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The Cases of Reservoir Water Allocation Management in Guanajuato, Mexico and Lambayeque, Peru

Miriam Juárez-Torres
Leonardo Sánchez-Aragón

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Inter-American Development Bank
Department of Research and Chief Economist

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Corresponding authors: Miriam Juárez-Torres (email: mijt77@hotmail.com)
and Leonardo Sánchez-Aragón (lfsanche@neo.tamu.edu)

Abstract[1]

Ongoing climate change will increase competition for water. Diversified demand for water—in contrast with the rigid design of water systems, institutions and infrastructure—could hinder the implementation of adaptation policies in water management for Latin American countries. In this context, weather derivatives are proposed as a complementary mechanism for the successful adoption of more efficient water allocations in irrigation districts. Weather derivatives spread risks and incorporate a better understanding of climate system behavior, strengthening irrigation districts' ability to deal with water availability and demand. The model uses a dynamic water resource allocation model, historical precipitation and Intergovernmental Panel on Climate Change (IPCC) scenarios to find optimal water allocation strategies for the baseline scenario and in the presence of climate change. This analysis is applied to two irrigation districts in Latin America: one in Mexico and the other in Peru, with their corresponding particularities and results.

JEL Classifications: G13, O13, O54, Q15, Q25, Q54

Keywords: Weather derivatives, Climate change, Irrigation districts, Water allocation policy, Weather index insurance, Climate change scenarios in precipitation, Reservoir management

[1] Miriam Juárez-Torres is a PhD candidate in the Department of Agricultural Economics, Texas A&M University. Leonardo Sánchez-Aragón is a Graduate Student, Department of Agricultural Economics, Texas A&M University.

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1. Introduction

In many Latin American countries, ongoing climate change has already posed major challenges to agricultural production, triggering crop losses and affecting the functioning of markets. Furthermore, in these countries, water allocation is a big issue, and water supply could be affected by changes in temperature and shifts in precipitation patterns. Still, there is no certainty on how climate change could alter precipitation.

Agriculture will no doubt be affected, primarily through impacts on irrigation. Although water markets and pricing can increase the efficiency of water use, the implementation of a price system for water is unfeasible because of its institutional, social and political connotations. In contrast, water is typically managed as a natural monopoly because of network externalities and underpriced by regulatory authorities.

Mitigation and adaptation have been identified as main strategies in dealing with climatic change. However, while in developed countries mitigation and adaptation are parallel strategies, the dominant strategy for developing countries is adaptation. Thus, the adaptation strategy to climate change in the agriculture sector that this paper proposes relies on potential improvements in water management in irrigation districts with two cycles—wet and dry seasons—by instrumenting weather derivatives as an insurance mechanism. Weather derivatives are able to incentivize the adoption of new allocation patterns that consider more generous allocations for dry seasons while providing reduced allocations for wet seasons, where the farmer is able to cope with the risk of water shortages by using weather derivatives.

In these circumstances, insurance schemes may compensate distortions in the intertemporal allocation of water by the regulation authority. At the same time, insurance supports the adoption of changes in allocation policy as an adaptation strategy to face climate change, and not only as a smoothing mechanism for farmers' income. In addition, weather derivatives can incorporate additional information to reflect climate change that historic data do not reflect, thus strengthening the ability of management entities (irrigation districts) to deal with water availability and demand. Weather derivatives could not only smooth farmers' income, but might also induce an intertemporal reallocation of water in irrigation districts, increasing the efficiency of water use in the long term. To test this assertion, the proposed instrument is applied in two cases that encompass a wide range of situations.

In the first case, the insurance scheme insurance is applied to the Alto Rio Lerma Irrigation District (ARLID) in the state of Guanajuato in central Mexico; in this case the effectiveness of that instrument, in the terms described above, is verified. In the second case, a weather derivative is applied to the Chancay-Lambayeque Irrigation District (CLID), located in the department of Lambayeque on Peru's northeast coast; in this case the instrument's efficiency is limited, acting only as a smoothing mechanism for farmers' income.

Both irrigation districts have experimented increasing variability in precipitation patterns and extreme weather events attributable to climate change. The analysis considers the current legal and institutional framework and water tariff system, as well as irrigation infrastructure management based on water rights. However, ARLID is able to cope effectively with the risk of rain shortage because one of its two seasons (Spring-Summer) is partially rain fed, which permits the introduction of weather derivatives to support allocative policy. In contrast, in the CLID crops are totally dependent on runoff from its basin's accumulated precipitation. These totally irrigation-dependent crops are grown with different temporalities, which makes crops grown in the rainy season the best candidates for insurance.

The analysis is conducted in three stages. In the first stage, the baseline scenario characterizes the authorities' optimal water allocation strategy among farms and farmers using an intertemporal optimal equilibrium and historical data on production, profits and precipitation. The second stage incorporates into the baseline Intergovernmental Panel on Climate Change scenarios (on precipitation) to determine optimal water allocation strategies.[2] Finally, the third stage introduces the weather derivative into the optimal water allocation model to compensate Spring-Summer producers for a shortfall in precipitation realization measured over a certain time period. Once more, optimal water allocation strategy is calculated under different climate change scenarios and using the weather derivative instrument. Weather derivatives contracts are structured as an option on a rainfall index.

[2] The model at this stage includes Global Climate Models' (GCM) predictions to allow the model to reflect climate change risks.

2. Literature Review

The assessment report of the Intergovernmental Panel of Climatic Change (IPCC) forecasts an increase of local temperature between 1°C to 2°C by 2100, especially in lower latitudes and in seasonally dry and tropical regions (IPCC, 2007). It is projected that by mid-century, crop yields and productivity could decrease across many regions and localities.

As Brown and Carriquiry (2007) observe, higher variability in precipitation and temperature patterns in irrigation districts could exponentially increase competition for water among users given high and diversified demand and the inflexible design of infrastructure systems, increasing challenges for water authorities and managers.[3]

Since the early 2000s, numerous cases have proven the benefits of weather insurance in transferring weather risk to global markets (Turvey, 2001; Mahul, 2001; Vedenov and Barnett, 2004; World Bank, 2005; Osgood et al., 2007). Weather derivatives can quickly provide financial resources and technical support to people at natural disaster risk because loss assessment is not required. As discussed in Agrawala and Frankhauser (2008), they can be a potential risk transfer mechanism with an inclusive strategy to manage the uncertainty associated with climate change in agricultural production for developing countries: Mexico (2001), Ethiopia (2007), Kenya (2007) and Mali (2007).

In basins, where irrigation districts are typically located, drought is a phenomenon that builds slowly over time based on shortages of runoffs from daily rainfall. There weather derivatives can map the costs associated with the provision of water during contingency situations from the hydrological space to the financial space through option contracts on a rainfall index. In addition, these instruments could incentivize farmers to switch between comprehensive strategies for adaptation. Thus, the combination of insurance, forecasting and adaptive operations strategies might improve the efficiency of reservoir operation (Block et al., 2007). Additional details on weather derivatives are provided in Appendix L.

The main advantage of weather derivatives over other insurance schemes is that they could effectively reduce future uncertainty through the incorporation of a better understanding of

[3] Irrigation districts are local farmer organizations that plan and decide on the allocation of water resources for agriculture, as well as manage and maintain the irrigation infrastructure systems. In Mexico, irrigation districts account for about 50 percent of the total value of agricultural production and 70 percent of agricultural exports. In Peru, the irrigation districts located on the Northeast Coast produce 70 percent of the total value of agricultural production. In addition, irrigated agriculture covers 1.7 million hectares, 70 percent of them in the coastal area.

climate system behavior over the coming decades. Then, in presence of climate change the main challenge is to overcome the problem of the increasing costs from higher expected losses and higher payouts. Agrawala and Frankhouser (2008) showed that these issues might create market imperfections, such as insurance overpricing or insurance companies' reticence to cover these risks, which require government intervention to subsidize insurance premiums and to improve access to insurance. Further details on design and pricing of weather derivatives considering climate change are found in Section 5.

Several works of applied research on this topic have arrived at useful findings. Zeuli and Skees (2005) designed a rainfall index contract for correcting the inefficiencies produced by water management systems in a drought situation. According to these authors, this instrument might reduce uncertainty in supply and demand, associated with the extremely conservative authority's estimations of available water creating inefficiencies in the allocation. The paper demonstrates the efficiency of index insurance in creating incentives for the authority to estimate more accurately the availability of water supply and demand and for farmers to trade water rights, because insurance replaces their need to self-insure. Zeuli and Skees' work does not, however, provide a clear insight into the effect of this instrument on water demand.

Leyva and Skees (2005) designed an index based on river flows to address the risk associated with water management for irrigation in the Rio Mayo Valle district in Northwest Mexico. In addition, these authors model the intertemporal operation of the reservoir through water release rules and planting response functions, and the effectiveness of this instrument is evaluated. However, as Block et al. (2008) observe, although the use of river inflows as rainfall indices are a direct measure of the available water in single-reservoir systems, it could be a poor option for hydrological systems with multiple reservoir systems and significant diversion of upstream flows. Systems of the latter type are predominant in Mexico and other Latin America countries, where irrigation districts are located within hydrological basins.

Brown and Carriquiry (2007) proposed an index insurance based in reservoir inflows for mitigating water supply cost incurred through an option contract purchase of water in drought years.[4] They considered that inflows have advantages over storage levels, because inflows to reservoir represent integration over space and time of the rainfall in a basin, while reservoir storage levels can be manipulated by the water authority.

[4] The authors based their study on the Angat reservoir in Manila, Philippines.

Although the studies previously mentioned contain relevant findings for this paper, their value as an adaptation strategy for climate change could be limited. Those studies' analyses do not incorporate the dynamic of the variability in climate variables and consequently do not provide a basis for policy. This paper's contribution is to incorporate new dimensions and challenges to the problem initially formulated by Leyva and Skees (2005). The paper proposes the use of weather derivatives as a helpful tool for the implementation of strategies that lead to higher efficiency in the management of the resources in the irrigation districts, which in the long term could represent an effective adaptation strategy. In addition, the operational configuration of the analyzed irrigation district entails a more complex problem because the model includes (in the case of Mexico) a wet season, which entails an extra source of uncertainty.[5]

3. Alto Rio Lerma Irrigation District (ARLID)

By 2050, the Mexican Institute of Water Technology expects a decline of between 7 and 12 percent in precipitation in the southern basins, 3 percent in the Gulf of Mexico basin, and 11 percent in the central basins; in addition, diminished river flows could contribute to higher evapotranspiration (Martínez, 2008). Other changes are already apparent. While in the early 1970s the average return period of extreme events was 12 years, by the early 2000s it had fallen to about five years (Groisman et al., 2005). In addition, the occurrence of heavy rains during the wet season has increased, followed by more severe droughts in the dry season (Aguilar, 2005). Finally, growth in Central Mexico's population by an estimated 12.3 million persons by 2030 is expected to place additional pressure on the hydrological regions of Lerma-Santiago-Pacifico and Valle de Mexico (CONAGUA, 2010). This situation could imply in the near future an adjustment in water allocation for irrigation districts with agricultural production, to which 70 percent of fresh water is allocated, and disturbing those districts' operation (CONAGUA, 2010).[6]

ARLID, the country's third-largest irrigation district, is located in the south of the state of Guanajuato in Central Mexico. Its average precipitation is 630 mm per year, with a rainy season mainly between May and July, and an average temperature between 18 and 20°C. With favorable

[5] While Skees and Leyva (2005) include two productive cycles completely dependent on irrigation water, this paper more broadly considers two seasons in the case of Mexico: a Fall-Winter season totally dependent on irrigation and a Spring-Summer season depending mainly on rain, with minimum irrigation requirements.
[6] CONAGUA stands for Comisión Nacional del Agua, the government water management authority.

soils, ARLID competitively produces a wide range of crops including grains, perennials and vegetables for export.[7]

ARLID obtains its water from the Lerma-Chapala Basin System, which is composed of 17 drainage basins with a multiple reservoir system in four states (Estado de Mexico, Guanajuato, Jalisco and Michoacán) and a significant upstream diversion where the Lerma River is the main collector of the system. Although significant runoffs (on average 1,000 million cubic meters, $Mm^{3,}$ annually) are generated upstream from the Solis reservoir, this reservoir is ARLID's main concentration of water. Downstream from the Solis dam, the Lerma River watercourse has been modified to meet ARLID's irrigation needs.

By law, ARLID's whole operation is based on a water-rights concession system which awards water users clear property rights and assigns specific roles, functions and responsibilities to users associations.[8] CONAGUA, is the water regulatory authority, determines fees based on the volume that each module is buying and receives part of those fees as a recuperation payment (Kloezen and Garcés-Restrepo, 1997).

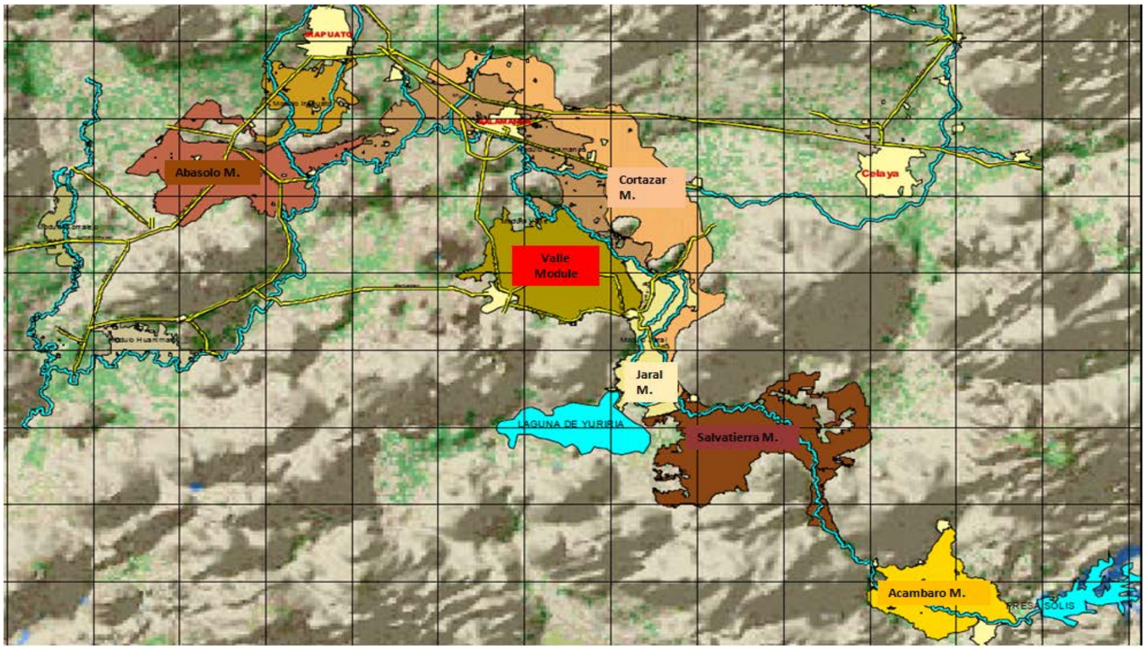
For the sake of the operation and management, ARLID is organized into 11 modules, and each module is entitled to a proportional share of the water available for the irrigation district (see Figure 1).[9] Every module is in charge of carrying out the final allocation of water and collecting fees from its users. Since 1996, ARLID's limited liability company (LLC) has been was awarded the irrigation infrastructure concession. Consequently, the LLC operates, manages, conserves and maintains the irrigation network—which includes primary canals, secondary canals, and drainage—and coordinates and monitors modules. The LLC additionally schedules deliveries of water resources to the modules and checks ditch tender reports at each module on a weekly basis.

[7] In the period 2008-09, ARLID produced 1.6 million tons of agricultural products (CONAGUA, 2010).

[8] The water-rights system requires the concessionaire pays for the volume of extracted water, and payment is theoretically set in relation to shortages in every region of the country and with different rates for every use. Industry and services pay more than urban users, while water for agriculture and farm-related activities is free. Thus, the fees that water users pay are related to the cost of operation fee for the irrigation district infrastructure and for the use of the main infrastructure (dams, channels, etc.) that CONAGUA operates.

[9] The 11 modules are: Acambaro, Salvatierra, Jaral del Progreso, Valle de Santiago, Cortazar, Salamanca, La Purisima, Irapuato, Abasolo, Corralejo, Huanimaro, and Pastor Ortiz, which was added in 2004.

Figure 1. Alto Rio Lerma Irrigation District, ARLID



Source: CONAGUA, 2011.

ARLID's irrigation cycle starts in early November, when the hydrological cycle of the basin begins and when CONAGUA, according to official rules of distribution, estimates the hydrological balance and allocates the water volumes for every one of the nine irrigation districts in the basin. CONAGUA quantifies the total supply of water based on the "restitution runoffs" methodology for every basin; see Appendix J for more details.[10]

The water volume that every module receives is the result of negotiations on irrigation plans between the CONAGUA, the LLC and every module. Within modules, water is allocated among users according to their water rights and the schedule of irrigations beginning in early November (Kloezen, Garcés-Restrepo and Johnson, 1997).

ARLID produces in two different cycles. Fall-Winter (FW), the dry season, is completely dependent on irrigation. Spring-Summer (SS), the wet season, depends mainly on rainfall for satisfying crops' water requirements. Due to a growing water shortage and low average efficiency in transmission (65 percent), ARLID provides irrigation water for only 70 percent of the registered physical surface, where the property rights on the water are concentrated. Since its

[10] Runoffs restitution is the institutional indicator provided by CONAGUA for the allocation of the volumes of water. This measure was not used to estimate the index because it is not a transparent; its methodology is complex, unverifiable, unobservable and unable to be reported in a timely manner.

establishment, ARLID's priority has been the dry season (FW) crop, which depends entirely on irrigation.

In contrast, although average rainfall is enough to grow the SS crop, increasing rainfall variability means that usually one "initial irrigation" is scheduled to ensure that sown seeds germinate. Hence, this "initial irrigation," which can be considered purely a hedge against the risk of low precipitation, could have deep repercussions for water allocation efficiency. This "initial irrigation" by definition creates inefficiency in allocations, which is exacerbated when irrigation districts face extreme weather conditions from climate change.

Thus, it could be the case that authorities are allocating water to an "initial irrigation" in the SS crop to ensure germination even when there is not enough rain to make that happen. Hence, the cost of this hedging strategy is less water for the dry season crop (FW) and therefore lower profits for barley, that season's principal crop.

This research effort relies on the premise that spreading risks through weather-based insurance can support the adoption of changes in water allocation strategies, improving the efficiency of irrigation districts' operations. Thus, weather derivatives based on a rainfall index could essentially substitute for the SS "initial irrigation," thereby spurring higher FW profits. Furthermore, weather derivatives are privately profitable because actuarially fair premiums are low relative to the opportunity cost of the "initial irrigation."[11]

This study will focus on the module Valle de Santiago (Valle). The module was selected for four reasons: i) productive efficiency; ii) proximity to weather stations, iii) cultivation of similar products in the same productive cycles, which is useful for calibration; and iv) a well-organized ownership structure, which is extremely useful for the functioning of insurance schemes.

Valle is the third-largest module in terms of irrigated area and also the most efficient module (with a transmission rate of 92 percent). Valle is located in the center of ARLID, mainly irrigated by gravity. The main products of Valle are barley for the FW cycle and sorghum and corn for the SS or second round of crops. Overall, sorghum represents 38 percent of Valle's production, and barley represents 35 percent.

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[11] This assessment is based on the historically low probability of a rain shortage at the beginning of the SS; even when climate change is considered, the probability remains low.

Based on historical data, the baseline model will provide the optimal water allocation path between both cycles. For hedging water supply risk, the contract's weather index is measured in the area of the isohyets with the highest rain intensity for the Solis reservoir Solis (167 mm/hour), where a significant proportion of the rain occurs.[12] This insurance scheme will cover SS farmers against negative precipitation shocks in Solis reservoir, and it provides incentives for SS farmers to accept a reduced allocation of water. In addition, the introduction of climate change will allow evaluating the effectiveness of this instrument.

4. The Model

This research effort is carried out in three stages. The first stage considers a baseline scenario, which estimates a dynamic water allocation model under uncertainty, originally developed by Miranda and Fackler (2002). Based on stochastic prediction of rainfall, the model characterizes authorities' optimal water allocation between two crop seasons for a single farmer. Then, water consumption is simulated for a planning horizon, and the farmer's welfare can be calculated.

The second stage incorporates IPCC climate change scenarios (on rainfall) into the optimal water allocation model described above. Based on the stochastic rainfall predictions a new optimal water allocation strategy is developed for the farmer.

The third stage introduces the weather insurance contract into the optimal water allocation model to compensate producers for a shortfall in realization of a particular weather variable measured over a certain time period. The model combines an analytical understanding of climate change risk through the inclusion of Global Climate Models predictions into the model and the use of simulation to estimate likely loss profiles to attain more accurate pricing of weather derivatives. Once more, optimal water allocation strategy is calculated under different climate change scenarios and a designated weather derivative instrument. Finally, the water consumption paths and the corresponding farmer's welfare are simulated.

4.1 The Baseline

The baseline scenario models the interaction between a farmer and a central planner in the context of a functioning water rights system with a well-defined regulatory framework. The following assumptions are made to simplify the analysis.

[12] An isohyet is a line that denotes an area of equal precipitation intensity.

Assumption 1: The central planner (water authority) allocates reservoir water among farmers, who are "water takers."

Basically, the central planner knows how many hectares will be planted and thus allocates a specific amount of water per hectare, based on how much water is available. Under this assumption, the farmer is a water taker in the sense that he uses what he receives. On the other hand, the central planner knows the amount of water needed for the farmer to maximize his profits. For that reason, there will be no situation where the farmer gets more water than the optimal amount.

Assumption 2: Under the baseline model there is no climate change and no insurance.

Assumption 3: The representative farmer approach is used to model the farmer's behavior.

The representative farmer approach conceptualizes all producers located in the irrigation district as a single farmer who makes production decisions. Thus, the representative farmer is composed of the aggregate of all farmers in the irrigation district, who have similar local features (farm structure, size, production practices, and production costs). Also, they are subject to the same regulatory framework.

Assumption 4: The farmer has divisible technology.[13]

Valle de Santiago has two main crop activities, and each is carried out during different seasons. The farmer grows barley during the FW season and cultivates sorghum in SS season. Thus, production decisions per hectare are analyzed under different water allocation strategies. For the sake of the analysis, it is assumed that the same farmer cultivates barley and sorghum. This assumption has powerful implications because the irrigation districts are water rights systems that provide water users in the module with the allocation determined by their non-transferable water rights, established by law and linked to a particular piece of land property. Consequently, this supposition simplifies the problem to an intertemporal reallocation of the same volume of water, which could represent an improvement in the efficiency of water efficiency.[14]

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[13] Henceforth, farmer and representative farmer will be used interchangeably.

[14] Since water rights are non-transferable, the introduction of insurance does not automatically affect water rates. However, this assumption can be relaxed for a deeper analysis of the issue.

Assumption 5: The farmer's technology is characterized by quadratic production functions.

The farmer's technology is characterized by quadratic production functions. Barley and sorghum crops are represented as a function of water used in a quadratic specification.

Because barley is cultivated in the dry season (fall-winter), it is totally dependent on water allocated by the central planner. Sorghum, however, which is raised during the rainy season (spring-summer), has two sources of water: rainfall and reservoir. The production functions for each crop are shown next,[15]

$$barley_t = a_0 + a_1(irrigated\ water)_t + a_2(irrigated\ water)_t^{\ 2} \quad (1)$$

$$sorghum_t = b_0 + b_1(irrigated\ water + rainfall)_t + b_2(irrigated\ water + rainfall)_t^{\ 2} \quad (2)$$

Note that the production function of sorghum production function, grown during the wet season, depends on the amount of water the farmer's field receives. Sorghum production and the farmer's profit are thus more uncertain than in the case of barley.[16]

Assumption 6: Each farmer is small enough that input and output prices are not affected by farmer's decisions.

Farmers' profits for each crop are expressed separately. The farmer's profit functions in the Fall-Winter (FW) and in the Spring-Summer (SS) are defined as

$$Profit_{\mathrm{FW}} = Price_{barley} \times barley - Price_{water} \times (Irrigated\ Water) - other\ cost \quad (3)$$

$$Profit_{SS} = Price_{Sorghum} \times Sorghum - Price_{water} \times (Irrigated\ Water) - other\ cost \quad (4)$$

The barley and sorghum prices are assumed to be stochastic. In both equations (3) and (4), the water price represents the cost of water allocation that must be paid by the farmers. This fee might represent the marginal cost of water provision, which is constant over time.[17] On the other hand, the planning authority may decide to vary the fee depending on the allocation level so as to regulate potential demand.

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[15] The constant terms in equations (1) and (2) represents conventional inputs (e.g., labor and capital) as constant.

[16] Appendix A shows estimation results for these equations. Estimated coefficients for both regressions are statistically significant at the 5 percent level. The r-squared for the barley regression is 30.3 percent, while it is 21.6 percent for the sorghum regression. In addition, all coefficients exhibit the expected sign. Water has a positive effect on yields in both cases and exhibits diminishing marginal productivity, which denotes the concavity of the production function.

[17] If it were not constant, it would be a decision variable for the planner. In that case the profit maximization problem for each farmer would give us water demand as a function of water price. Thus, the dynamic optimal allocation would depend on the optimal path of the water price established by the planner.

Assumption 7: Inputs for production are classified into two groups: water and other inputs. It is assumed that the farmer has already decided the amount of other inputs used.

The current model evaluates the marginal effects of irrigation water and rainfall on crop output, holding other conventional inputs constant. However, the input usage depends on the weather because of pest intensity. Thus, it could be the case that input costs increase over time, especially if extreme weather events occur. In that case, the simulations might not reflect how this input issue affects the farmer's profit and welfare.

Assumption 8: The representative farmer is risk-averse and derives utility from profits.

Financial and economics literature suggest the use of Constant Relative Risk Aversion utility (CRRA) to represent the agent's preferences (Boulier, Huang and Taillard, 2001; Cairns, Blake and Dowd, 2006). Bradt, Santa-Clare and Valkanov (2009) point out that CRRA possesses desirable properties such as double differentiability and continuity that increases the efficiency of numerical optimization algorithms, while incorporating preferences toward higher-order moments in a simpler way. Thus, the representative farmer's utility function in any year is equal to:

$$utility = \frac{profit_t^{1-\gamma}}{1-\gamma} \quad (5)$$

The risk aversion parameter γ in (5) reflects producers' willingness to forgo a certain amount of risk-premium in exchange for elimination of uncertainty.

Assumption 9: The amount of available water per hectare at the beginning of t+1 for the irrigation module must be at least equal to the volume of available water per hectare at the beginning of t minus the released water during seasons FW and SS per hectare plus the random inflow (runoff) to the reservoir attributable to that module, also per hectare.

The amount of water needed to carry out planting activities is provided by CONAGUA, which manages water in the Lerma-Chapala Basin and the Solis reservoir. CONAGUA makes up the difference between supply and demand for water in period *t*, which is obtained by estimating the amount of available water at the end of period *t*-1. Demand for water is estimated on the basis of the intended planting estimates that ARLID submits to CONAGUA. Once the balance is known, CONAGUA allocates a specific amount of water to the Valle de Santiago module[18]

[18] The module Valle de Santiago is located in the Municipality of Valle de Santiago.

according to its water rights at the beginning of agricultural year t (prior to the start of the fall-winter season).[19] Finally, the LLC and Valle de Santiago module must distribute water volumes among their users in the module. Additional details on the procedures and institutional framework of water management in ARLID are found in Appendix I.

Let S_t be the amount of available water for irrigation in module per hectare in the dam. During the rainy season the reservoir levels are replenished by random inflows to the reservoir with the volume of ε_t units of water per hectare from reservoirs belonging to the module. The local water authority releases $X_{FW,t}$ units per hectare for irrigation during the FW season (the dry season) and $X_{SS,t}$ units per hectare for irrigation during the SS season (the rainy season). The reservoir level at the beginning of each year is then represented by a controlled Markov process.[20] This dynamic, which summarizes the assumption, is represented by the following transition equation:

$$S_{t+1} \geq S_t - X_{FW,t} - X_{SS,t} + \varepsilon_t \quad (6)$$

Assumption 10: The objective of the central planner (LLC authority) is to find the optimal water allocation strategy for both seasons, maximizing the total discounted expected utilities over the planning horizon.

This means, the sum of means for farmers' expected utilities from farming profit over a certain number of periods expressed in present-day monetary units. This approach assumes that production decisions are made centrally. Thus, the optimal allocation strategy satisfies the Bellman equation

$$V(s_t) = \max_{x_{fw,t}, x_{ss,t}} \{u(Profit_{FW} + E(Profit_{SS})) + \delta EV(s_{t+1})\} \quad (7)$$

Bellman equation (7) is maximized subject to equation (6). Given that SS-profit depends on x_{SS} and random rainfall in Valle, equation (7) considers the expected utility for the SS-farmer. Parameter δ represents the discount factor. It can be rewritten as the Euler equilibrium condition on the shadow price of used water $\lambda(s)$ so that

[19] Kloezen and Garces-Restrepo (1998), Kloezen, Garces Restrepo and Johnson (1997).

[20] Markov process is a random process in which the probability of any outcome in a given period depends only on the events in the previous period (no long-term memory). A controlled Markov process is a Markov process in which the outcome is also affected by a deterministic decision made each period.

$$\frac{\partial u(\cdot)}{\partial x_{FW}}\left[p_{barl}\frac{\partial Barley}{\partial x_{FW}}-q\right]-\frac{\partial u(\cdot)}{\partial x_{SS}}E\left[p_{sorg}\frac{\partial Sorg}{\partial x_{SS}}-q\right]-\delta E\lambda(s_{t+1})=0 \quad (8)$$

$$\lambda(s_t)=E\left\{\frac{\partial u(\cdot)}{\partial x_{SS}}\,E\left[p_{sorg}\frac{\partial Sorg}{\partial x_{SS}}-q\right]\right\}+\delta E\lambda(s_{t+1}) \quad (9)$$

It follows that the condition that must be satisfied along the optimal path is

$$\frac{\partial u(\cdot)}{\partial x_{SS}}E\left[p_{sorg}\frac{\partial Sorg}{\partial x_{SS}}-q\right]=\frac{\partial u(\cdot)}{\partial x_{FW}}\left[p_{barl}\frac{\partial Barley}{\partial x_{FW}}-q\right]+\delta E\lambda(s_{t+1}) \quad (10)$$

Equation (10) specifies the central planner's objective. On the margin, the benefit received by the SS farmer from releasing one unit of water must be equal to the FW farmer's marginal benefit from retaining the unit of water plus the discounted expected benefits of having that unit of water available for either the SS farmer or the FW farmer in the following year.

Hence, equation (10) along with constraint (6) makes it possible to calculate the reservoir's optimal allocations for both seasons (SS and FW) for all possible reservoir storage levels s_t. Under this scheme, optimal water allocations are made at the beginning of period t, so that the farmer uses x_{FW}, and $x_{SS}+\eta_t$. It could be the case that the farmer is using more water than he needs in SS. In that case, the model assumes he uses that excess water in different activities that provide residual utility.

Once, these allocation strategies are known, the allocated water volumes for each farmer can be projected over the planning horizon. Numerical analysis is used to obtain optimal allocation strategies.

4.2 Incorporating Climate Change

In the previous section, an optimal water allocation model was presented. This was required in order to obtain historical time series data for η and ε to estimate their probability distribution functions. Now, we focus on how to introduce climate change in that model.

The precipitation projections for different regions around the world can be obtained for some climate change scenarios. Thus, once the geographic zones for both the field and the dam are identified, rainfall projections for η and ε can be obtained for some scenarios. Based on those projections, the probability distribution functions h_η and h_ε can be re-estimated and incorporated into the model and new irrigation policy can be derived.

4.3 Incorporating Weather Insurance

The general idea of a weather-based insurance (or weather derivatives) is to compensate producers for a shortfall in the realization of a particular weather variable (e.g., precipitation) measured over a certain time period. If weather variable is sufficiently correlated with producers' profit, the payoff of the weather derivative would then offset the producers' loss.

During the FW season, crop activities depends exclusively on irrigation water x_{FW}, but in the SS the farmer has two sources of water: rainfall η and irrigation water x_{SS}. In this context, when there is not enough water flowing into the reservoir to meet all of the water demand ($x_{FW} + x_{SS}$), barley production can be compromised because the FW season is the drier one. However, if that were the case, sorghum production could depend more on water from rainfall. In this context, the central planner would like to prioritize water requirements in the dry season (the first one).

In this work, an index insurance scheme is proposed based on the rainfall level (ε) at Solis Dam. It is assumed that farmer is willing to use β% of the original x_{SS} during the rainy season. Moreover, the total amount of irrigated water available during the first season should be $x_{FW} + (1 - \beta\%)x_{SS}$. However, given that rainfall η is a random variable, the farmer could be better off if he would be compensated in the event of rainfall shortages. Based on this new water allocation, the representative farmer's profit can be derived.

Farmer should choose the parameter β such that it maximizes his expected utility assuming that he would buy weather insurance contract.

4.4 Designing the Weather Insurance Contract

As was stated above, the farmer is willing to give up $(1 - \beta\%)x_{SS}$ units of water unless he is compensated for rainfall shortages. This section is established how parameter β is chosen, together with the insurance contract. Following Vedenov and Barnett (2004), a weather derivative is modeled as an "elementary contract" with the payoff according to the schedule:

$$I(\varepsilon|x, \varepsilon^*, \mu) = x \times \begin{cases} 0 & if\ \varepsilon > \varepsilon^* \\ \frac{\varepsilon^* - \varepsilon}{\varepsilon^* - \mu\varepsilon^*} & if\ \mu\varepsilon^* < \varepsilon \leq \varepsilon^* \\ 1 & if\ \varepsilon \leq \mu\varepsilon^* \end{cases} \qquad (11)$$

where ε is a realization of the rainfall at Solis Dam. The contract starts to pay when ε falls below the specified "strike" ε^*. Once rainfall falls below the limit $\mu\varepsilon^*$, the insured receives the maximum indemnity x. When rainfall falls between the strike and the limit, the contract pays a proportion of the maximum indemnity. The parameter μ varies between 0 and 1, with the limiting case of 0 corresponding to the conventional proportional payoff with deductible, and 1 corresponding to a "lump-sum" payment once the contract is triggered regardless of the severity of the shortfall. The contract is completely designed once the values of strike, limit and maximum indemnity are specified.

In order to price the designed contract for a given set of parameter values, the probability distribution of ε is used. The actuarially-fair premium is set equal to the expected payoff of the contract, i.e.,

$$P(x, \varepsilon^*, \mu) = \int I(\varepsilon | x, \varepsilon^*, \mu)\, h_\varepsilon(\varepsilon) d\varepsilon \quad (12)$$

The parameters in equation (11), together with parameter β, are selected so as to provide maximum risk reduction for the farmer who is exposed to the risk of area-wide yield loss. For the sake of simplicity, the strike is selected as the long-term average of rainfall. In particular, the parameters are selected so as to maximize the expected utility

$$max_{\beta,\mu,x} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} u\big(Profit_{FW} + Profit_{SS} + I(\varepsilon | x, \varepsilon^*, \mu) - P(x, \varepsilon^*, \mu)\big)\, h(\eta, \varepsilon) d\eta\, d\varepsilon \quad (13)$$

where the profits defined in (13) take into account water allocation defined in the previous section. $h(\eta, \varepsilon)$ is the joint probability distribution of η and ε. In this work, it is assumed that $h(\eta, \varepsilon) = h_\eta(\eta) h_\varepsilon(\varepsilon)$. In other words, rainfall on the field and on the location of the dam location are independent of one another.

5. Data Selection Process

SIAP[21] provides historical data series from 1985 to date on sorghum and barley yields at the module level, and CONAGUA provides historical water allocation for both sorghum and barley crops from 1985 to date. SMN[22] provides monthly rainfall data on Valle de Santiago and on Solis

[21] SIAP stands for Sistema de Información Agropecuaria y Pesquera (Information System for Agricultural and Fisheries).
[22] SMN stands for Sistema Meteorológico Nacional (National Meteorological System).

Dam, which are available since 1910 to date.[23] Reservoir storage levels and volumes of water available in the Lerma–Chapala basin were obtained from Organismo de Cuenca Lerma-Santiago-Pacífico, CONAGUA central headquarters in Mexico City and CONAGUA offices in Guanajuato. Climate change scenario data were obtained from the Instituto Nacional de Ecología (INE).[24] INE developed an application of the climate prediction and predictability mechanism originally developed by the National Oceanic and Atmospheric Administration (NOAA).[25] This mechanism simulates data on climate change scenarios based on 24 General Circulation Models for all Mexican territory. Thus, precipitation projections from the Geophysical Fluid Dynamics Laboratory Coupled Model, Version 2.X (GFDL.CM2.X) were incorporated into the model.

5.1 Descriptive Statistics

Table 1 displays descriptive statistics for sorghum and barley yields and water allocated.[26] The average for barley and sorghum yields were 5.06 and 8.46 tons/ha, respectively, during the study period. The highest standard deviation was 0.99 tons/ha for sorghum yield. The average irrigated water for barley and sorghum were 5,778 and 5,438 m3/ha, respectively. The highest standard deviation was 1,072 m3/ha for sorghum. Figure 2 shows the average annual rainfall distribution by month during 1985-2010. It suggests rainfall is heavy in June through September, which is part of the Spring-Summer in Mexico.

Before estimating weather-yield and weather-water models, several unit root tests were performed to detect whether yields and weather variable have stochastic trends. We followed the unit root test strategies of Elder and Kennedy (2001) and Harvey et al. (2009). Results suggested most of the series do not exhibit unit root. The trend stationary variables were detrended following the procedure describe in (Vedenov and Barnett, 2004); and for those stationary in difference, we applied procedures suggested by Enders (2004).[27]

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[23] Rainfall data were collected from weather station 11079 for Valle de Santiago and from 11076 for Solis Dam.
[24] http://zimbra.ine.gob.mx/escenarios/
[25] http://www.gfdl.noaa.gov
[26] Sample statistics on rainfall level at Valle de Santiago and the Solis Dam Solis are available upon request.
[27] Unit root results are available upon request.

5.3 Estimating the Production Function

Estimation results for barley and sorghum production function (see equations (2) and (3)) are presented in Table 2.[28] Estimated coefficients for both regressions are statistically significant at the 5 percent level. The r-squared is 30.3 percent for the barley regression and 15.6 for the sorghum regression. In addition, all coefficients exhibit the expected sign. Water accessibility has a positive effect on yields in both cases and exhibits diminishing marginal productivity.

5.4 Estimating Probability Distribution Functions

A gamma distribution was used to estimate the probability distribution for cumulative rainfall. Cumulative rainfall was modeled as a discrete variable by applying the following steps. First, 1,000 random numbers were generated from the continuous gamma distribution, and these random values were used to create six intervals.[29] Thus, the discrete probability distribution of cumulative rainfall suggests six possible levels, with their respective probabilities.

Precipitation projections were generated for two regions in the State of Guanajuato, Mexico: Municipality of Valle de Santiago, where the Valle module is located, and Acambaro Municipality, where the Solis Dam is located. Those projections, which range from January 2012 to December 2050, were used to estimate the probability distribution under different climate change scenarios.

6. Results

In this section, the simulation results for the model presented above are displayed. It is solved by using the numerical solution for a stochastic infinite discrete-time dynamic model developed by Miranda and Fackler (2002). In that setup, the reservoir level (S_t) and irrigated water (w_1, w_2) are defined to be the state and control variables, respectively, and those variables are defined as discrete and finite.

The simulations were performed using the risk aversion parameter (γ) obtained from the application of the method suggested by Babcock, Choi and Feinerman (1993). A 5 percent discount rate is assumed,[30] and the price of water was set at 160 pesos per 1,000 m^3. Barley and

[28] Based on a box-plot analysis, outliers were not considered.
[29] Six intervals were used to avoid "out of memory" computer problems.
[30] The model was also estimated using discount factors of 1 percent and 10 percent. In general, the results were consistent.

sorghum prices were assumed to be stochastic. Thus, autoregressive models for those output prices were estimated based on historical time-series data. Based on that, predictions were made and incorporated into the dynamic model. First, results for the baseline scenario are shown, followed by simulation results under climate change and specific insurance schemes.

6.1 Baseline Model

Figures 3 and 4 show the optimal irrigation policy for both seasons. For example, when the water available is 6.8 thousand of cubic meters per hectare (TM3H), barley and sorghum farmers receive 4 and 2.6 TM3H, respectively. It means that FW-and-SS farmers receive 60.6 percent and 39.39 percent of the total amount of water allocated, respectively.

Figure 5 shows the optimal state path. Based on simulated results for 50 years, the steady state for reservoir level is 10.81 T3MH. In other words, in the long run the central planner would have 10.81 T3MH of water to allocate between FW and SS farmers.

Figure 6 shows the steady-state distribution for the reservoir level, and Figure 7 shows the allocation of water between FW and SS farmers for different reservoir levels. For each reservoir level, FW farmers receive more water than SS farmers do.

This result is consistent with the model. When the central planner allocates water between both types of farmers, he knows that SS farmers are able to use rainfall in their crops. For that reason, the central planner allocates more water for FW farmers, maintaining this policy for different reservoir levels. This optimal policy is quite similar to that observed in the historical data (see Figure 8). Since 1989, water allocated to FW farmers has on average represented 66.7 percent of total water allocations.

6.2 With Climate Change

In its special report, the Intergovernmental Panel on Climate Change (IPCC, 2000) considers future greenhouse emissions as the result of a very complex dynamic system, determined by driving forces such as demographic development, socio-economic development and technological change.[31] The IPCC developed 40 different scenarios, grouped into families according to common themes, to evaluate the possible states of the world given different assumptions on global population, economic growth, and final energy use. For the sake of the

[31] Textual citation from IPCC (2000).

analysis, this study focuses on A2 and B1, which are more consistent with conditions in Mexico. However, only results for the A2 scenario are displayed. A brief resume of the scenarios' features is cited.[32]

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

In Appendix C, simulation results are shown for a 5 percent discount rate. Figure 9 shows the optimal irrigation policy for both seasons under scenario A2 scenario.[33] For example, when the water available for irrigation in the reservoir is 6.8 thousand cubic meters per hectare (TM3H), barley and sorghum farmers receive 3.8 and 2.8 TM3H, respectively. This means that FW and SS farmers receive 57.58 percent and 42.42 percent, respectively, of the total amount of water allocated. Figure 10 shows the allocation of water allocated between FW and SS farmers for different reservoir levels. For each reservoir level, FW farmers receive more water than SS farmers do.

This result is consistent with the model. Given that the SS farmers may also use rainfall for their crops, the central planner allocates more water for FW farmers. This policy holds for different reservoir levels.

Figure 11 shows the optimal state path. Based on simulated results for 50 years, the steady state for reservoir level is 8.09 TM3H. This is the long-run volume of water available that the central planer would allocate between FW and SS farmers (see Figure 12).

[32] The description of each scenario is taken textually from IPCC (2000).

[33] Simulations for scenario B1 were also carried out, but the results were significantly different from those presented for scenario A2. For that reason they are not shown here but are available upon request.

Figure 13 shows the optimal value function for different water levels with and without climate change. For all these cases, the greater the reservoir level per hectare, the higher the utility obtained by farmers. The steady state for reservoir water, however, is higher in historical data than in scenario A2. In addition, extreme events (excessive rainfall or lack of rain) are more likely in scenario A2 than in the basic case. Finally, optimal allocations made by the central planner produce higher utility with historical data than in Scenario A2.

6.3 With a Weather Insurance Scheme

The present section shows the simulation results for the dynamic water allocation model with IPCC scenarios predictions for precipitation. The simulation procedure was carried out in two steps. First, equation (10) is modeled to estimate the optimal value for β and the contract parameters. Second, new water allocation patterns are calculated based on those estimations.

The simulation results suggest that the optimal value for β is 75 percent, while the contract parameters are the following: ε^* is equal to 562.77 mm, λ is equal to 0, and the maximum liability is 4600 pesos per hectare. The premium is equal to 243.8 pesos per hectare. This standard contract is graphically illustrated in Figure 14.

In Appendix D, simulation results are shown for a 5 percent discount rate. Figures 15 and 16 show the optimal irrigation policy for both seasons in scenario A2 with insurance.[34] It is important to note that irrigated water during the fall-winter seasons increases when the reservoir level is less than 4.5 TM3H. However, when the level is greater than 5 TM3H, the farmer receives around 3 TM3H. On the other hand, the irrigated water has a different pattern. When the reservoir level is less than 8 TM3H, the farmer receives around 1 TM3H; after that he receives 5.2 TM3H.

Figure 17 shows the optimal path for the reservoir level. After 10 years, that level is 8.60 TM3H. Figure 18 shows the steady state distribution, which as expected is centered on the steady state.

Figure 19 shows the optimal value function under Scenario A2 with and without insurance. As expected, under different reservoir levels farmers are better off when they are able to buy weather insurance.

[34] Simulations for Scenario B1 were also carried out, but the results were significantly different from those presented for Scenario A2. For that reason they are not shown here but are available upon request.

7. Chancay-Lambayeque Irrigation District (CLID), Lambayeque, Peru

For the next two decades, higher temperatures predicted for the Andean highlands might lead to rapid glacier retreat. In Peru this this situation could disrupt the water cycle in the glacier-dependent basins, affecting water regulation and availability (Servicio Nacional de Meteorología e Hidrología, SENAMHI, 2009).[35] Without glaciers to regulate water flow, flood will alternate with drought. In addition, coastal rivers will become more irregular, triggering conflicts over water use for irrigation vs. other economic activities such as mining industry and urban consumption.

According to the SENAMHI (2009), in the next several decades the Northeast highlands (Cajamarca) will experience precipitation deficiencies of between 10 and 20 percent. Although precipitation shortages in that area will to some extent be offset by precipitation increases in the Central East highlands, the predicted rainfall deficiency could have important implications for irrigation districts in Peru because the main rivers originate in the Andean highlands (SENAMHI, 2009).

The CLID is located in the Chancay-Lambayeque lowlands basin on the Northeast Coast of the Department of Lambayeque. A desert sub-tropical ecosystem with semi-desert climate and vegetation is predominant, which makes agriculture completely dependent on irrigation.[36] The CLID is one of the four largest irrigation districts in Northern Peru, representing 10 percent of the country's irrigated area. For the period 2009-10, CLID produced 3.7 million tons of agricultural products. In the decade of the 2000s, the CLID produced on average 16 percent of the country's rice, 26 percent of its sugarcane, 10 percent of its yellow corn and 10 percent of its mango crop (MINAG, 2011).[37]

The CLID obtains all of its water supply from the Chancay River, which originates in the Mishacocha lagoon in the Andean highlands, at 3,800 meters above sea level. Consquently, rain delays or shortages reduce the Chancay River's flow, in turn causing decrease in yields (or crop losses) due to water stress.

From east to west, the Chancay River flows from San Juan River, in the Andean zone, to the center of the Basin Lambayeque and within the Tinajones system. There, the Raca Rumi

[35] National Service of Meteorology and Hydrology.
[36] According to the Autoridad Nacional del Agua (ANA), the CLID has 118,835.71 hectares with irrigation, and 87,245.52 of them are under concession.
[37] Ministry of Agriculture.

water intake captures part of the water for its storage in the Tinajones Reservoir. The remaining flow continues through the Chancay River to the Puntilla distributor channel, where flows from the Tinajones Reservoir and Chancay River are divided into three watercourses (or channels of distribution): the Taymi Channel, which flows to the North; the Reque River, which flows south to the Pacific Ocean; and the Lambayeque River. Waters from the Taymi Channel and Lambayeque River are completely consumed by the CLID.

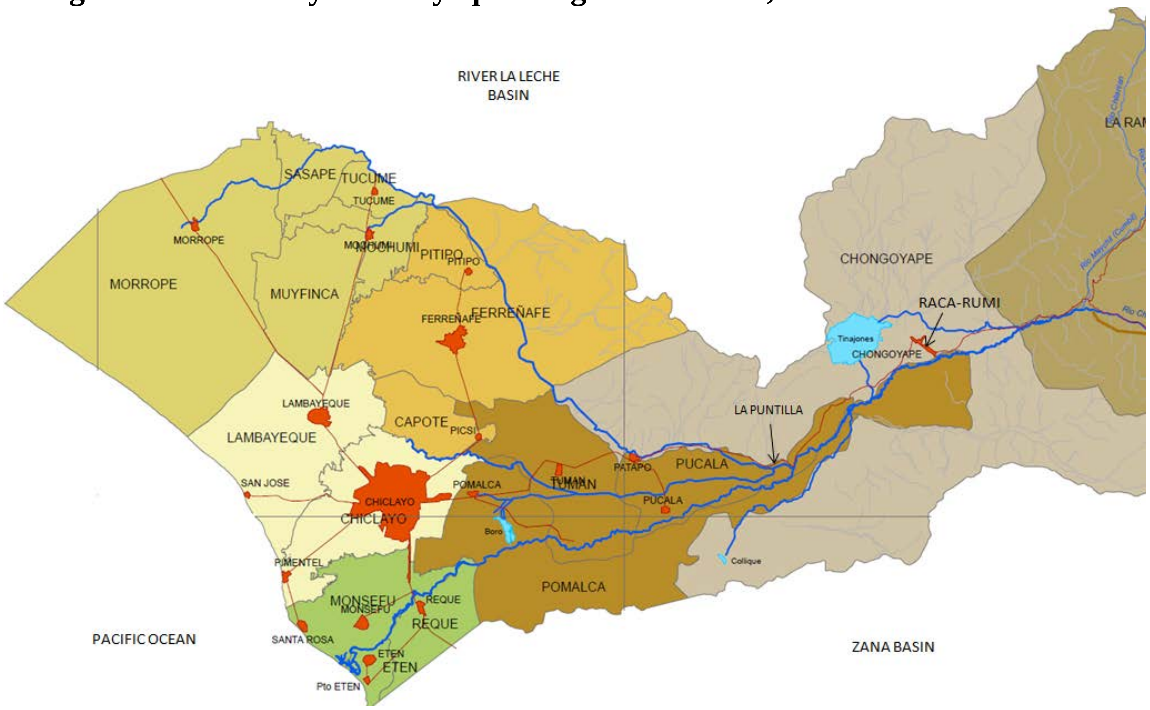
The Tinajones hydrological system is basically a run-off-river system with a relative small off-river storage reservoir, where both structures function complementarily (Vos, 2005). Chancay River discharges are abundant but irregular and depend mainly on precipitation in the Cajamarca Highlands (4,000 – 6,000 m), which take place between December and March and account for 60 to 70 percent of the annual unloading of the rivers. The role of the Tinajones Reservoir is primarily to store water from the Chancay River's during the wet season (December-March) for distribution during drier months, usually from July to September. Also, the Tinajones Reservoir complements the Chancay River's to provide regular flows into the three channels of distribution during the rainy season.

Thus, the Chancay River and Tinajones Reservoir's combined capacity guarantees the efficiency of the on-request delivery schedule. This system is a result of the volumetric irrigation service fee payment, which has been enforced since 1992 instead of an area-based fees system. Under this regime, water is submitted to the users in water turns after they buy *riegos* (one hour of water delivery with a constant 160.1 liters per second or a 576-m3 flow).

For purposes of operation and management, the CLID is organized in 15 Irrigation Commissions (IC) managed by a Weather Users Association, WUA (in Spanish, *Junta de Usuarios*), which formalized and issued individual water rights. The National Water Authority (NWA) along with the WUA charge and deliver the water for all Irrigation Commissions, which monitor the allocation of the resource.[38]

[38] The updated registry of irrigators, with their irrigated area and their water rights, has made it possible to improving water distribution, billing and collection of water charges.

Figure 20. Chancay-Lambayeque Irrigation District, CLID



Source: Autoridad Nacional del Agua (2011).

Every year, water users (cane farmers in early July, and in September rice farmers), register their sowing intention areas with their Irrigation Commissions. In late July, prior to the beginning of those crops' seasons, the National Water Authority (Spanish acronym, ANA) issues its forecast on the Chancay River's flows at the 75 percent persistence level.[39] This monthly forecast is then used as a reference point to contrast with the actual flows of the river. These guidelines subsequently determine the approval of the requested planting area. Final planning of the campaign is carried out in November, based mainly on the analysis of the ANA's persistence flow, the remaining water in the reservoir, the recuperation water and the underground water.

For example, if the Chancay River's flows are low (around 30m3/second), and the reservoir has a level storage below 60,000 m3, then 70 percent of the registered area is approved. On the other hand, if the Chancay River's flow discharge increases above 80 m3/sec, then 100 percent of the registered area is approved. For this reason, the rice farmers are willing to wait for an increment on the river flow. However, the resulting delay of planting season, from December

[39] The hydrological year of the Chancay-Lambayeque basin starts in September and finishes in August; while the agronomic year starts in August and finishes in July.

to January, could bring negative consequences in the rice yields, because of insufficient temperatures.

Annually, the ANA authorizes a volume between 600-700 millions of cubic meters (Mm3), which is about 40 percent of the area that farmers request.[40] Because of this situation, the CLID has adopted strategies to cope with water shortage. Crops such as rice, with a high demand for water and with five-month growing season that match with the rainy season in highlands, are restricted.[41] Before the growing season begins in late November, the ANA authorizes the hectares of rice that will be planted and applies row restrictions on rice cultivated area according to the volume of available water in the reservoir and the forecast on the Chancay River's flows.

In the case of sugar cane, a 12-month crop with year-round water requirements, with a high demand for water during the three-month planting season and only maintenance needs during the remainder of the year.[42] No row restrictions are applied to the sugarcane area, but the coefficients of monthly irrigation are reduced. For example, if during July the level of reservoir storage and the river flows are low, the irrigation coefficient will be reduced from 1,200 m3/ha to 480 m3/ha, which is 40 percent of the original volume.

Rice usually suffers more than sugar cane from water stress. When drought occurs, water shortage has more serious repercussions for rice because of a flood irrigation system that requires the reapplication of periodic irrigations. In contrast, sugarcane can smooth water stress, as its fields are located near large channels and have access to underground water. Furthermore, sugarcane farmers traditionally have more political influence and are able to lobby ANA and CLID authorities for higher water allocations.

Thus, in the hypothetical case of a drought in the CLID, given the number of rice hectares approved, the rice farmers receive their payments and the CLID authority could reallocate the available water for the remainder of the season. Thus, the perennial crop (sugarcane) will not receive adjustments in its irrigation coefficients, while rice farmers smooth their income. The rice crop would therefore absorb the rain shortage risk and, through the weather derivative

[40] The approval of planned planting for the whole CLID (118,835.71 hectares) would require a volume of at least 1,656 (Mm3).
[41] Rice requires on average 12,000 m3/ha of water, and its growing seasons goes from December to May.
[42] Sugarcane requires in average 20,000 m3/ha. The planting-harvesting periods in sugar cane plant are 20 months for the first harvest and 14 months for the second and subsequent harvests is 14 months. In some irrigation commissions farmers start the planting season when the river flows are higher, but this is not a necessary condition.

indexed to the precipitation that occurs in the Cajamarca Highlands, would transfer weather risk to global markets.

This study will focus on Ferrenafe Irrigation Commission (FIC), which was selected for its high degree of water conduction efficiency (55 percent) and its advanced organizational structure. The FIC has the highest water demand among irrigation commissions in the CLID, and the main crops in its boundaries are rice and sugarcane.

For the sake of the analysis, the baseline model considers a representative farmer who grows two crops, rice and sugar cane. Each irrigation commission receives a certain share of the total volume awarded to the CLID as a result of negotiations on irrigation plans between the National Water Authority (ANA) and the farmers. The baseline uses a dynamic allocation model to obtain the optimal water allocation for the two types of farmers, given that the index insurance scheme will provide incentives for farmers to carry out the planting stage in the right period.

In a second stage, alterations in precipitations patterns associated with climate change are added to the model and optimal allocations of water are again determined. In the third stage, precipitation in the Cajamarca highlands, where the isohyets with the highest precipitation intensity occur, was selected to estimate the index.[43] This index satisfies the conditions of being transparent, readily verifiable, objective and measurable. The vulnerability of this index to spatial basis risks, however, depends on the index itself as well as the risks being targeted (Hellmuth et al., 2009).

Finally, the effectiveness of this insurance scheme will be verified by the implementation of Climate Change Scenario A2. This scenario anticipates for 2030 a 10-20 percent in the Northeast Region and the Cajamarca Highlands, where the runoffs of the Chancay River Basin originate, and a change in the seasonal pattern for rain (SENAMHI, 2009).

8. The Model

As the IPCC (2007) suggests, potential effects of climate change include increasing variability of precipitation patterns and higher probabilities of extreme event. In particular, SENAMHI has forecast important precipitation deficiencies in the Andean highland (Cajamarca), where the CLID's main rivers originate.

[43] The selection of the weather stations was also limited by the availability of information. The SENAMHI did not have complete historical records from all existing weather stations.

As stated above, the goal of this section is to determine the optimal water allocation for the CLID under different climate changes scenarios and according to when farmers can buy weather insurance. In this context, the same dynamic water allocation model is applied for the CLID with its differences and particularities.

Since all crops in the CLID are totally dependent on its basin's run-offs, cycles are not distinguished. Instead, it is noted that every crop is grown in different periods during the year. Consequently, the best candidate for insurance is the crop most temporally associated with the rain season in the Cajamarca highlands. Thus, although the occurrence of precipitation differs spatially, the uncertainty of rain is temporally associated with the crop.

The representative farmer approach is used to model the farmer's behavior in the Ferrenafe Irrigation Commission (FIC).[44] The area served by Ferrenafe mainly grows two crops, sugarcane and rice; the former has year-round water requirements. So, from May to October, when the Chancay flow is almost dry, water from the Tinajones Reservoir is mainly used to irrigate this perennial crop.

In contrast, rice has a six-month production cycle (December to May), which coincides with the Chancay's peak flow and the hottest summer months, which meet rice cultivation's high temperature and water requirements; about 63 percent of the water volume supplied by FIC is for rice irrigation. At the beginning of November, the National Water Authority (ANA) agrees to provide a specific volume of water per hectare to rice farmers and sugarcane farmers.[45]

In years with low river flows, severe water scarcity exists and the cultivated area of rice is reduced. In this case, even rice fields with guaranteed irrigation can struggle with reduced water supply. Thus, rice farmers are particularly vulnerable to alterations in precipitations patterns in the Cajamarca Highlands (delays and reductions), and climate change will increase the risks those farmers already face.

As noted above, in the case of the CLID, the baseline scenario models the interaction between farmers and a central planner in the context of a functioning water rights system with a well-defined regulatory framework. While the following assumptions are made to simplify the analysis, they will be described only briefly here because a more detailed analysis is available in Section 5 above.

[44] Hence Ferrenafe refers to the irrigation Commission of Ferrenafe.
[45] For additional details on procedures and institutional framework for the management of water in CLID, see Appendix J.

After the National Water Authority issues its forecast on flows of the Chancay River at the 75 percent persistence level, water allocations for the agricultural season are approved in November. Those allocations are based mainly on ANA's forecast, the amount of water remaining in the reservoir, water recovery and underground water. This monthly forecast on the River's flows is used as a reference point to contrast with the true flows of the river and to approve the requested area for planting in the CLID. For example, if the Chancay River's flows are low (around 30m3/second) and the reservoir has a storage level below 60,000 m3, then 70 percent of the registered area is approved. If the Chancay River's flow is higher than 80 m3/sec, then 100 percent of the registered area is approved.

Let S_t be the amount of available water storage in the Tinajones Reservoir for irrigation in the district. During the rainy season, the Chancay River's flows (ε_t), which replenish the reservoir and supply water for irrigation to the whole CLID, are fed by random rainfalls in the Andean highlands. The correlation between Chancay river flows (ε_t), measured in the Raca Rumi water intake, and the average accumulated precipitation for the three weather stations (Chancay-Banos, Santa Cruz and Llama) is 71 percent.[46] The local water authority releases $X_{Sugar,t}$ units for irrigation during sugarcane activities (throughout the year) and $X_{Rice,t}$ units for irrigation during rice activities (December-May). The available water for irrigation in the CLID at the beginning of each year is represented by a controlled Markov process.[47] This dynamic is represented by the transition equation

$$S_{t+1} \geq S_t - X_{Sugar,t} - X_{Rice,t} + \varepsilon_t \tag{14}$$

8.1 Incorporating Climate Changes Scenarios for CLID

In 2001, the IPCC developed several climate scenarios to investigate alternative future developments under a set of assumed conditions. In this section, the effects of climate change scenarios on the baseline model are analyzed.

[46] The high correlation between Chancay River flows and average accumulated precipitation could imply a reduction of the basis risk in the proposed insurance scheme.
[47] A Markov process is a random process in which the probability of any outcome in a given period depends only on the events in the previous period (no long-term memory). A controlled Markov process is a Markov process in which the outcome is also affected by a deterministic decision made each period.

SENAMHI (2009) carried out an evaluation on different climate change scenarios in Peru according to IPCC (2007) definitions. Six General Circulation Models were analyzed to obtain Scenario A2 on changes in greenhouse gas emissions for the year 2030.[48]

Conclusions derived from SENAMHI's study indicate that precipitation for the next two decades will be similar to historical averages in terms of its intensity and distribution. For this reason, the scenario's predictions for the year 2030 are given in terms of anomalies or percentage variations from historical averages.

Thus, in Scenario A2, SENAMHI (2009) projected for the next two decades a 10 percent deficiency in precipitation for the Northeast Highlands (Cajamarca). For the sake of the analysis, an impact evaluation of climate change on water allocation policy in two different A2 scenarios will be carried out. The first scenario assumes a 5 percent deficiency in precipitation and the second a 10 percent deficiency. In both cases, the river's flow (ε_t) is modified, and consequently its probability distribution.

8.2 Incorporating Weather Insurance

As the case of Module Valle in ARLID, Mexico, for Ferrenafe the idea of weather-based insurance (or weather derivatives) is to compensate producers for a shortfall in realization of a particular weather variable (e.g., precipitation) measured over a certain time period. If the weather variable is sufficiently correlated with producers' profit, the payoff of the weather derivative would then offset the producers' loss.

Sugar and rice farmers may run out of enough water for many reasons—the reservoir level at the beginning of period *t* is not high enough, rainfall was not enough in Northeast highlands (Cajamarca), etc.

For each period *t*, the central planner allocates X_{Sugar} , X_{Rice} units of water between Sugar and Rice farmers, respectively. Under the climate change scenario, lower volumes of *X* are likely, which affect farmers' profit. For that reason, farmers of both crops would be better off if they were compensated when the highlands experienced rainfall shortages (which would affect inflow to the reservoir).

[48] SENAMHI (2009) analyzed models from the following institutions: Max Planck Institute für Meteorology; Hadley Centre for Climate Prediction and Research; Australia's Commonwealth Scientific and Industrial Research Organization; National Centre for Atmospheric Research; Canadian Center for Climate Modeling and Analysis; Geophysical Fluid Dynamics Laboratory and National Institute for Environmental Studies (NIES).

In this context, the objective is to evaluate how sugar and rice farmers' welfare could be increased if they bought a weather insurance contract. In this case, no farmer could substitute irrigated water for rainfall. Both farmers are completely dependent on irrigation because the irrigation district is located in the Chancay-Lambayeque basin lowlands with a semi-desert climate.[49] Thus, optimal water allocation should not be affected by insurance policy as was the case in Mexico's model.

Following Vedenov and Barnett (2004), weather derivatives are modeled for yields of both crops as an "elementary contract," as in equations (8) and (9) of Section 4.3. The parameters for both contracts are selected so as to provide the maximum risk reduction for the farmer who is exposed to the risk of area-wide yield loss. For the sake of simplicity, the strike is selected as long-term average rainfall. In particular, the parameters are selected so as to maximize the expected utility, as was done in equation (10).

9. Data Selection Process

Official sources were consulted to gather the necessary information and carrying out this study. Yield and price data were collected from the MINAG, Dirección Regional de Lambayeque. Weather data were provided by the SENAMHI, Direccion Regional de Lambayeque, and Reservoir's storage levels were obtained from ANA, Administración Chancay-Lambayeque. Climate changes scenarios predictions were obtained from SENAMHI (2009).

9.1 Descriptive Statistics

Descriptive analysis for sugarcane and rice yields and water allocation for those crops are shown in Table 3 (see appendix E). The averages for sugar and rice yields were 100.66 tons/ha and 7.16 tons/ha, respectively. The highest standard deviation was 16.31tons/ha for sugar yield. The averages of irrigated water for sugar and rice were 11.92 and 9.68 thousand m3/ha, respectively. The highest standard deviation was 4.44 thousand m3/ha for sugar.

Before estimating weather-yield and weather-water models, several unit root tests were performed to detect whether yields and weather variable have stochastic trends. We followed the unit root test strategies of Elder and Kennedy (2001) and Harvey et al. (2009). The results suggested most of the series do not exhibit unit root. Trend stationary variables were detrended

[49] This approach is different from Mexico's model, where one type of farmer could use either rainfall or irrigated water.

following the procedure described in Vedenov and Barnett, 2004); we applied the procedures suggested by Enders (2004) to variables stationary in difference.[50]

9.2 Estimating the Production Function

Estimation results for the sugarcane and rice production function per hectare are presented in the Table 4.[51] Estimated coefficients for both regressions are statistically significant at the 5 percent level. The R-squared for sugarcane regression is 46.3 percent, while it is 37.1 percent for the rice regression. In addition, all coefficients exhibit the expected sign. Water accessibility has a positive effect on yields in both cases and exhibits diminishing marginal productivity.

10. Results

The baseline model for the CLID was solved by using numerical analysis. This section performs the simulation procedure and explains all assumptions made to obtain optimal allocation strategies. The baseline scenario is modeled as a dynamic discrete-time model where the water authority observes the current reservoir level(s_t), takes an action x_t.[52] In this case, actions refer to how much water is released for irrigation during sugarcane and rice activities. Thus, a reward is earned that depends on the actions taken.

The unit of analysis is the hectare. This idea is based on the assumption of a perfectly divisible model, so the entire production process can be scaled up or down. The maximum amount of water that a hectare can receive is fixed at 24 thousand m^3 per hectare.

The state space and the action space are both modeled as finite. The state space, which enumerates all the states attainable by the model, goes from 0 to 24 thousand per hectare with increments of 0.5 thousand m3 per hectare. The action space enumerates all action.

The simulations were performed using different risk aversion parameter values.[53] In the same way, simulations were undertaken assuming three different discount rates: 1 percent, 5 percent, and 10 percent.[54] Water prices per thousand m3 were set to 19.09 and 15.62 soles per hectare of sugarcane and rice, respectively, and the prices of sugarcane and rice were set to 60

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[50] Unit root results are available upon request.
[51] Outliers shown in Figure B-2 were not considered.
[52] Both the state and the action taken are discrete.
[53] These values were obtained using the method suggested by (Babcock, Choi and Feinerman, 1993).
[54] The discount factor δ is equal to $1/(1+r)$, where *r* is the discount rate.

and 720 soles per ton, respectively.[55] The production function coefficients were set according to the estimations shown in Table 4. The profit and utility functions for sugarcane and rice farmers, respectively, were calibrated on the basis of these parameters.

As was stated above, the state of reservoir level is a controlled Markov process. That is, the probability distribution of the next period's reservoir level, conditional on all currently available information, depends only on the current reservoir level, and the released water for irrigation (the actions). That transition probability matrix was constructed based on the transition equation.

10.1 Baseline Model

The results of a simulation with a 5 percent discount rate are shown in Appendix F.[56] Figures 21 and 22 illustrate the optimal irrigation policy for both crop activities. For example, when the water available is 10 thousand cubic meters per hectare (TM3H), sugarcane and rice farmers receive 5 and 4.5 TM3H, respectively. In proportional terms, sugarcane and rice farmers receive 52.6 percent and 47.4 percent, respectively, of the total amount of water allocated. The results also suggest that, for each reservoir level, sugarcane farmers receive more water than rice farmers.

Figure 23 shows the steady-state distribution of the optimal-state path. Based on simulated results for 50 years, in the long run the central planner would have 14.27 TM3H of water to allocate between sugarcane and rice farmers.

In general, results from the simulation model reproduce consistent irrigation patterns with historical data. For the periods 1992-2003 and 2005-2010, sugar farmers have received most of the allocated water (53.9 percent on average). Results for the simulation model confirm the same pattern between sugar and rice farmers.

Next, different climate changes scenarios are incorporated to estimate optimal policies under several sets of conditions.

[55] These prices correspond to the rural prices observed in 2005 (MINAG).

[56] Estimations were carried out with other discount rates (1 percent and 10 percent). The results were consistent because higher discount rates result in higher allocations of water given the same volume of water.

10.2 With Climate Change

10.2.1 Scenario A2 with a 5 Percent Deficiency in Rainfall[57]

Simulation results are shown in Appendix G, when the discount rate is 5 percent. Figures 24 and 25 show the optimal irrigation policy for both crops under Scenario A2 with a 5 percent deficiency in rainfall. For example, when the water available is 15 TM3H, sugarcane and rice farmers receive 6.5 and 5 TM3H, respectively, or 56.58 percent and 42.42 percent, respectively, of the total amount of water allocated. The results suggest that, for any reservoir level, sugarcane farmers receive more water than rice farmers do.

Figure 26 shows the steady-state distribution of the optimal-state path. Based on simulated results for 50 years, the steady state for the reservoir level is 13.24 TM3H. In the long run, the central planner would have 13.24 TM3H of water to allocate between sugarcane farmers and rice farmers.

10.2.2 Comparison among Scenarios

Figure 27 shows the optimal value function for different water level in the case with historical data and in Scenario A2 with 5 percent deficiencies. The following facts can be derived:

- For all these cases, the higher the reservoir level per hectare is, the higher the utility farmers get.
- The steady state for reservoir water is higher under historical data than under the climate change scenarios considered.
- The steady state for reservoir water is higher with a 5 percent deficiency than with a 10 percent deficiency.
- Extreme events (excessive rainfall or lack of rain) are more likely in A2 scenarios than in the baseline scenario case. It suggests that extreme weather events are more likely in this A2 scenario than in a scenario with historical data.
- Optimal allocations made by the central planner produce higher utility in the historical data scenario than in the climate change scenarios considered.

[57] Simulations results under 10 percent deficiency are not shown, but they do not have significant differences respect to those under 5 percent deficiency.

10.3 With Weather Insurance Scheme

Based on SENAMHI's prediction scenarios for Peru, this section show simulation results for the dynamic water allocation model when sugarcane and rice farmers buy a weather insurance contract. Climate change scenarios were applied to both rainfall level in Cajamarca (used to construct the index) and inflow to the Tinajones Dam.

The present section shows the simulation results for the dynamic water allocation model with IPCC Scenario A2 predictions for precipitation, namely a 5 percent deficiency in rainfall. The simulation procedure was carried out in two steps. First, equation (10) is modeled to estimate the optimal value for β and the contract parameters. Second, based on those estimations new water allocation patterns are calculated.

The simulation results suggest that the contract parameters for sugar cane are as follows: ε^* is equal to 710.70 mm, λ is equal to 0.8, and the maximum liability is 2,500 soles per hectare. The premium is equal to 620 soles per hectare.

The simulation results suggest that the contract parameters for rice are as follows: ε^* is equal to 600.10 mm, λ is equal to 0.75, and the maximum liability is 5,000 soles per hectare. The premium is equal to 1,232 soles per hectare.

In Appendix H, the simulation results are shown when the discount rate is 5 percent. Figures 28 and 29 show the optimal irrigation policy for both seasons under Scenario A2 with insurance.[58] It is important to note that irrigated water during the fall-winter season increases when the reservoir level is less than 4.5 TM3H. However, when the level is greater than 5 TM3H, the farmer receives around 3 TM3H. On the other hand, irrigated water has a different pattern. When the reservoir level is less than 8 TM3H, the farmer receives around 1 TM3H, but if the reservoir level is greater, he receives 5.2 TM3H.

Figure 30 shows the steady-state distribution of the optimal-state path. After 10 years, that level is 8.60 TM3H.

11. Institutionalization and Implementation of Weather Derivatives

The market for weather derivatives started operations in 1997, and its dynamic was only interrupted by the 2008-2009 crisis. In Latin American countries, the use of weather derivatives

[58] Simulations for Scenario B1 scenario were also carried out, and the results did not show significant differences with respect to those presented under Scenario A2. For that reason they are shown here, but are available upon request.

as an instrument to cope with climatic risks has not become widespread, mainly because the institutional framework is not sufficiently mature to embrace such operations. Public policies to develop the weather derivatives market in Latin America countries have made some advances in institutional issues and in the adoption of technology adoption for reducing costs. However, those policies have, however, have shown poor results in reducing market failures, improving access to information and credibility, and creating favorable environments for the operation of these instruments (Arias and Covarrubias, 2006).

The use of weather derivatives as insurance mechanisms requires the intervention and support of bilateral and multilateral institutions: government, NGOs, private foundations, intermediaries, insurance companies, credit companies, agribusiness firms, savings and loan organizations and cooperatives, among others. In addition, the operation of weather derivatives operation depends on the development of multiple mechanisms and processes, such as delivery channels, marketing, promotion, training of retailers, and investments in education for clients and end-users (Hellmuth et al., 2009). The channel of implementation is a primary issue because it must be selected according to the available resources in the target population's location, minimizing transaction and administrative costs (Arias and Covarrubias, 2006).

In developed countries with a consolidated financial structure, the main channels are energy companies, insurance and reinsurance companies and hybrid companies offering insurance, reinsurance and derivatives (Arias and Covarrubias, 2006). In contrast, in developing countries the use of available channels for commercialization implies taking advantage of existing social networks and social capital. For this reason, the best conditions for weather derivatives as a financial tool occurs when they are integrated into a broader comprehensive risk management strategy, such as rural development programs (Hellmuth et al., 2009).

In the case of Mexico, irrigation districts are a potential target population for the action of these instruments.[59] Mexican government has a network of weather stations around the country,

[59] Agroasemex, the Mexican government-owned reinsurance company, launched the Programa de Atención a Contingencias Climatológicas (PACC) during the 2001-2002 fall-winter cycle to cover three Mexican states (Sinaloa, Tamaulipas and Sonora) against catastrophic exposure related to agriculture. The objective was to increase the efficiency, timeliness and distribution of federal funds to farmers after a weather disaster. The index insurance package covered drought and flood, and their transactions in the international weather derivatives market had an approximate value of US$15 million (World Bank, 2005).Although no studies for evaluating the performance of this insurance were carried out, and the collocation was successful, in 2005 triggers caused payouts when farmers had not actually experienced crop damage. The opposite occurred in 2006, when some farmers experienced crop losses but no payments were triggered (Hellmuth et al., 2009).

with available information in some cases since 1900. The modules as an entity are able to purchase weather derivatives because they operate as productive organizations with similar production conditions, under the same regulatory framework and the same operational structure, and they already work as productive organization to access credit.

The Mexican government, particularly the governmental reinsurance company Agroasemex, could use its experience in the emission of weather derivatives and also serve as a reinsurer. Numerous channels of commercialization can be used; for instance, weather derivatives could even be introduced to potential purchasers by rural financial agents. In addition, financial government institutions such as the Trust Funds for Rural Development (Fideocomisos Instituídos en Relación con la Agricultura, FIRA) or Financiera Rural could tie their loans to the purchase of insurance schemes using climate derivatives. Finally, the Mexican government could support the development of agreements between microfinance organizations and insurance companies to incentivize the introduction of climate derivatives into the market.[60]

In the case of Peru, the government's experience in the operation of agricultural insurance schemes is limited and largely quite recent.[61] A massive insurance scheme started during the agricultural cycle 2009-2010 for the Southwest regions of Huancavelica, Apurimac, Ayacucho, Puno, Cusco, Huanuco and Cajamarca. The Peruvian government, in collaboration with MAPFRE and La Positiva insurance companies, launched the Agroprotege Fund with three types of insurance: catastrophic insurance for the poorest farmers located in upland in the mountains or the Amazonas; traditional insurance for medium producers with indemnities linked to production costs; and livestock insurance for medium producers.[62]

Insurance options for Northeast farmers have been scarce. La Positiva introduced weather index insurance based only on sea temperature, but with a threshold fixed at 24.5 ^{o}C there was an extremely low probability of occurrence. This temperature was recorded only during the 1982-83 El Niño Southern Oscillation (ENSO) and the 1997-98, ENSO while weak and moderate ENSO events do not trigger the indemnity.

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[60] Two successful experiences in life insurance tied to personal loans awarding have been already implemented in Mexico, see Alpizar and González-Vega (2006).

[61] In 2003 Peruvian government created a special Commission to implement crop insurance programs. The Technical Committee for the Development of Agriculture Insurance (TCDAI), created in September 2004, worked on the design of the prototype index contract and its implementation (World Bank, 2005).

[62] Catastrophic insurance covered drought, excessive humidity, freezing, flooding, high temperatures winds, crop disease, avalanche, fire, hail and pests.

Moreover, information from Peru's weather stations is limited, with historical records of at most 50 years. In particular, no records exist in the highlands with the highest-intensity precipitation events, even when there are weather stations such as the Tongod Weather Station. In 1999, because of serious damage from the 1997-1998 ENSO caused two year before, the SENAMHI installed a network of 50 weather stations. More recently, in 2010 the World Bank and the Peruvian government supported the installation of new equipment in the highlands.

On the other hand, the advantage of CLID is an operative and organizational structure that increases the possibility of success in the adoption of these schemes. Irrigation commissions are highly organized, and they have a well-established delivery system with an efficient fee recovery method. In addition, the Peruvian government could take advantage of microfinance institutions that have a good penetration in rural markets, which can serve as channels of commercialization to implement the use of weather derivatives for irrigation commissions as productive organizations.[63]

12.Policy Conclusions, Challenges and Final Considerations

In most of developing countries, efficient pricing mechanisms to optimize water use are impossible in institutional, political and social terms. Furthermore, in the coming decades higher variability in precipitation associated with climate change will make evident the need for reinforcing mechanisms that address efficient allocation of water in agriculture as an effective adaptation strategy.

This study proposes the adoption of more efficient water allocation policies in irrigation districts supported by weather derivatives to cope with precipitation shortages as an effective strategy against climate change, such as in ARLID. Weather derivatives are able to incorporate the analytical understanding of future climate change risks that historic data do not reflect.

Weather derivatives, as insurance schemes, are more effective at compensating distortions in the intertemporal allocation of water by the regulation authority when at least one of irrigation districts' seasons depends on precipitation in situ.

Institutionally speaking, success in the adoption of weather derivatives as adaptation strategies to climate change requires several initial conditions in irrigation districts. First, a

[63] Commercial banks specializing in microfinances (Banco Sol, Banco del Trabajo and MiBanco); Municipal Savings and Loan Institutions (MSLI); Rural Savings and Loan Institutions (RSLI); and Entities for the Development of Small and Microenterprise (EDPYME).

certain level of organization in irrigation districts is required in order to purchase weather derivatives. In addition, before irrigation districts can purchase weather derivatives, they must establish well-defined water rights and attain an acceptable rate of efficiency in conduction to ensure that their systems are functioning adequately.

The dynamic allocation model characterizes the historical allocation pattern that awards higher water volumes to farmers who are not able to diversify their risk, while providing smaller water allocations to farmers who are able to diversify their risk. The inclusion of the climate change scenarios in the model introduces more dispersion into the steady-state distributions because of an increased frequency of extreme weather situations.

Higher variability in precipitation patterns due to climate change results in higher premiums that reflect the high level of risk that an insurance company would have to absorb in the future, as shown in Scenarios A2 and B2. Thus, higher insurance prices from higher expected losses and higher payouts might create market imperfections that only government could help to reduce through creating and developing healthy public-private partnerships (PPPs), avoiding the creation of perverse incentives and supporting adaptation decisions.[64] PPPs could overcome the operational and financial constraints resulting from higher premiums due to climate change and facilitate risk-sharing between private insurance companies and the state. In addition, public policy could make important contributions to the functioning of weather derivatives by adapting laws and regulations and by amending legal and regulatory gaps to facilitate the operations of insurance companies.

Modules of irrigation districts are a potential target population for the action of these instruments. Governments could support the operation of this scheme as an integral strategy against emergencies and disasters, and they could assist modules in developing the institutional characteristics needed to utilize weather insurance. Once weather insurance is working, it is likely to be an effective tool in improving water management in irrigation districts and in improving the dynamics of weak water markets.

Strong assumptions were adopted into the model to simplify the initial analysis. However, numerous dimensions can be incorporated into the analysis by relaxing every

[64] An inappropriate public policy for developing the insurance market might worsen the negative effects of natural disasters on the target population and facilitate the capture of public resources by the private agents (Arias and Covarrubias, 2006).

assumption in the model. In particular, interesting results can be derived when water rights are allowed to be traded.

The main limitations of the study come from the inability of climate change scenarios to anticipate the future performance of precipitation patterns. Also, as in any index-based insurance scheme, basis risk imposes some level of vulnerability on the model. In both cases basis risk is reduced. In the case of ARLID, basis risk is minimized by using data from a weather station located in the isohyets with the highest intensity precipitation at the Solis Reservoir. In the case of the CLID, basis risk is reduced by using the average of the three weather stations, which located in the isohyets with the highest precipitation intensity, for the construction of the index. This average precipitation has a high correlation with Chancay river flows, which feed the reservoir and the Chancay-Lambayeque Basin.

Finally, some enrichment experiences of the application of the weather derivatives as a potential risk transfer mechanism in developing countries has been applied. As examined in Agrawala and Frankhauser (2008), an inclusive strategy to manage the uncertainty associated with climate change in agricultural production has been implemented in developing countries such as Mexico (2001), Ethiopia (2007), Kenya (2007), and Mali (2007).

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Appendix A

Table 1. Descriptive Statistics for Valle de Santiago, 1985-2010

Variables	Mean	Std. Dev.	Min	Max
Yield Barley (tons/hectare)	5.06	0.77	3.42	6.35
Yield Sorghum (tons per hectare)	8.46	0.99	6.02	10.92
Irrigated Water Barley (thousands of m3/hectare)	5.778	0.358	4.663	6.201
Irrigated Water Sorghum (thousands of m3/hectare)	5.438	1.072	2.399	7.545

Note: Std. Dev. stands for standard deviation.

Figure 2. Valle de Santiago, Average Annual Rainfall (mm), 1985 – 2010

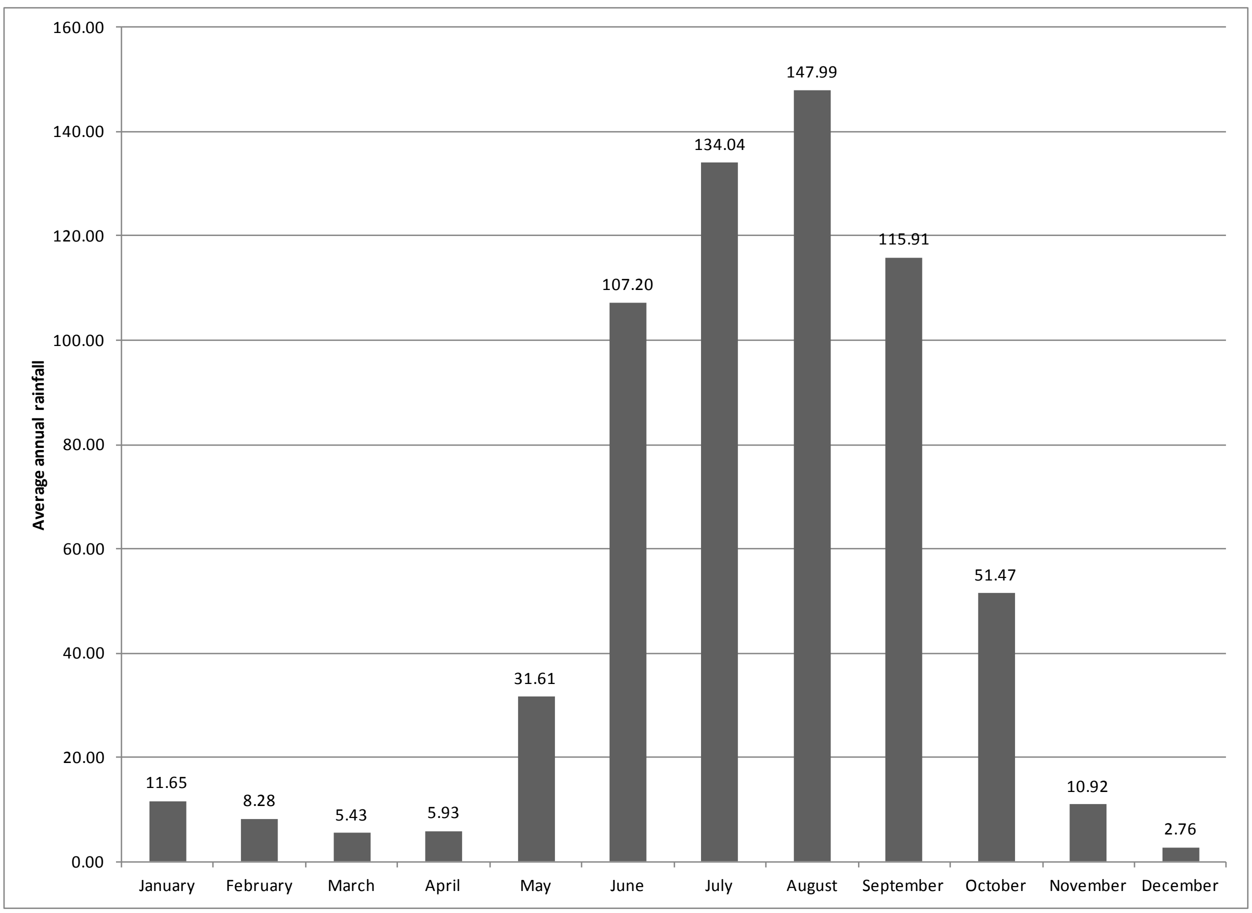


Table 2. Estimation Results for Production Functions

	Barley	Sorghum
Water Accessibility	50.47*	4.042*
	(2.46)	(2.57)
Water Accessibility square	-4.389*	-0.237*
	(-2.45)	(-2.64)
Constant	-144.6*	-16.97*
	(-2.46)	(-2.55)
Number of Observations	17	17
R-square	0.303	0.216

Note: t statistics in parentheses. Coefficient is significant at the 10 percent level; * at the 5 percent level; ** at the 1 percent level.

Appendix B. Simulation Results under No Climate Change and No Insurance

Figure 3. Optimal Irrigation Policy Fall-Winter

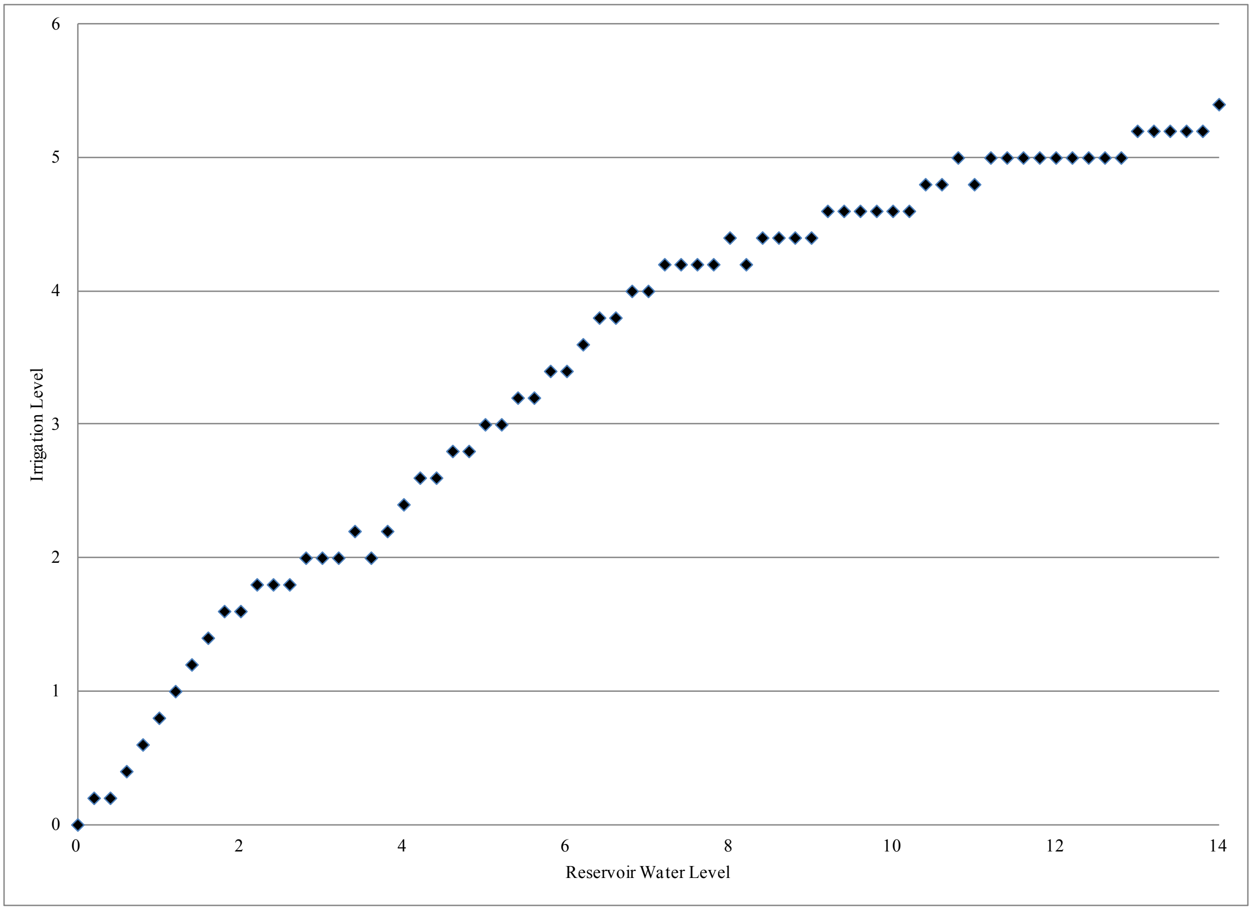


Figure 4. Optimal Irrigation Policy Spring-Summer

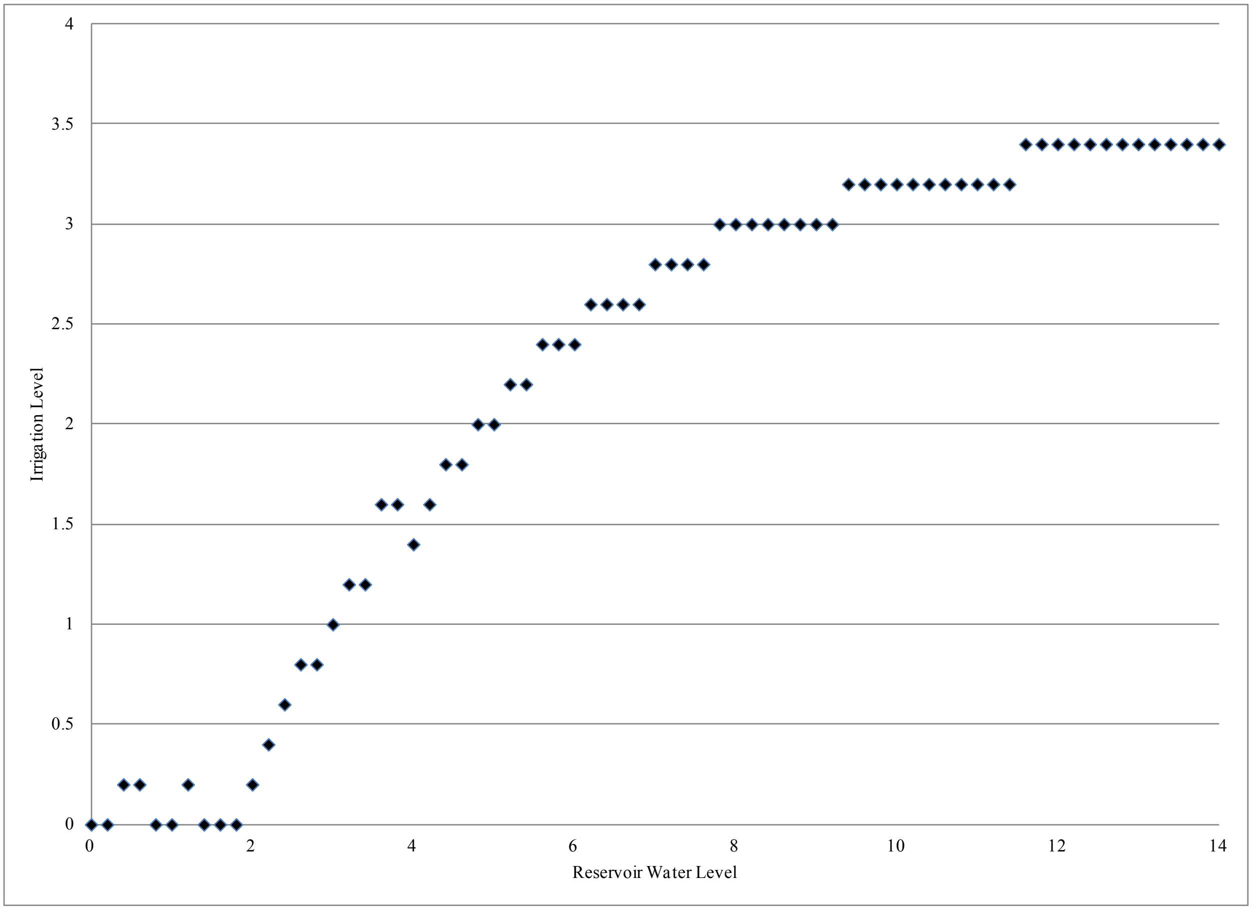


Figure 5. Optimal State Path

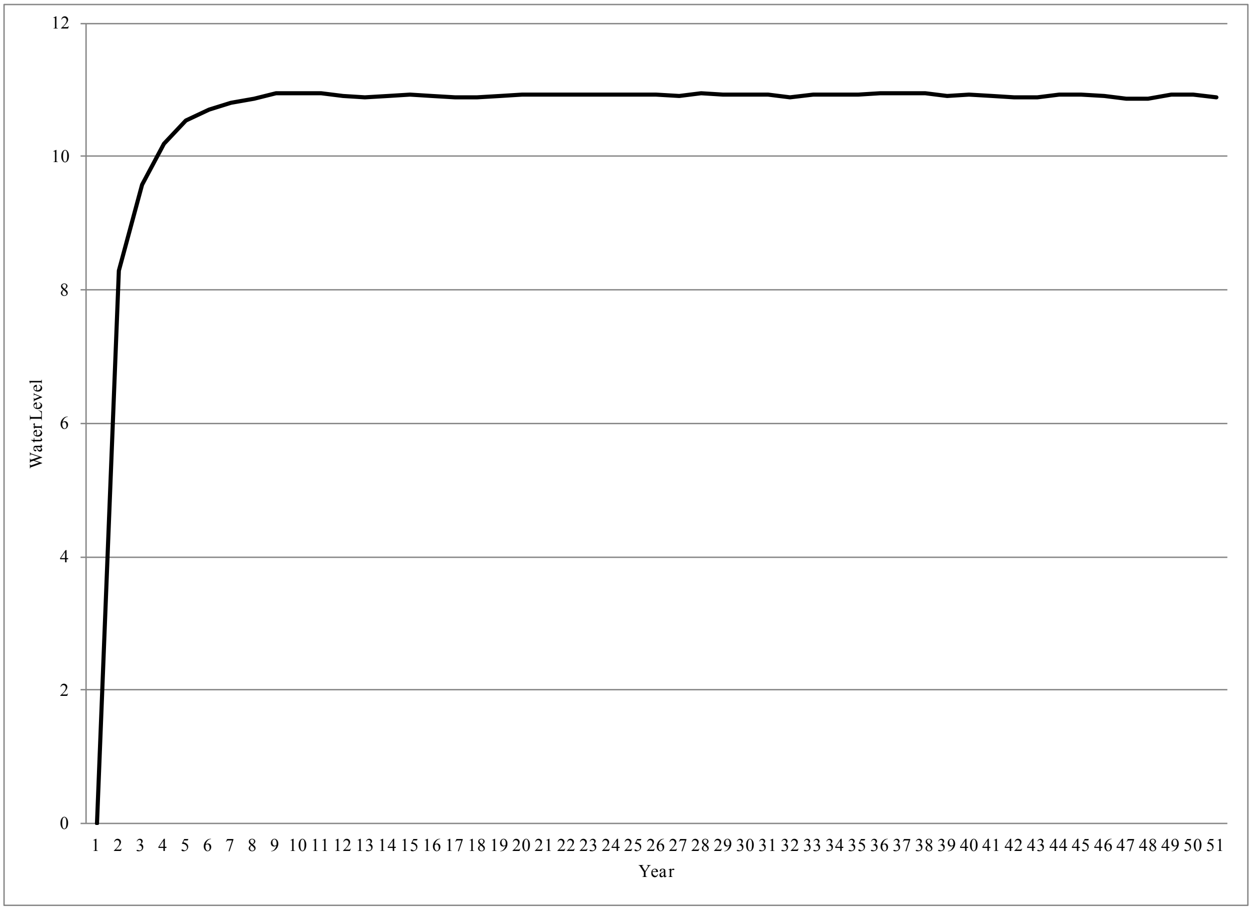


Figure 6. Steady State Distribution

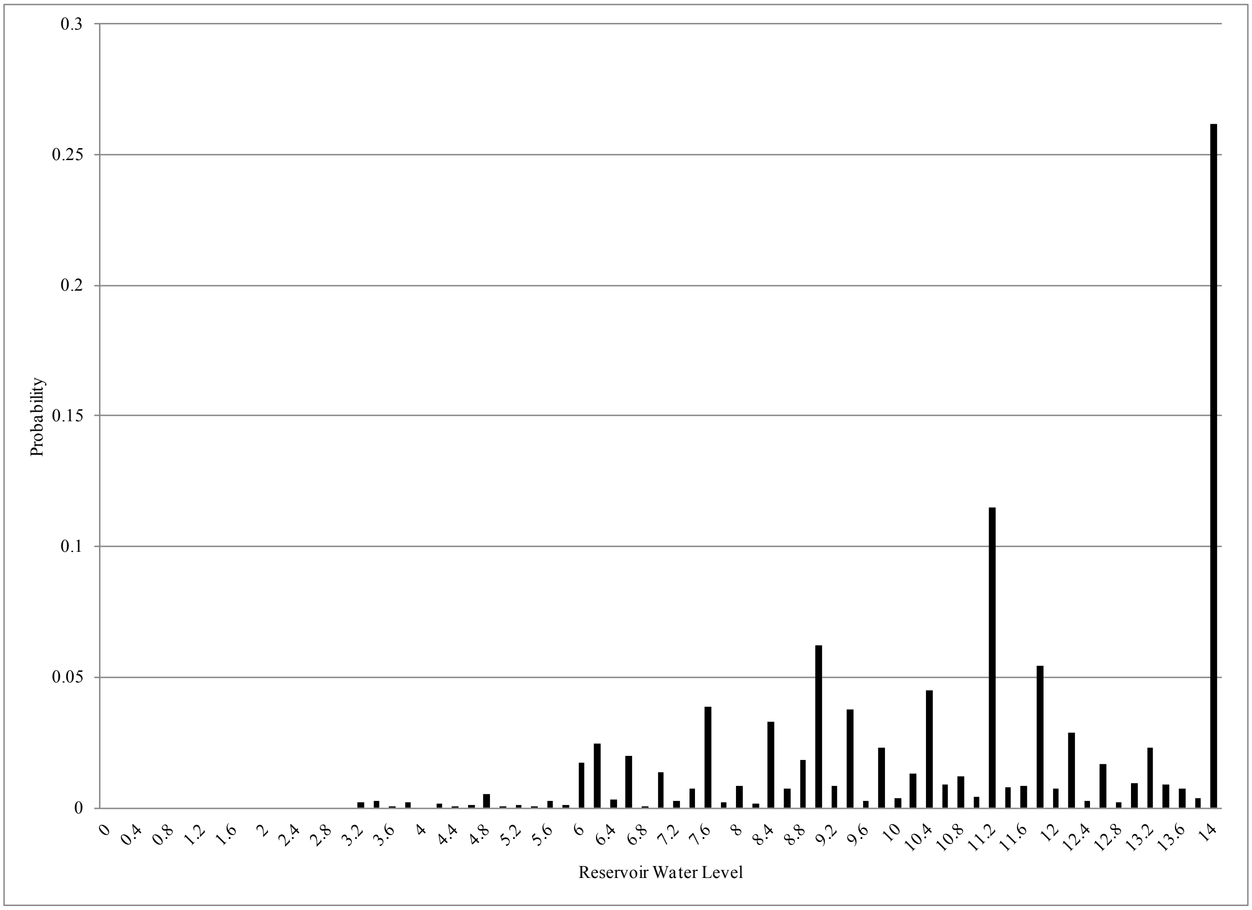


Figure 7. Proportion of Water Allocated between FW and SS farmers

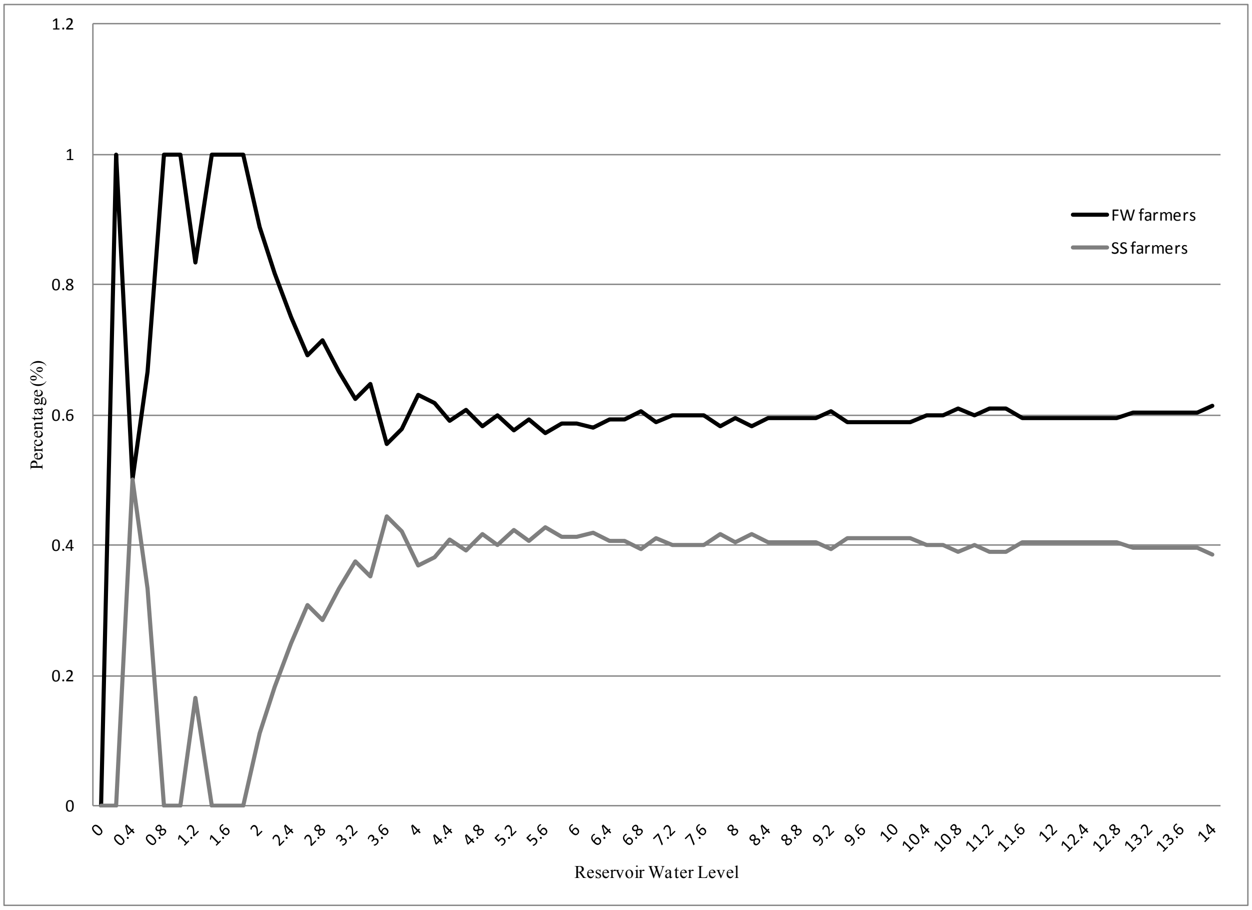
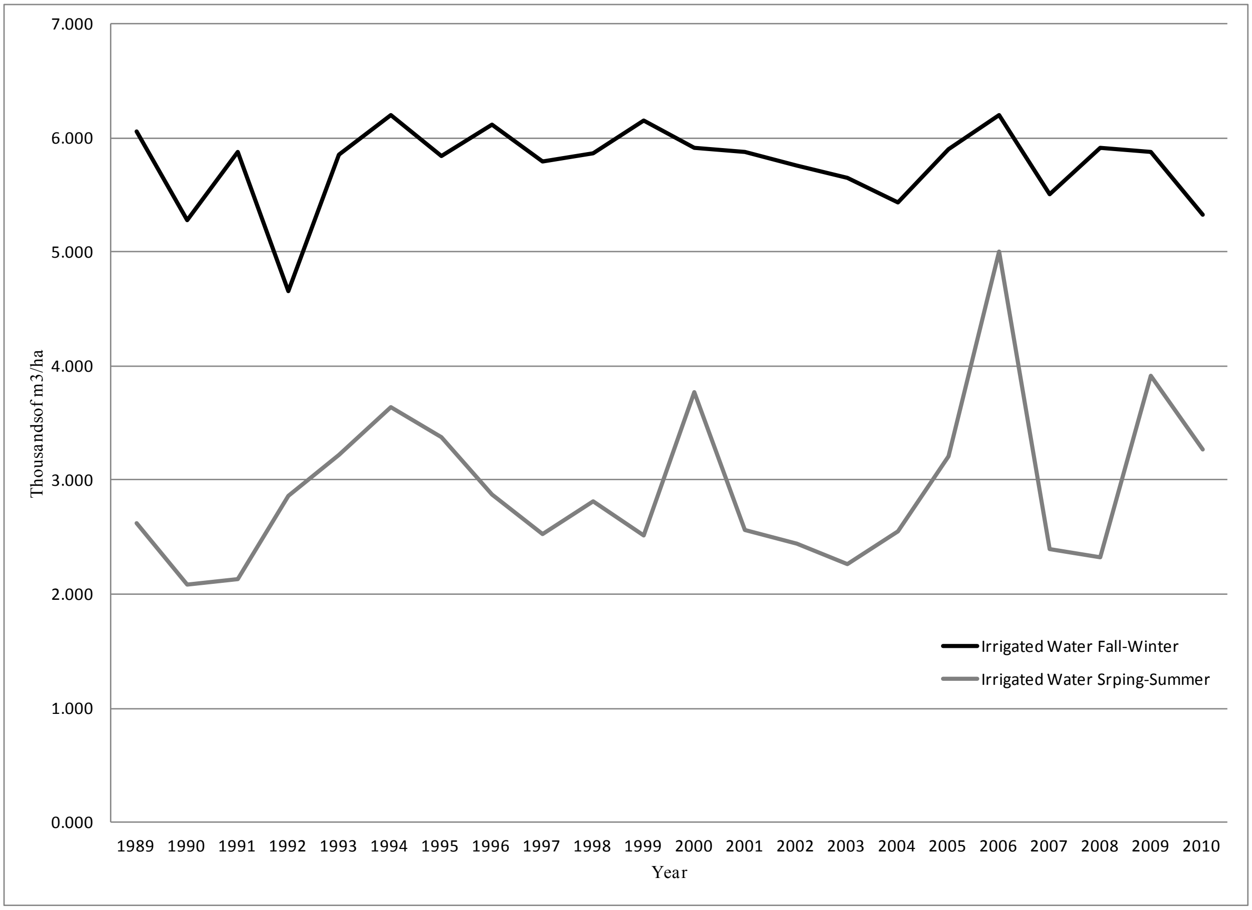


Figure 8. Evolution of Water Allocated in Valle de Santiago



Appendix C. Simulation Results with Climate Change

Figure 9. Optimal Irrigation Policy Fall-Winter

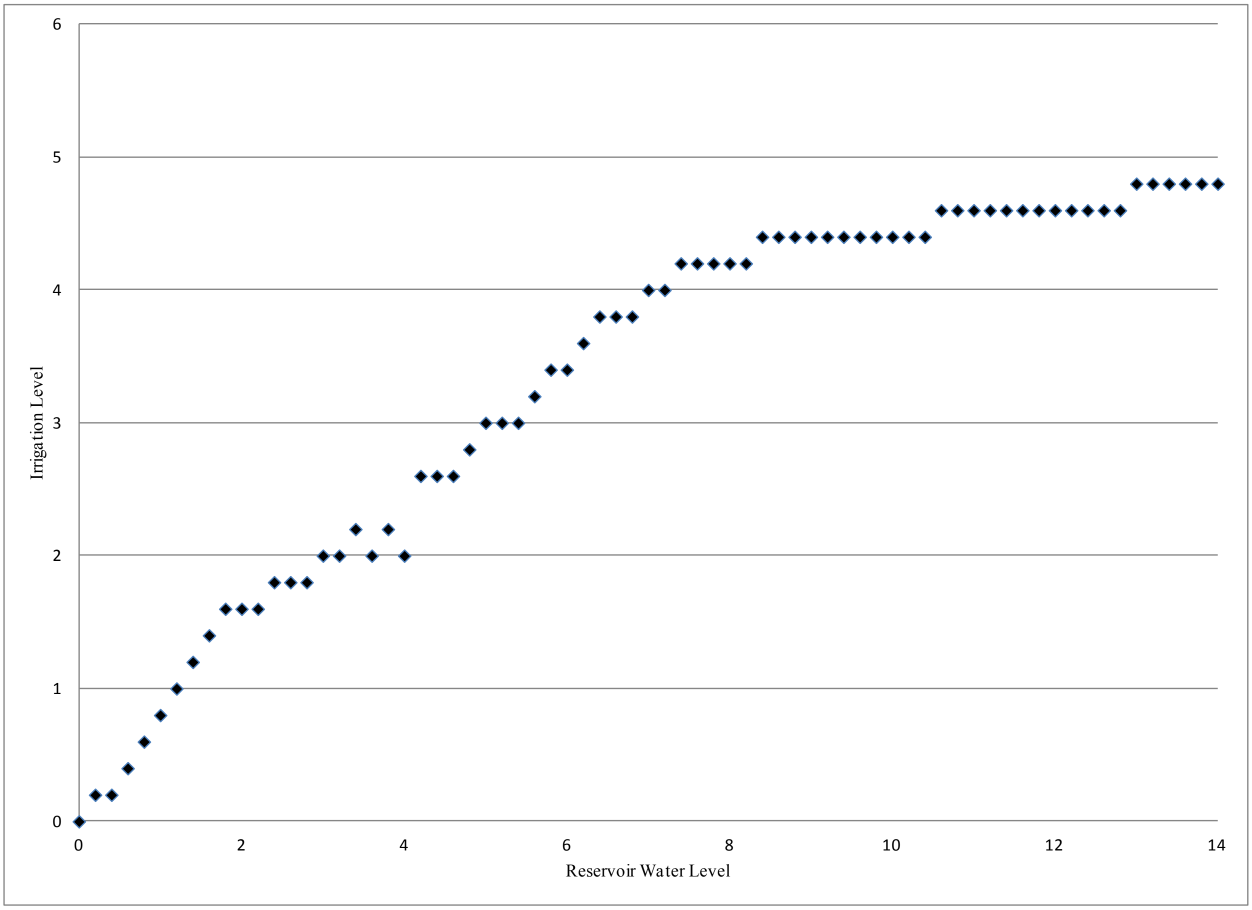


Figure 10. Optimal Irrigation Policy Spring-Summer

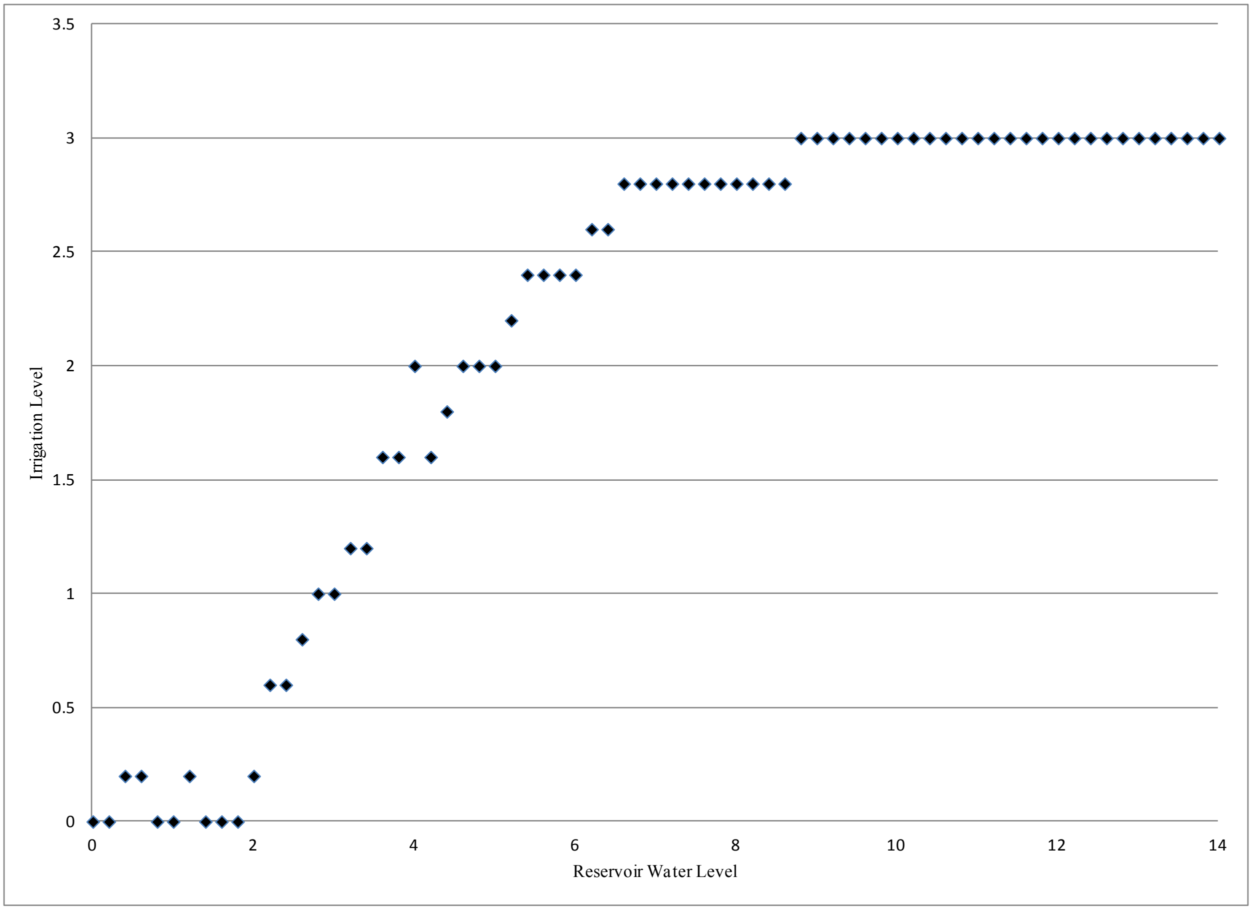


Figure 11. Optimal State Path

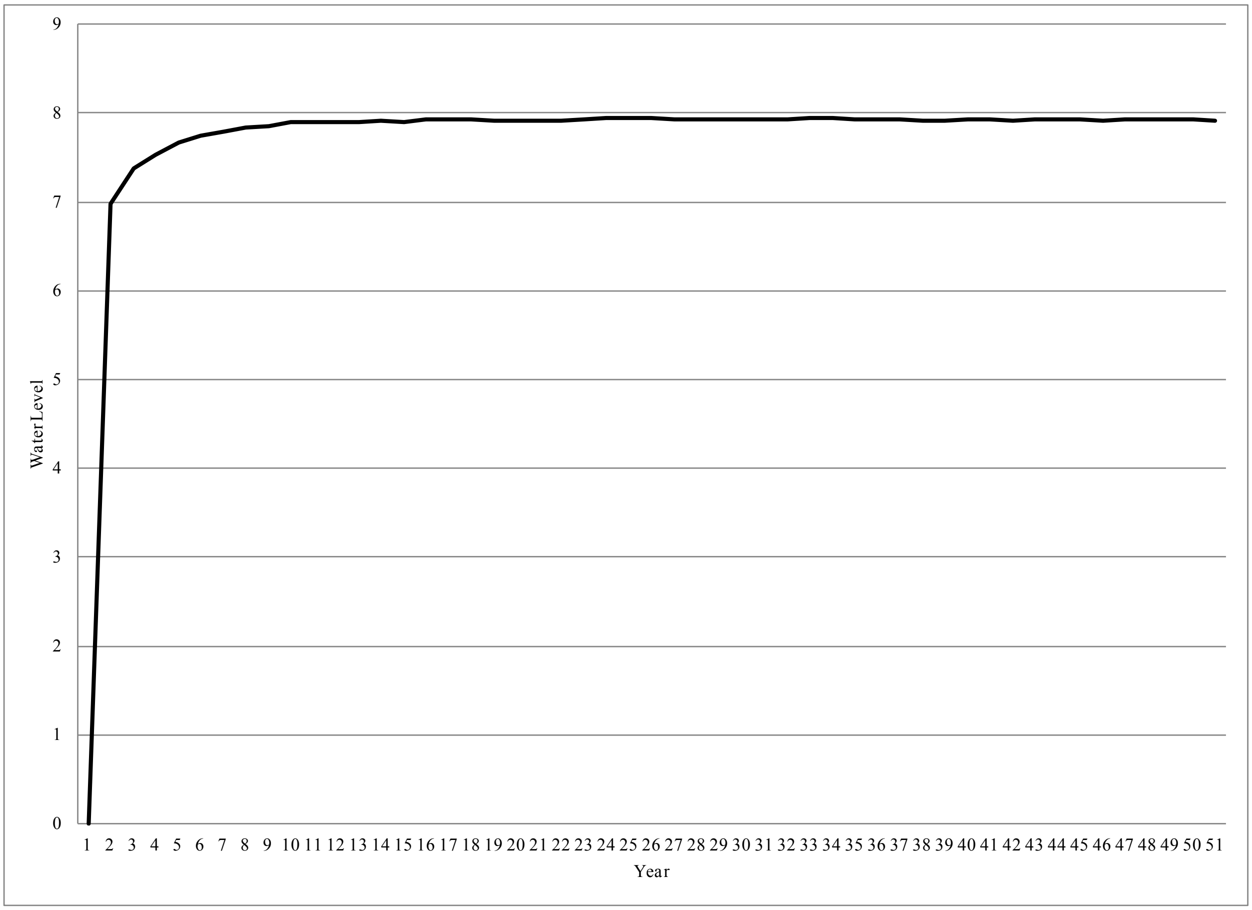


Figure 12. Steady State Distribution

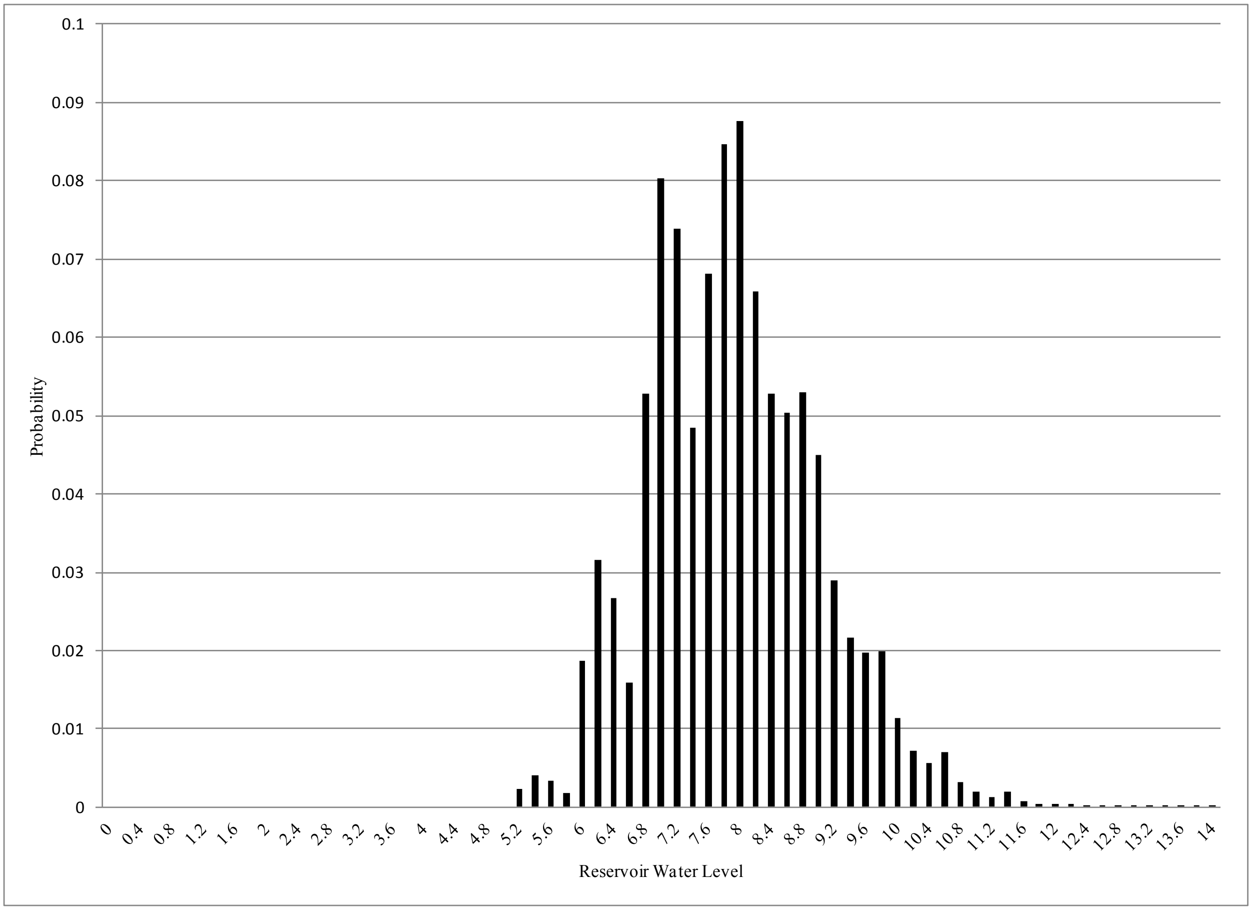
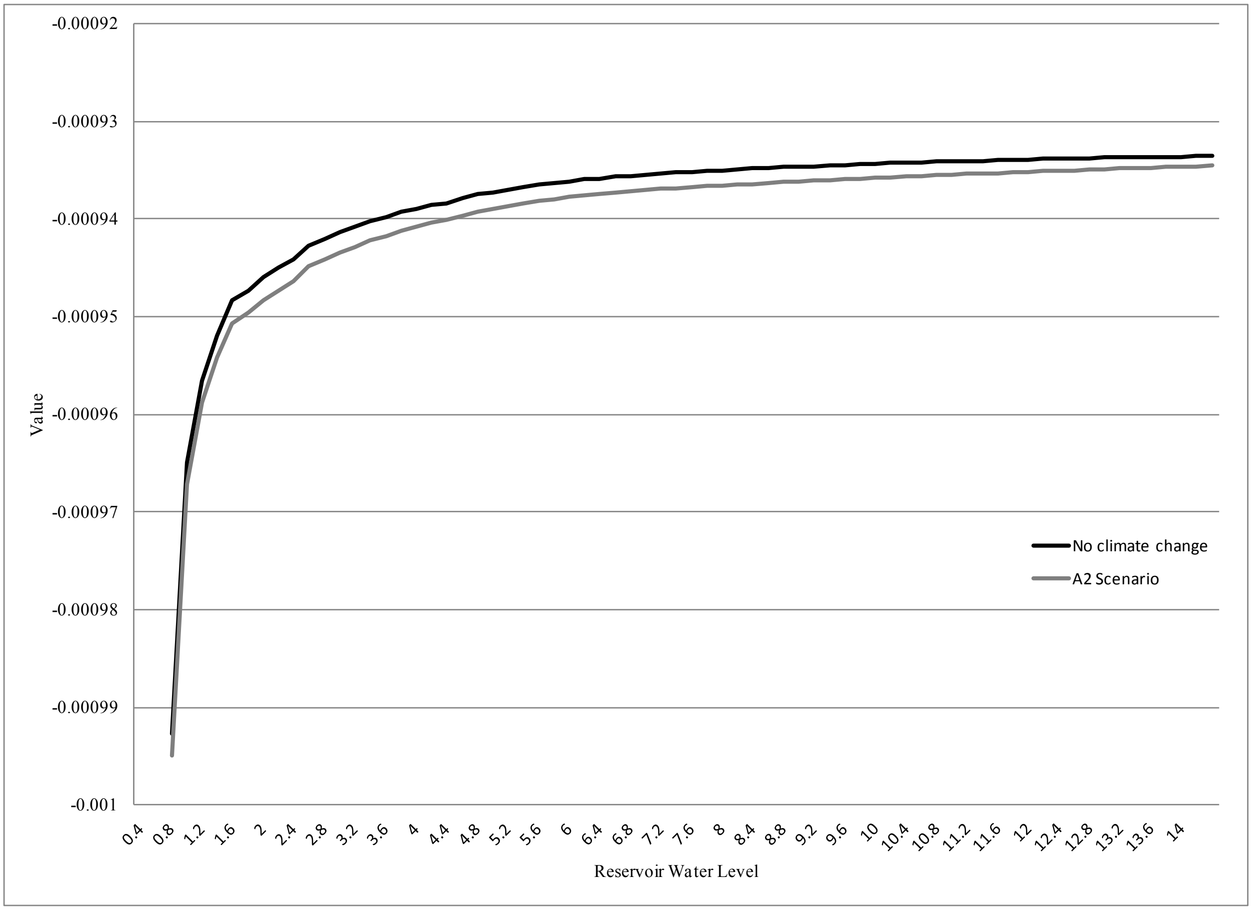


Figure 13. Optimal Value Function



Appendix D. Simulation Results under Scenario A2 and Insurance

Figure 14. Payoff Structure of an Elementary Contract

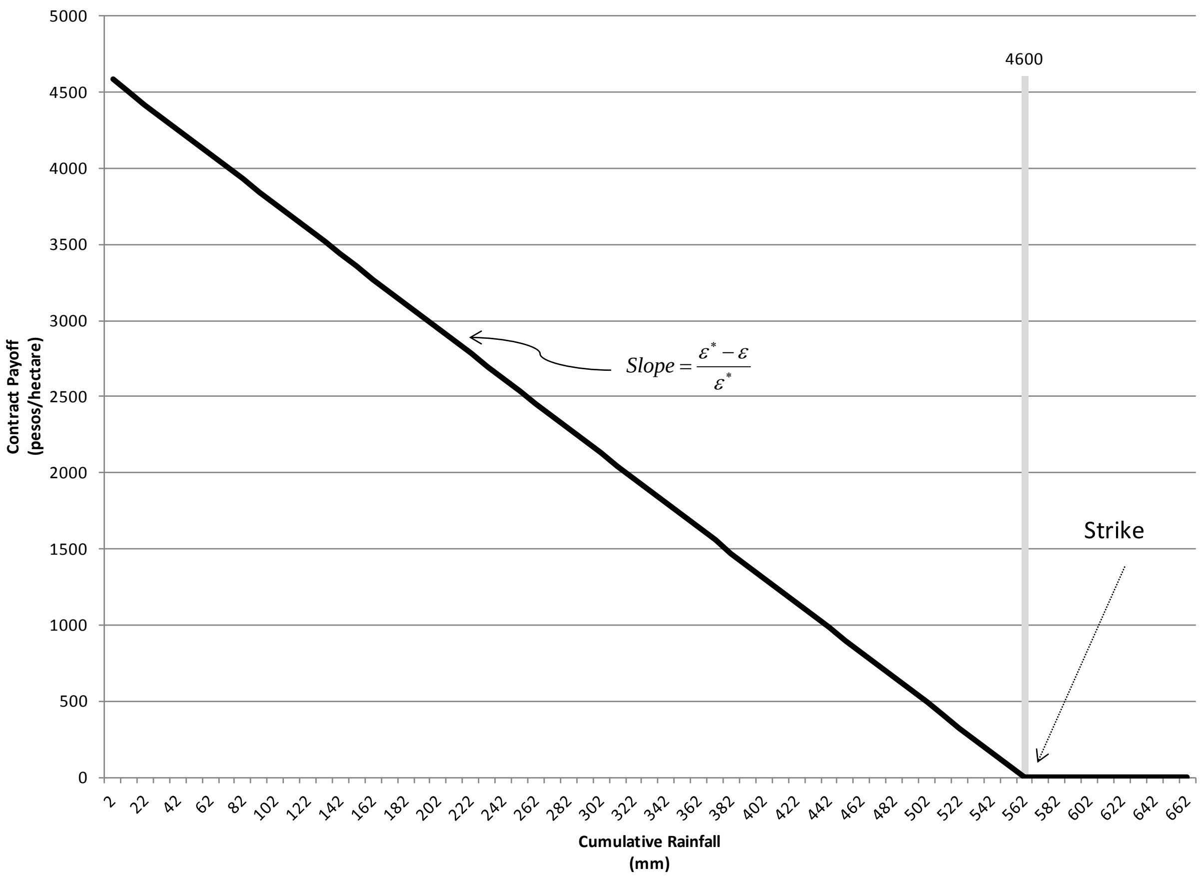


Figure 15. Optimal Irrigation Policy Fall-Winter

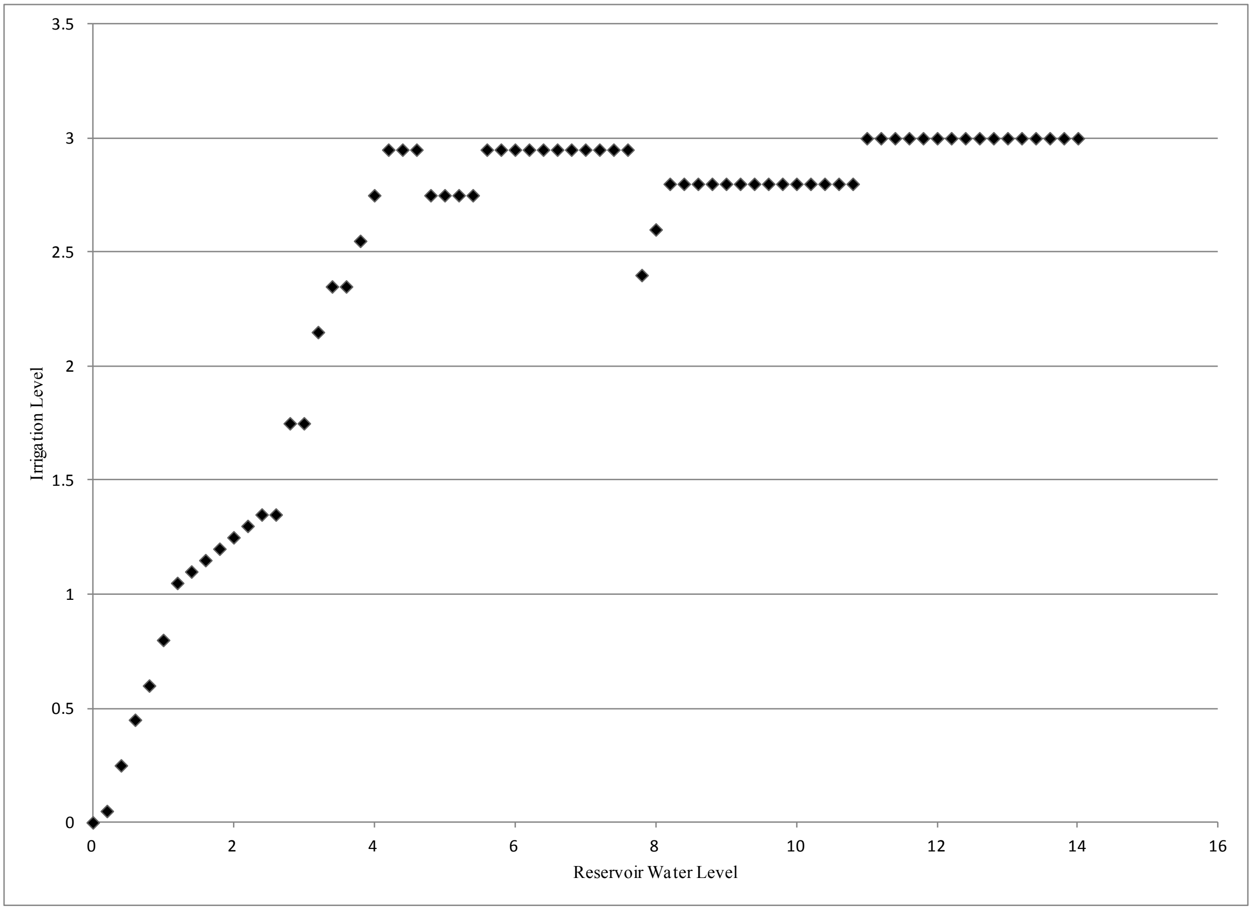


Figure 16. Optimal Irrigation Policy Spring-Summer

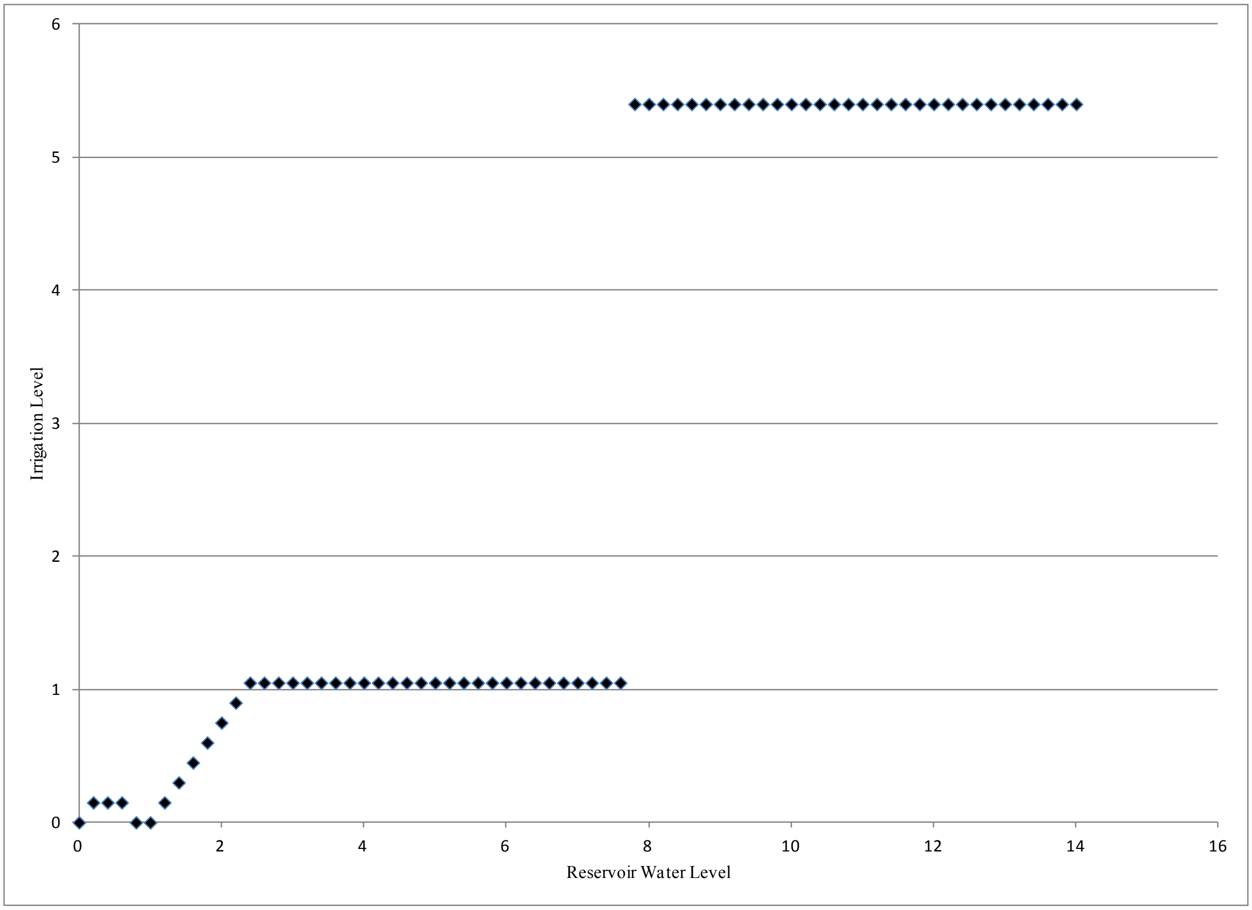


Figure 17. Optimal State Path

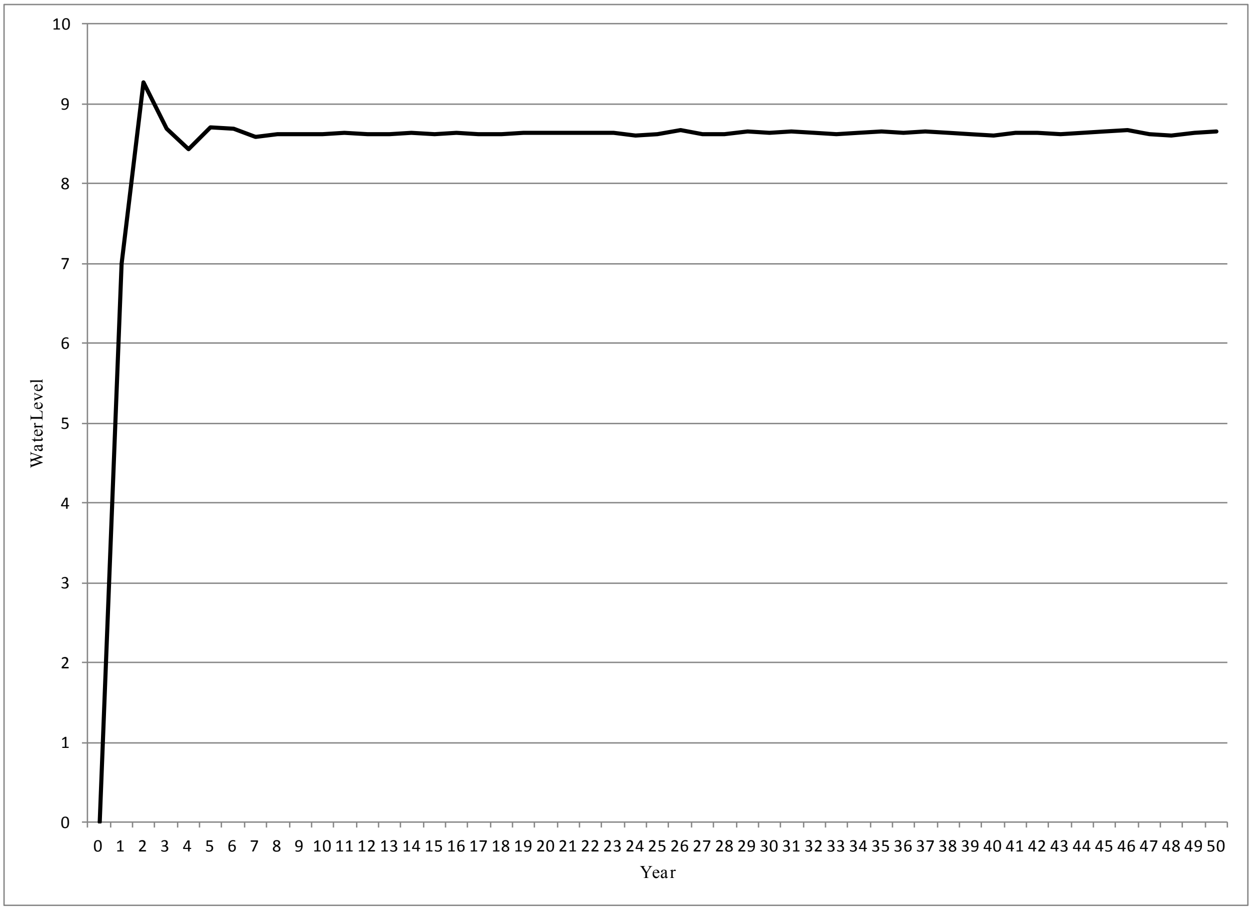


Figure 18. Steady State Distribution

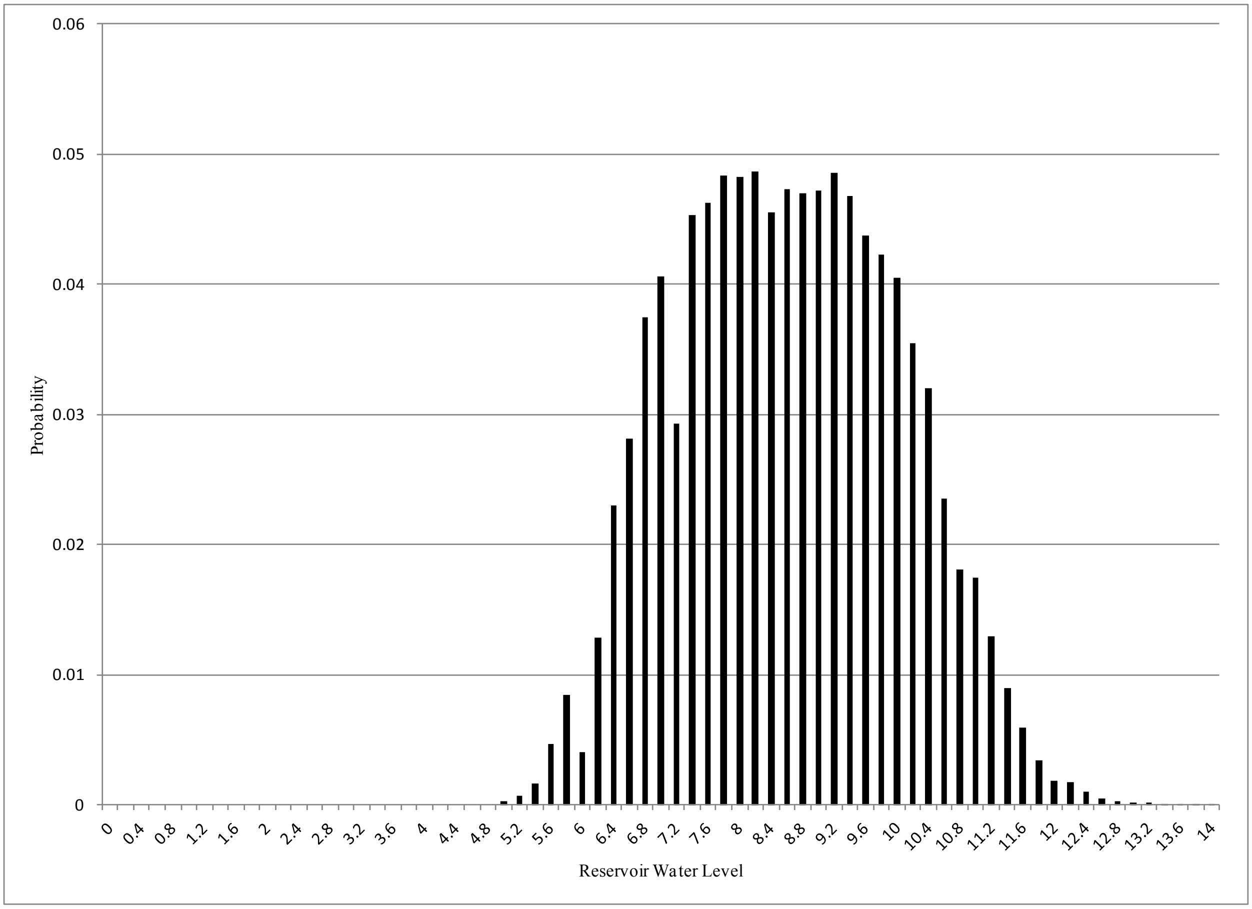
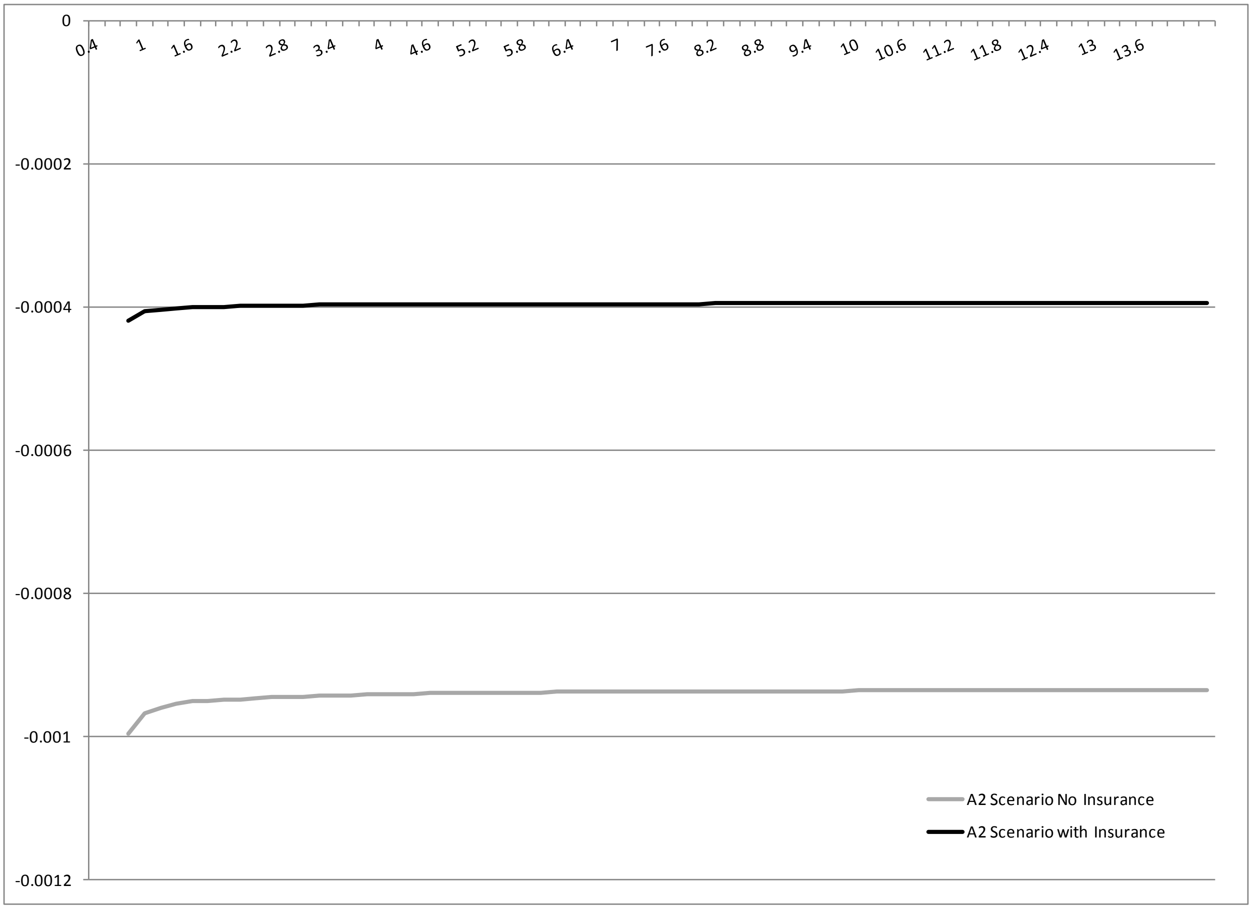


Figure 19. Optimal Value Function State Distribution



Appendix E

Table 3. Descriptive Statistics for Ferrenafe, 1990-2010

Variable	Mean	Std. Dev.	Min	Max
Sugar Yield (tons/hectare)	100.66	16.31	67.45	124.46
Rice Yield (tons/hectare)	7.16	2.01	2.27	9.91
Irrigated water sugar (thousands of m3/hectare)	11.92	4.44	4.73	22.17
Irrigated water rice (thousands of m3/hectare)	9.68	2.25	5.93	13.12

Note: Std. Dev. stands for standard deviation

Table 4. Estimation Results for Production Functions

	Sugar	Rice
Water Accessibility	6.462***	4.968***
	(2.47)	(3.24)
Water Accessibility square	-0.203**	0.257***
	(-1.95)	(-3.04)
Constant	-41.26**	-15.62**
	(-2.72)	(-2.30)
Number of Observations	21	21
R-square	0.463	0.371
Adj. R-square	0.374	0.302

Note: t statistics in parentheses. Coefficient is significant at the 10 percent level; * at the 5 percent level; ** at the 1 percent level.

Appendix F. Simulation Results under No Climate Change

Figure 21. Optimal Irrigation Policy for Sugar Cane

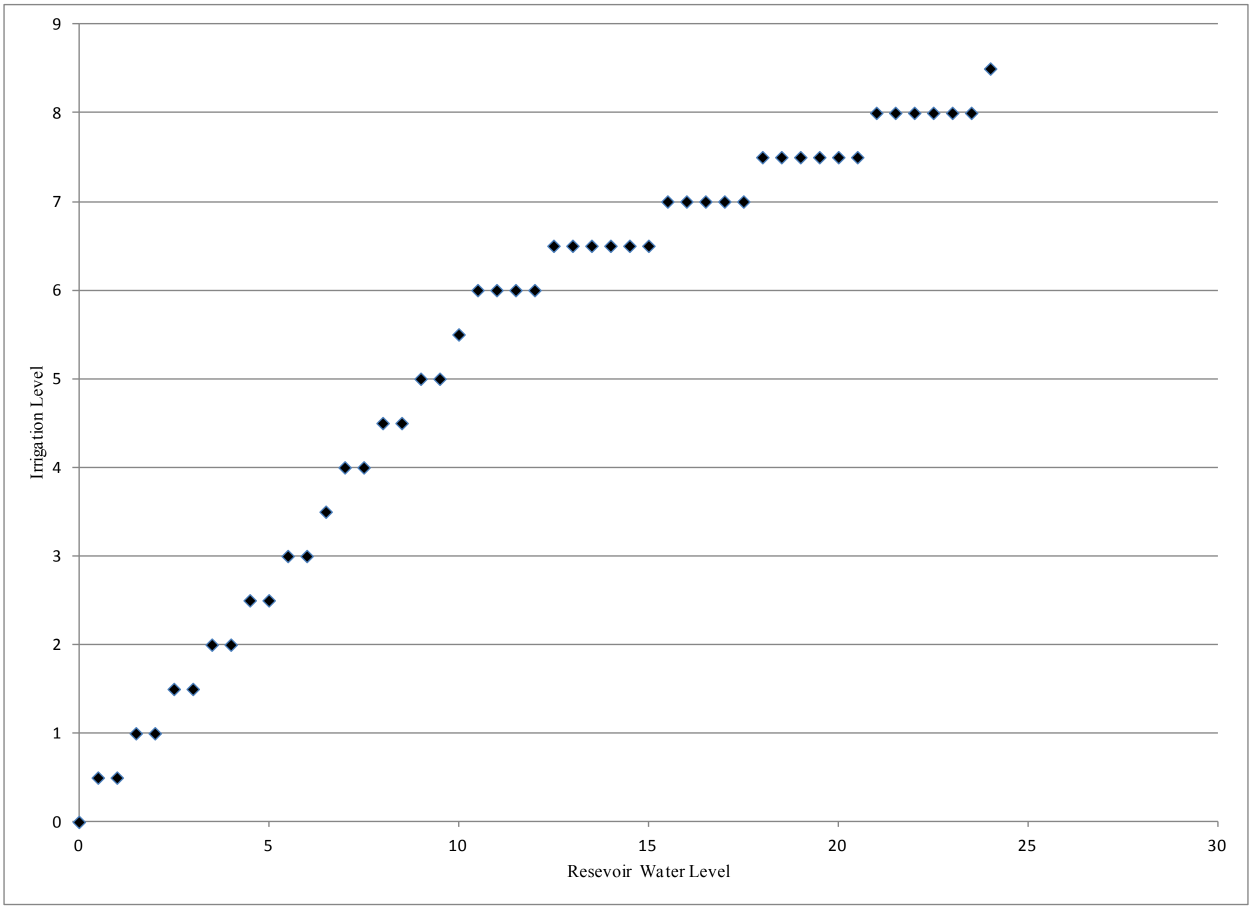


Figure 22. Optimal Irrigation Policy for Rice

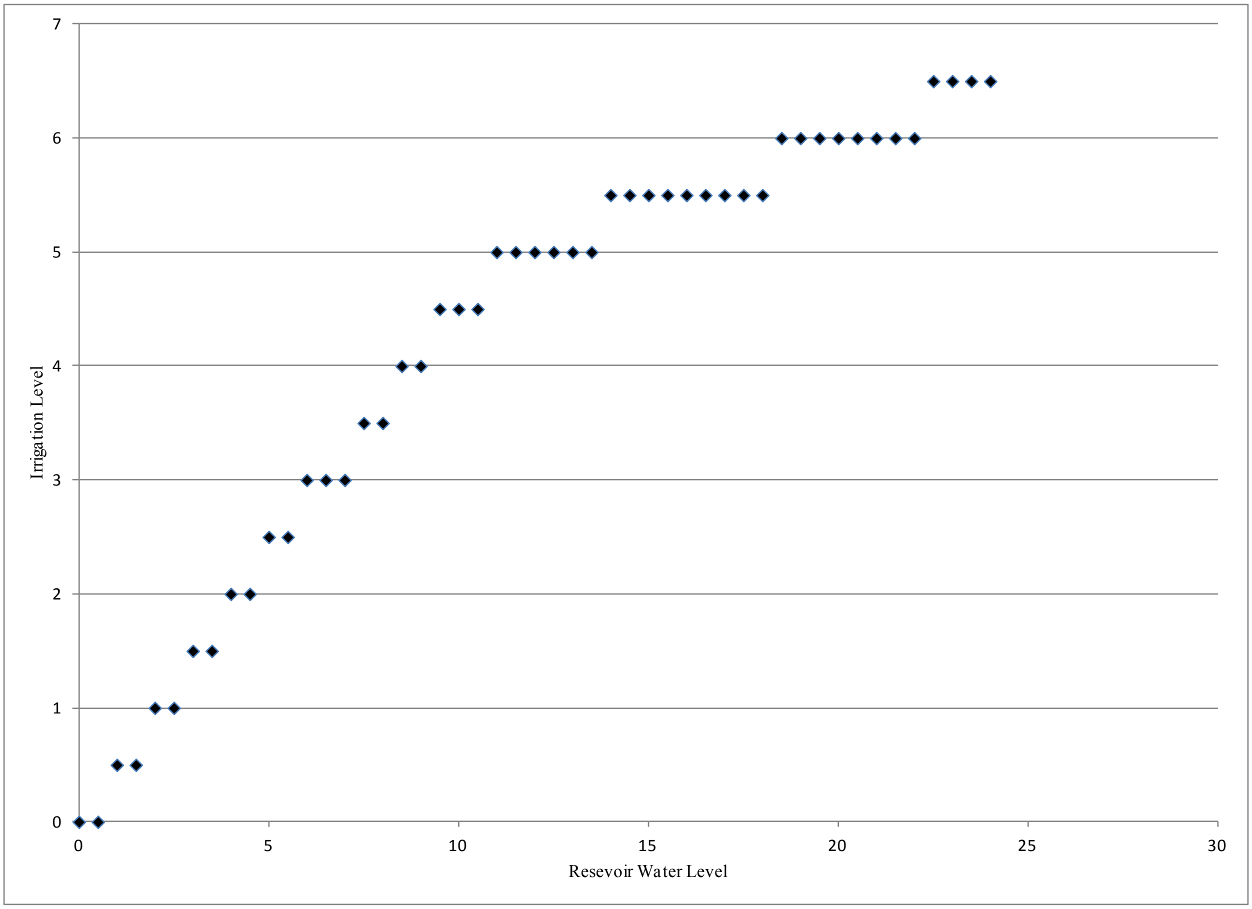
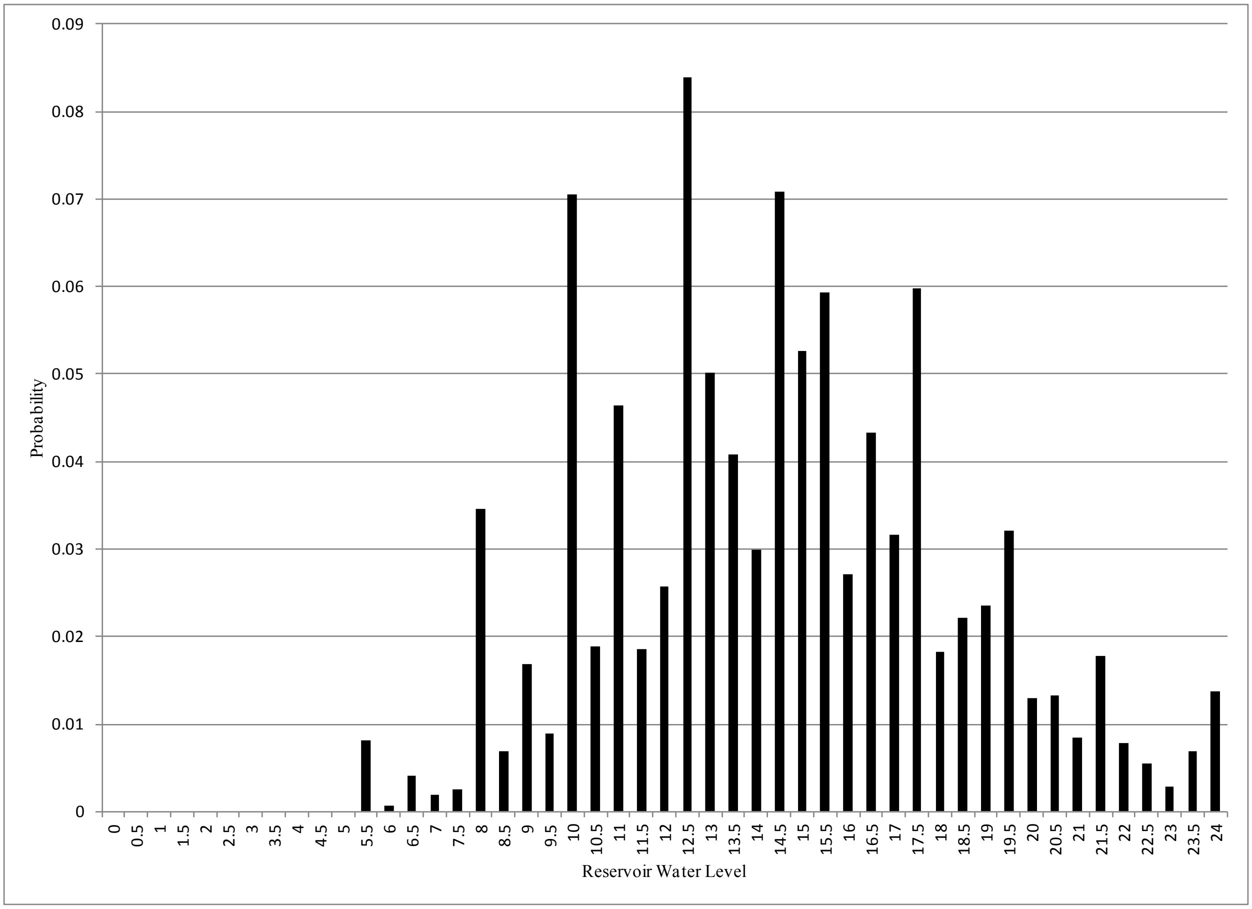


Figure 23. Steady State Distribution



Appendix G. Simulation Results with 5 Percen Deficiency under Scenario A2

Figure 24. Optimal Irrigation Policy for Sugar Cane

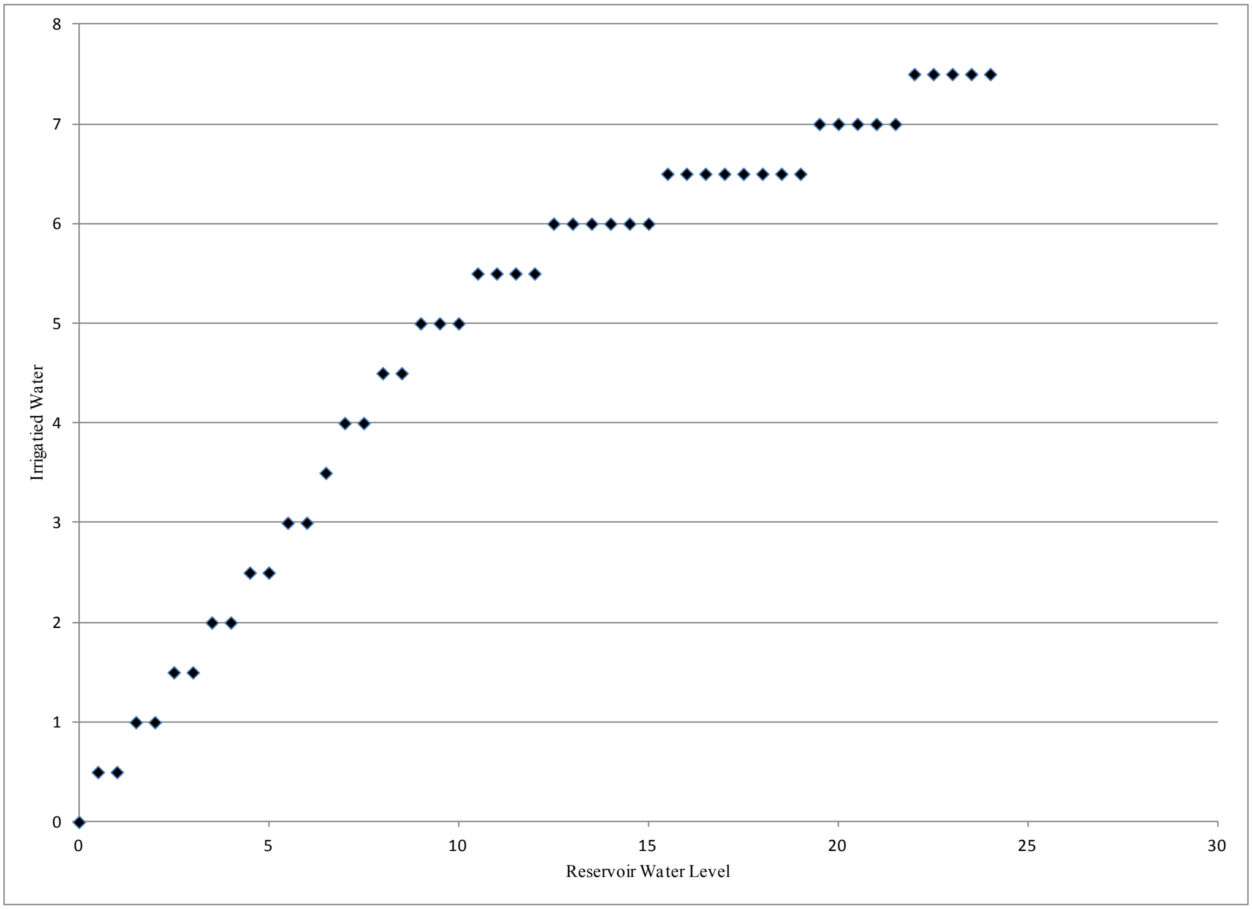


Figure 25. Optimal Irrigation Policy for Rice

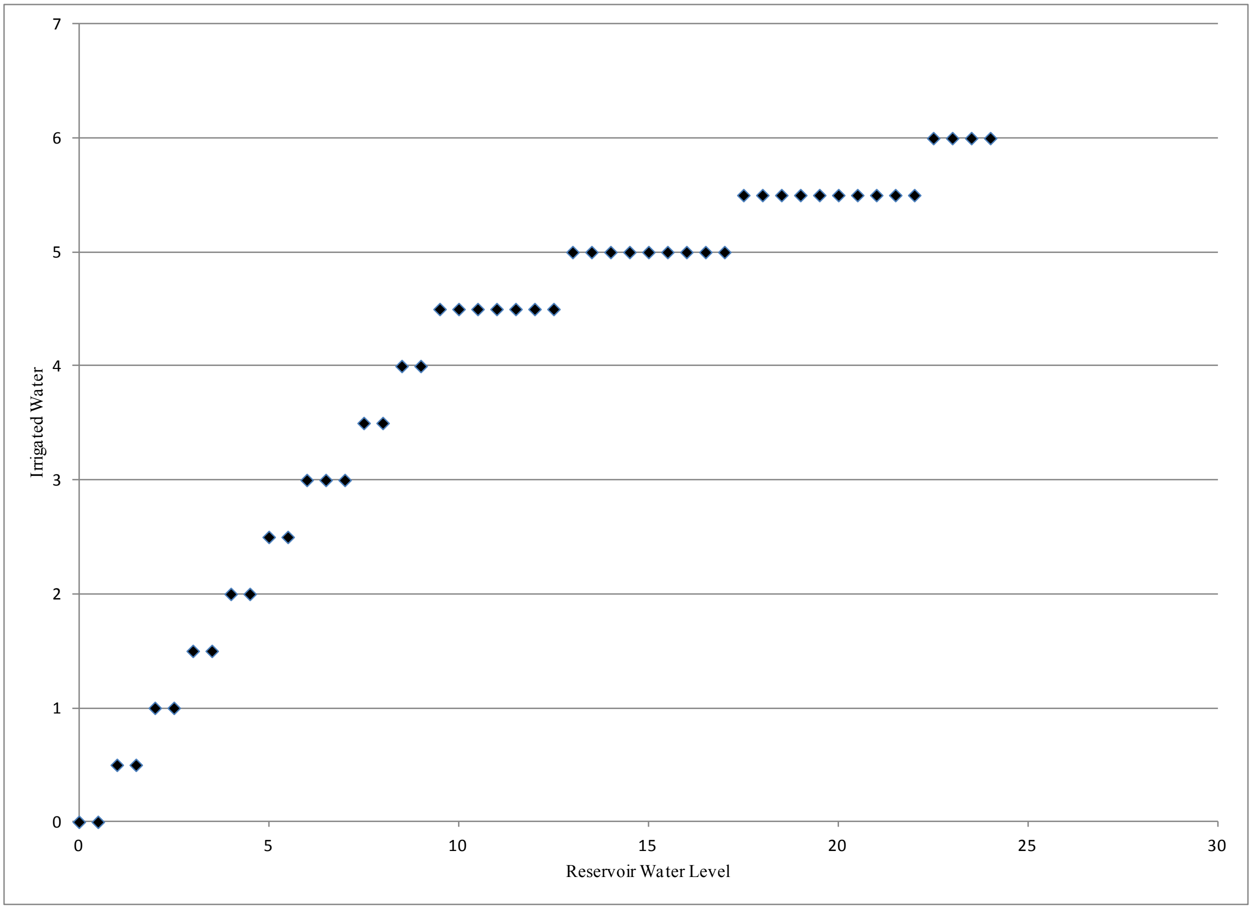


Figure 26. Steady State Distribution

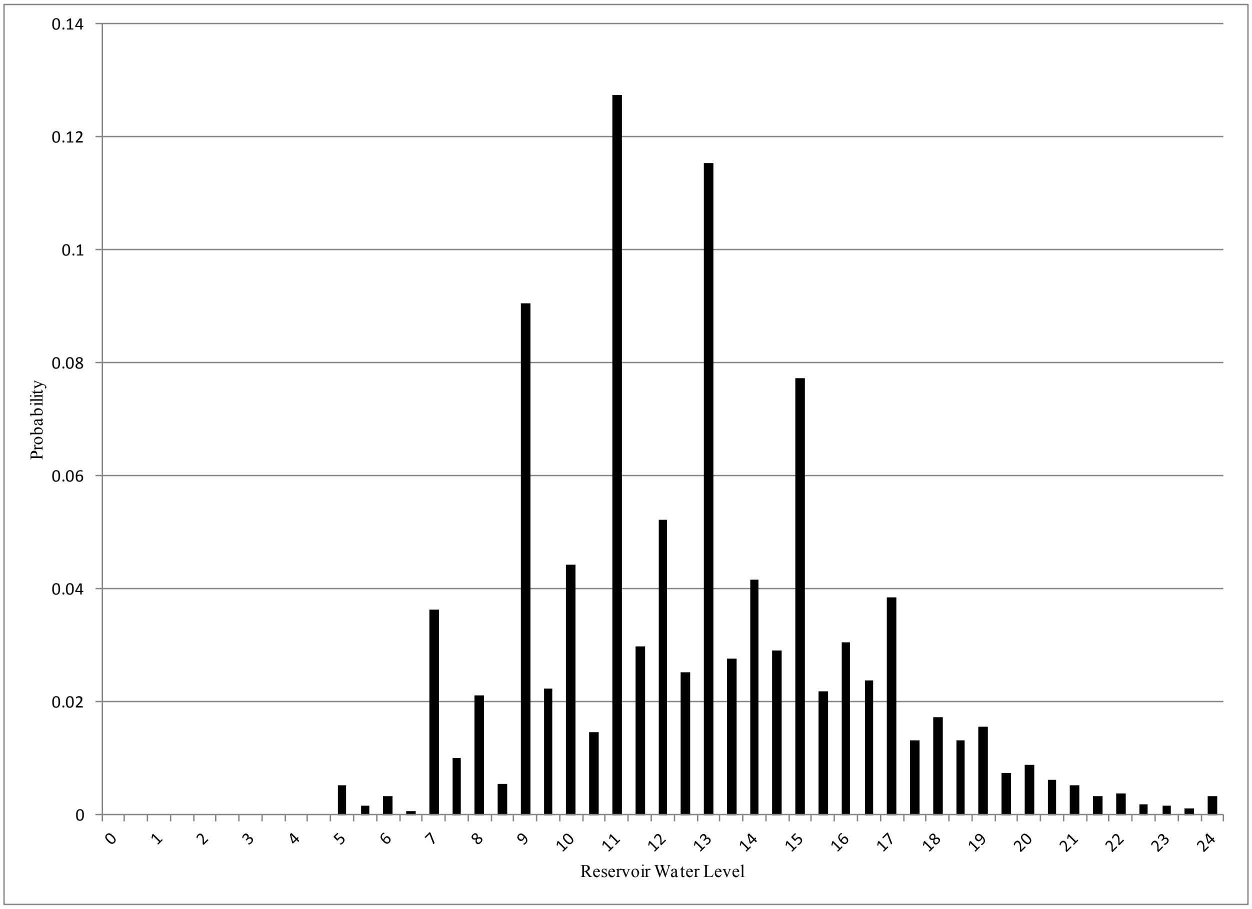
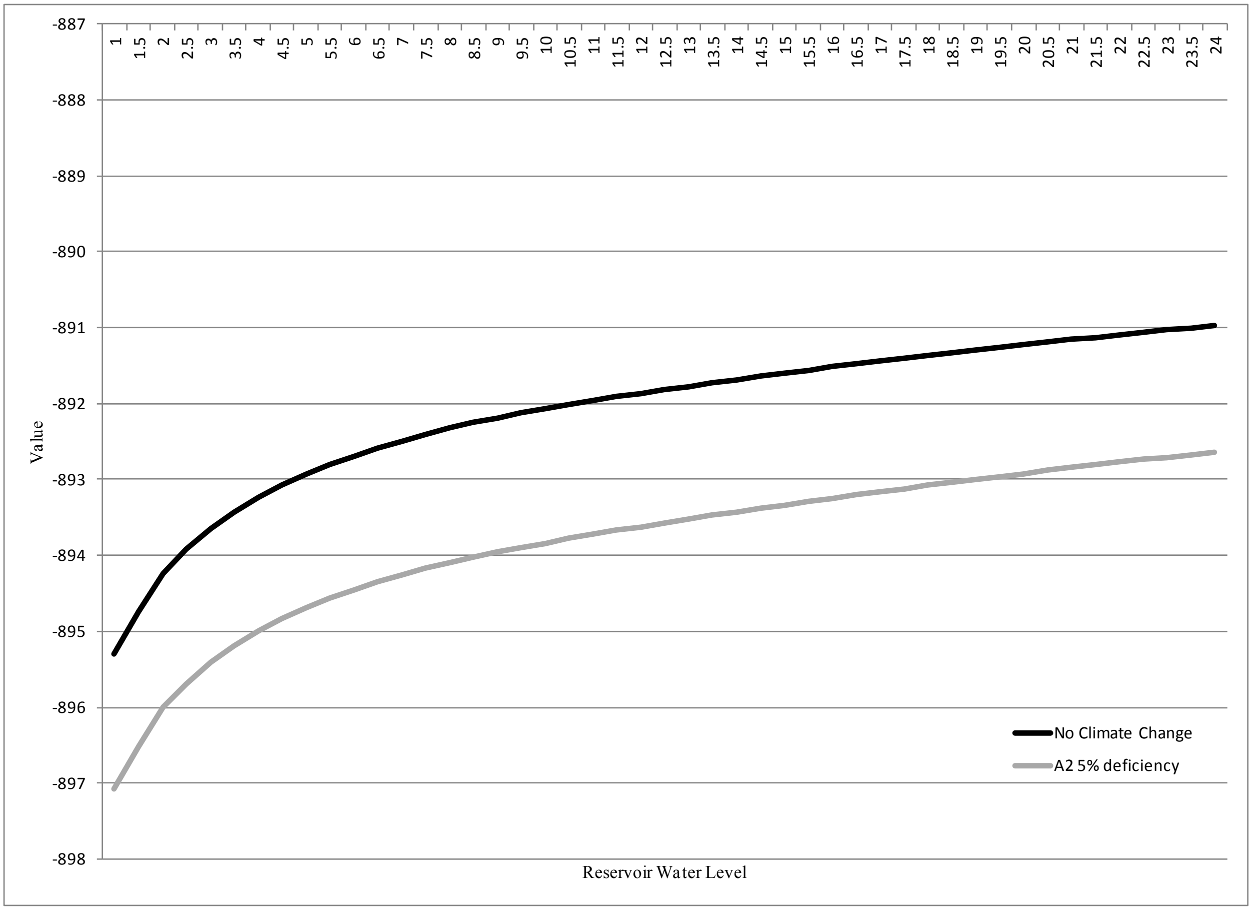


Figure 27. Optimal Value Function



Appendix H. Simulation Results under 5 Percent Deficiency with Insurance

Figure 28. Optimal Irrigation Policy for Sugar Cane

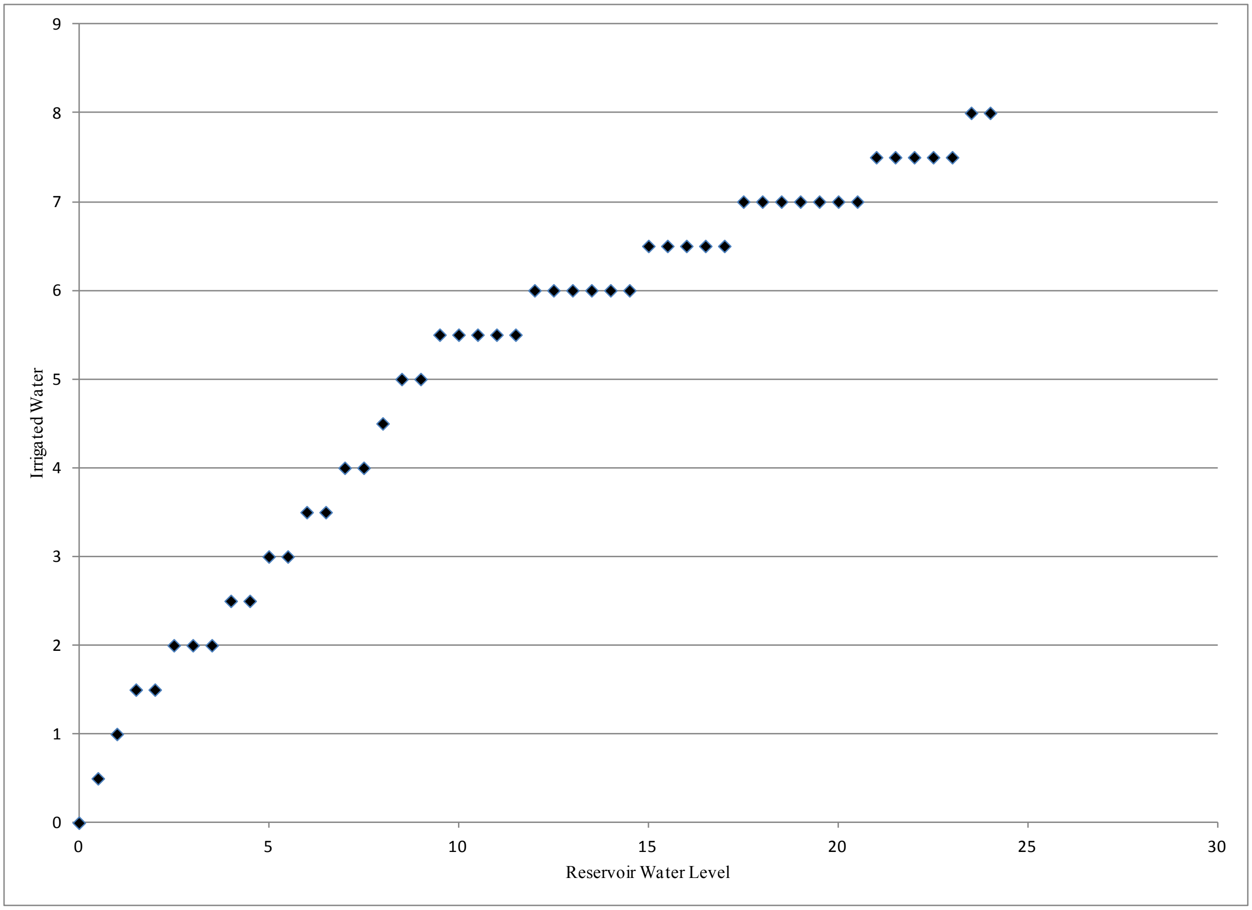


Figure 29. Optimal Irrigation Policy for Rice

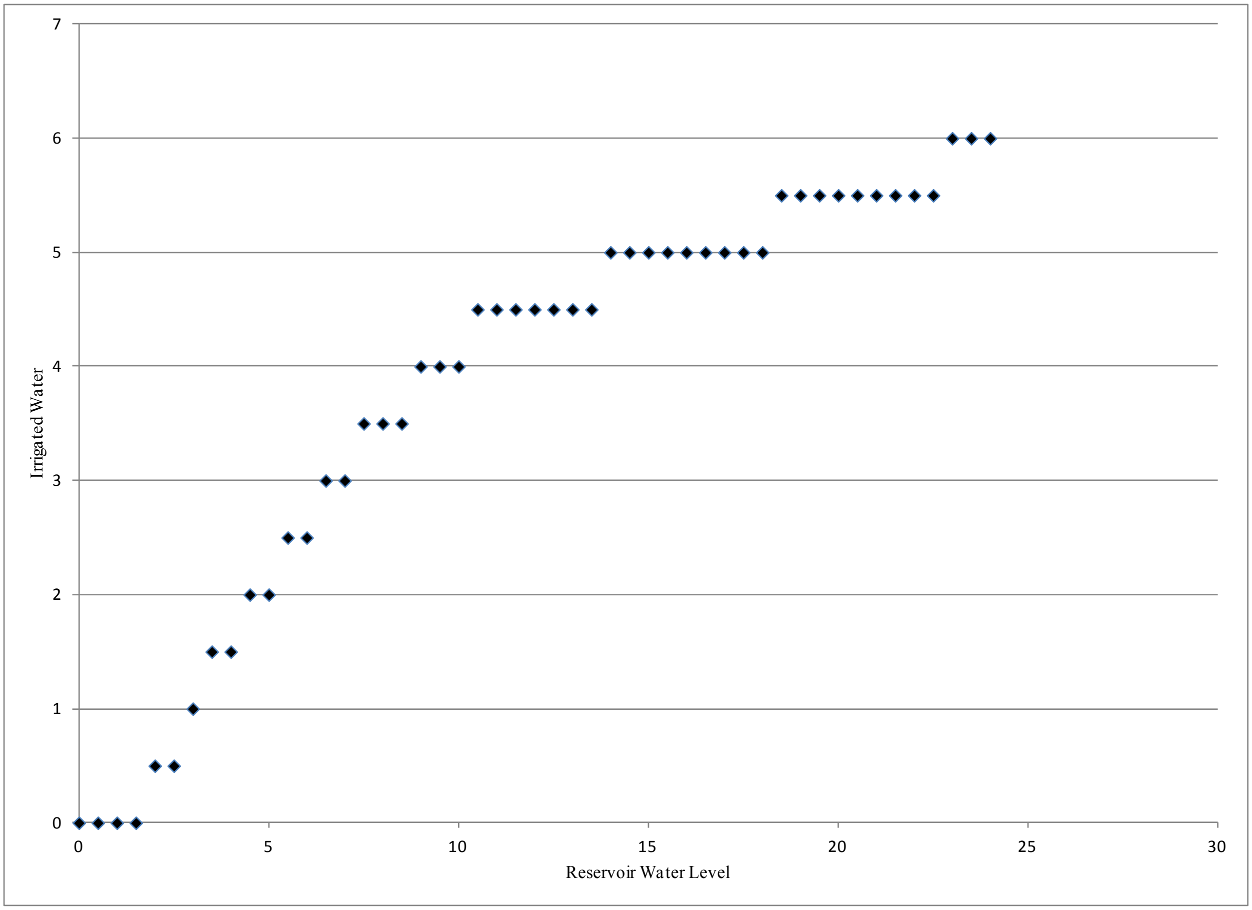
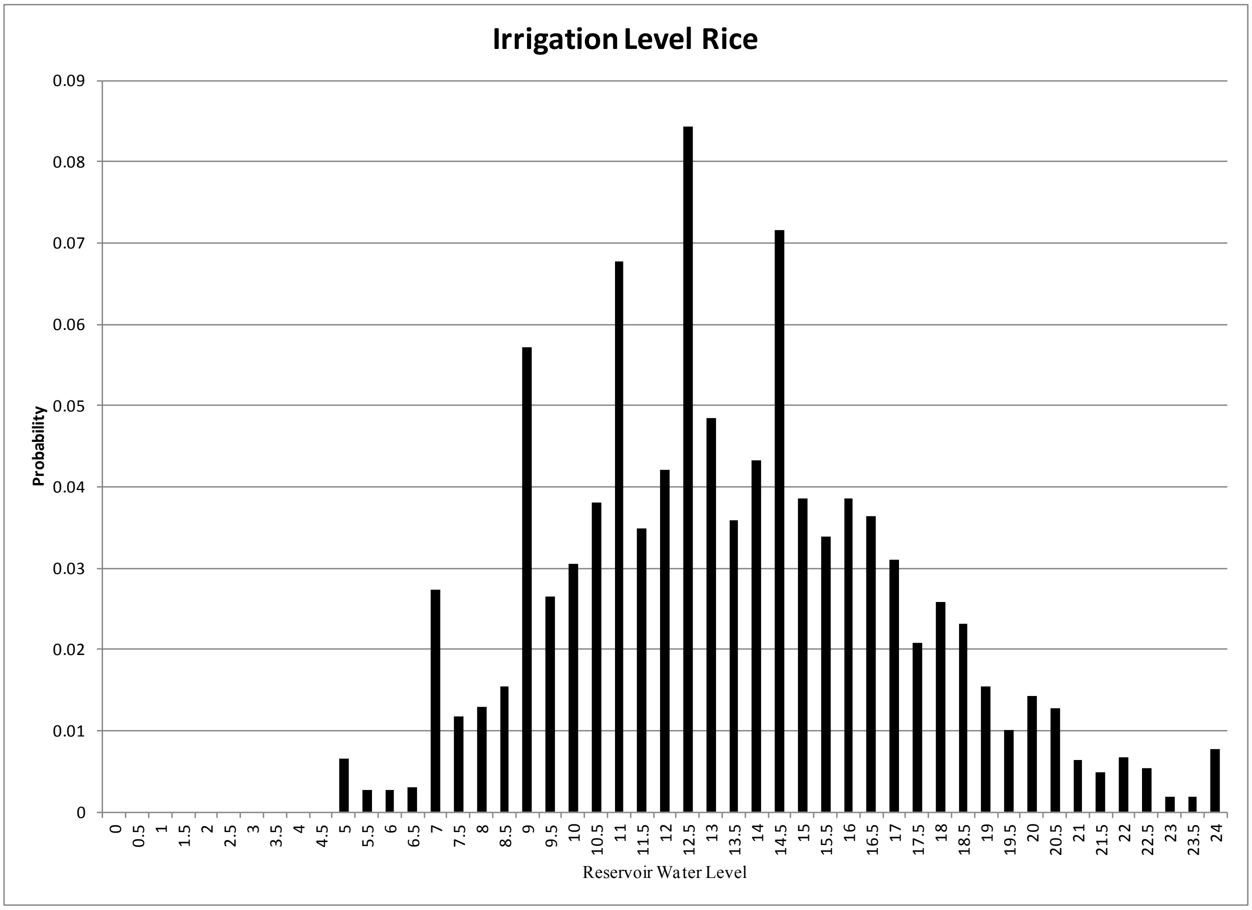


Figure 30. Steady State Distribution



Appendix I. Institutional Framework for the Management of Surface in ARLID, Guanajuato, Mexico

The Alto Rio Lerma irrigation district (ARLID) obtains its water for irrigation from the Lerma-Chapala Basin System which is divided in 17 drainage basins.[65] This system is located in the central region of the country with a surface of 47,116 km^2. The main collector in the system is the Lerma River, which along its 700-km is fed by the Gavia, Jaltepec, Laja, Silao-Guanajuato, Turbio, Angulo and Duero tributaries.

Since 1991, the water supply for irrigation in the ARLID was determined under the Federal Agreement for the Distribution of the Superficial Water in the Lerma-Chapala Basin. Under this Agreement the supply water for ARLID was determined as a percentage of the storage levels from dams Solis and Tepuxtepec. The water for irrigation within the ARLID was distributed according to the licenses and rights.

In 2004, a new agreement with a global basin management was incorporated. The water supply for the ARLID was determined by the calculation of the total runoffs restitution for five of the seventeen basins located in the Upper Lerma region: Lerma River (Alzate), River La Gavia River (Ramirez), Jaltepec River (Tepetitlan), Lerma River 2 (Tepuxtepec) and Lerma River 3 (Solis).[66] Once the annual volume of restitution run-off is calculated, the following allocation rule for the ARLID is applied.

"When the maximum volume of the total surface runoffs generated by the five basins (Alzate, Ramirez, Tepetitlan, Tepuxtepec and Solis) of the previous period is between 0 and 999.00 hm^3, then the maximum extraction volume will be 477.06 hm^3. When the runoffs are higher than 999.00 hm3 and less than 1,644.06 hm^3, the maximum volume of extraction will be 74.08% of the sum of the set of the basins minus 263.12 hm^3. Finally when the total maximum leakages generated in the basins would be higher than 1,644.06 hm^3, the maximum volume of extraction will be 955 hm^3." (CONAGUA, 2006)

[65] Lerma River 1 (Alzate); La Gavia River (Ramírez); Jaltepec River (Tepetitlán); Lerma River 2 (Tepuxtepec); Lerma River 3 (Solis); La Laja River (Begoña); Querétaro River (Ameche); La Laja River 2 (Pericos); Yuriria Lagoon; Lerma River 4 (Salamanca); Turbio River (Adjuntas); Ángulo River; Lerma River 5 (Corrales); Lerma River 6 (Yurécuaro); Duero River; Zula River; Lerma River 7 (Chapala)

[66] Total runoff volume = downstream runoffs – upstream runoff – imports – returns + uses (irrigation districts+ small scale irrigation + potable water) + evaporation from bodies of water inside the basin + variation of the storage in bodies of water inside the basin + exports.

Thus, by the second week of September of every year, the Commission calculates the basin's runoff generated during the 10 months (from November to August), along with a forecast for September and October (based on historical records for the same periods). In particular, more weight is given to years with similar runoff volumes during September and October. Averages are also calculated, as well as minimum and maximum values to compute their variations.

Although the allocation rule considers five basins before the Solis dams, in practice ARLID extracts water mainly from Solis reservoir and from other watersheds not considered in the initial accountability for allocation (Yuriria Lagoon and Purisima reservoir).

For the sake of the operation and management, the ARLID is organized in 11 modules. The main ARLID's task is to distribute the allocated water to those modules. Each module is entitled to a proportional share of the water available in those four reservoirs. Those entitles are determined by the water rights module users own, provided that the volume is available at the start of the season in November (Kloezen et al., 1997). Water Users Associations operate individual modules. Every module must collect fees from its users. The CONAGUA receives part of those fees collected. The irrigation fees are determined by the CONAGUA based on the volume that each module is buying. A single limited liability company (LLC) created in 1996 operates, manages, conserves and maintain the irrigation network that includes primary canals, secondary canals and drainage.

The CONAGUA schedules deliveries of water resources to the modules, performs monitoring at the field, module, and district levels, and checks the weekly reports of the ditch tenders at each module (Kloezen and Garcés-Restrepo, 1997).

Appendix J. Institutional Framework for the Management of Surface Water in CLID, Lambayeque, Peru

The CLID is located in Northeast coast in the basin Chancay-Lambayeque, in the Department of Lambayeque, Peru. CLID is one of the four largest irrigation districts in North Peru, and its agriculture is completely dependent on irrigation. According to the National Water Authority, the CLID have 125,238.27 hectares of irrigated land. Seventy percent of this land operates with permanent licenses and 30 percent with permits.[67]

The water supply for the CLID comes from the Chancay River, which originates in the Mishacocha Lagoon in the Andean highlands at 3,800 meters above sea level. From east to west, the Chancay River flows from the San Juan River, in the Andean zone, to the center of the Lambayeque Basin where the Raca-Rumi water intake captures part of the water for its storage in the Tinajones Reservoir. The remaining flow continues by the Chancay River to the Puntilla distributor channel, where flows from the Tinajones River and the Chancay River are divided into three watercourses: the Taymi Channel, which flows to the North; the Reque River, which flows south into the Pacific Ocean; and the Lambayeque River. Waters from the Taymi Channel and the Lambayeque River are completely consumed by the CLID.

The system is basically a run-off-river system with a relative small off-river storage reservoir (Vos, 2005). Thus, the role of the Tinajones Reservoir is primarily to store water from the Chancay River's surplus during the wet season, which will be reallocated in the valley for irrigation during drier months, July to September. Chancay River discharges are abundant but irregular, depending on the precipitation that occurs in Cajamarca highlands (4,000 – 6,000 m) between December and March, when 60 to 70 percent of the river's discharges take place.

Since 1969 the irrigation district has been managed by the Ministry of Agriculture (MINAG), but in 1992 the system management was awarded in concession to the Water Users Association (WUA). Under this regimen, farmers started paying for requested volumes of water under a volumetric irrigation service fee. In 1994, the Assembly of Water Users of the CLID established the firm ETECOM to get the concession of the irrigation services directly from the Tinajones System. ETECOM is in charge of the main system, while the irrigation commissions

[67] An area of 118,835.71 hectares is under irrigation, of which 87,245.52 hectares are under concession.

are in charge of the secondary canals. No subsidies are awarded to the CLID; the operation and maintenance of the system is paid from the volumetric water fees.

Each water user with water rights is allocated a maximum volume of water each year depending on the requirements of the crop to be grown.[68] Farmers must to buy water turns in the irrigation commission offices to receive one *riego* into their fields.[69] The system of deliveries, schedules and allocation considers two types of water rights. The percentage of losses of water in the infrastructure is officially considered to be 25 percent.

For purposes of operation and management, the CLID is organized into 15 Irrigation Commissions[70] (IC) managed by a Water Users Association, WUA, which formalized and issued individual water rights. The National Water Authority determines the volume of the water for irrigation based on a hydrological balance of the basin. On one hand, the demand is based on the planting intentions that users submit ever early June to their irrigation commissions. In the other hand, the supply is based on the levels of storage, historical records or the Chancay's flows at the 75 percent confidence level, along with the forecast for the downstream runoff of the Tinajones reservoir and weather information that considers the precipitation in the upper land of the basin. The final allocation between irrigation commissions is determined by the waters rights that users of every commission own.[71]

Every year, in early July for sugarcane farmers and September for rice farmers, the water users register their sowing intention areas with their Irrigation Commissions. After, in late July, previous to the beginning of the agricultural campaigns, the National Water Authority issues the forecast on flows of the Chancay River at the 75 percent persistence level.[72] This monthly forecast is used as a reference point to contrast with the river's actual flows, and these results will define the approval of the requested area for planting in the CLID. Thus, planning of the agriculture season is carried out in November, based mainly in the analysis of the ANA's persistence flow, the remaining water in the reservoir, the recuperation water and the underground water.

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[68] Rice requires in average 14,000 m3/hectare and sugar cane requires 20,000 m3/ha.
[69] One *riego* is an hour of water delivery with a flow of 160 liters/second equivalent 576 m3/hour.
[70] The Irrigation Comissions are Chongoyape, Ferrenafe, Pitipo, Capote, Chiclayo, Lambayeque, Reque, Mosefu, Eten, Mochumi, Muy Finca, Tucume, Sasape, Morrope. The former three are sugarcane cooperatives.
[71] The updated register of irrigators with their irrigated area and their water rights, have allowed improving water distribution, billing and collection of water charges.
[72] The hydrological year of the Chancay-Lambayeque basin starts in September and ends in August; while the agronomic year starts in August and finishes in July.

However, the ANA annually authorizes for the CLID an allocation between 600-700 millions of cubic meters (Mm3). In contrast, for the approval of the planting intentions of the whole CLID (118,835.71 hectares), at a volume of at least 1,656 Mm3 would be necessary. Because of this situation, the CLID has adopted strategies to cope with water shortage. Crops such as rice are restricted applying ranks or restrictions on the cultivated area, according to the volume of available water in the reservoir and the flows of the river.[73] For example, if the Chancay river flows are low (around 30m3/second), and the reservoir has a level storage below 60,000 m3, then 70 percent of the registered area is approved. If the flow discharge of the Chancay River is higher than 80 m3/sec, then 100 percent of the registered area is approved.

Appendix K. Weather Derivatives

This section attempts to explain some of the differences among weather-based derivatives. In the context of the present research, the purpose of weather derivatives will be to compensate farmers for the loss due to insufficient water allocation or precipitation. Weather derivatives are defined by three main criteria: the insured event, the duration of the contract, and the location at which the event is insured. There exist different methods for calculate the indemnities paid by the contract and to calculate the actuarially-fair price of the contract (see Turvey, 2001; Mahul, 2001; Vedenov and Barnett, 2004; Zeuli and Skees, 2005).

According to Turvey (2001), weather derivatives can be brokered as an insurance contract or as an over-the-counter traded option. Weather derivatives can be structured as swaps, futures, or option contracts. In general terms, any derivative is indexed to a weather variable such as temperature or cumulative rainfall measured in a specific location over a specified period. All derivatives contracts specify a level keyed to the index (strike level) and the payments are calculated at the contractual rate "tick rate." All payments accumulate over the contract period and are payable after the contract period. The contract duration varies, and contracts could include specific instructions to measure an index, make payments and place an upper bound on payments called a "cap" (Dischel and Barrieu, 2002).

There are important differences between derivatives and their characteristics define their utility as instruments to cope with agricultural risks. Swaps and collars usually operate with no initial exchange of money, which makes them attractive to speculators, because they can assume

[73] Rice requires in average 12,000 m3/ha of water, and its growing season is from December to May.

risk positions, and even build a risk portfolio, with no initial outlay of capital. Swaps can be more risky than options, as downside risk can be better controlled with options. In swaps and collars the buyer is the one who benefits from the rising index; the swap buyer receives a payment from the seller only when the index is greater than the swap level, up to the cap. Conversely the swap seller benefits from a declining index, and would receive a payment only when the index is less than the swap level (Dischel and Barrieu, 2002).

In the case of options, the buyer pays to enter into a contract that may requires the seller to pay at the end of the option period, an amount calculated from a specified measure of the weather, the weather index (Dischel and Barrieu, 2002). The insured can buy a put option that would provide an indemnity if the weather index is lower that the attachment strike at the end of a specified period. Also, the insured can buy a call option and, if the weather index exceeds a specified level (the attachment strike) he will receive a payment at the end of the specified period. Also the insured could select both (collar). Payments are keyed to the difference between the index and the strike level, for each millimeter of rainfall that the option is in the money, a payment per unit is made. While a detailed discussion of these derivatives lies beyond the scope of the present study, such a discussion is available in Dischel and Barrieu (2002).