Water Efficiency in Agriculture: a Study of the Adoption of Water Conserving and Profitable Irrigation Technology in Arizona.

by

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ABSTRACT

With the projected population growth, the need to produce higher agricultural yield to meet projected demand is hindered by water scarcity. Out of many the approaches that could be implemented to meet the water gap, intensification of agriculture through adoption of advanced agricultural irrigation techniques is the focus for this research. Current high water consumption by agricultural sector in Arizona is due to historical dominance in the state economy and established water rights. Efficiency gained in agricultural water use in Arizona has the most potential to reduce the overall water consumption. This research studies the agricultural sector and water management of several counties in Arizona (Maricopa, Pinal, and Yuma). Several research approaches are employed: modeling of agricultural technology adoption using replicator dynamics, interview with water managers and farmers, and Arizona water management law and history review. Using systems thinking, the components of the local farming environment are documented through socio-ecological system/robustness lenses. The replicator dynamics model is employed to evaluate possible conditions in which water efficient agricultural irrigation systems proliferate. The evaluation of conditions that promote the shift towards advanced irrigation technology is conducted through a combination of literature review, interview data, and model analysis. Systematic shift from the currently dominant flood irrigation toward a more water efficient irrigation technologies could be attributed to the followings: the increase in advanced irrigation technology yield efficiency; the reduction of advanced irrigation technology implementation and maintenance cost; the change in growing higher value crop; and the change in growing/harvesting time where there is less competition from other states. Insights learned will further the knowledge useful for this arid state's agricultural policy decision making that will both adhere to the water management goals and meet the projected food production and demand gap.

I dedicate this work to my parents, in my gratitude for your endless love and support. Also in loving memory of my grandmother, Sien Sulu — a strong woman who instilled the importance of education and faith in God in me and all around her.

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INTRODUCTION

"Since the Industrial Revolution, a new era has arisen, the Anthropocene,
in which human actions have become the main driver of global
environmental change." (Rockström et al., 2009).

According to the United Nations Population Division, the world population will reach 9.6 Billion in 2050 from 7 Billion in 2011 (DESA, 2013), with urbanization representing 70% of the population (DESA, 2012). These changes, exacerbated by climate change, increase the demand for all natural resources and challenge the ability to obtain sustainability. While the scope of this issue is broad, this research limits the scope of sustainability to the agricultural sector and water use in Arizona.

1.1 Water Problem in AZ

Early 20th century development of major water delivery systems and the production of cheap power for pumping, projects such as the Roosevelt Dam and later the Central Arizona Project (CAP), meant that agriculture become prominent in Arizona. With the rapid population growth following WWII the demand in urban areas also increased. As portrayed in figure 1.1, all agriculture in Arizona accounts for 75% of water use; urban uses consume 20%. Groundwater usage is approximately 43% of the total consumption. Renewable surface water, which is most at risk from climate change (Redman and Kinzig, 2008), amounts to 54% of the total consumption

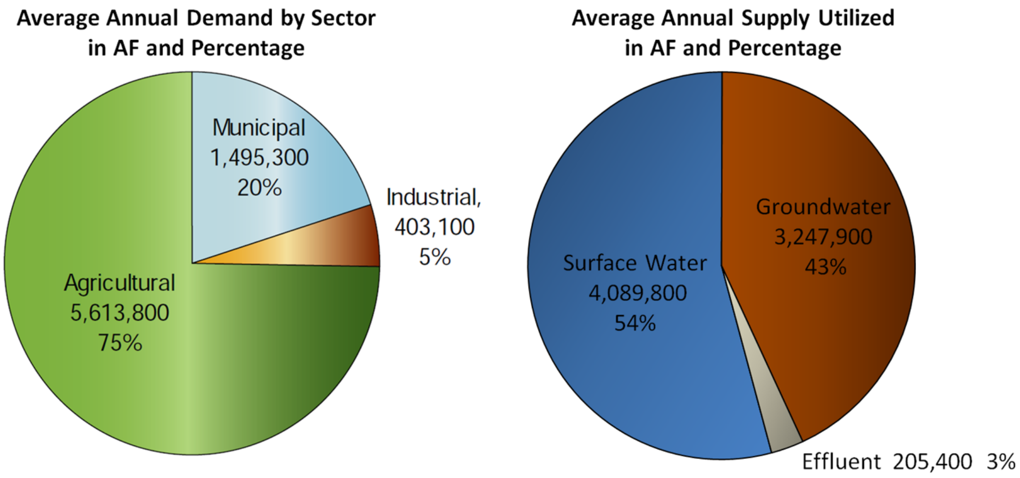

Figure 1.1: Average Annual Water Demand and Supply in Arizona, 2001 - 2005, Adapted from Arizona Department of Water Resources (2010a).

(Arizona Department of Water Resources, 2010a). Even with the increased supply of water from the Colorado River through the CAP and with the continued delivery of water from the Verde and Salt River through the SRP the state has not achieved a sustainable level of water consumption and continues to deplete groundwater supplies greater than replenishment level (Arizona Department of Water Resources, 2010a).

Arizona's water supply may not be able to meet water demands in the future. Water demand will continue to grow due to population growth. This arid state is the 8th fastest growing state in the nation and home to 6.6 million people (U.S. Census Bureau, 2013). Surface water supply is declining because the West has been in a long term drought as can be seen in the figure 1.2 (Arizona Department of Water Resources, 2010a) (Billings, 2013). The Colorado River Basin Water Supply and Demand Study, by using median projection of Colorado River water supply and demand, revealed that critical imbalance will happen as early as 2025. By 2060 the projected long-term imbalance is to be about 3.2 MAF (U.S. Bureau of Reclamation, 2012).

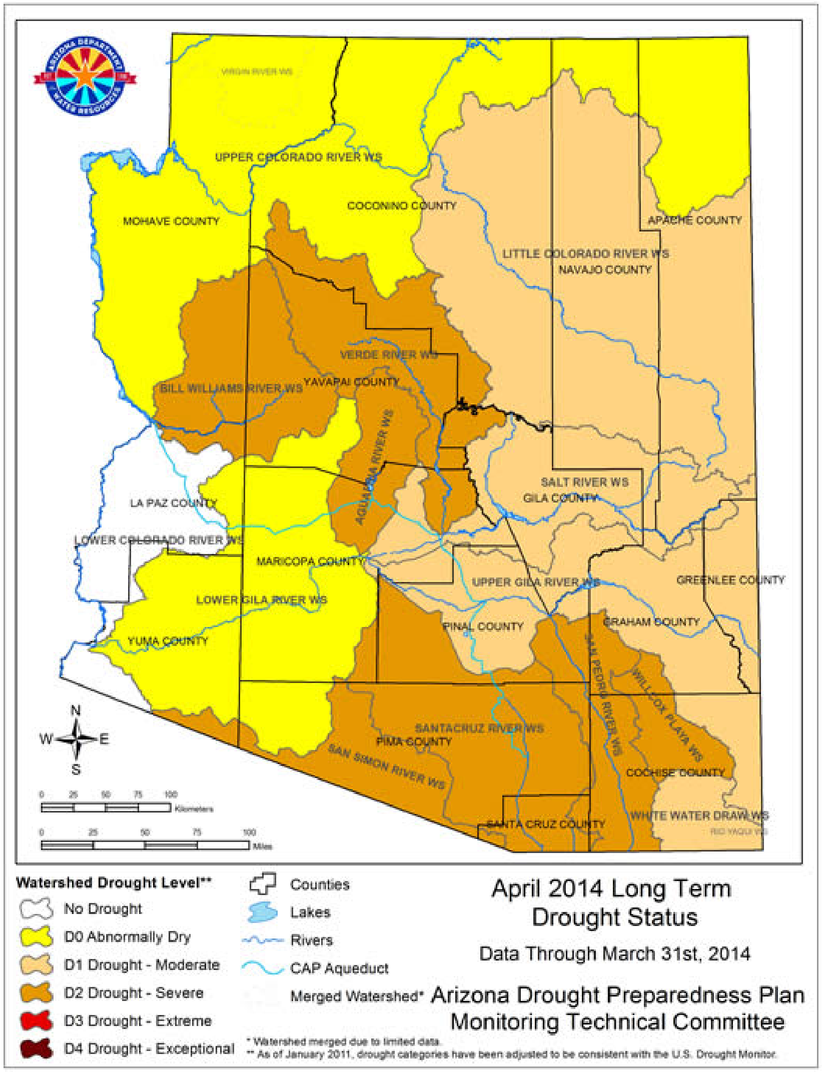

Figure 1.2: Map of Arizona Long Term Drought Status Adapted from Arizona Department of Water Resources (2010a).

Between agriculture and residential, the disparity in planning horizons for water projections leads to different standards of water consumption (Smith, 2012). Farmers project water availability for 5 years. (Ollerton et al., 2012). Proof of legal, physical, and continuous water availability for 100 years are required by the Assured Water Supply (AWS) program before new urban areas within Active Management Areas can be developed (Arizona Department of Water Resources, 2010b). A long planning horizon increases the responsibility of users to ensure efficient use of water.

Historically agriculture contributed significantly to Arizona's GDP, but today, the state's largest water user, contributes only 0.79% of the state's economy (Morrison Institute for Public Policy, 2012). This disparity of water use and economic contribution is clearly demonstrated by Robert Glennon in his book,

> It takes roughly 135,000 gallons of water to produce one ton of alfalfa, but it takes fewer than 10 gallons to produce [an Intel] Core 2 Duo microprocessor...Each acre-foot [of water] used to grow alfalfa generates at most $264. That same acre-foot used to manufacture Core 2 Duo chips generates $13 million (Glennon, 2009)."

Agricultural water consumption and the economic contribution imbalance pose a worrying outlook for agriculture water users i years to come.

The most likely solution to achieving an overall sustainable level of water consumption requires a reduction in agriculture water use. The reduction in surface water availability due to changing climate conditions will also exacerbate the water problem in this growing desert state. With a continuing decades-long drought in the region affecting the on-going supply of water from the Colorado River through the CAP, the state is in peril of not being able to meet the current demands for water for all uses – agriculture, urban, and industrial, which implies there is a need to make trade-offs in allocating water for disparate uses.

Chapter 2

OVERVIEW

While the water problem in Arizona is a local problem, it has global ramifications. Global food demand will increase due to continued population growth. Farmers in the state that produce to meet global production demands could ultimately aggravate the local water problem. This status quo of agricultural water use exists because, as suggested by Foster et al. (1987), water is an underpriced resource. Transformation in agriculture through intensification enables meeting the increased global agricultural demand (United Nations Food and Agriculture Organization, 2011). Irrigation is one of many intensification methods that can help meet the global demand for more commodity and the local pressure to use water more efficiently.

Research Question

My research objective is to investigate the conditions for acceptance of advanced irrigation technology. More specifically, through interviews, literature review, and dynamical modeling, I seek to answer the question regarding the conditions for adoption of advanced irrigation technology. In answering the question I work toward understanding the following questions:

> How is water being used, transported and managed in Arizona?
>
> How do water users and managers interact in this system?
>
> What conditions promote the adoption of advanced irrigation technology?

2.1 Physical Boundary

The boundary of this research project is chosen to encompass the diversity of the state's agricultural water user and account for 80% of the water consumed in Arizona (Arizona Department of Water Resources, 2009) (Arizona Department of Water Resources, 2010b). Agricultural data is compiled in the counties. Water management information is organized in ADWR planning areas as defined in the AZ Water Atlas. ADWR defined Active Management Area (AMA) and Planning Area according to groundwater basins and sub-basins, so the boundaries overlap counties and municipalities (Arizona Department of Water Resources, 2010a). This study covers three counties with their respective water management and planning areas, which are:

Phoenix AMA [Maricopa County]

The physical boundary of the Phoenix AMA encompasses most of Maricopa County and includes the municipalities of Tonopah in the east, Superior in the west, Anthem and Cave Creek in the north, and Sacaton in the south. This makes the Phoenix AMA the largest at 5,646 square miles with altitudes from 755 feet to 5,868 feet. There are seven groundwater sub-basins each with its own unique hydrogeological characteristics: East Salt River Valley, West Salt River Valley, Hassayampa, Rainbow Valley, Fountain Hills, Lake Pleasant, and Carefree. The principal rivers are the Gila, Salt, Verde, Aqua Fria and the Hassayampa. The agricultural area under cultivation encompasses 287,000 acres and over 2 MAF of annual water use (Arizona Department of Water Resources, 2010b). Water salinity is a problem in some parts of this area which limits farmers to only growing salt tolerant crops. Farmers in this area are enticed to sell their land to developers. Some have sold the land to developers and continue to farm on it until developers are ready to build (Water Manager A, 2014).

Pinal AMA [Pinal County]

The Pinal AMA is south of the Phoenix AMA, encompassing all of Pinal County and some of Maricopa County plus the municipalities of Maricopa and Florence; additionally over 50% of the land is in the tribal areas of Tohono O'odham, Gila River and Ak-Chin. The total land area is 4,200 square miles. There are five sub-basins with unique groundwater underflow, storage, and surface water characteristics. These sub basins are: Maricopa-Stanfield, Eloy, Vekol Valley, Santa Rosa Valley, and Aguirre Valley. The principal rivers are the Gila and Santa Cruz. The agricultural area under cultivation is 260,000 acres with 0.8 MAF of annual non-tribal water use (Arizona Department of Water Resources, 2010b). Being downriver of the Phoenix AMA, some water conservation measures have been done by farmers. (Water User B, 2014).

Lower Colorado River Planning Area [Yuma County]

The LCRPA is bounded by the Colorado River and Mexico, and covers all of Yuma County 91% of La Paz county, 38% of Maricopa county, and 43% of Pima county. The total land area is 17,200 square miles. There are eleven groundwater basins in this area that encompass the driest and hottest portions of the state of Arizona with elevations ranging from 70 feet where the Colorado River enters Mexico to over 7,700 feet in the Baboquivari Mountains. Approximately 98% of all the water or 2.8 MAF is used annually in this planning area for all agriculture which is approximately 4% of the entire state's demand (Arizona Department of Water Resources, 2009). Water availability is a concern to farmers because this area is a downriver community. Agriculture is the main driver of the region's economy. (Water User A, 2014).

2.2 Methods

To answer the research questions, several interviews, reviews, and modeling are done simultaneously. Interviews with stakeholders provide insights that are not available through literature review. Organization of information gained from interviews and reviews is done through the application of the Robustness of SES framework. Modeling was done in tandem with this information organization. Some information concerning irrigation technology adoption in Arizona gained from the interviews and literature review are incorporated into the model. A replicator dynamic model is developed to understand the conditions that will lead to the adoption of advanced irrigation in Arizona.

Data Collection

Interviews with water users and managers in the research boundary were done to gain understanding of the system. In order to determine which stakeholders would be fruitful to interview, a preliminary literature review of water management and agricultural business was done. After that process this research selected three water management agency representatives (ADWR, AMWUA, and Buckeye Water District), one farm lobbyist (AZFB) and three farmers (one from each county) from January 7th to April 28th, 2014, in Arizona. The interviews conducted were designed to elicit information relevant to the Robustness Framework and the entities involved, namely, the resource, the resource users, the public infrastructure, and the public infrastructure providers. Other numerical data related to water availability was gathered from Bureau of Reclamation of US Department of Interior and agricultural data was gathered from USDA National Agricultural Statistics Service.

Systematic Organization of the System

Interview data and water management information are organized into the system components and interactions of the Robustness of Social Ecological System (SES) Framework. This systematic organization facilitates understanding information and aids in modeling. This framework is a versatile lens to systematically investigate the components and relationship of common pool resource management (Janssen and Anderies, 2007). As it is used in Anderies (2006), it can be used to organize knowledge of complex systems in a simple manner to assist modeling. As explained in Anderies et al. (2004), it also enables comparison to other complex water management systems, or of the same system at a different point in time like in Anderies (2006).

Replicator Dynamics Model

Within a replicator dynamics model, decisions of an agent occur through comparison of individual payoff to the average payoff of all agents. This bounded rationality depicts profit maximization with sluggish learning. Replicator dynamics assumes that farmers change their farming irrigation systems not just based on information of the benefit, but also through the examples of other farmers. Insights gained from the literature review and interviews are implemented in this model. This process allows for the inclusion of interesting conditions or changes as parameters. Conditions that promote the adoption of advanced irrigation technology will be derived.

Chapter 3

CHARACTERIZING ARIZONA WATER USE AND MANAGEMENT

To understand water use and management in Arizona, I conducted stakeholder interviews and reviewed water history and laws. Interview insights and information gathered from the reviews are then organized systematically using the robustness framework. Arizona water resource management is complex and covers a broad geography of the Lower Colorado River Basin. The complex system of water use and management is put into the Robustness of Socio Ecological System (SES) framework. Such organization is useful in understanding the whole system and in developing model of the adoption of irrigation technology. Beyond this thesis, this framework is also useful for comparison with other complex water social-ecological systems or with the same system at a different point in time. In this chapter, I elaborate on the research questions posed in Chapter 2 by asking the following questions:

- What is the developmental history of water infrastructure and laws in Arizona?
- How does Arizona use and manage water resources?
- How do these components interact and affect each other?
- What is the reason for the ubiquity of the flood irrigation technology in Arizona?

3.1 Overall History of Water in Arizona

In the Four Corners region of the Southwest (AZ, NM, CO, UT), the Anasazi had managed water for several thousand years from 1200 BC to 1300 AD through cobble mulch, graded fields, check dams in streams and man-made canals (Periman et al., 1995). In southern Arizona, the Hohokam from 200 AD to 1450 AD, built 500 miles of irrigation ditches with stone and wood tools to manage the water from the Salt and Gila Rivers that served a population of over 50,000 (Salt River Project, 2014a; Reiner, 2014).

In the mid-1800's, the Gila River-Pima area was being used for ranching and farming by the settlers in the region (Arizona Bureau of Land Management, 2014). In 1863, Arizona became a territory of the United States when separated from New Mexico by declaration of President Lincoln. In the following year, the Arizona Territorial Legislature adopted the Howell Code, 'First in Time, First in Right' which provides a right to use water to all prior appropriations of surface water. In the following year, the Arizona Territorial Supreme Court affirmed the doctrine of prior appropriation for establishing water rights as well as defining beneficial use as the limit of the water right (Arizona Department of Water Resources, 2014).

The Supreme Court held in 1908 that Indian tribal water rights were established when their reservation was created, regardless of whether the water was used by the tribe or not, so that the tribe may reserve their use of the water for future purposes, including irrigation (Native American Rights Fund, 1981). The Arizona Constitution was adopted in 1910 and became effective in 1912 when Arizona became the 48th state. The constitution affirmed that riparian water rights are not to be considered in Arizona which means that water does not belong to the land that borders the water source. (Arizona Department of Water Resources, 2014).

In 1902, President Roosevelt signed the National Reclamation Act to provide for the sale of public lands for water reclamation projects (Pitzer et al., 2007), which created funding for developing irrigation projects in the western states. The next year, the Salt River Project was created as a multipurpose reclamation project authorized by the National Reclamation Act to store water from the Salt River and provide irrigation for over 200,000 acres of private land belonging to farmers and ranchers. The Roosevelt Dam was operational by 1911 to generate hydroelectric power for central Arizona which allowed groundwater pumping to meet agricultural water needs in areas that were not serviced by irrigation canals (Salt River Project, 2014b).

As technologies facilitate comfortable living in Arizona, the population and economy of the state grow. Up until World War II, Central Arizona economic activity consisted of ranching and irrigated agriculture (Halseth, 1947). After WWII, the Phoenix metropolitan area experienced a dramatic population increase from returning military personnel that had trained in the area. The advent of air conditioning made living year round in the Valley of the Sun feasible. Rapid urbanization in the Valley increased the demand for electricity.

Steam power generating stations were built to meet the Valley's electric demands (Salt River Project, 2014b). Available power generation and improvements in pumping technologies increase groundwater overdraft. In the period leading to the development of the Groundwater Management Act, there were concerns about continual groundwater overdraft and the state's future water. One opportunity was to replace groundwater use with the Colorado River. The Central Arizona Project (CAP) funding from the federal government requires Arizona to have a means to manage the use of the groundwater (Reisner, 1993). In order to illustrate that the State was serious about managing groundwater resources, the Groundwater Management Act (GMA) was adopted in a 1980 special session of the Arizona Legislator (Redman and Kinzig, 2008). As a result of the GMA, the ADWR was created to administer the Groundwater Code (Code). The Code's aim is to control overdraft, allocate groundwater, and augment groundwater supply (Upper Agua Fria Watershed Partnership, 2001). There are two principal parts of the Code. The first is definition and transferability of groundwater rights. The second is that, by 2025, groundwater use will be restricted to the rate at which recharge is equal to depletion or the safe yield rate (Holland and Moore, 2003).

The creation of ADWR enables the management of the state's water sources under one state agency (Arizona Department of Water Resources, 2010a). The ADWR organized the state into Water Planning and Active Management Areas (AMA), each defined by the water basins and sub-basins. The goal in the AMAs is to affect a safe yield which is defined in the Code as, a groundwater management goal with attempts to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an active management area and the annual amount of natural and artificial groundwater recharge in the active management area. ADWR mandates the assured water supply for all new developments. (Arizona Department of Water Resources, 2010b). The Pinal AMA allows development of non-irrigation uses and aims to preserve its agricultural sector for as long as feasible. The Santa Cruz AMA's goal is to maintain a safe-yield condition to prevent the water table for declining. Any new development within an AMA must demonstrate that a 100 year supply of water exists (Arizona Department of Water Resources, 2010b). Phoenix, Prescott and Tucson AMAs have the goal of achieving a safe yield.

The Central Arizona Water Conservation District (CAWCD) manages the Central Arizona Project (CAP) which transports Colorado River water to central Arizona. The Colorado River is primarily under the jurisdiction of the federal government with the Law of the River a compilation of laws, compacts and treaties establishing the amount of water supplied to Mexico, the Upper Basin states and the Lower Basin states. The CAWCD is a tax-levying public improvement district managed by a General Manager that reports to a Board of Directors who are popularly elected from three counties, Maricopa, Pima and Pinal. (Arizona Department of Water Resources, 2010a). Arizona's allocation of the Colorado River water is 2.8 MAF per year, half of which is transported through the CAP.

The Arizona Water Banking Authority (AWBA), created by the Arizona legislature in 1996, allows for the organization to contract with various authorities to bank surplus water primarily from the Colorado River, including California and Nevada, and to manage the withdrawals as well. This is a way for the communities drawing Colorado River water to have a method of storage for future use. In the future, Arizona can draw on those stores, less a 5% cut to the aquifer and the interstate partner will withdraw a similar amount from the Colorado River. Water exchanges are permitted that allow a trade between one or more persons and tribal communities, providing that the water withdrawn is used for the same purpose that the entity exchanging the water had a right for.

The safety of dams constructed in Arizona is the responsibility of the ADWR, while federal dams are exempt from state regulations. The governor established a Drought Task Force in 2003 to prepare an Arizona Drought Preparedness Plan, primarily for rural communities that have few water supply options (Arizona Department of Water Resources, 2010a).

3.2 Water Laws

Arizona water laws are different for each type and source of water: effluent, surface water, and groundwater. Importantly, effluent is considered separate from surface and underground water laws, and subsequently is not bound by the same rules applied to groundwater and surface water.

Surface water rights are being adjudicated for thousands of claimants for the Little Colorado River systems and the Gila River, which includes the Salt, Gila, San Pedro and Verde River watersheds, although no stream has yet to be fully adjudicated. Arizona's first in time, first in right' does not mean that water can be wasted, and what is not used by the first person senior appropriator or the user with the earliest approbation date must be allowed to flow to the next senior appropriator. This process is managed through a permit program administered by the ADWR (Arizona Department of Water Resources, 2010a).

Groundwater is regulated through the Arizona Groundwater Code that established the ADWR. The ADWR intensively manages water in the active management areas (AMAs) and in designated irrigation non-expansion areas. Outside of these areas, water may be used for any beneficial purpose subject to groundwater transportation laws (Arizona Department of Water Resources, 2010a).

Native American water rights have claimed first rights to water as defined in the Winters Doctrine. The United States Supreme Court has decided on legal principles by which water rights for Native American tribes, military bases, and national forests are determined (Ranquist, 1975).

3.3 Arizona Water Use and Management System

In understanding the system, I conducted stakeholder interviews and reviewed water related legal and historical documents. This research organize Arizona's water use and management system, using the Robustness of Social-ecological Systems (SES) conceptualization. This SES depicted in 3.1 includes the social units (blue) that are interdependently related with biophysical units (green). The resource users and public infrastructure providers explained within the *3.3.2 Attributes of the community* section are the social units of the SES. The *3.3.1 Biophysical context* section contains the resource and the public infrastructure of the system. The relationship within the system is manifested in maintenance, management and use of the resource which are represented in relationship 1 to 6. The shocks 7 and 8 are shocks toward the biophysical context and attributes of the community, respectively.

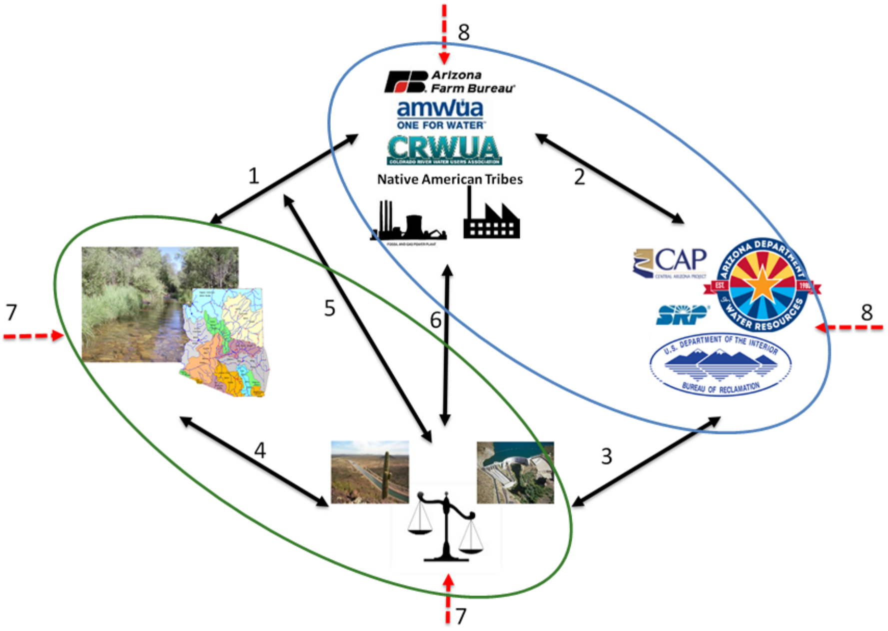

Figure 3.1: System Representation: Robustness of SES Framework Populated with Components of the Water Use and Management System

3.3.1 Biophysical Context

The biophysical context of this system encompasses the Colorado River Basins and sub-basins that represent the groundwater sources, crossing county and municipal boundaries. The majority of surface water sources on this basin comes from precipitation and melting snow in the mountains of Wyoming, Colorado, Utah, and New Mexico. In Arizona, the abundance of water is created by three major public works projects: the Central Arizona Project with a 336 mile canal to bring Colorado River water to Phoenix and Tucson; the Salt River Project with associated dams and canals that deliver water in the Phoenix AMA; and the Colorado River Planning Area with associated dams for storing water from the Colorado River as well as creating hydroelectric power. The water resource is shared with Mexico, Federal Government, and seven states in the Colorado River Basin.

Resource

Water is the resource in the system. It is supplied from these sources: the Colorado River either directly or transported through the Central Arizona Project canals; groundwater is pumped; water from streams or stored in dams are delivered through the Salt River Project canals; and effluent.

Public Infrastructure

Hard infrastructure, ex. dams and canals, are administered and maintained by various government agencies. The groundwater and surface water laws are the soft infrastructure. These soft infrastructures specify use, rights, and sanctions. The management of the water is directed by the Law of the River with respect to Colorado River water or managed through the directives of the ADWR.

3.3.2 Attributes of the Community

The management of these water resources is shared by federal and state agencies that allocate water to the seven states in the region plus Mexico. Native American tribes and Mexico have the highest level of water claim as defined by the federal government's agreements with the tribal units and Mexico. These allocations have first priority. Second level of priority resides with inter-state agreement among the seven states that share the Colorado River, with California receiving first priority of water in the event of a shortfall (Ranquist, 1975) (Water Manager B, 2014).

Internally within the state, there are many competing users for water, such as agriculture, municipalities, power plants, industry, mining, and neighboring water rights holders (tribal units; other states; and Mexico). Each resource user receives a stream of benefits from the availability of relatively inexpensive water and support policies that are in line with their economic interests.

Farmers are represented locally with the lobbying entity, AZ Farm Bureau. Urban users are represented by mostly municipal water districts that deliver the water to individual customers. Industrial users are robustly represented by economic group, such as Arizona Association for Economic Development or individually by themselves, e.g. Freeport or APS.

Resource Users

Arizona's agricultural community is comprised of ranchers and farmers. There are a total of 3,979 farms using 1,865,300 acres of land for agriculture. In this state, 4% of farms utilize 89% irrigated land in producing 98% of the total sales (Smith, 2012). This fact present a big opportunity for impactful change in water use because by only influencing 4% of Arizona farms could yield almost a system wide impact.

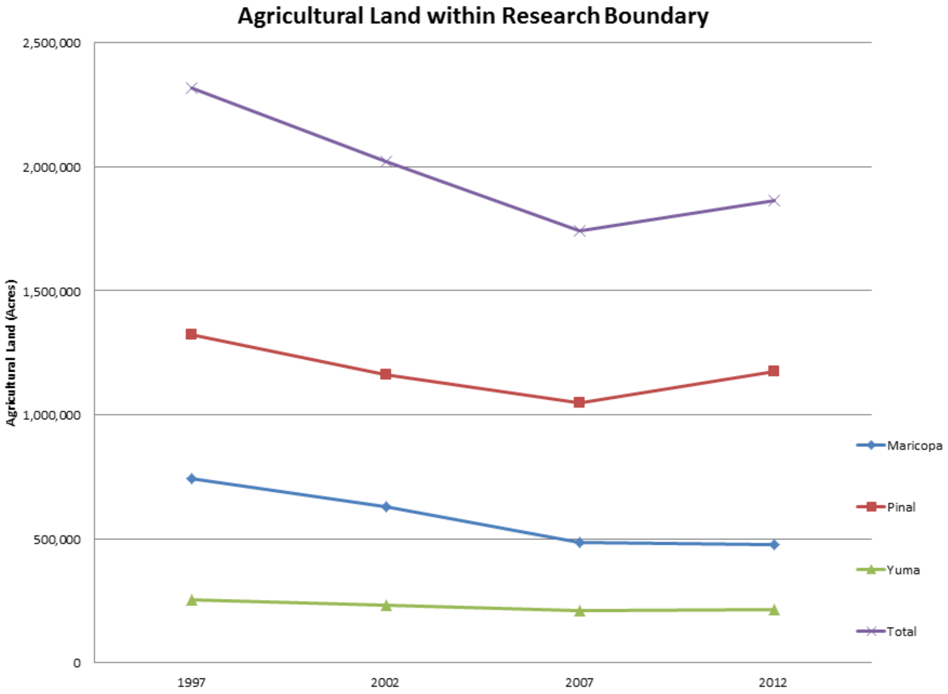

Figure 3.2: Agricultural Land Use Within the Research Boundary. Data Obtained From National Agricultural Statistics Service (2014).

Public Infrastructure Provider

The entities in this category are responsible for maintaining the infrastructures and delivering water to farms as well as other industrial and urban users. The public infrastructure providers are Arizona Department of Water Resources, Central Arizona Project, US Department of Interior, and Salt River Project. The ADWR manages the state's water resources through coordination and planning with all other state agencies and the US Department of Interior. Water delivery is administered by the SRP and CAP within their regions. The administration of the AMAs is also conducted by the ADWR and aided by a governor-appointed counsel representing interests from agriculture, cattle, and industry. The challenge comes from dealing with a shortfall in availability due to a long-term drought situation and an overdraft pumping of

Table 3.1: Water Management Entities

	ADWR	CAWCD	SRP	USBR
Leader	Directors	Board of Directors	Board of Directors	Deputy Regional Director
Selection	Appointed	Elected	Elected	Appointed
Manages	AZ Water Laws	CAP Canals	SRP Dam and Power	Colorado River Allocation

groundwater. Governing authorizes will need to balance the demands of the disparate groups in order to meet the needs of all the groups given that there are looming shortages.

3.4 Interactions of the Components in the System

The irony in the southwest is that while the climate provides for an abundant crop yield with year round sunshine, the same climate also contributes to a scarcity of water in a desert region. Abundant sunshine needs no artificial control; the availability of water is affected by many faceted components, both man-made and nature provided. Water needs in agriculture can vary by the type of plants grown, when they are planted, as well as the method of irrigation together with the variable conditions of the soil. Water available for agriculture competes with society's needs for food resources as well as recreation, human consumption, waste management, and industrial requirements.

The hard infrastructures for delivering water to farmers also delivers water to urban and industrial users. The allocation of water, (identified as #5 in Fig. 3.1), is a delicate balance between current needs and long term sustainability objectives, challenged by uncontrollable climate variables and exacerbated by a decade's long drought in the region (shock #7 in Fig. 3.1).

Independent irrigation districts pump groundwater and report their usage to the ADWR, who is responsible for the allocation of groundwater pumping. In 2013, the Phoenix AMA pumped 0.6 MAF, Pinal AMA 0.3 MAF (Arizona Department of Water Resources, 2010b) and the LCRPA 51,500 estimated AF (United States Geological Survey Representative, 2014). The farming community engages with the various government agencies that allocate water. These interactions correspond to relationship #2 in Fig. 3.1. As a predominant user of water, agriculture is also a contributor to the economy. The Arizona GDP is approximately $256BB and the total value of agriculture, including indirect effects is approximately $12BB or about 4.6% of the total GDP (The University of Arizona, Department of Agricultural and Resource Economics, The College of Agriculture and Life Sciences, 2009).

The Arizona Legislature has directed the ADWR to administer a sustainable level of water consumption by balancing industrial, agriculture, urban, and tribal needs. The agricultural industry has a voice through the Arizona Department of Agriculture, which encourages farming and ranching while protecting consumers and natural resources. The governor appoints an agricultural advisory board, which by statute must include two council members from the livestock industry, two members from plant products, and one member involved in agribusiness. This Council reviews agricultural policy to assist the director in developing administrative rules and budgets. (Water Manager C, 2014).

The House Committee on Agriculture, with forty four legislatures elected from throughout Arizona, oversees issues related to farming. The Arizona Cattlemen's Association is a trade association that serves as a body of influence to the House Committee on Agriculture.

The Central Arizona Project and Salt River Project provide the infrastructure to deliver surface water. The water delivered through these agencies is directed by a complex set of federal treaties, interstate agreements, plus federal and state legislative statutes. The water resources are achieved through the natural flows of the Colorado

River and other rivers in Arizona, and groundwater supplies, as well as the man-made structures of the Central Arizona Project and Salt River Project with dams and canals.

The communities are diverse, both in geography, corporate and public entities, and multiple entities of users competing with the farmers for water. A political process is in play regarding allocating water with the foresight to achieve sustainability in the long run. Given these diverse interests as well as forecasts that are unreliable for long-term water availability, it is a challenge to achieve a balance that services everyone's' needs.

To meet the water needs in the AMAs on a sustainable basis is the directive of the Arizona State legislature in the creation of the Arizona Department of Water Resources. The ADWR sets the policies through directors for each area with oversight from an advisory council appointed by the governor from each of the areas. The directive mandating a sustainable water supply is stressed by achieving the political will due to a long-term drought and increased demand from agriculture, urban and industrial users. In the two of the AMAs, water resources include SRP, groundwater, and CAP water. In the Lower Colorado River District, only Colorado River water, its tributaries, and groundwater are included. Each AMA is unique regarding the water basins, population, and use. Achieving water sustainability is a moving target due to changing water availability and demands of agriculture, commercial and urban users.

The water provided through the rivers, canals, and pumping groundwater are each allocated or directed by separate entities. Water provided through the Colorado River is allocated by Law of the River; SRP water delivered through canals is allocated by the SRP shareholders.

3.5 Summary

This information organization provides a relationship map between entities and possible shocks in the systems. The interactions of the components within the Water SES in Arizona as portrayed in Fig. 3.1 are documented as relationships in this section in order to understand how the system functions. A review of water history and policy is valuable for the understanding of the complex water use and management in Arizona. Stakeholder interviews augment understanding of the system. Water laws developed in Arizona along the lines of first-in-time, first-in-right' regarding surface water, although federal law trumps Arizona law. Federal law applies to international treaties with Mexico, adjudicated allotments for tribal units, and arrangements with neighboring states. Expanding delivery through massive public works projects like the CAP and dams highlighted the need to manage water resources to a sustainable level, which led to the creating of the Arizona Groundwater Code.

The history of water use in Arizona explains the inertia of change in terms of water use. This is clearly seen in the existence of grandfather rights and farmer's strong feelings against the Code (Water User B, 2014). Arizona manages water resources through the overarching mandates of the Arizona Department of Water Resources that strives for a safe yield while balancing all economic users, including agriculture and urban.

Concerns about water-related problems were expressed by the entire stakeholder pool. These concerns exist because of deficit groundwater pumping coupled with a long drought. Farmers worry about future water limitation within the AMA as the safe yield deadline looms (Water Manager A, 2014). The recent drought problem in California foretell Arizona's problem. "Arizona have invested a great deal in water delivery and storage infrastructure which would provide a drought buffer. Prolonged drought will be problematic." (Water Manager B, 2014). Every type of water user has an opportunity to use water more efficiently and reduce their water consumption. Agriculture water use reduction is the most impactful reduction measure because of its current largest share of consumption. Changes in farming practice could be costly for farmers, but preparation today will increase agricultural sector's preparedness.

The information compiled paints a complex picture of water use and management in Arizona. Agricultural water use is influenced by the historical agriculture's water importance in the state, established laws and cultural inertia in farming community. The currently prevalent flood irrigation practice is in most cases the only type of irrigation farmers have known. All of the infrastructure, culture, and types of crops are around a system in place for several generations (Water User B, 2014). Currently there is no reason to make any changes since the water still flows at about the same price. That water is still priced relatively inexpensive for farmers represents is a de facto subsidy of water for agriculture. Change occurs when there is some pain level to avoid, such as higher water prices, or an incentive to change, such as the threat of less water. All of the government programs support the existing structure and little assistance for the unfamiliar advanced irrigation technology. Aid for purchasing existing types of farm equipment exists, but is not yet directed toward the new irrigation technologies. In interviews with the stakeholders, the dominant theme related to all the existing technology and approaches, never revealing any awareness of new approaches that could be considered nor recognition that the current water policies are unsustainable. Unless the factors discussed in this chapter sufficiently change, it will be difficult for the water-efficient advanced irrigation technologies to be widely adopted in Arizona.

Chapter 4

REPLICATOR DYNAMICS MODEL

In the last chapter, information from the literature review and interviews are organized under the Robustness of SES framework. Such organization provided a qualitative overview of the social and biophysical intricacies of Arizona's water system. In this chapter, that overview is supplemented by a quantitative model that focuses on only parts of this complex system, primarily the resource users and the economic drivers that may lead them to adopt the water-efficient technologies. The three irrigation technologies under consideration—flooding, sprinkling, and dripping—are briefly described in Table 4.1, with details more available in Appendix A. This modeling exercise is aimed at deriving the analytical relationship between some of the factors at the expense of other realistic and important factors. The limitations and caveats of the model's findings will be discussed in the next chapter. The model scope is

Table 4.1: Irrigation Technology Overview

	Evaporation	**Overall Cost**	**Advantage**	**Disadvantage**
Flood	High	Low	Simple to implement Low Maintenance Common Knowledge	Less uniformity Contributes to soil salinity Submersion cause yield decrease
Sprinkler	Medium	Medium	Increase yield Uniformity Targeted fertilization	Medium complexity Medium maintenance Energy required
Drip	Low	High	Highest yield High Uniformity Targeted fertilization	High complexity High maintenance Energy required

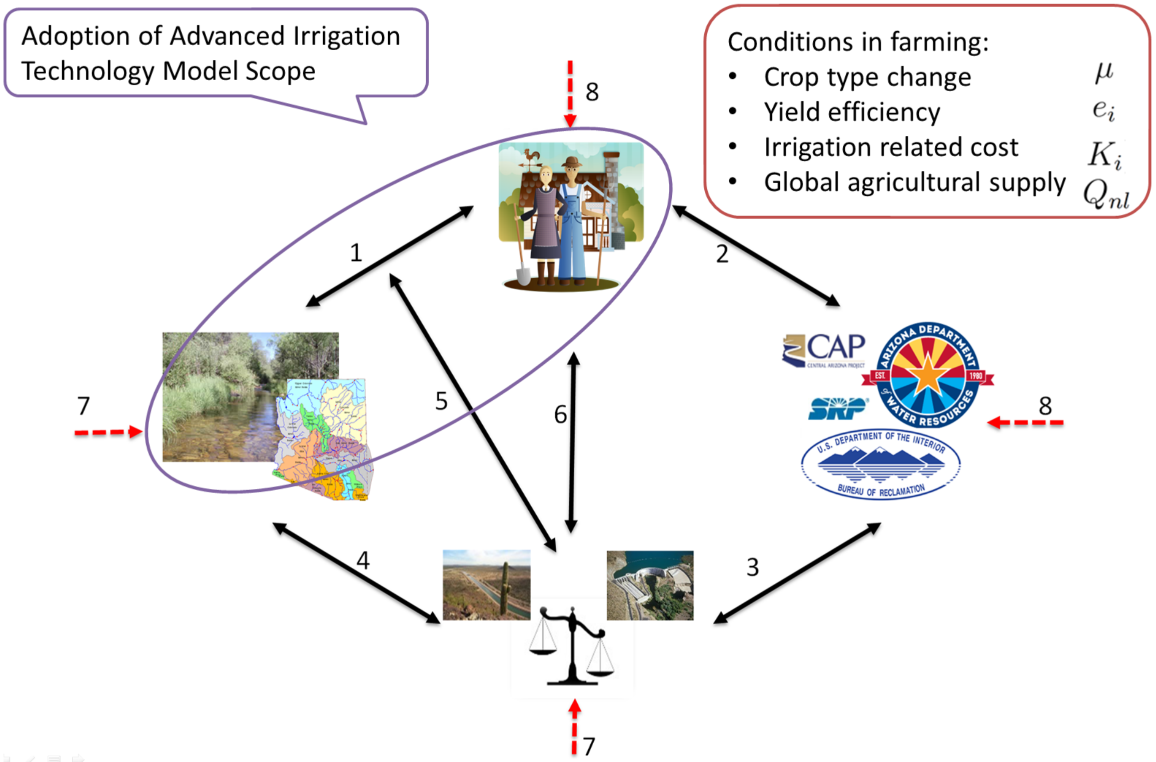

Figure 4.1: System Representation: Robustness of SES Framework Including the Modelling Scope and Conditions.

depicted by the purple circle on the SES system representation in Figure 4.1.

Development of the model of advanced technology adoption is done concurrently with the qualitative research activities. The interview process is used to gain understanding of the agricultural water management social-ecological system in Arizona. This enables the implementation of some insights from interviews with water managers, farmers, and other water users into the model. The model does not attempt to capture the complexity of the full systems, but it aims at finding clear relationships among factors/reasons for potential irrigation technology shift from current flooding dominated regime. From the interviews and literature review, I have made the following observations:

- The cost of agricultural activities are the land, equipment, irrigation systems, ground water well, harvesting equipment, labor, processing, transportation, seeds, fertilizer, and insurance.

- The profit from agricultural activities is derived from the income gained from selling the agricultural goods. The price of agricultural commodity is set by the commodity market based on the availability of that particular commodity.
- The commodity price fluctuates responding to availability, future projections, and changes in cost. These fluctuations raise and lower the net income of the farmers.
- Farmers have the freedom to choose types of crop to grow, the growing layout, and the types of irrigation technologies.
- They can change these after every growing cycle.
- Changing the choices listed about would incur costs.

Based on these observations and a number of simplifying assumptions, the developed model will focus on the following factors: changes in crop types, yield efficiency, irrigation-related costs, and non-local market competition. In the next section, I will mathematically formulate the model.

4.1 Replicator Dynamics Model: Development and Assumptions

A replicator dynamics model is developed to capture the evolution of the technology adoption discussed above. As discussed in Section 2.3, in a replicator dynamics model, decisions of a farmer to change are based not only on information of the benefit of the technologies but also on the examples of other farmers. This model is based on bounded rationality, corresponding to profit maximization with sluggish learning. This approach is more appropriate, as compared to the commonly assumed strong rationality from classic economic theory, as it is more realistic in many social situations.

The model deals with the evolution of strategy distribution within a population. The payoff to a user of each strategy depends on what strategies are being used, and how frequently they are being used by others. Each individual attempts to maximize his/her payoff by adopting a strategy that pays better. Over time, the strategy mix will converge to an equilibrium point.

Model Assumptions

The model represents a system of particular crop farmers who do not change crop overtime. These farmers produce irrigated crops that are sold in a commodity market. The market share of non-local commodity remains constant. Land fertility is assumed to be unaffected. Each farmer has the choice of irrigation technology types and can change irrigation types after harvest. The costs of agricultural activities are the same per land areas, except irrigation technology-related costs. Net Income from agricultural activities becomes one deciding factor for the decision on what change one should do. All other agricultural factors are held constant.

Land ownership was not explicitly addressed in this model because the adoption of technology for a farmer is considered to be independent of the ownership of the property. Many businesses lease the property used for manufacturing and adopt technology without consideration of who owns the land since a business decision is made considering the operating costs, which are independent of the ownership. For accounting purposes, the expense of a rent for property is relatively equivalent to the cost of ownership given the mortgage payments or depreciation expenses for capital improvements. The question of land ownership can become more complicated if there are considerations for opportunity costs.

Model Description

The model considers three different irrigation technologies: flooding, sprinklers, and dripping.

$$x_f + x_s + x_d = 1 \tag{4.1}$$

$$q_i = e_i q_f \tag{4.2}$$

$$a_i = x_i A \tag{4.3}$$

x_i is the proportion of local farmers with irrigation technology i out of all local farmers.

e_i is the relative efficiency of irrigation technology i compared to flooding, $e_i > 1$ & $e_f = 1$

q_i is the agricultural output per unit area using irrigation strategy i $(\frac{CWT}{Acre})$

q_f is the agricultural output per unit area using flood irrigation strategy $(\frac{CWT}{Acre})$

a_i is the local agricultural area using irrigation strategy i at a time period $(Acre)$

A is the total local agricultural area at a time period $(Acre)$

The change of the overall proportion of farmers with a certain irrigation technology over time is represented in the following equation (Taylor and Jonker, 1978).

$$\dot{x_i} = x_i(\pi_i - \bar{\pi}) \tag{4.4}$$

$\dot{x_i} = dx_i/dt$ is the rate of change of the proportion of local farmers with irrigation technology i.

π_i is the payoff of an area of agricultural output at a time period $(\frac{\$}{Acre})$.

$\bar{\pi}$ is the average payoff of an area of agricultural output at a time period $(\frac{\$}{Acre})$.

Payoff of irrigation technology decision is represented here. This is the individual farmer's net income.

$$\pi_j = pq_j - K_j \tag{4.5}$$

where subscript $j = f, s$, and d represents the different irrigation technologies.

p is the price of a unit agricultural product $(\frac{\$}{CWT})$

q_i is an agricultural output per unit area (Acre) using irrigation strategy i $(\frac{CWT}{Acre})$.

K_i is the cost that a unit area of land needs in producing a specific crop $(\frac{\$}{Acre})$.

Price of an agricultural commodity is simplified to only be affected by total quantity of the market.

$$p = \frac{\mu}{[Q_t]^b} \tag{4.6}$$

μ is the price coefficient for a specific agricultural product (crop).

b is elasticity coefficient of an agricultural product.

Q_t is the sum of local and nonlocal agricultural output at a time period (CWT).

Total agricultural production is the factor that affects the market price.

$$Q_t = Q_l + Q_{nl}$$

where Q_l and Q_{nl} denote the local and nonlocal agricultural outputs of a specific crop (product), respectively. The local agricultural outputs, Q_l is defined as follows:

$$Q_l = \sum_{j=f,s,d} q_j a_j. \tag{4.7}$$

Using the relations indicated by Eq.4.2 and Eq.4.3 we obtain,

$$\begin{aligned} Q_l &= \sum_{j=f,s,d} e_j q_f x_j A \\ &= (x_f + e_s x_s + e_d x_d) q_f A, \end{aligned} \tag{4.8}$$

where we have used the fact that $e_f = 1$. If we substitute for $x_f = 1 - x_s - x_d$ as a result of Eq.4.1, the above equation can then be written as follows:

$$Q_l = [1 + (e_s - 1)x_s + (e_d - 1)x_d]\, q_f A. \tag{4.9}$$

As a result, Eq.4.7 becomes:

$$Q_t = [(1 + (e_s - 1)x_s + (e_d - 1)x_d) q_f A] + Q_{nl} \tag{4.10}$$

Q_l is the sum of local agricultural output at a time period (CWT)

Q_{nl} is the sum of non-local agricultural output at a time period (CWT)

Price Function

Substituting the expression of Q_t shown in Eq.4.10 in Eq.4.6, we obtain:

$$p = \frac{\mu}{([1 + (e_s - 1)x_s + (e_d - 1)x_d] q_f A + Q_{nl})^b} \tag{4.11}$$

Payoff Function

Including the price equation, Eq.4.11 into the payoff equation, Eq.4.5 of technology i, we obtain

$$\pi_i = \frac{\mu\ e_i\ q_f}{([1+(e_s-1)x_s+(e_d-1)x_d]q_f A + Q_{nl})^b} - K_i \tag{4.12}$$

Average Payoff

$$\begin{aligned} \bar{\pi} &= x_f \pi_f + x_s \pi_s + x_d \pi_d \\ \bar{\pi} &= (1-x_s-x_d)\pi_f + x_s \pi_s + x_d \pi_d \end{aligned} \tag{4.13}$$

$$\bar{\pi} = \frac{\mu q_f}{[Q_t]^b}\left[(1-x_s-x_d)+e_s x_s + e_d x_d\right] - \left[K_f + (K_s-K_f)x_s + (K_d-K_f)x_d\right] \tag{4.14}$$

Replicator equation

$$\frac{dx_i}{dt} = x_i\left(\pi_i - [(1-x_s-x_d)\pi_f + x_s\pi_s + x_d\pi_d]\right). \tag{4.15}$$

Substituting the expressions of $\bar{\pi}$ and π_i, and perform some algebra, we obtain:

$$\frac{dx_i}{dt} = x_i\left[\frac{\mu\ q_f}{[Q_t]^b}\left[(e_i-1)(1-x_i)+(e_j-1)x_j\right] + (K_i-K_f)(x_i-1) + (K_j-K_f)x_j\right] \tag{4.16}$$

where $i, j = s, d$ and $i \neq j$

Stability analysis

Let's write Eq.4.16 as:

$$\frac{dx_i}{dt} = F_i(x_i, x_j). \tag{4.17}$$

To perform the local stability analysis, we need to calculate $\partial F_i/\partial x_i$ and $\partial F_i/\partial x_j$. These are:

$$\begin{aligned}\frac{\partial F_i}{\partial x_i} &= \tfrac{\mu\ q_f}{[Q_t]^b}\left[(1-x_i)(e_i-1)+x_j(e_j-1)\right]+(x_i-1)(K_i-K_f)+x_j(K_j-K_f) \\ &\quad -\tfrac{\mu\ q_f\ (e_i-1)}{[Q_t]^b}\ x_i\left[1+\tfrac{b\ q_f\ A}{Q_t}\left[(1-x_i)(e_i-1)+x_j(e_j-1)\right]\right]+x_i(K_i-K_f), \\ \frac{\partial F_i}{\partial x_j} &= \tfrac{\mu\ q_f\ (e_j-1)}{[Q_t]^b}\ x_i\left[1-\tfrac{b\ A\ q_f}{Q_t}\left[(1-x_i)(e_i-1)+x_j(e_j-1)\right]\right]+x_i(Kj-Kf)\end{aligned} \tag{4.18}$$

Stability analysis of the equilibrium point $(x_i^*, x_j^*) = (0, 0)$

To perform the local stability analysis, we calculate the Jacobian matrix as follows:

$$J = \begin{pmatrix} \frac{\partial F_s}{\partial x_s} & \frac{\partial F_s}{\partial x_d} \\ \frac{\partial F_d}{\partial x_s} & \frac{\partial F_d}{\partial x_d}. \end{pmatrix} \tag{4.19}$$

We then use Eq.4.18 with $x_s = x_d = 0$, to obtain:

$$J = \begin{pmatrix} \frac{(e_s-1)\mu\ q_f}{\left[q_f A+Q_{nl}\right]^b}+(K_f-K_s) & 0 \\ 0 & \frac{(e_d-1)\mu\ q_f}{\left[q_f A+Q_{nl}\right]^b}+(K_f-K_d) \end{pmatrix} \tag{4.20}$$

which is a symmetric matrix. As a result, the eigenvalues are:

$$\lambda_i = \frac{(e_i-1)\mu\ q_f}{\left[q_f A+Q_{nl}\right]^b}+(K_f-K_i) \tag{4.21}$$

where $i = s, d$. Note that the eigenvalues are real.

4.2 Results and Discussion

I will now use the model results to understand the effects of each factor on the adoption of these technologies and discuss some implications of these effects. According to the model analysis in the last section, the condition under which either advanced irrigation technology (sprinkling or dripping) would replace the less water-efficient flooding technology can be described as

$$\frac{(e_i - 1)\mu \; q_f}{[q_f A + Q_{nl}]^b} + (K_f - K_i) > 0. \tag{4.22}$$

Basically, Equation 4.22 suggests that adoption of these water-efficient technologies can be promoted by a mix of the following conditions: the reduction in the advanced irrigation technology related cost (K_i), increase in advanced irrigation technology yield efficiency (e_i), increase in crop value through crop type change (μ), and a decrease in non-local market competition (Q_nl)

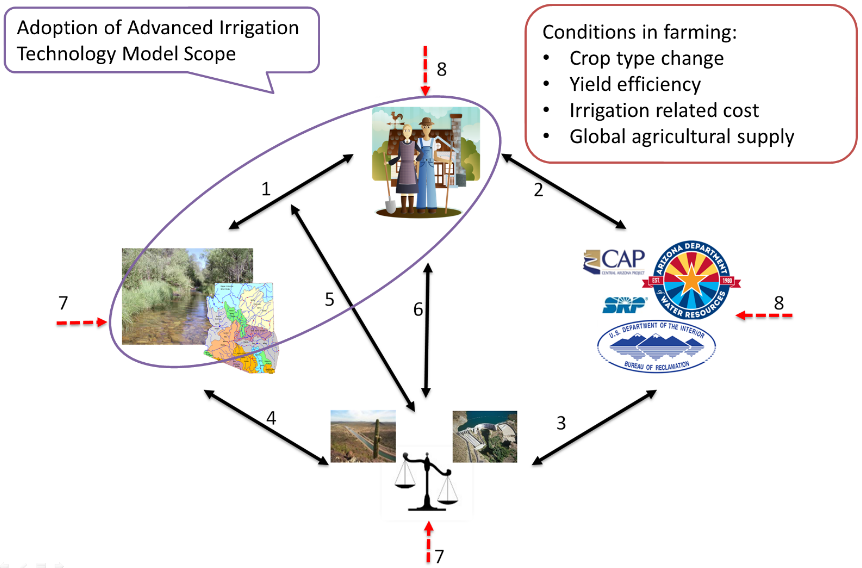

Figure 4.2: System Representation: Robustness of SES Framework Highlighting the Conditions Tested in the Model.

Cost K_i

Cost associated in using a certain irrigation technology has an negative relationship on the adoption of the particular irrigation technology in the system. Cost of an irrigation technology is a simplified cost parameter clumping the implementation cost and variable cost. This could be thought of as an amortized loan for farmers. Agricultural support through insurance and loan is a common governmental intervention. Government, through cost reduction policy, could increase the rate of adoption of advanced irrigation technology. While this might be intuitive, the model results quantitatively show how it is related to other factors.

The model could accommodate some climate change-related paradigm shifts, e.g., institutions governing water suddenly are forced to increase water pricing. One of the water pricing methods could be through volumetric usage. To accommodate volumetric water delivery and usage accounting, water managers could use the Supervisory, Control, and Data Acquisition (SCADA) system. SCADA system will automate delivery and accounting. Which would provide reliable water use-based costing to farmers. Assuming such volumetric water billing in place, adoption to advanced irrigation system will increase in order to squeeze out water inefficiencies. In such a paradigm, farmers would also be inclined to change to low water intensity crop from currently common highly water intensive crops.

Crop yield efficiency e_i

The growth efficiency associated with irrigation technology is directly related to the adoption of irrigation technology. Crop growth rate impacts the income of the farmer. Different irrigation technologies provides different growing rate. Drip-irrigated crop use less water and increase yields. This is clearly explained by an alfalfa farmer with drip irrigation technology,

> "After the change [in irrigation technology], I can continue my drip irrigation schedule without worrying that the buds are going to be underwater. This continuous irrigation enables the plant to continue growing.
> We're using about one-third less water to grow alfalfa with subsurface drip irrigation (SSDI) compared to traditional flood irrigation. With SSDI we apply 7 to 8 inches directly to the root zone per alfalfa cutting (28 to 30 days) compared to about 12 inches that's typically applied through one or two flood irrigations to the soil surface. I have a neighbor who gets 1.3 tons of alfalfa per acre per cutting with flood irrigation. Our production under SSDI averages 1.75 to 1.8 tons per acre/cutting. That's one heck of a story (Blake, 2009)."

Additionally fertilizer improves crop growth rate. Advanced irrigation technology such as drip and sprinkling allows for inclusion of fertilizer inside irrigation systems, which is called fertigation. Such systems can mix fertilizer in water more evenly and allow even distribution of fertilizer throughout the land, which is impossible with flood irrigation technology. Such difference in agricultural harvest growth rate is captured with the irrigation technology specific growth efficiency.

Crop Type Change μ

Changing crop type would change the income of the farmer. Crop value has a direct relationship with adoption of advanced irrigation technology. The more valuable the crop is, the more likely the farmer invest in advanced irrigation technology. The investment in costly advanced irrigation technology occurs in the population because the income from harvest covers the higher cost associated in that investment. For example, during a switch in farming decision to growing dates the Martha's Garden, the Yuma date farmer implemented a drip irrigation system (Water User E, 2014). The Duncan Family Farm grows conventional vegetables and organic vegetables which increase their profit margins which enables them to implement sprinkler and drip systems (Water User F, 2014).

Global Agricultural Supply or Non-local Competitor Q_{nl}

Understanding market demands and capturing the opportunity to make more income is not a simple task. The valuation of the harvest yield in this model is done through a simple inverse quantity model. Harvest of crops usually occurs at the same time. Demand of a particular agricultural good could be conceptualized as a steady demand, while the supply may vary seasonally. For example, Duncan Family Farms operates in several state and harvest carrots on different schedule in order to capture this opportunity (Water User F, 2014).Yuma vegetable farmers are able to thrive and invest in advanced irrigation technologies due to climatic advantage during the winter months when there are no harvest competition from non-local farmers (Water User A, 2014).

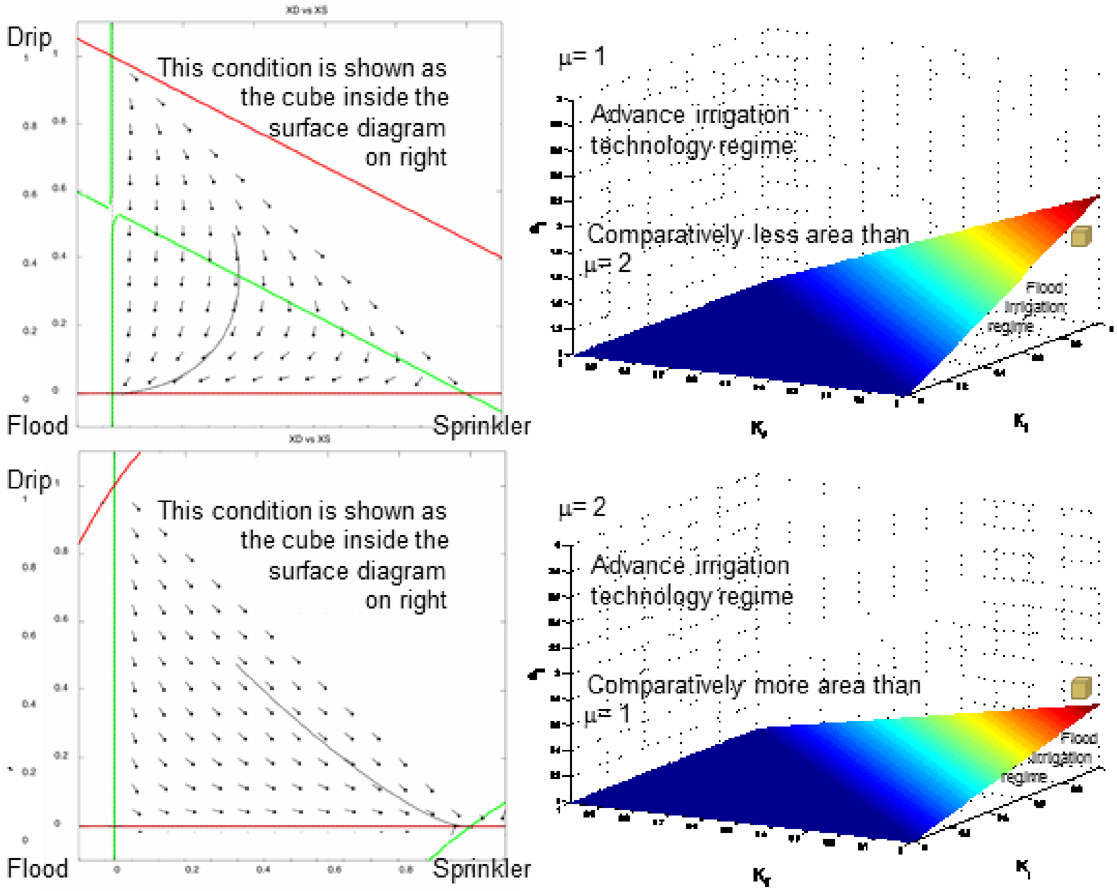

Figure 4.3: The Effect of the Change in Crop Type or Crop Value (μ). Two conditions–one with and the other without adoption of the irrigation technology–are depicted. Each condition is presented by its corresponding phase plane (left) and critical stability surface (right). The condition on the top is a condition where μ is 1, whereas the condition below, μ is doubled to 2. The space above the surface is an area describing condition where advanced irrigation technology will be adopted. The flooding technology dominated regime, like it is today, corresponds to the space below the surface. The effect of doubling the crop value leads to more opportunity for advanced irrigation technology to be adopted.

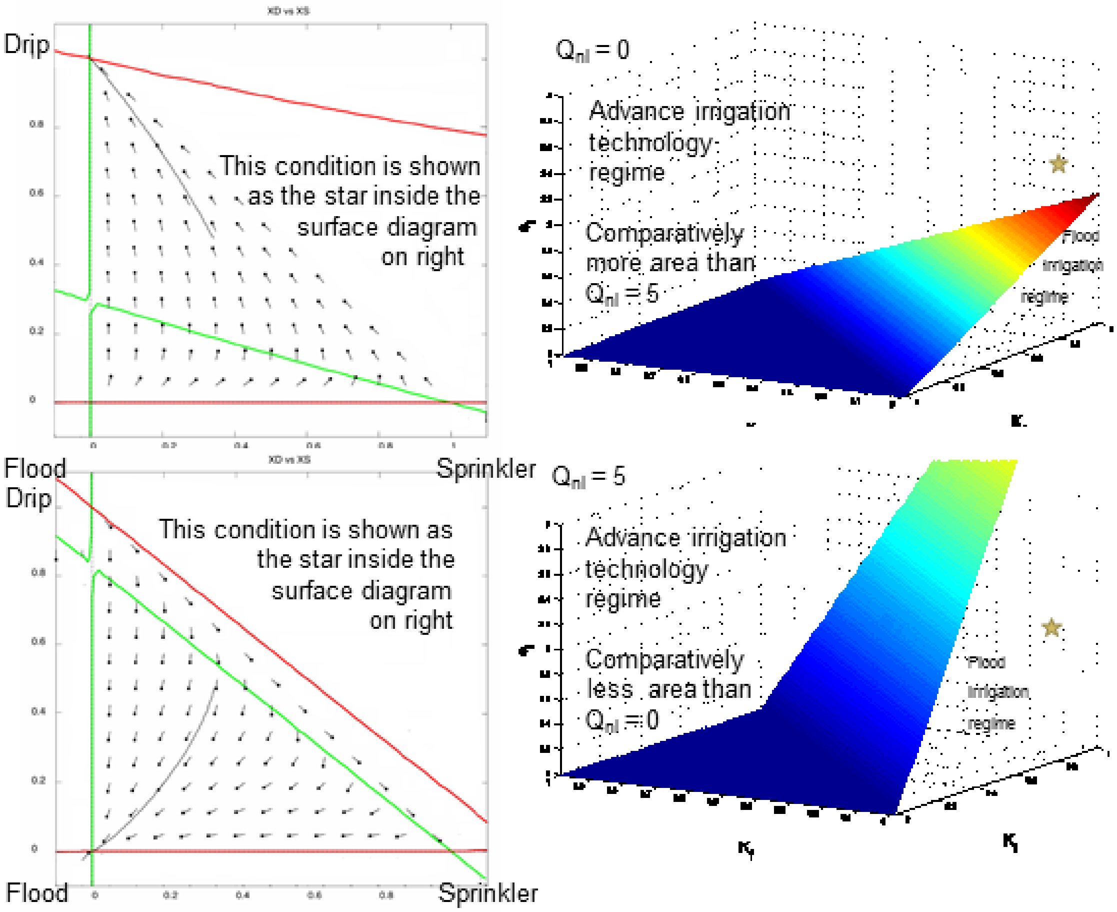

Figure 4.4: The Effect of Non-Local Market Competition (Q_{nl}). Two conditions–one with and the other without adoption of the irrigation technology–are depicted. Each condition is presented by its corresponding phase plane (left) and critical stability surface (right). The condition on the top is a condition where Q_{nl} is 0, no competition. Whereas the condition below, Q_{nl} is increased to 5, where non local production is 5 times more than local production. The space above the surface is an area describing condition where advanced irrigation technology will be adopted. The flooding technology dominated regime, like it is today, corresponds to the space below the surface. The effect of increasing outside market competition leads to reluctance in advanced irrigation technology adoption.

Chapter 5

CONCLUSIONS AND FINAL REMARKS

Conditions that promote farmers' adoption of water-efficient advanced irrigation technologies in Arizona constitute the question to be addressed in this research project. I have employed several complementary approaches to address this question, namely, literature review, stakeholder interviews, robustness of SES framework, and dynamical modeling. The information gathered from literature review and interviews is organized using the robustness of SES framework in Chapter 3. This organization provides a qualitative big picture that captures the complexity of Arizonas water system. Augmenting this qualitative picture, a quantitative dynamical model—a replicator dynamics model—is applied to a subset of this complex system. The analytical result from the model clearly links various factors that will promote the adoption of better irrigation technologies. In this last chapter, I will draw connections among the findings in these approaches and offer some final remarks.

Arable water is a finite resource that is already stretched to the limits in the desert Southwest and is exacerbated by the decades long drought. Historically in Arizona, water resources infrastructures such as Salt River Project dams and canals were first developed for agriculture, which was the dominant economic sector. As industry and urban development grew, agriculture shrank to 0.79% of the state's economy (Morrison Institute for Public Policy, 2012). Consequently, agricultural sector‘s influence with state water management has been eroding. The looming water problem will require balancing the needs for water among agriculture, urban and industrial uses. It is obvious that agriculture, the dominant water user, has the most impact when its consumption is reduced. Given the current trend and agriculture's low contribution to AZ's economy, water reduction in agriculture will continue to be a called-upon solution. Other than reducing crops and cropland, which reduce revenue, one solution for agriculture water consumption reduction is to embrace technological advancements in irrigation.

The currently dominant irritation technology is flood irrigation due to its historical practices and the existing government programs and policies that were formed since the beginning of development in Arizona. We know from interviews with farmers and other stakeholders that the agricultural support in place focuses on the current flood irrigation practice. This setting offers little incentive for farmers to adopt new irrigation technologies.

Replicator dynamics model in Chapter 4 is developed to analytically provide the intuitive conditions that promote adoption of better irrigation technology under a setting with several simplifying assumptions. Achieving clear analytical relationship comes at the expense of several important realistic factors discussed in Chapter 3. The model results suggest that lower costs, increased yield efficiency, crop types of higher value, and less market competition from out of state would lead to the adoption of the technologies. Equation 4.22 summarizes the quantitative relationship of these factors. Therefore, water policies that facilitate these conditions will help promote the technology adoption.

These findings must be viewed in the context of the bigger picture presented in Chapter 3; such a perspective helps highlight the applicability and, importantly, limitations and caveats of the model. For example, cost is currently represented by a simple parameter in the model; other cost-related complications, such as land ownership and volumetric pricing can be incorporated in future work. In addition, the way in which cost is represented in the model is akin to installment payments; in reality, a switch in irrigation technology may require a big upfront investment, which may be possible only for those with large land or access to farm loans.

Land ownership or lease is not explicitly represented in the model. The complexity of farmers who plan for future sale of their land could not be included in the model because the income from this activity does not come from agricultural activities. The income from agricultural activities is the only source of income in the current payoff equation. From the interviews, long-term investment on the land, such as changing into a better irrigation technology, will be likely to occur only if the farmer owns the land and is not planning to sell the land for urban development (Water User B, 2014). Future development of this study should make this effect explicit.

Volumetric pricing, a potentially critical and controversial factor, has not been explicitly included in the model either. With volumetric water pricing, the costs associated with water-efficient advanced irrigation technology or less water-intensive crops will be lower, compared to the costs associated with flooding or more water-intensive crops. With such pricing, advanced irrigation technology and less water-intensive crops will likely become more common. The future development of this study should incorporate this important factor as well.

This research project offers a number of findings that could be used to increase preparedness of the agricultural sector in a reduced water availability condition. I hope that the findings are meaningful and accessible for use by policy makers in their work on improving water problems in Arizona.

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APPENDIX A

IRRIGATION TECHNOLOGIES

IRRIGATION TECHNOLOGIES

Agriculture in Arizona would not be possible without irrigation technology and the results are astounding yields.The yields for corn in Arizona are the highest in the country producing 36% more bushels per acre than Illinois, the state that is known for corn. This is possible because the Arizona climate promotes year round growing and the crop is under continuous irrigation until it is harvested (US Environmental Protection Agency, 2012). The irrigation technologies included in this research are Flood, Sprinkler, and Drip systems.

Flood Irrigation

Flood irrigation has been around for millenniums. The early Native Americans created over 500 miles of canals in what is now the Phoenix metro area for the purpose of channeling water from rivers and seasonal rains, storing the water, and using it for crops. While as a nation over all, less that 15% of cropland is irrigated (US Environmental Protection Agency, 2012), in Arizona it is 100% since there is no dependable rainfall during the growing season with an average of 15cm annually. This irrigation method is the comparative base in modeling the diffusion of irrigation technology in the system.

Advantages
Leveling the field with laser technology creates a more uniform distribution of the water. A technique called surge flooding reduces the amount of water by releasing the water in timed batches. Runoff water that would have been wasted is recaptured in ponds and re-used. Even though used for thousands of years, within the past decade, technology and understanding of different methods of delivering flood water has yielded an increase in efficiencies.

Disadvantages
The amount of water required depends on the type of crops, the timing in the growing season, the soil's ability to absorb moisture (US Environmental Protection Agency, 2012). The use flood irrigation exacerbates these issues that are not unique to surface irrigation method, such as:

- waterlogging can cause the crops to shut down when the roots are flooded which stunts growth;
- over irrigation can cause the water to move below the root system and bring salt up and into the root zone.

Drainage reduces this effect while using more water than necessary. Depending on the quality of the water there is an issue with salinization although not as much as other methods since there is a higher leaching fraction, which means more water infiltrates past the root zone of the plants. Deep drainage has been an issue in Arizona that caused the water table to rise in the early days of irrigation in the Phoenix area which increased the salinity in the soil (Water User D, 2014). Flooding irrigation increased the water's opportunity to evaporate and since plants grow year round the evaporation of irrigation water is year round.

Sprinkler Irrigation

Sprinkler irrigation was first patented by (Lessler, 1871). It is an irrigation system that most approximates natural rainfall by spraying water in the air through a sprinkler system that breaks the water into small drops. There are rotary sprinklers that distribute the water in a circle or stationary pipes in rows or overhead pipes that move. Either way, the conditions must be suitable for distributing water in the air which can be affected by wind and evaporation rates.

Advantages
Sprinklers in general use less water when compared to flood irrigaton. Sprinkler irrigate is suitable for most any type of crop, either planted in rows or field and tree crops, except those that might be damaged by larger drops produced by the sprinklers. Since the water is delivered evenly from the spray heads, fertilizer could be delivered while irrigating the plants.

Disadvantages
Using overhead pipes, moving or stationary and rotating sprinkler is a method of applying water to specific crops. Since the water is shot through the air to reach the fields it is highly susceptible to wind and evaporation which is why it is seldom used in the desert Southwest since much of the water would not even reach the crops. Since the water drops can be quite large they are not suitable for lettuce. Lettuce are suspectable to fungi if the leaves are wet for as little as ten hours at a time.
Most sprinkler systems are somewhat labor intensive, especially the overhead systems with moving pipes. While portable to an extent, they do require more labor than flood or drip irrigation. Drip irrigation, which is also labor intensive, requires a different type of skill than for sprinkler irrigation.

Drip Irrigation

Drip irrigation is a surface irrigation with water dripping at the root stem and also buried cables with water applied to the root. While plants need the same amount of water to grow with either drip, sprinkler, or flood irrigation methods, the basic savings with drip irrigation comes from the savings in reducing evaporation from the soil, eliminating surface runoff and the need for deep percolation. To achieve a level of water reduction requires the skills to manage the system depending on the type drip irrigation used (Natural Resources Management and Environmental Department - FAO, 2014). Typically high value crops are considered suitable because an increased yield quickly recovers the capital to install drip irrigation. With water scarcity and rising prices, drip irrigation will be suitable for most any crop (Water User A, 2014).

Advantages

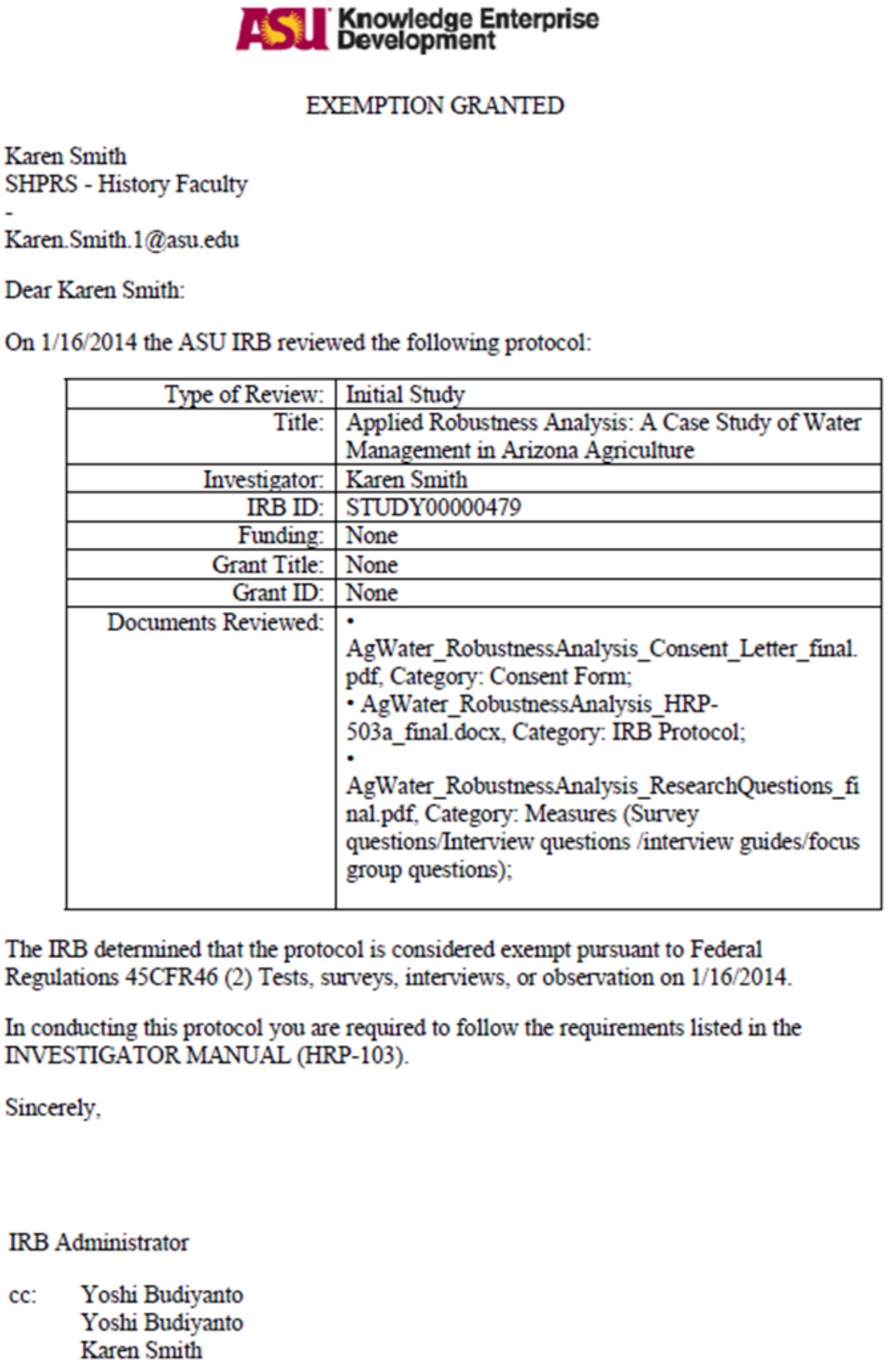
The economics of switching from furrow irrigation to drip irrigation for green chile peppers are documented in this example of a farm in New Mexico in 1993. The yield increase from an average 16 tons per acre, averaging about $4,400 per acre to 33 tons per acre for an average yield of $9.735 per acre. Additionally, with the furrow irrigation about 30% of farmland was out of production because of the limited availability of water and that has been eliminated. The amount of nitrogen has been reduced by over half from 90 gallons to 40 gallons (Laws, 2009). Similar reduction in fertilization also apply when farmers use drip irrigation in growing corn (Lamm et al., 2001). Other advantages are that heavy equipment can be used all the time because with the water applied through drip irrigation to the roots the land is dry enough to handle heavy equipment. With these yields for this type of crop the payback for the capital investment is multiple times over the first year.

Disadvantages

Once the drip irrigation is in place the cost of moving it is prohibitive. The design is inflexible with no capability of adapting to a different design. The one-time investment cost is relatively flat with no anticipated technological enhancements that might reduce costs and most of the cost attributed to labor. The implementation design needs to account of the limitations in the length of tubing that is practical. When emitters clog there is additional labor required to locate the source of the problem that is not required in flood or sprinkler systems. The overall operation will likely require additional management oversight to insure a continuous operation.

APPENDIX B

IRB APPROVAL FORM



ASU Knowledge Enterprise Development

EXEMPTION GRANTED

Karen Smith
SHPRS - History Faculty
-
Karen.Smith.1@asu.edu

Dear Karen Smith:

On 1/16/2014 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Applied Robustness Analysis: A Case Study of Water Management in Arizona Agriculture
Investigator:	Karen Smith
IRB ID:	STUDY00000479
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• AgWater_RobustnessAnalysis_Consent_Letter_final.pdf, Category: Consent Form; • AgWater_RobustnessAnalysis_HRP-503a_final.docx, Category: IRB Protocol; • AgWater_RobustnessAnalysis_ResearchQuestions_final.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 1/16/2014.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Yoshi Budiyanto
Yoshi Budiyanto
Karen Smith

Figure B.1: IRB Approval Form