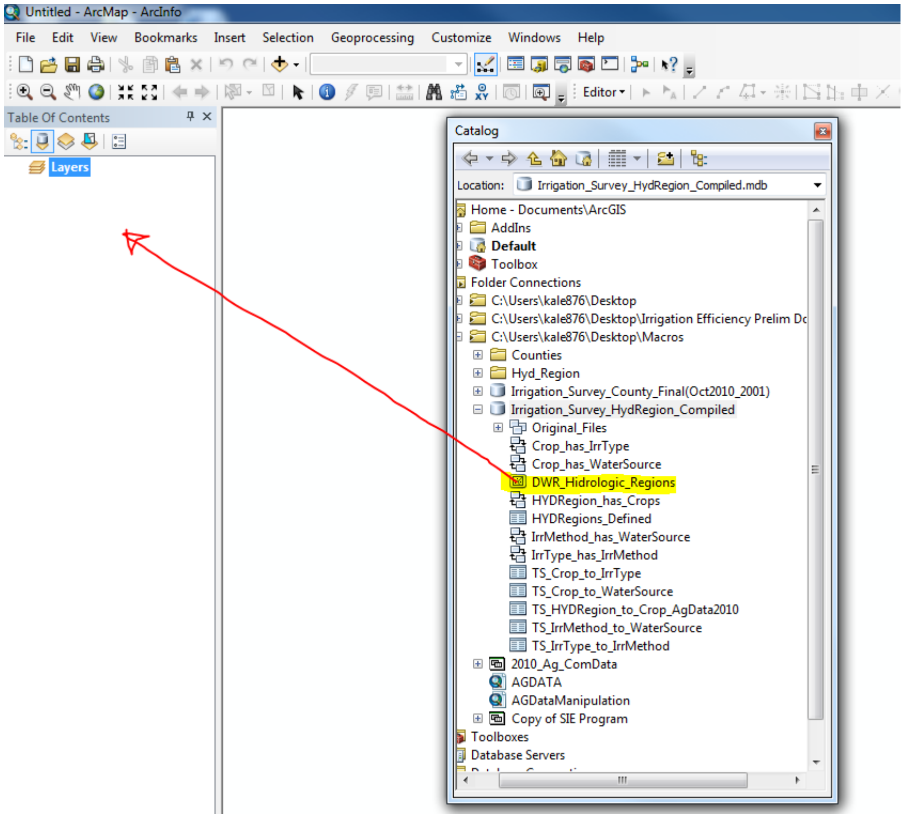
If the icon is not visible in the toolbar select File, then click on the 'Connect to Folder.'

After ArcCatalog is connected to the geo-database folder save and exit out of ArcCatalog. This is to trouble shoot possible errors that occur when both ArcCatalog and ArcMap are open. Now open ArcMap and open the Catalog Window located in the right side of the upper toolbar.

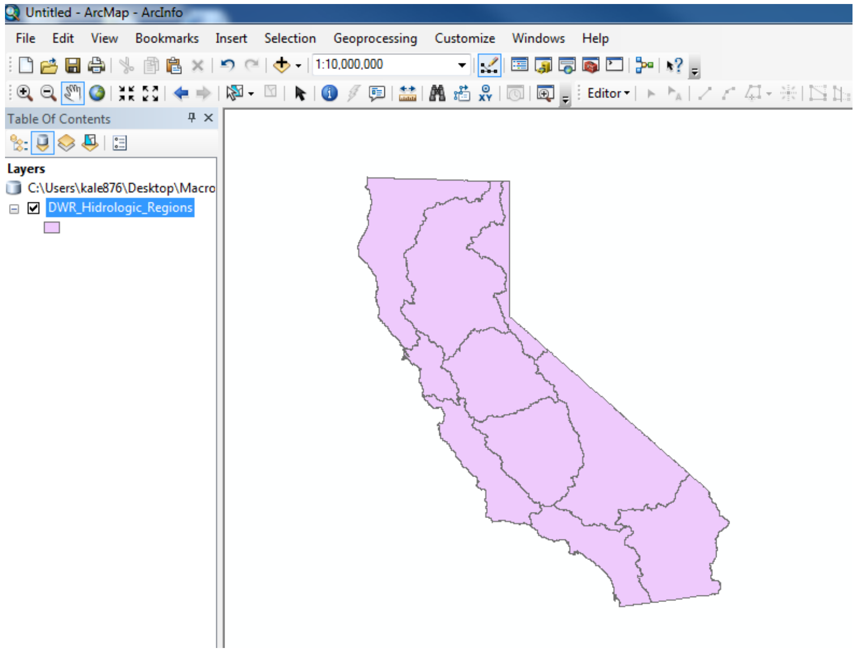


Now that ArcMap is connected to the Geo-database and the catalog window is open, right click the geo-database line and select 'Make Default Database'. In order to have a visual map appear, left-click the database to expand the list of feature and relationship classes. Highlight the shape file named "DWR_Hidrologic_Regions" and drag it into the Table of Contents of the ArcMap window.

- 82 -


Untitled - ArcMap - ArcInfo
File Edit View Bookmarks Insert Selection Geoprocessing Customize Windows Help
Editor
Table Of Contents
Layers
Catalog
Location: Irrigation_Survey_HydRegion_Compiled.mdb
Home - Documents\ArcGIS
AddIns
Default
Toolbox
Folder Connections
C:\Users\kale876\Desktop
C:\Users\kale876\Desktop\Irrigation Efficiency Prelim Dc
C:\Users\kale876\Desktop\Macros
Counties
Hyd_Region
Irrigation_Survey_County_Final(Oct2010_2001)
Irrigation_Survey_HydRegion_Compiled
Original_Files
Crop_has_IrrType
Crop_has_WaterSource
DWR_Hidrologic_Regions
HYDRegion_has_Crops
HYDRegions_Defined
IrrMethod_has_WaterSource
IrrType_has_IrrMethod
TS_Crop_to_IrrType
TS_Crop_to_WaterSource
TS_HYDRegion_to_Crop_AgData2010
TS_IrrMethod_to_WaterSource
TS_IrrType_to_IrrMethod
2010_Ag_ComData
AGDATA
AGDataManipulation
Copy of SIE Program
Toolboxes
Database Servers

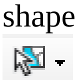
The map of California's Hydrologic Regions should appear in the window as displayed below. From this view we are able to use ArcMap and the data in the geo-database in a visually integrative analysis.



UTILIZING GEODATABASE FEATURES

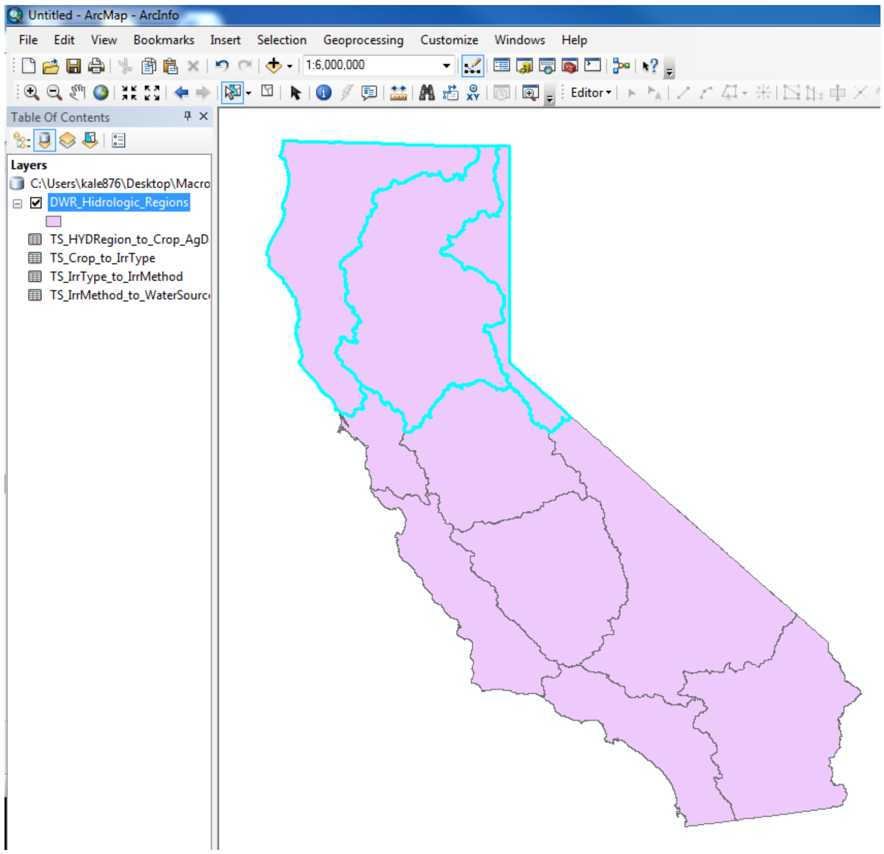
There are two ways to select data and features within ArcMap. This includes manual selection (i.e. dragging the cursor over the desired region or selection by attribute (i.e. specify region with more than 20,000 acres of corn). Below are two examples that show the inquiry interface of ArcMap and how this tool is useful for the spatial and temporal analysis of the Irrigation Survey and Agriculture Commissioner Data.

2. MANUAL SELECTION

Make sure that ArcMap is open and connected to the Hydrologic Regions database so that the shape file displays the regional map as seen in the last figure. In the lower toolbar, left click the  icon. A list of options will appear including: 'Select by Rectangle' and 'Select by Polygon'. After selecting an option, double-click the area on the map of the region (s) of particular interest. The borders of the regions touching the shape that is created will become highlighted showing that the features have been selected.

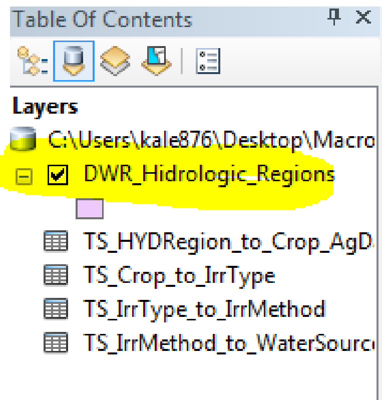
EXAMPLE

Select the three hydrologic regions that border the state of Oregon. First, double click the icon in the toolbar and select the option to 'Select by Rectangle'. Click, hold, and drag to create a rectangle on the map that touches all three regions (North Coast, Sacramento River, and North Lahontan). Once the rectangle is in the desired area release your click and the desired regions should be outlined in a different color signifying that they have been selected.

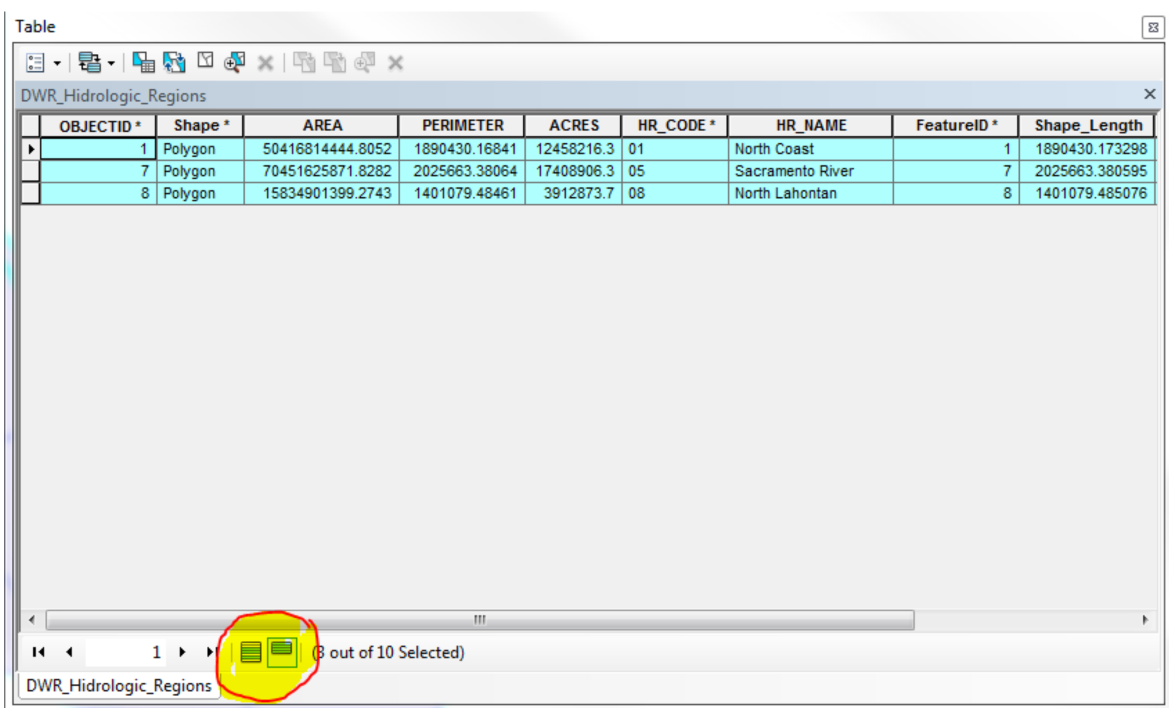


3. ACCESSING THE ATTRITUBE TABLE AND RELATED TABLES

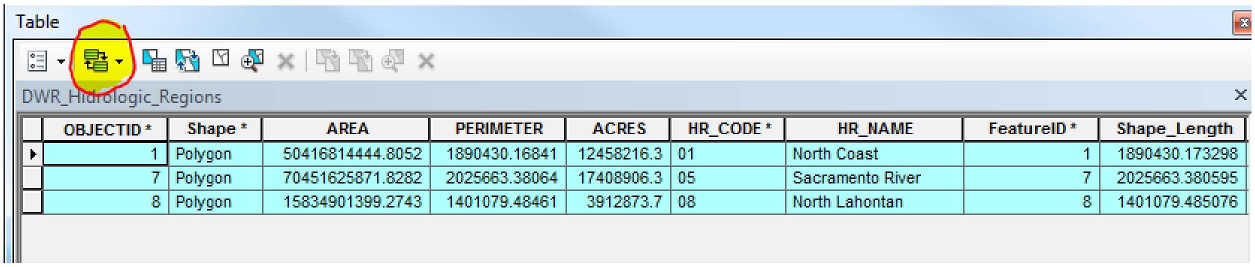
After the selection has been made, then we can open the attributes tables in order to see more detailed data regarding our selection. To open the attributes table right-click the 'DWR_Hidrologic_Regions' line displayed in the layers.



From the drop down menu select 'Open Attributes Table'. The titles in the attribute table are termed 'fields' and have different values for the properties of the regions. The tab at the bottom of the table enables the viewing of all of the data as well as only viewing the data of the selected features.

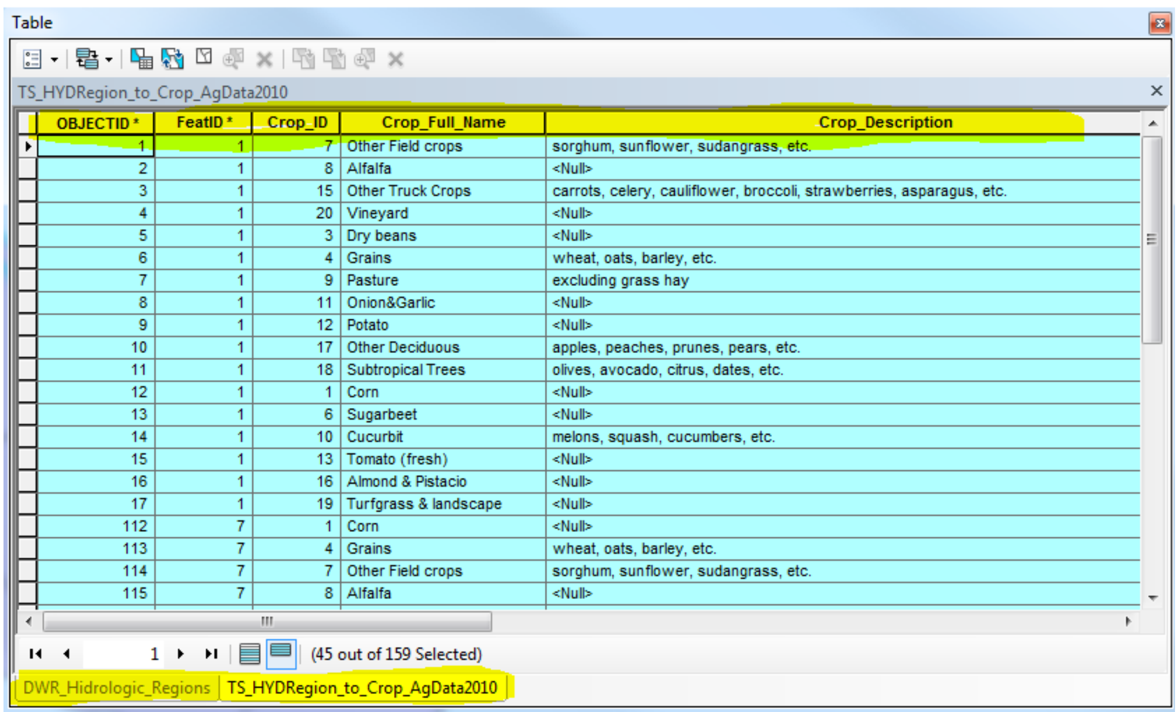


The creation of relationship classes within the database enables access to additional information pertaining to the hydrologic regions including: crops, irrigation methods, water source, etc. To access these data values from the attribute table click on the ‘Related Tables’ icon in the attributes table toolbar.



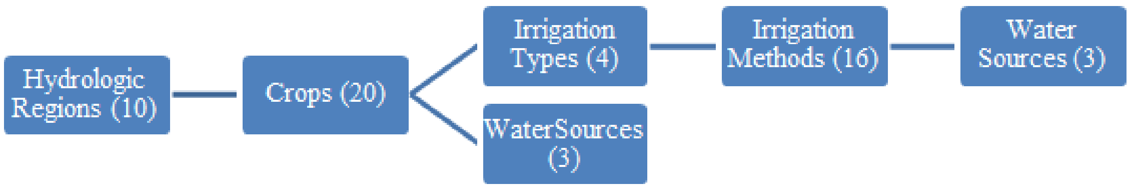
OBJECTID *	Shape *	AREA	PERIMETER	ACRES	HR_CODE *	HR_NAME	FeatureID *	Shape_Length
1	Polygon	50416814444.8052	1890430.16841	12458216.3	01	North Coast	1	1890430.173298
7	Polygon	70451625871.8282	2025663.38064	17408906.3	05	Sacramento River	7	2025663.380595
8	Polygon	15834901399.2743	1401079.48461	3912873.7	08	North Lahontan	8	1401079.485076

From the drop down menu we see that the hydrologic regions are connected to the data time series for the crops. This is labeled by the name of the relationship class and then the table for the time series of crops. Left-click and notice that the field names in the table have changed. The new table displays the crop time series data. Note that there are tabs at the bottom of the table to navigate back to the original hydrologic regions table.



OBJECTID *	FeatID *	Crop_ID	Crop_Full_Name	Crop_Description
1	1	7	Other Field crops	sorghum, sunflower, sudangrass, etc.
2	1	8	Alfalfa	<Null>
3	1	15	Other Truck Crops	carrots, celery, cauliflower, broccoli, strawberries, asparagus, etc.
4	1	20	Vineyard	<Null>
5	1	3	Dry beans	<Null>
6	1	4	Grains	wheat, oats, barley, etc.
7	1	9	Pasture	excluding grass hay
8	1	11	Onion&Garlic	<Null>
9	1	12	Potato	<Null>
10	1	17	Other Deciduous	apples, peaches, prunes, pears, etc.
11	1	18	Subtropical Trees	olives, avocado, citrus, dates, etc.
12	1	1	Corn	<Null>
13	1	6	Sugarbeet	<Null>
14	1	10	Cucurbit	melons, squash, cucumbers, etc.
15	1	13	Tomato (fresh)	<Null>
16	1	16	Almond & Pistacio	<Null>
17	1	19	Turfgrass & landscape	<Null>
112	7	1	Corn	<Null>
113	7	4	Grains	wheat, oats, barley, etc.
114	7	7	Other Field crops	sorghum, sunflower, sudangrass, etc.
115	7	8	Alfalfa	<Null>

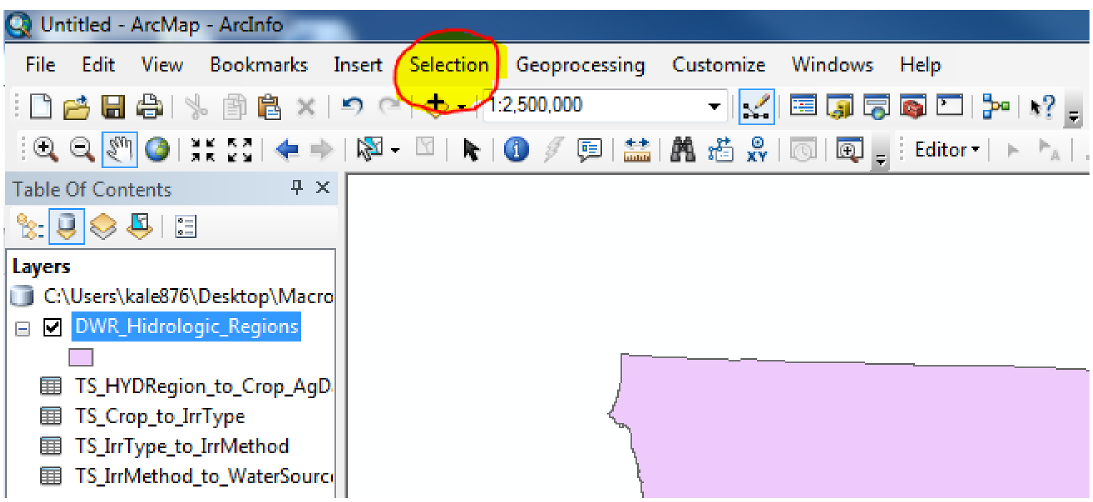
The data in the newer table pertains to the crops that are grown in the selected regions and their acreage and yield. By scrolling to the right, notice that there are fields for data from the Irrigation Survey for 2001, 2010, and Agriculture Commissioner for 2010. Click the 'Related Tables' icon while the crops table is open to see that the crops are connected to values for the water source and the irrigation type. To more easily visualize the connections between the data in the attributes table refer to the figure below.



4.

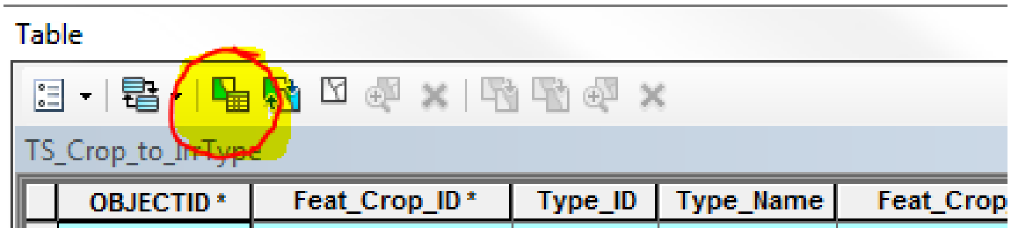
5. SELECTION BY ATTRIBUTES

Selection by attributes is one of the most useful features obtained by transferring data from an excel file into a geo-database. In order to select by attribute, left-click the 'Selection' tab in the toolbar of ArcMap.



- 88 -

The ‘Select by Attributes’ dialogue allows us to make statements to refine the data selection. To visibly see the selections have the ‘DWR_Hidrologic_Regions’ attribute table open along with the ‘Select by Attributes’ dialogue box. The Attributes dialogue box can also be accessed through the Attributes table toolbar by clicking on the ‘Select by Attributes’ icon.

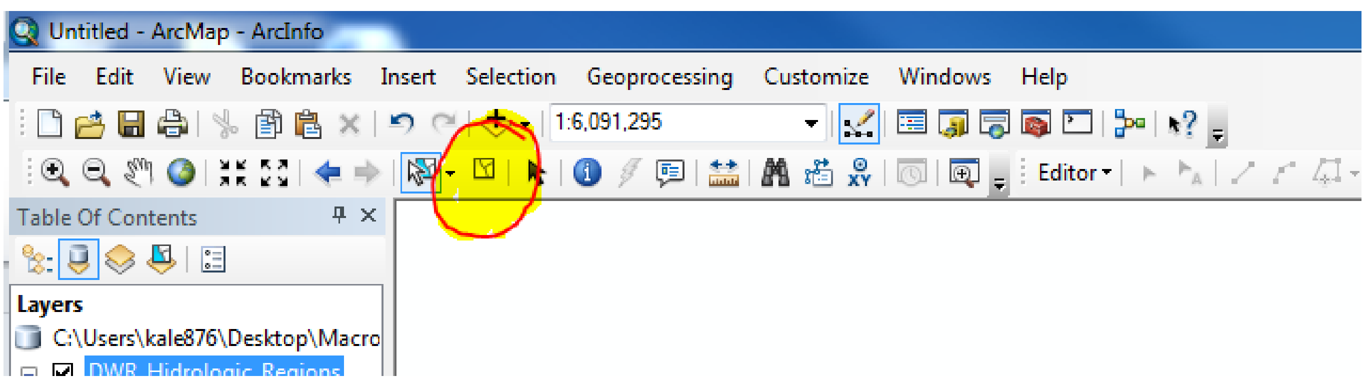


Attributes are selected in the dialogue box through the formation of statements, which will be further displayed in the example below. After the statement is form, Select Apply. The highlighted data displayed will adhere to the criteria of the statement.

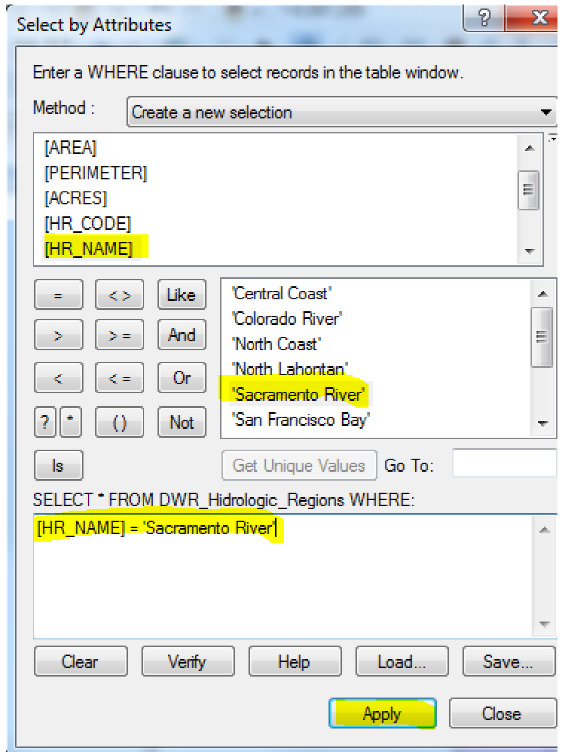
EXAMPLE:

Goal: Specify the Crops in the Sacramento River Hydrologic region that have greater than 150 acres of Gravity driven irrigation type for years of 2001 and 2010 of the Irrigation survey data.

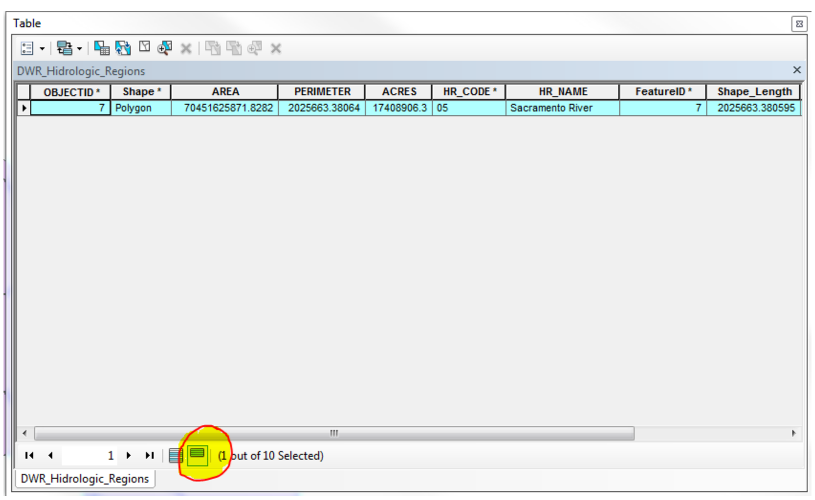
Clear any previous selections of the data by left-clicking the ‘Clear Selected Features’ icon in the toolbar.



Left click the ‘Select by Attributes’ icon in the Attribute table in order access the dialogue box. From here create the first statement: ‘[HR_NAME] = ‘Sacramento River’. Scroll down in the top box to find [HR_NAME] and then double click. Create a statement by selecting the equals sign, then ‘Get Unique Values’ and double clicking ‘Sacramento River’.

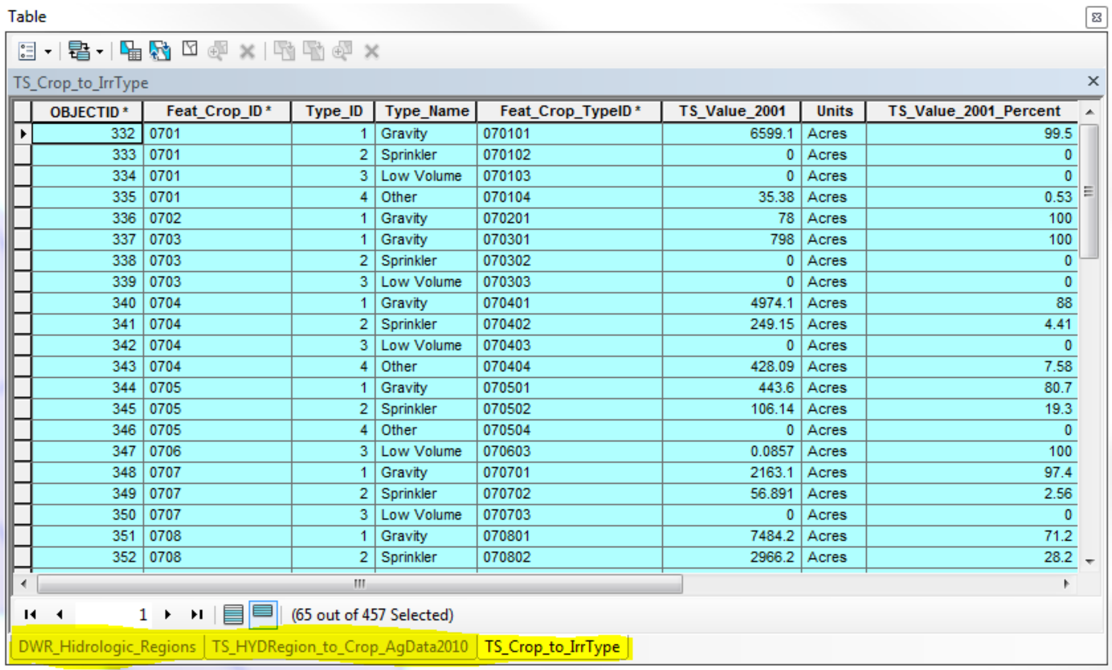


Once the statement is made, click ‘Apply’. This selects the Sacramento River Hydrologic region. Click ‘View Selected Records’ at the bottom of the attribute table window in order to ensure that the correct region is selected.



Now that the Sacramento River region is selected in order to refine the search further go to the related tables tab. Navigate from regions to crops by selecting the related table labeled

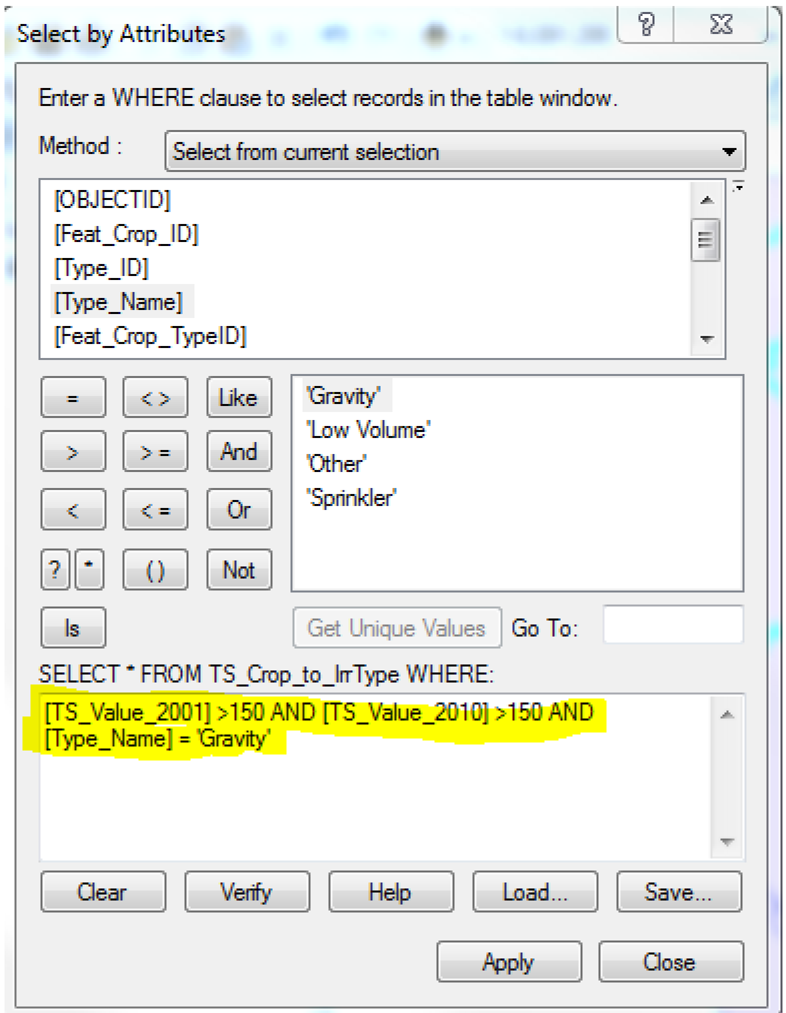
'TS_HYDRegion_to_Crop_AgData2010'. This opens the crop data. From here navigate to 'TS_Crop_to_IrrType'. There should now be three related opened in tabs in the attribute table window.



OBJECTID *	Feat_Crop_ID *	Type_ID	Type_Name	Feat_Crop_TypeID *	TS_Value_2001	Units	TS_Value_2001_Percent
332	0701	1	Gravity	070101	6599.1	Acres	99.5
333	0701	2	Sprinkler	070102	0	Acres	0
334	0701	3	Low Volume	070103	0	Acres	0
335	0701	4	Other	070104	35.38	Acres	0.53
336	0702	1	Gravity	070201	78	Acres	100
337	0703	1	Gravity	070301	798	Acres	100
338	0703	2	Sprinkler	070302	0	Acres	0
339	0703	3	Low Volume	070303	0	Acres	0
340	0704	1	Gravity	070401	4974.1	Acres	88
341	0704	2	Sprinkler	070402	249.15	Acres	4.41
342	0704	3	Low Volume	070403	0	Acres	0
343	0704	4	Other	070404	428.09	Acres	7.58
344	0705	1	Gravity	070501	443.6	Acres	80.7
345	0705	2	Sprinkler	070502	106.14	Acres	19.3
346	0705	4	Other	070504	0	Acres	0
347	0706	3	Low Volume	070603	0.0857	Acres	100
348	0707	1	Gravity	070701	2163.1	Acres	97.4
349	0707	2	Sprinkler	070702	56.891	Acres	2.56
350	0707	3	Low Volume	070703	0	Acres	0
351	0708	1	Gravity	070801	7484.2	Acres	71.2
352	0708	2	Sprinkler	070802	2966.2	Acres	28.2

Note that highlighted values are still values associated with the Sacramento River Hydrologic Region.

From The ‘TS_Crop_to_IrrType’ tab we refine the search to those values of our specifics. Those values include all of the crops with >150 acres for Gravity Type irrigation for both 2001 and 2010. From the ‘TS_Crop_to_IrrType’ tab click ‘Select by Attributes’ in the window toolbar. Make sure and change the ‘Method:’ to ‘Select from current selection’. Create the statement: [TS_Value_2001]>150 AND [TS_Value_2010]>150 AND [Type_Name]= ‘Gravity’.
Select ‘Apply’.

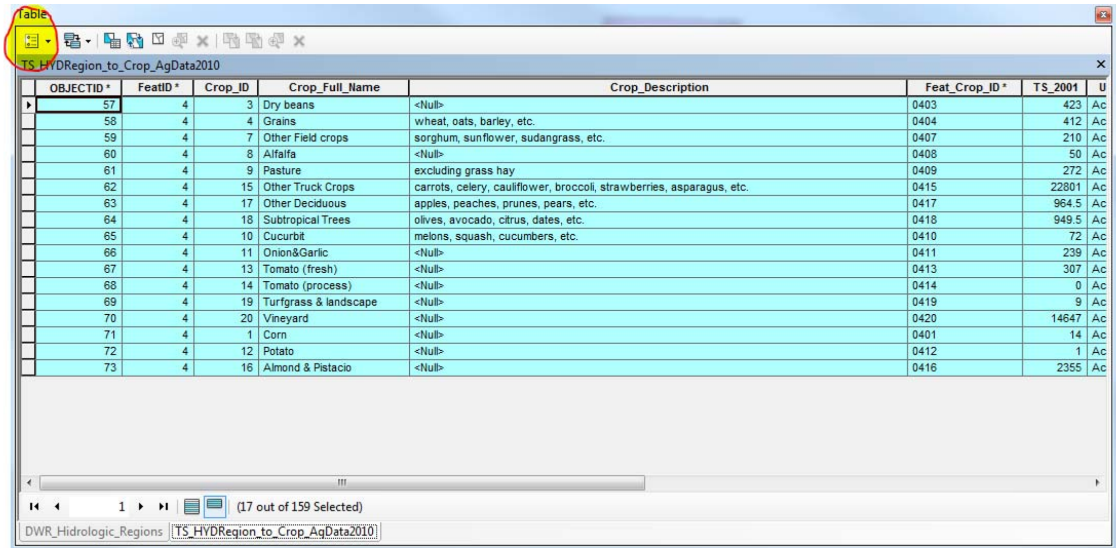


The final selection should have 12 out of 457 total values.

Note that there are many options and operators in order to form statements and refine the data, along with all of the different tabs for the related tables.

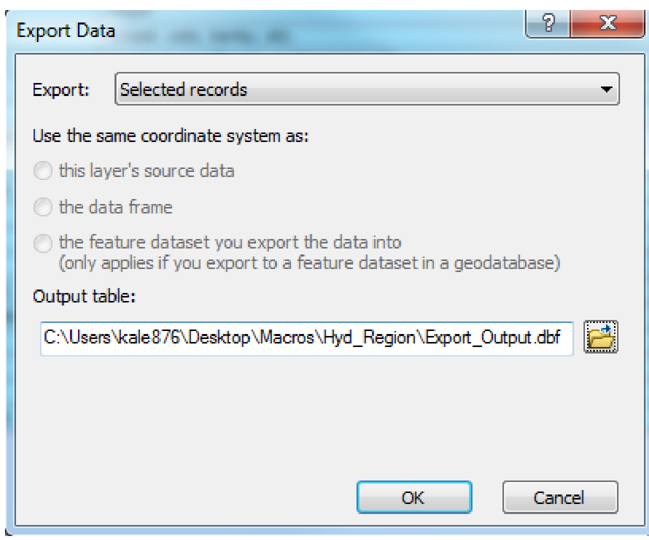
EXPORTING DATA

After manipulating data in the attributes table to specified values it is possible to export data as a table into Excel. First left click the ‘Table Options’ in the Toolbar. From here select the Export… option.

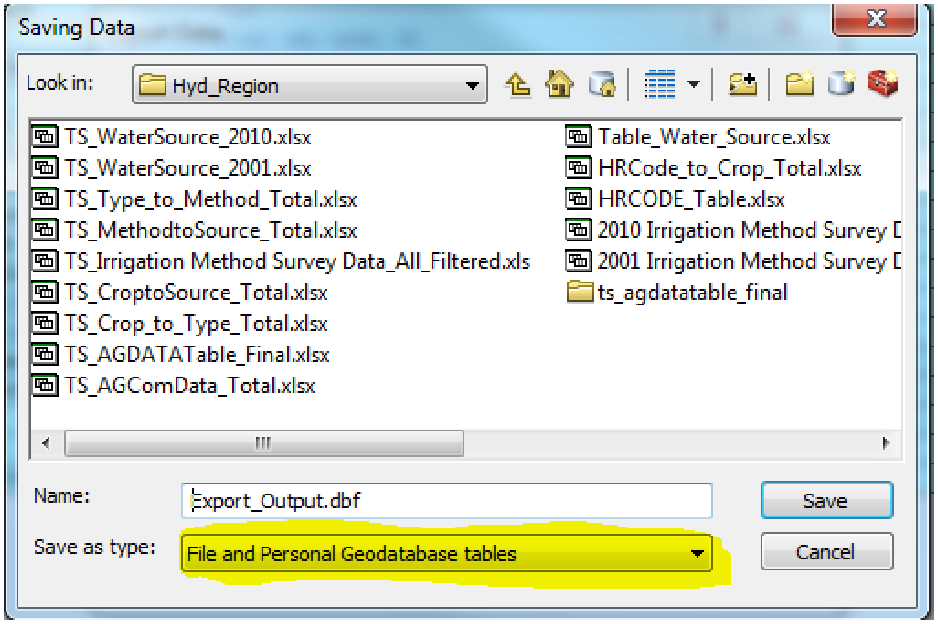


OBJECTID *	FeatID *	Crop_ID	Crop_Full_Name	Crop_Description	Feat_Crop_ID *	TS_2001	U
57	4	3	Dry beans	<Null>	0403	423	Ac
58	4	4	Grains	wheat, oats, barley, etc.	0404	412	Ac
59	4	7	Other Field crops	sorghum, sunflower, sudangrass, etc.	0407	210	Ac
60	4	8	Alfalfa	<Null>	0408	50	Ac
61	4	9	Pasture	excluding grass hay	0409	272	Ac
62	4	15	Other Truck Crops	carrots, celery, cauliflower, broccoli, strawberries, asparagus, etc.	0415	22801	Ac
63	4	17	Other Deciduous	apples, peaches, prunes, pears, etc.	0417	964.5	Ac
64	4	18	Subtropical Trees	olives, avocado, citrus, dates, etc.	0418	949.5	Ac
65	4	10	Cucurbit	melons, squash, cucumbers, etc.	0410	72	Ac
66	4	11	Onion&Garlic	<Null>	0411	239	Ac
67	4	13	Tomato (fresh)	<Null>	0413	307	Ac
68	4	14	Tomato (process)	<Null>	0414	0	Ac
69	4	19	Turfgrass & landscape	<Null>	0419	9	Ac
70	4	20	Vineyard	<Null>	0420	14647	Ac
71	4	1	Corn	<Null>	0401	14	Ac
72	4	12	Potato	<Null>	0412	1	Ac
73	4	16	Almond & Pistacio	<Null>	0416	2355	Ac

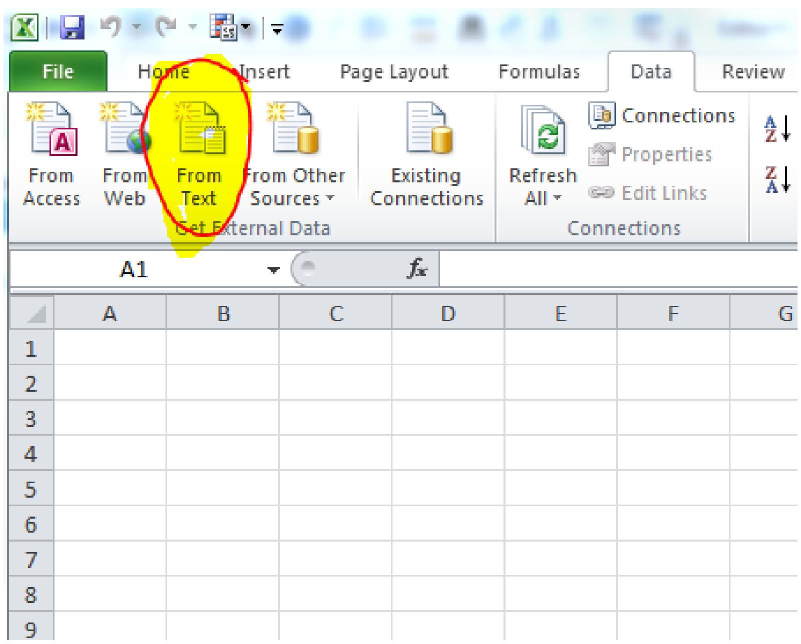
The ‘Export Data’ pop up window will have a top drop- down menu. From here either export the entirety of the attribute table or only the selected features. From the Export table: left-click the folder at the end of the ‘Output table:’ line to open the ‘Saving Data’ pop up window.



In the Saving Data pop up window create a recognizable name for the exported data. In the “Save as type:” Select “Text File” and then ‘Save’.

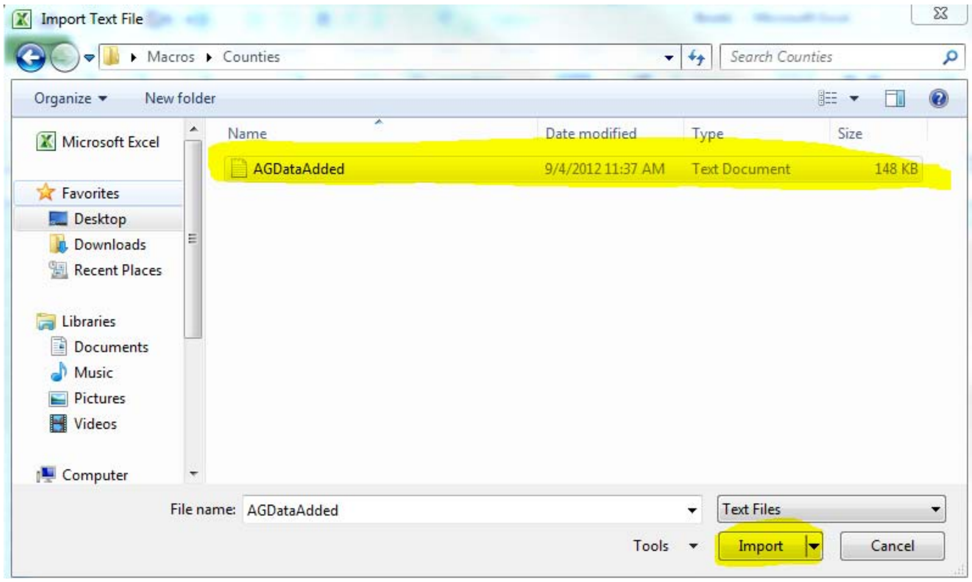


In order to retrieve the data, open Microsoft Excel and create a new workbook. In the data tab of the toolbar select ‘Get External Data From Text’.

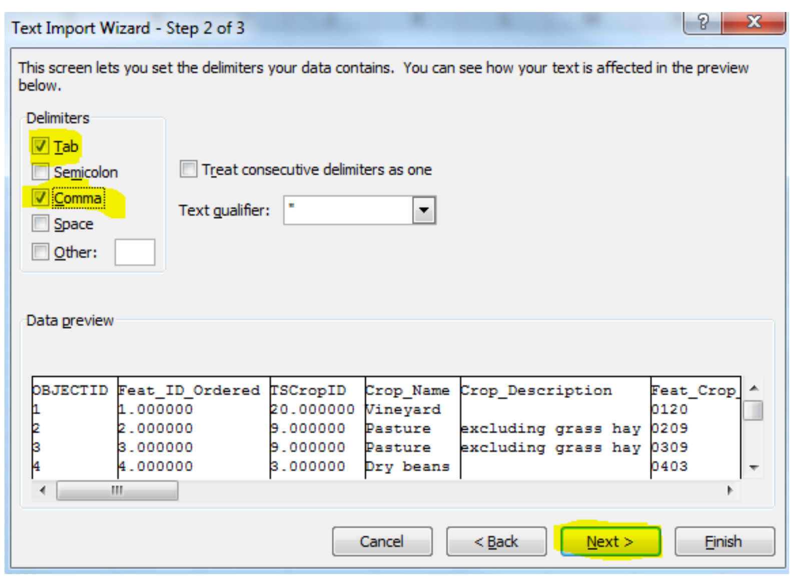


- 94 -

In the 'Import Text File' dialog box navigate to the folder with the previously exported text file and select the name and 'Import'.



The 'Text Import Wizard' pop up window should appear. The data exported from ArcMap is delimited, which should be the default option. Click Next. In Step 2 of the Import Wizard make checks next to the 'Tab' and 'Comma' then click Next.



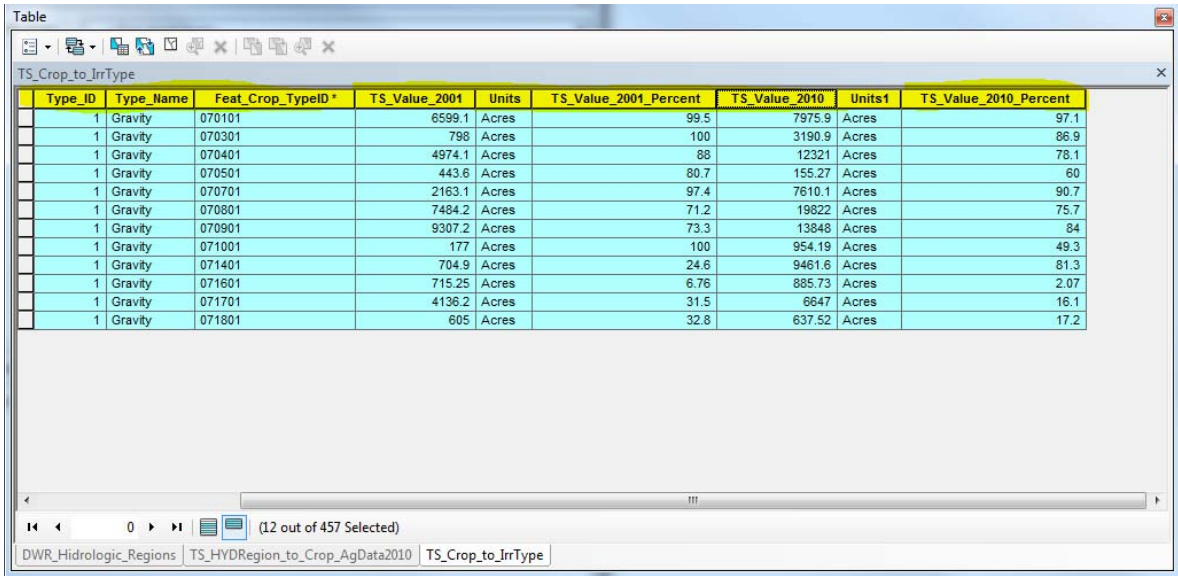
Default settings for Step 3 are sufficient, click Finish. A small import data window appears and unless the data must be put in a specific area of the workbook the settings should be appropriate, so click 'OK'. The data along with the headings should now appear in the columns of the workbook page. From excel it is possible to further filter the data (also located in the Data tab of the toolbar). If the workbook is saved in this format with titles in Line 1 and data in the

- 95 -

preceding columns it is easy to add this data as a table to the existing or to a new database. This is further explained below in the ‘Creating a Feature Classes’ section.

STATISTICAL ANALYSIS FEATURES OF ARCMAP

There are built in statistical analysis features within ArcMap that can be accessed through the attributes table. Right click the field title (highlighted below) and select ‘Statistic…’ from the drop down menu.



Table

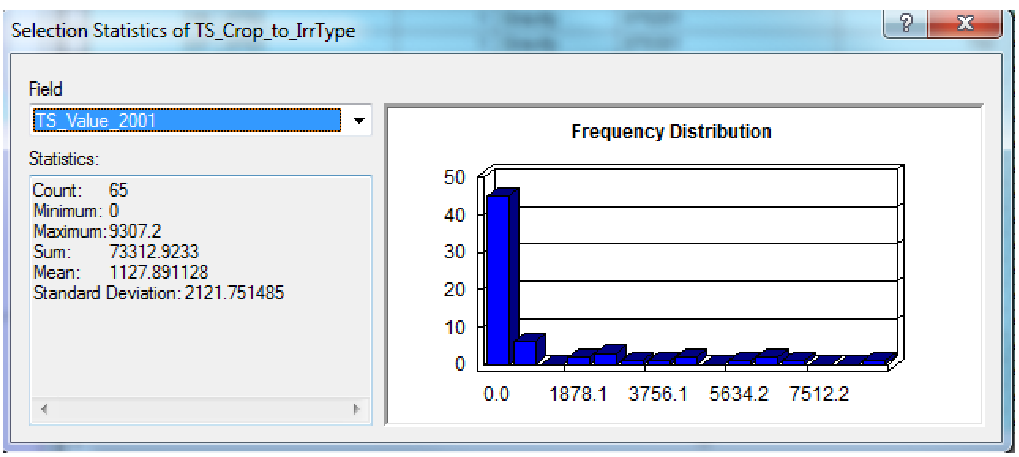
TS_Crop_to_IrrType

Type_ID	Type_Name	Feat_Crop_TypeID *	TS_Value_2001	Units	TS_Value_2001_Percent	TS_Value_2010	Units1	TS_Value_2010_Percent
1	Gravity	070101	6599.1	Acres	99.5	7975.9	Acres	97.1
1	Gravity	070301	798	Acres	100	3190.9	Acres	86.9
1	Gravity	070401	4974.1	Acres	88	12321	Acres	78.1
1	Gravity	070501	443.6	Acres	80.7	155.27	Acres	60
1	Gravity	070701	2163.1	Acres	97.4	7610.1	Acres	90.7
1	Gravity	070801	7484.2	Acres	71.2	19822	Acres	75.7
1	Gravity	070901	9307.2	Acres	73.3	13848	Acres	84
1	Gravity	071001	177	Acres	100	954.19	Acres	49.3
1	Gravity	071401	704.9	Acres	24.6	9461.6	Acres	81.3
1	Gravity	071601	715.25	Acres	6.76	885.73	Acres	2.07
1	Gravity	071701	4136.2	Acres	31.5	6647	Acres	16.1
1	Gravity	071801	605	Acres	32.8	637.52	Acres	17.2

0 (12 out of 457 Selected)

DWR_Hidrologic_Regions | TS_HYDRegion_to_Crop_AgData2010 | TS_Crop_to_IrrType

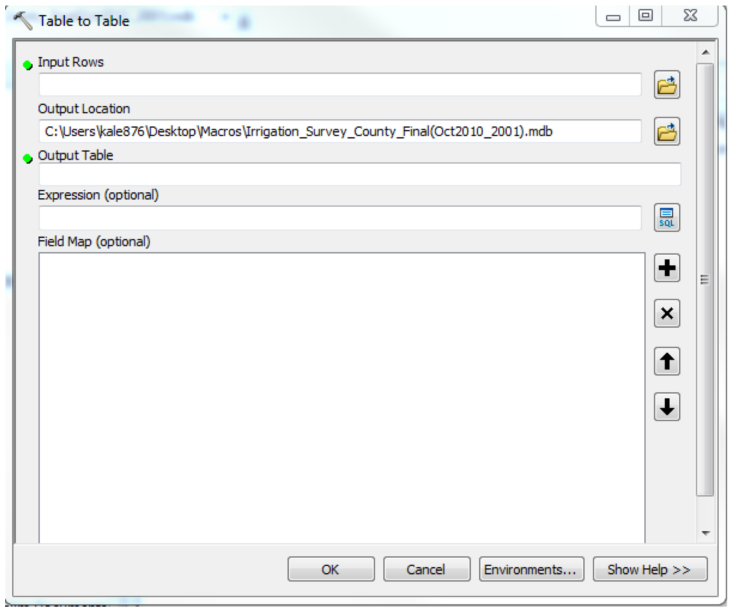
The new pop up window shows standard statistical analysis features including: frequency distribution, count, minimum vales, maximum vales, sum, mean, and standard deviation.



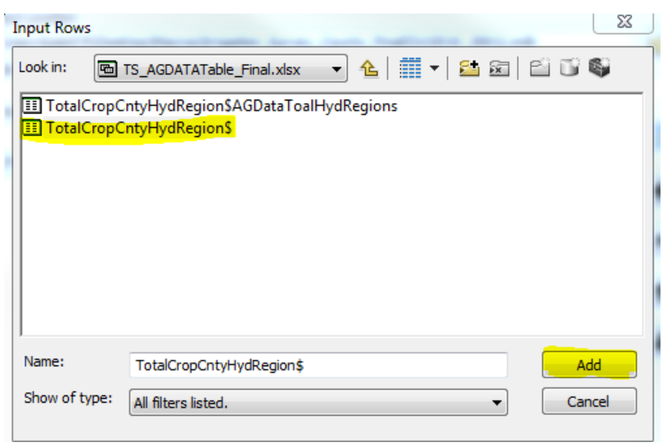
ADVANCED: REDEFINING THE DATABASE

IMPORT A TABLE TO DATABASE

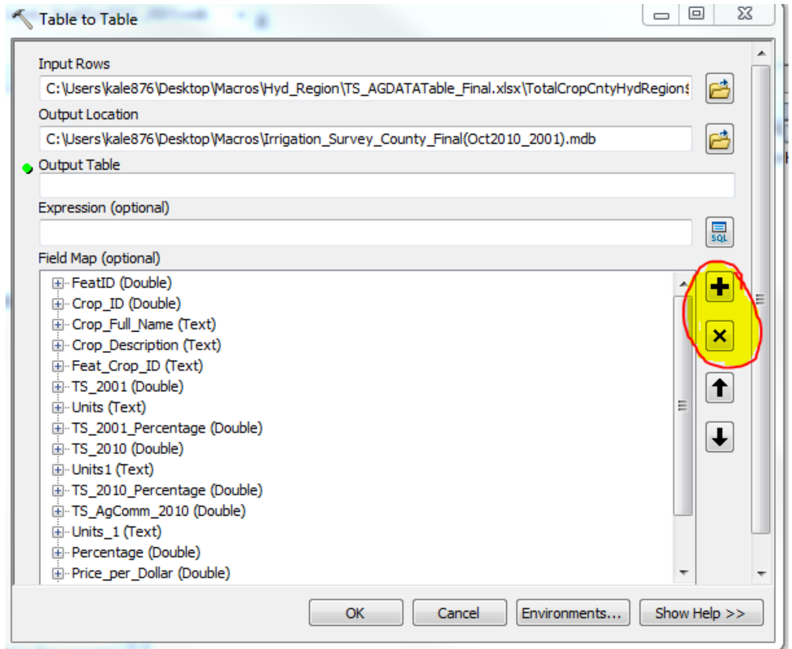
First, format data in Microsoft Excel so that row A are desired field titles and columns are the data values. Save the file in an easily retrievable place and with a descriptive title. Open ArcCatalog and navigate to the database. Right click the database and select ‘Import’ from the drop-down menu. From the expansion of the ‘Import’ select ‘Table (Single)’. The Table to Table pop up window should appear.



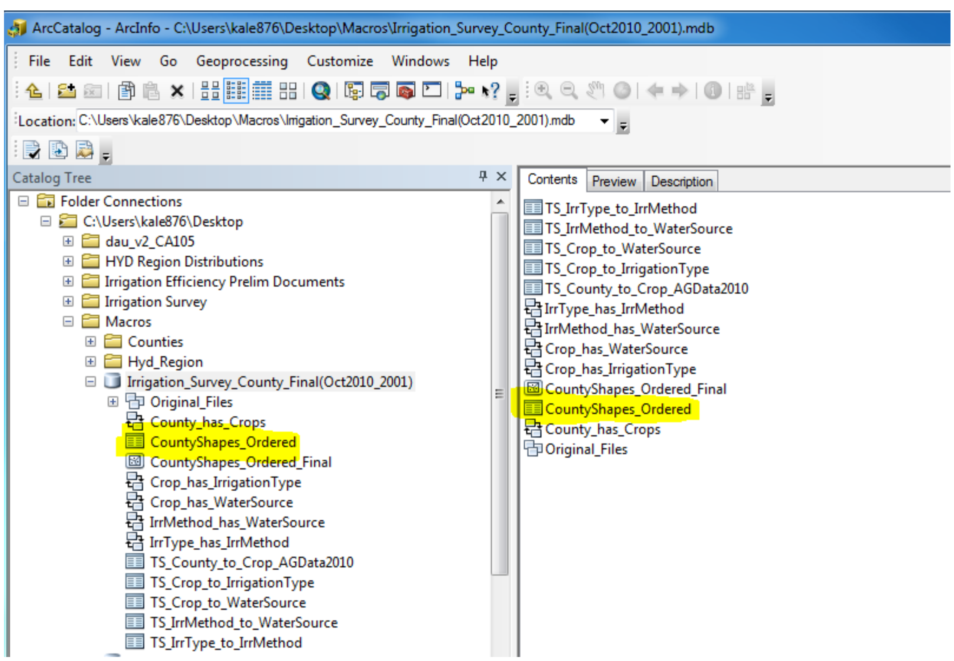
In the “Input Rows” line select the folder at the end of the line and navigate to the Microsoft Excel file where the data is saved. Once the correct workbook sheet is selected, click ‘Add’ in the bottom right hand corner.



Next, in the 'Output Table' line create a name for the table that will appear in the database. Within the 'Field Map' make sure that the desired fields of data are present. Use the "+" and 'X' to add and delete necessary fields.



Select OK. The newly created table should appear under the geo-database title when expanded in the Catalog Tree or in the 'Contents' when the database is selected in the Catalog Tree window.

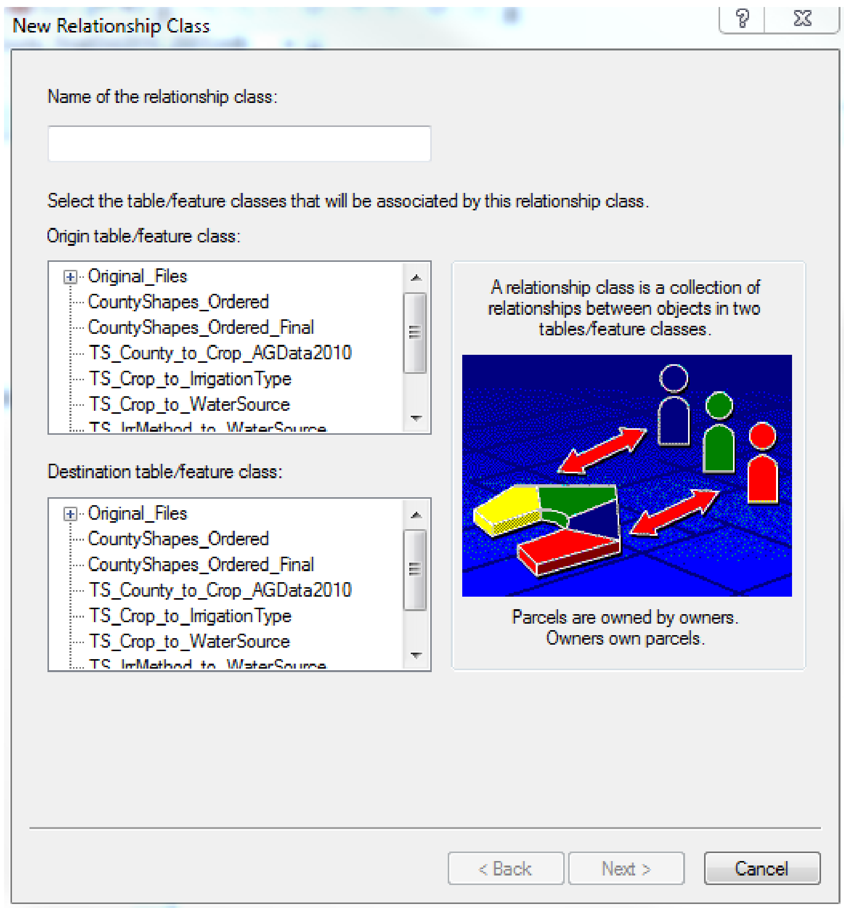


- 98 -

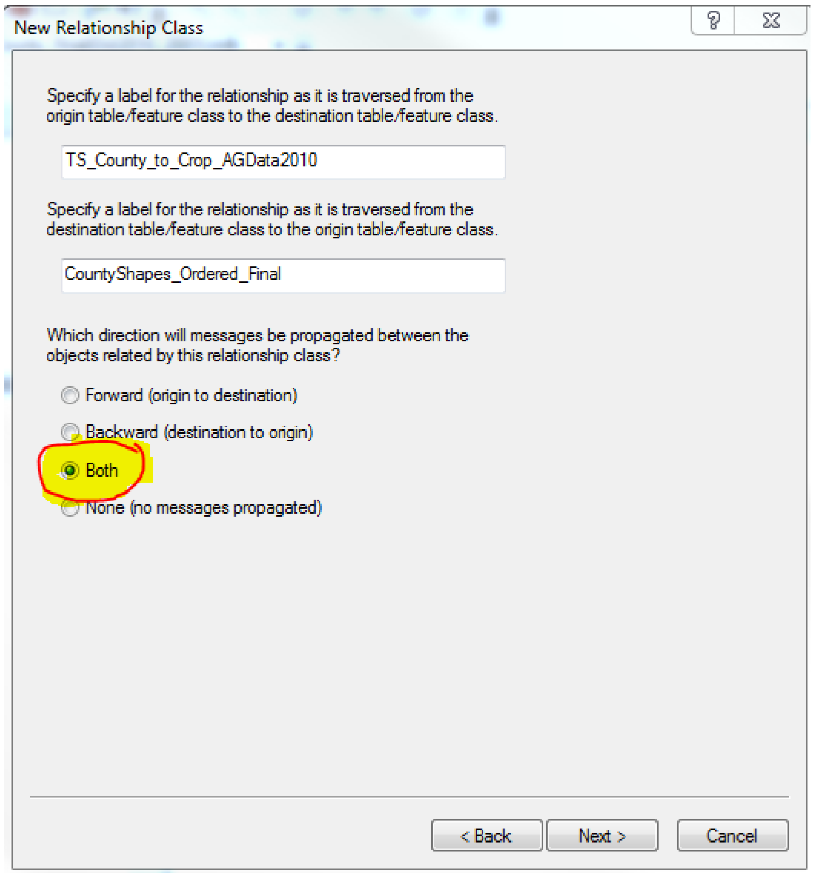
CREATING RELATIONSHIP CLASSES

A relationship class connects two tables within a database based on one overlapping field index in each table, while still keeping the tables separate. This enables the connection of one feature in a table to many related features in another table. For example, to connect from one hydrologic region to twenty crops. This organizes data in a branching network that can be easily accessed in ArcMap.

In order to create a relationship class open ArcCatalog and make sure that the geo-database has the two tables present, with one shared field between the two tables. Right-click the geo-database title in the 'Catalog Tree'. From the drop down menu select 'New' and from the expansion select 'Relationship Class…' The following 'New Relationship Class' pop-up window should appear.

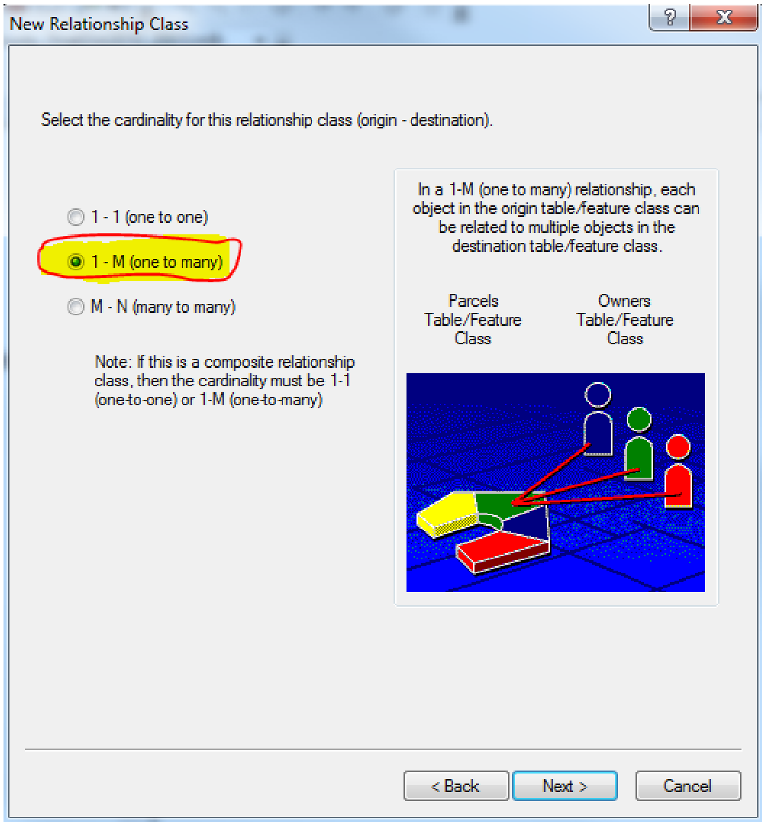


First create a name for the relationship class. Select one line in the 'Origin table/feature class:' and one from the 'Destination table/feature class:'. These are the two titles of the existing tables that are being related to one another. Then select Next. For the construction of the Hydrologic Regions database a simple (peer to peer) relationship class has been made. This is the default setting so select 'Next'. On the next screen select 'Both'. This allows for navigation both forwards and backwards within the attribute table selections in ArcMap.



Select Next.

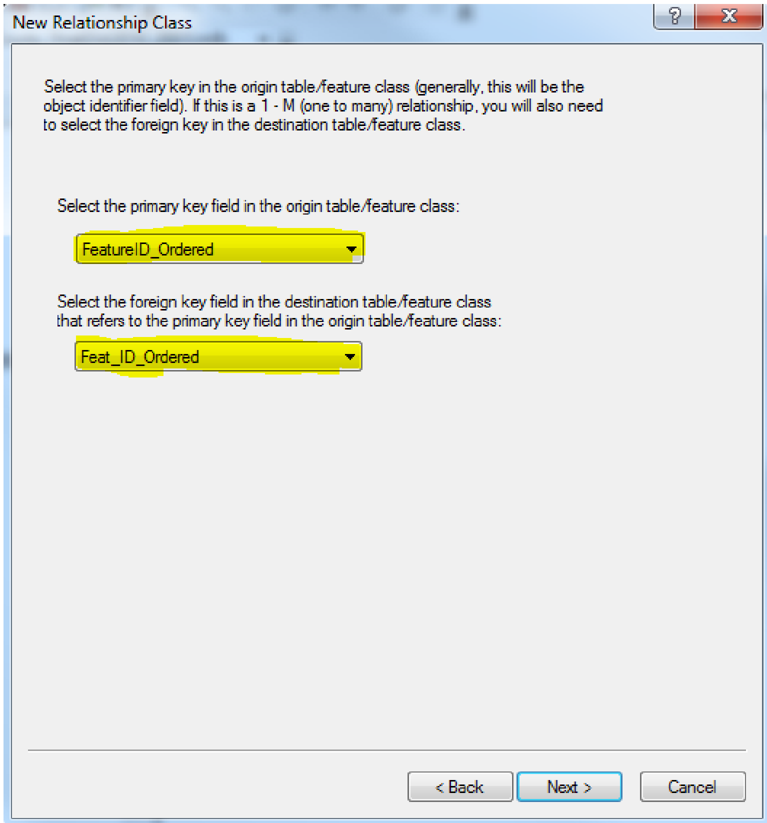
Based on the type of data that is being added the relationship between values in one table to the other may have one to one relationship, a one to many relationship, or many to many relationship. The Hydrologic Regions database uses a one to many relationship class.



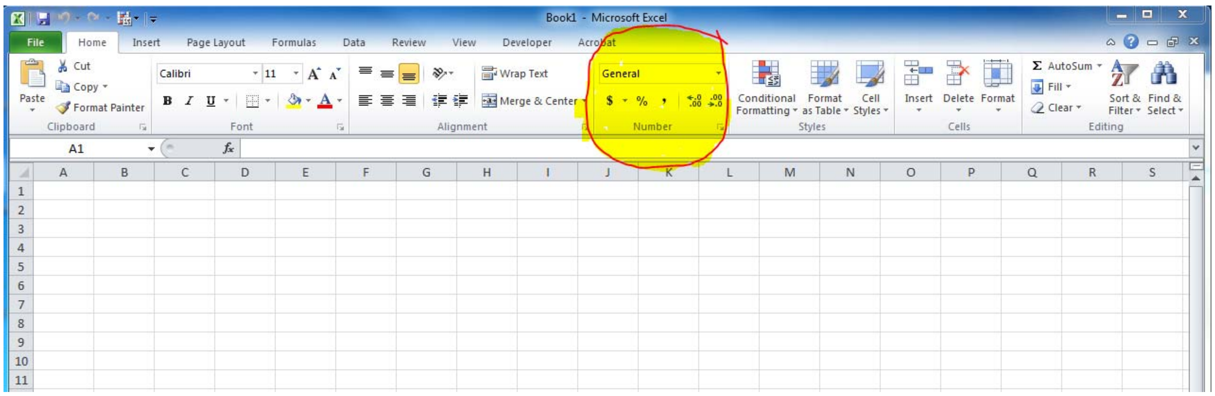
Select the appropriate and 'Next'.

The next prompt asks if the data should have attributes, default settings are most typically used so select 'Next'.

The next prompt indicates the specific fields that relate the data in the two tables. From the drop down lists select the desired fields. When formatting data in Excel it is convenient to have the same title for the related field for clarity.



**Trouble-shooting: If the fields that are desired to be connected do not appear in the crop down menu then, open up the properties of the tables and make sure that the fields desired to be joined are of the same type (i.e. text, double). To fix this go back to Excel and change the 'Number' type to the appropriate type. The two most common types include 'Number' and 'Text'.

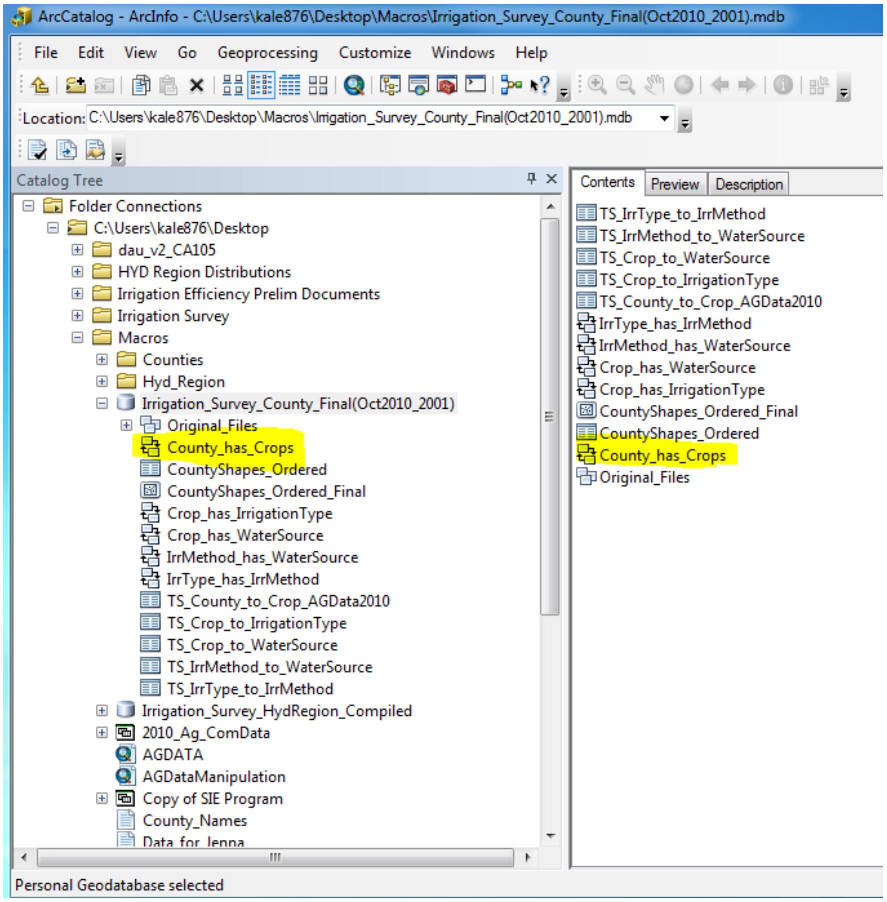


Select Next.

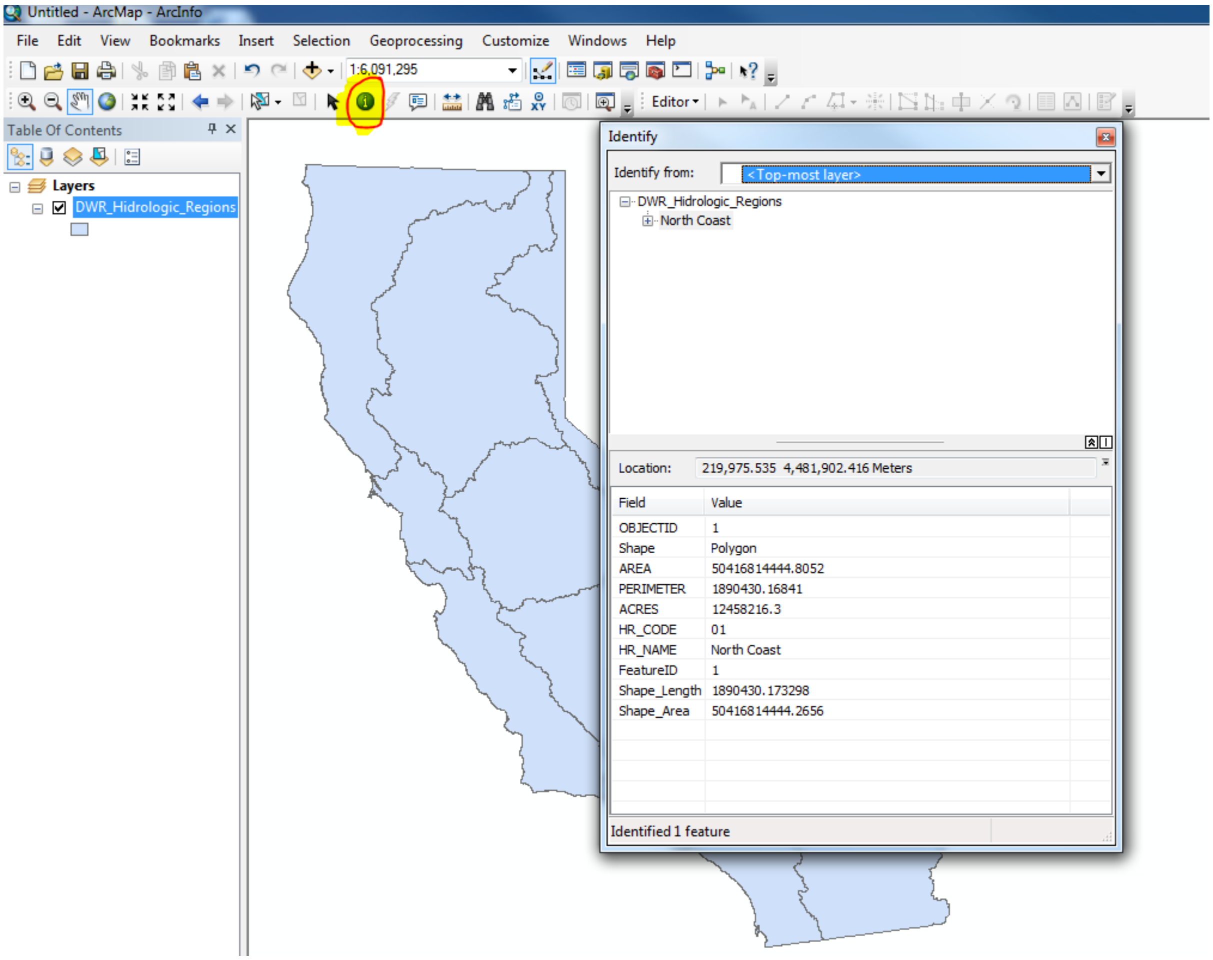
Select Finish.

- 102 -

The new relationship class should appear in the Catalog Tree underneath the geo-database title as well as in the 'Contents'.

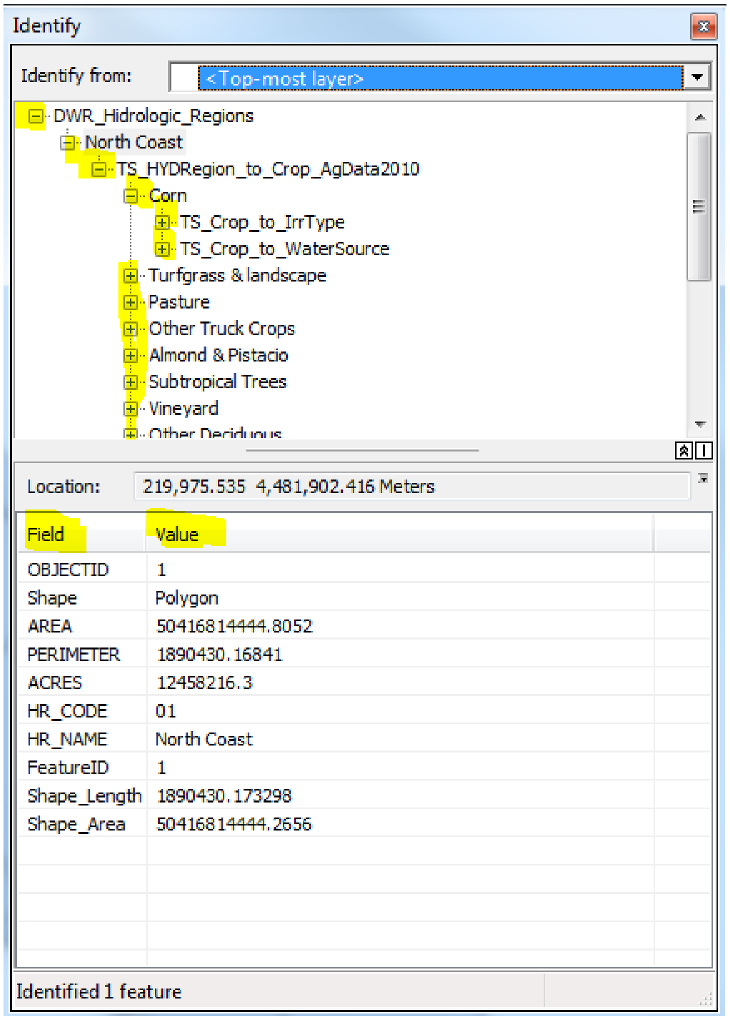


The relationship class is now created, however, to ensure that it functions correctly exit ArcCatalog and open ArcMap. Navigate to the database and drag the shape file into the Table of Contents so that the map appears and a layer is created. Open the attribute table and select the 'Related Tables'. The new relationship class should appear. Another way to visualize the branching network created by Relationship classes is to select 'Identify' in the toolbar. Then select the region of interest. The region will change color to denote that it is selected and an 'Identify' pop up window will appear.



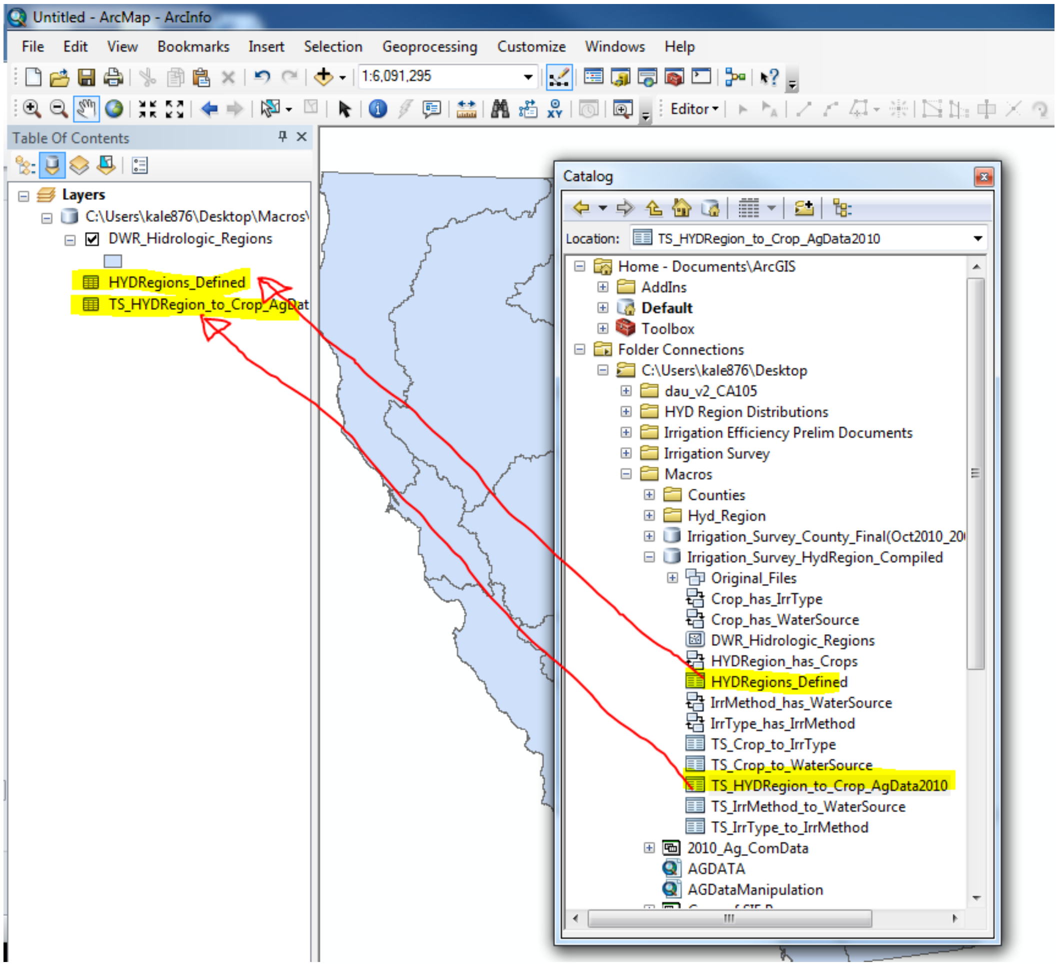
- 104 -

From the Identify window it is we are able to navigate through expanding the plus and minus signs. Information retaining data is displayed in the 'Field' and 'Value' areas below.



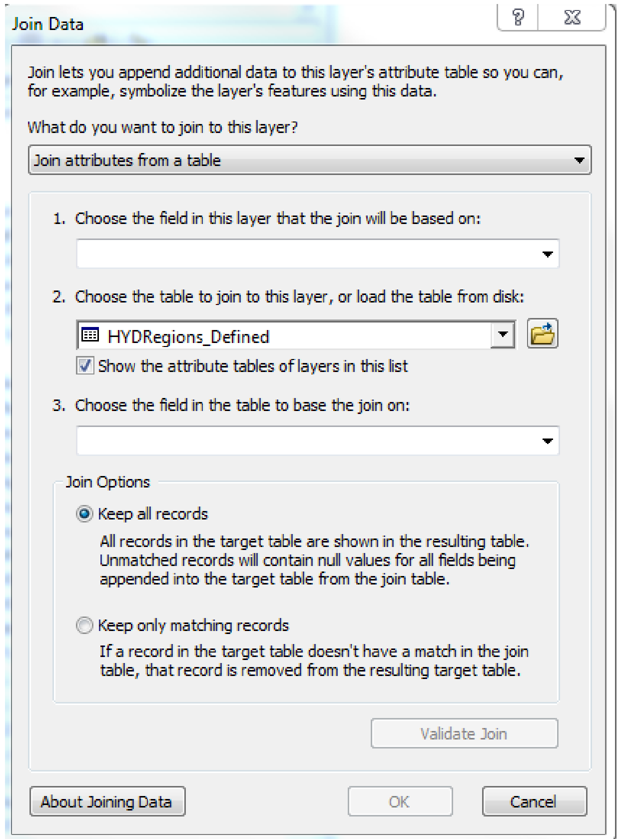
JOIN FEATURES IN ARCMAP

If there is data in two tables that are related by an index or specific field the data can be joined into one table within ArcMap. In order to join tables make sure that both tables are imported to the geo-database in ArcCatalog. Connect to the database in ArcMap. Click and drag the two tables from the database in the Catalog Window into the Table of Contents window in ArcMap.



- 106 -

Right-click the destination table and from the drop down menu select ‘Joins and Relates’. From the expansion select ‘Join’. The Join Data pop up window should appear as below.



In the ‘Join Data’ window, fill in the desired information as prompted including: choosing the field in the layer to be joined, choose the table to join to this layer, and choose the field in the table to bas the join on. There are options to keep all records or keep only matching records. Note that if all records are kept, it is possible to delete unwanted fields in a later editing process of the table.

Click ‘OK’.

Open the attributes table of the already highlighted destination table. Scroll to the right in order to see that all of the features of both tables are present. This data can now be exported, saved as a text file, imported into ArcCatalog for storage in a geo-database.