Managing Irrigation Risk with Inflow-Based Derivatives: The Case of Rio Mayo Irrigation District in Sonora, Mexico

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Abstract: Uncertain reservoir inflows represent a major source of risk for irrigated agriculture. A derivative instrument that uses reservoir inflows as the underlying variable is designed and tested with a recursive stochastic simulation of Rio Mayo irrigation system. The results indicate that the instrument effectively protects against downside risk.

I. Introduction

Water is perhaps the most precious natural resource for humankind. Unfortunately, water is seldom present at the exact place, time, quantity and quality to satisfy the uses it serves in different aspects of human life. In regions where rains are scarce, communities rely on hydraulic works for supplying populations with water, irrigating large cropping areas, drainage, and sometimes generating power. Equally unfortunate is the fact that if the replenishment of reservoirs depends on streamflows from a river or system of rivers, the process is characterized by high degrees of uncertainty. While some years experience extremely low levels of replenishment that lead to water shortages; other years will experience replenishment at levels that exceed the storage capacity of the hydraulic works and produce floods.

In the particular case of irrigated agriculture, a large number of systems around the world are characterized by a highly variable supply of surface water and a relatively abundant endowment of land. The combination of these characteristics implies that water is the limiting factor of production and that the uncertainty surrounding its supply translates into likewise uncertain streams of income for irrigators. The multiplier effects of the uncertainty in water supply extend to issues of food security and rural employment for economies based on irrigation. In addition, the water supply uncertainty deters irrigators from making investments in water technology that improve the utilization of water at the farm level, and keeps away creditors and investors from financing projects that maintain and develop the irrigation infrastructure for the system.

Mexico serves as a good example of the problem described above. According to *Comision Nacional del Agua* (CNA, 2004), the Mexican authority in charge of regulating the use of water resources, there is a disparity between the natural availability of water and the locations where the resource is needed the most. In particular, 64 % of the resource availability occurs in the south of the country where only 11% of the land suitable for agriculture is located; whereas in the north side, where 53% percent of land suitable for agriculture is located, only 7% of the water resources are available. Due to the relative scarcity of rainfall, cropping activities in the most productive lands of the Mexican Northwest depend almost entirely on irrigation. Furthermore, the disproportionate endowment of the water resources is accompanied by rapidly growing populations in the water scarce areas; consequently the country has witnessed serious water conflicts among water users when the replenishment of reservoirs is low.

Although CNA employs elaborate hydrological models that provide some guidance in the allocation of reservoir water for irrigated agriculture, these plans do not include any type of formal financial assistance or water banking scheme to mitigate the opportunity costs imposed by the uncertain availability of water. The only type of financial assistance available to farmers is the occasional ad hoc disaster payment disbursed from the state governments. Thus, a typical irrigator in the Mexican Northwest operates in a risky environment characterized by the random availability of the most limiting factor of production and without access to formal risk sharing markets to hedge against such a risk.

Considering the problems stated above, the goal of this research is to investigate the feasibility of introducing an inflow-based derivative in one irrigation district of the Mexican Northwest, namely Rio Mayo. Although we have chosen this particular district to carry out the analysis, this research is relevant to any irrigation system in the world that depends on surface waters to supply irrigation. In order to achieve the goal of this research, we frame a model with the most relevant variables for the operation of an irrigation district. First, we develop a model of the operation of the Adolfo Ruiz Cortinez (ARC) reservoir, including its release rules and most relevant physical characteristics. This component is recursive in nature and aims at depicting the inter-temporal dimension of the problem. Second, based on historical data on reservoir releases and hectares planted, we fit planting response functions to represent the physical relationship between irrigation water, conveyance efficiency and the size of the irrigated area. Finally, we design a contract that derives its value from the inflows to the ARC reservoir. The derivative is designed as a put contract that pays indemnities when reservoir inflows are below a strike.

Our findings indicate that the proposed derivative is feasible when designed such that payments are discounted by the occurrence of higher than average inflows in the Fall-Winter season. Since inflows during this period allow irrigators to carry out production activities in the end of the season, farmers can naturally use these inflows to mitigate the cost of water shortages. In other words, inflows that accumulate between October and March serve as a natural hedging mechanism for irrigators.

II. Literature Review

A. The Technical and Institutional Views of Water Supply Risk Management

The random nature of water supply represents a major source of risk in irrigated agriculture and has been the subject of many research reports in the agricultural economics literature. Proposals to deal with this risk fall into two different, but complementing views: the technical and the institutional. While the technical view's main focus is the optimal management of the resource at the supply side through reservoir operation rules; the institutional view broadens the spectrum of policy action by seeking rules that link the supply and demand for water through markets, particularly for resolving water shortages. Despite their apparent differences, researchers have combined the methodological developments of the technical view with institutional arrangements to provide general frameworks in the study of water allocation when the availability of the resource is uncertain.

Researchers in the technical view have developed methodologies to manage the random component of streamflows in the design and operation of reservoirs. For instance, stochastic dynamic programming (SDP) is a powerful tool that allows decision makers to solve the inter-temporal dimension and derive operation rules. The optimal rules equalize the marginal benefit of current usage with the discounted expected marginal benefits of future resource usage, taking into account that current usage impacts the availability of water in the future.[1] Alternatively, planners can develop probabilistic models using chanced-constrained programming (CCP), taking into account the random availability of the resource constraint and developing risk premiums to represent the costs of adopting aggressive operation policies. The method is based on the notion that the irrigator is willing to accept a given level of risk, expressed as a percentage of time, at which the water demand is satisfied (or violated).[2] The major contribution of the technical view is that it provides an array of techniques that provide planners with useful insights into the economic impact of random inflows and incorporate risk management components in the reservoir operation rules.

However, the application of such optimized operation rules only limits the consequences of water supply shortages to a certain extent. While it is true that a reservoir is by itself a risk management tools that allows planners to store water for future use, there are two types of costs associated with this alternative. One the one hand, when water is the limiting resource or binding constraint in the production process, high opportunity costs are associated with water left idle in the reservoir. Operators strive to achieve a delicate balance between conservative operation rules and high opportunity costs. On the other hand, high transaction costs are incurred in storing water because water evaporates and leaks. Furthermore, storage of water creates the risk of flooding in the event that higher than expected inflows are accumulated during the replenishment season. In summary, the operation policies derived from DSP and CCP do not insulate the system from the economic consequences of uncertain reservoir inflows. Therefore, there is a clear need for other mechanisms that supplement operating rules in the management of water supply risk.

The institutional view proposes the use of market-based arrangements to deal with the problem of uncertainty in the supply of water. In particular, economists propose the

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[1] Applications of DSP in the operation and planning of reservoir systems can be found in the works of Dudley, Howell and Musgrave (1971a, 1971b); Dudley, Musgrave and Howell (1972); Dudley (1972, 1988a, 1988b); Dudley and Burt (1972), Mawer and Thorn (1974); Sobel (1975); Dudley and Musgrave (1988); Rao, Sarma and Chander (1990); Dudley and Hearn (1993).

[2] Application of CCP to the operation of reservoir for irrigated agriculture can be seen in Maji and Heady (1978), Eisel (1972), and Askew (1974, 1975).

establishment of a system of well-defined water rights. Such a system is fundamental for the development of water markets. It has been well established that these markets can potentially achieve efficient outcomes in allocating scarce water resources, particularly in times of water shortages (Randall 1981; Young 1986; Livingston 1998). In order to deal with the uncertain availability of water, several water right systems have been proposed. For instance the prior appropriations doctrine assigns water rights with different security clauses that clearly establish which rights are to be fulfilled first in the event of water shortages. The classic example of how this system is implemented is the water markets in the Western United States, where agriculture shares a good proportion of the senior rights to water.[3] Alternatively, water rights systems could be designed such that the risk of water supply is equally shared among water users. Three approaches that have been considered in previous studies, but never implemented in practice, are reservoir content, volume and capacity sharing (Dudley 1988b; Dudley and Musgrave 1988).

Despite their potential, very few water markets have been established. Young (1986) and Howitt (1998) suggest that the major challenges in implementing such institutions include high transaction costs associated with water transactions and third-party effects associated with the physical transfer of water. For example, the physical losses during the conveyance of water might exceed the potential benefits of the transaction. In addition, water markets achieve efficient allocation of water only when the proper compensation procedures exist to resolve third-party effects or externalities imposed by water transfers.

B. The Use of Risk-Sharing Institutions

Alternative risk-sharing institutions have the potential of transferring the water supply risk to agents outside the irrigation district. Thus, one could think about a synergistic approach in which the markets for risk and water blend with operation rules. Such an approach would potentially generate a more efficient allocation of the resource, not only through space, but also through time.

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[3] Examples of market-based proposals to deal with water supply risk can be found in Michelsen and Young (1993), Hamilton, Whittlesey and Halverson (1989), Taylor and Young (1995), Turner and Perry (1997).

Traditionally, agricultural insurance schemes usually protect farmers, including those in irrigated agriculture, against yield losses caused by multiple perils. The experience with such schemes indicates they are expensive to run, often financed by government subsidies, and plagued with problems of asymmetric information. In the literature of agricultural insurance there is no evidence of insurance markets being used to protect against the economic impact imposed by water shortages in irrigated agriculture.

In lieu of expensive agricultural insurance schemes, weather derivatives could be used in the management of water supply risk in irrigated agriculture. In spite of the popularity they have encountered in the energy markets of the US, very few applications can be found in the agricultural sector. To date, only two proposals are found in the literature regarding the use of derivative contracts in the hedging of water supply risk in irrigated agriculture.

The first study is by Skees and Zeuli (1999), who study the feasibility of introducing a rainfall derivative to protect against the variability of the storage levels into a reservoir. In their application to the Blowering reservoir in Australia, the authors are able to explain 70% of the variation of the water levels in the reservoir using a rainfall index based on three rainfall stations surrounding the reservoir area. However, correlating rainfall to the storage level implies a caveat. Specifically, the storage variable is basically the outcome of reservoir management decisions, and as such it is subject to manipulation. Variables subject to manipulation are also subject to moral hazard problems in insurance schemes. Furthermore, in order to establish the correlation between rainfall and storage levels in the reservoir the participants need to understand the operation rule of the reservoir and the effect of rainfall on reservoir inflows. Such relationships might prove difficult to understand, especially in cases where snow melting is a factor that influences the inflows into the reservoir.

In a similar proposal, Agarwal (2002a, 2002b) favors the design of a derivative contract using the water table as the underlying index. While a water table index provides a very strong correlation with the soil water contents and the availability of underground water, the author fails to recognize the fact that water tables are subject to man-made changes. Although part of the variation on the level of water in aquifers, similar to surface reservoirs, is directly explained by the variations in the replenishing rate from water that filters to the soil from rainfall and snowmelt, the underground water stock is also subject to management-induced variations. In the particular case of irrigated agriculture, there is evidence that the unregulated pumping of the underground water might lead to the over-exploitation of aquifers. Therefore, the use of the water table as the underlying index of the weather contract might be subject to moral hazard problems and diminish the feasibility of the contract.

Two features distinguish this paper from the work described in the literature. First, we propose using reservoir inflows as the variable underlying the derivative instrument. While it is true that rainfall is an “act of God,” indexing this variable to account for reservoir inflows is a difficult task. Moreover, when the irrigation area is located in a desert-like region, as is the case of Northwestern Mexico, establishing the correlation between rainfall and storage proves almost impossible. Thus, our choice of inflows as the underlying variable is justified by three factors: data availability, ease of understanding (for irrigators) and prohibitive manipulation (i.e. “act of God”). In most irrigation systems there are quality historical measurements of reservoir inflows. This piece of information is critical even before the reservoir is put in place. Furthermore, irrigators trust and clearly understand these measurements. Thus, for them the relationship between storage and inflows and their plantings is relatively easy to establish. Finally, reservoir inflows are an “act of God,” thus they are not subject to manipulation or tampering. As a matter of fact, these irrigation districts usually exercise monitoring activities among the water users to make sure that no water usage goes unaccounted or unmeasured.

The second feature that differentiates this paper is the integration of certain aspects of the technical and institutional views. Specifically, we value the inflow-based derivative simulating the operation of the ARC reservoir. We include release rules and planting response functions that allow us to incorporate the inter-temporal dimension of operating a reservoir. This approach is suitable for embedding in the model structure the tradeoff between aggressive release rules and increasing risk of system failure, as studied in the technical view of water risk management. Finally, we suggest a practical institution to administer this program. Namely, the SRL (collective group of irrigators) can serve as collective decision maker that collects the insurance premium from its members and distributes the indemnities according to their rules.

III. Background Information on the Rio Mayo Area[4]

A. Location

The Rio Mayo irrigation district, also known as No. 038 in CNA's inventory of irrigation districts, is located in the southern part of the state of Sonora, 27°54'' north and 109°36'' west of the Greenwich meridian. The district includes an area of 98,598 ha suitable for irrigated agriculture. In the north, the area is bounded by mountains which comprise part of the Sierra Madre mountain range, and on the southwest by the Gulf of California. The closest cities to the district are Navojoa, Huatabampo and Etchojoa. The regional climate is desert-like, characterized by deficient humidity during all the seasons. Moreover, mean temperature and rainfall in the area are 23°C (F) and 260mm, respectively. More importantly, most of the precipitation occurs between July and October, although occasionally cold fronts bring some rain between December and January. For water users in the Mayo Valley the July-October period is critical because it determines the level of replenishment of the reservoir.

B. Source of Water Supply

The main source of water supply for the irrigation district is the watershed of the Mayo River (hence the name Rio Mayo), which covers an approximate area of 11,000 km^2. The river extends for approximately 350 km and averages 1000 million m^3 in streamflows. The hydraulic work used to secure the flows from the river is the ARC reservoir, also known as Mocuzari. The ARC reservoir was built in 1955 and its infrastructure consists of an earth-filled structure 81 m high above the river bed, 775 m long, and 10 m wide at the crest, and 440 m wide at the base. After an expansion project in 1968, the storage capacity increased from 1,100 million m^3 to 1,300 million m^3. However, the silting that

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[4] This information was obtained from the CNA report (2004) and personal communications with SRL.

occurs through the years has reduced the capacity. According to the inventory of reservoirs of CNA, the ARC reservoir is classified as a mid-size reservoir in Mexico[5].

C. Cropping Patterns

The production activities during the agricultural year are divided into two cropping seasons, and with an appropriate water supply cropping activities can run throughout the year. During the first season, which runs from October to April (Fall-Winter), farmers grow wheat (the main crop of the region), maize, safflower, potato, and other minor crops. In the second season, which runs from February to October (Spring-Summer), the main crops are cotton, sorghum, and maize. In addition, a small fraction of the irrigated land is dedicated to perennial crops.

D. Farmer Organizations and Decision-making Process

Farmers in the Mayo Valley are organized in a water user association known as SRL, which stands for *Sociedad de Responsabilidad Limitada*, which stands for limited responsibility association in Spanish. The SRL groups 11,642 irrigators, which in turn fall into two categories: small property owners and *ejidatarios*. Small property owners have private property tenure over their landholdings and include 3,857 irrigators, whereas *ejidatarios* exercise common property rights over their landholding and make up 7,785 irrigators. The average landholding in the former group is 11.8 ha and 6.5 for the latter. Furthermore, the landholdings of irrigators are divided into 16 irrigation modules of different sizes and water conveyance efficiencies.

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[5] Of the 51 reservoirs in Mexico, the Adolfo Ruiz Cortines ranks 25th in size. The largest system is over 10,000 million m^3 and the smallest is around 270 million m^3 (CNA, 2004).

IV. Modeling Decisions in the Irrigation District

A. Data Description

CNA and the SRL provided the hydrologic and economic data relevant to this study. The hydrological data includes monthly records of reservoir inflows, storage, and releases. The quality of the hydrological data seems highly acceptable since they have daily observations, which they post on a bulletin board in the SRL. Irrigators use this information for planning purposes. The descriptive statistics of these series are given in table 1. The mean inflows accumulation to the reservoir over one agricultural year is 1,034 million m^3. The mean annual agricultural releases are 832 million m^3. This number does not account for releases for municipal use (around 20 million m^3), reservoir spills and evaporation losses. In addition, the history of plantings of seasonal plantings was also provided. The series suggests that mean plantings have been around 104,000 hectares per year. However, in the last 5 years plantings have experienced a downward trend due to the water scarcity. Please refer to figures 1 and 2 for a depiction of the time series for releases and plantings.

B. Understanding the Decision-Making Environment

The next step is to test some relationships that help us understand the decision making in the Mayo Valley. Thus, we need to answer some questions. First, what is the relationship between reservoir inflows and releases to the agricultural sector? This question is very important because the released volume is the most important resource endowment for irrigators.[6] As a matter of fact, in this part of the world, land without water has a very low value. Then, it is important to understand the process that drives release decisions.[7] A

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[6] Reservoir releases account for 80% of the total water supply for the irrigation district. The rest is extracted from aquifers. Although aquifers could be used as buffer stock to mitigate the water shortages, we have left aside this issue for three reasons. First, the data on underground pumping is not readily available. Second, according to water users, farmers prefer to use the surface supplies because of its lower cost (i.e. no pumping required). Third, data on these well extractions is not readily available.

[7] Although CNA implements statistical and hydrological models to control the reservoir, the implementation of the operation policy is quite questionable. The political economy usually leads to releases that exceed the prescription of the models.

second question is: what is the effect of release on the annual plantings of the irrigation district? In other words, we need to establish response functions that characterize the impact of releases on the hectares planted in the district. Finally, we need to test if the annual series of inflows exhibits autocorrelation. From the perspective of an insurance provider it is desirable that the time series does not show signs of strong autocorrelation because that makes the pricing of the instrument more challenging.

In order to answer the first question, we have run a simple regression to explain releases. The first explanatory variable is the level of the reservoir as of October 1 of each year. This variable is a stock variable that provides information about the certain availability of water at the beginning of the agricultural year. The second variable is the inflows into the reservoir in the period that falls between October and April. This variable has a twofold importance: one the one hand, it allows irrigators to carry out supplementary irrigation for the crops already established in the FW season; on the other hand, it replenishes the reservoir for future irrigation in the SS season. Please refer to table 2 to see the results of the regression.

The regression explains about 85% of the variation in releases. More importantly it confirms that the storage level of the reservoir as of October 1 of each year is not only statistically significant, but also significant in magnitude. Holding all other things constant, for an additional million m^3 in storage in the reservoir, more than half (55%) of that number will be released for irrigation purpose throughout the year. Second, although the inflows that occur in the October-April period lead to higher levels of releases, the relationship of this variable is not linear, but decreasing. In other words, there is a certain level of inflows (around 800 million m^3) after which annual releases will become negative (i.e., water will be stored). Basically, it takes close to 800 million m^3 for farmers to irrigate most of their land. Any additional supply of water has more value as storage for the beginning of the next agricultural year. Therefore, any release rule in place at the ARC reservoir must be based on two variables: beginning-of-year storage and October-April inflows.

Establishing the relationship between release volume and number of hectares cultivated is a challenging task for several reasons. First, the crop data reveals that the portfolio of crops grown in the region has not remained constant over time. The reason for those changes might be due to economic factors (i.e. prices, subsidies, technical change) as well as institutional factors (i.e. water law, land reform, etc). Unfortunately, not having a fixed crop portfolio does not allow us to estimate precisely the water needs of the crops. Second, the small data sample does provide a robust estimation. Despite these challenges the data was carefully selected to fit a response function. Furthermore, we corroborated the results of the fitted functional forms with the technical engineers of the SRL officers in Navojoa.

The specific functional form of the response functions is provided in table 3. Using actual data on releases we generated fitted plantings. There is a strong and statistically significant correlation between the predicted plantings and the actual plantings for the period 1969-2002. Please refer to figure 3 for a visual representation of this correlation, and figure 4 for a representation of the seasonal response functions.

There are two important features in the fitted response functions that play an important role in the inter-seasonal allocation of water. First, the curvature of both response functions reflect the fact that there are diminishing marginal returns to the application of water to land parcels located at a greater distance from the main irrigation canals. Since the water conveyance structure is highly inefficient, growing crops in the more marginal areas of the district requires very large releases of water from the reservoir. In fact, for an additional million m^3 released from the reservoir, only 55% of this volume is actually received at the farm level. Please refer to table 4 for the estimated efficiency in water conveyance at different points of the distribution system. The second feature relates to the inter-seasonal conveyance efficiencies. Since the average temperature during the SS season is higher, the conveyance inefficiencies in this season are relatively higher. Therefore, for each unit of water released from the reservoir, more land can be employed in FW than in SS.

Examining the production history of the district indicates that wheat is the main crop grown in the FW season. The second most important crops are maize and safflower. In terms of the profitability of these crops, it is important to notice that besides the market price, they receive government supports in the form of a per-hectare subsidy. This makes the relative profitability of the crops in the FW season higher. In terms of the SS season, the crop portfolio is highly variable. The evidence suggests that in SS oilseeds are the recommended crops, particularly cotton and safflower. According to farmers in Rio Mayo the production of SS crops has decreased dramatically due to the depressed prices and the lack of water for this season. Unfortunately, we could not obtain prices and costs of production for the SS season since production activities have been suspended during the last three years. We relied on the information provided by irrigators in Rio Mayo to propose that the portfolio of crops in the SS season carries a lower value than the FW portfolio. In order to overcome the limited information, we have decided to express the revenues of the district in a per-hectare equivalent. Thus, we normalize the return of the FW season to 1 and express the profitability of the SS season as a fraction. We further assume that the relative profitability of the SS season is 70%.

Finally, we test the inflows for autocorrelation. The purpose of this exercise is to determine if the insurance provider needs to adjust the premium for the possibility of back-to-back drought periods. The presence of autocorrelation might prove difficult for the insurer because of indemnities would have to be paid in consecutive years. In order to visualize and test for autocorrelation we use the correlogram and the BJ statistic. Please see figure 5 to see the correlogram. The resulting autocorrelation coefficient (first lag) indicates the presence of first lag autocorrelation. Although, the tests indicate statistical significance, the magnitude of the coefficient is small. The remaining coefficients are not significant at any level, indicating that the autocorrelation does not prevail after one lagged period. Therefore, we conclude that insurers would not have any considerable problems with a derivative contract based on the inflows to the reservoir.

C. Water Supply Risk

Given that we have monthly observations of the inflows, we decided to group the data in three sets. The first set is the annual data and includes the accumulation of inflows for the period October-September. The other data sets were organized in semesters. The first semester corresponds to the accumulation of inflows between October and March. This accumulation is important because it determines whether agricultural production occurs in the SS season. According to the data, 30% of the annual accumulations occur in this semester. The second semester corresponds to the period April-October and is the most critical to replenish the reservoir. The data shows that 70% of the inflows occur in this period.

After visually inspecting the data we decided a normal distribution is not suitable to the data. The normality tests performed confirmed our expectation. Thus, using the nonparametric kernel smoother in Simetar we generated PDF and CDF distributions for reservoir inflows of the three data sets described above. Please refer to figure 6 and 7 for a representation of the PDFs and CDFs. Taking into account that inflows during the October-March period is correlated at 0.23 with inflows in the April-September period, we generated a bi-variate empirical marginal distribution. From this distribution we generated 10,000 random draws with the Latin Hypercube procedure in Simetar. These synthetic inflows are used to simulate the reservoir operation model with and without the derivative.

D. The Reservoir Operation Model

The reservoir operation model is driven by the objective of maximizing plantings. Since we do not take into account the price for water and the payment of O&M, maximizing plantings is equivalent to maximizing net returns. The model features release functions and physical characteristics of the dam. Since cropping activities in Rio Mayo are divided in two seasons, one operational rule will be applied to each season. In particular, the release rule for the FW season is a more aggressive rule due to lower water transmission losses included in this season and to the higher value of the corresponding crop portfolio. Please refer to table 5 for to see the specific form of the release functions.

Thus, given a beginning-of-the-year stock of water (October 1), the operator releases water according to the release rule for the FW season. This allocation of water is used to grow crops between October and March and the number of hectares planted is computed using the planting response function for the FW season. In the month of April, the operator computes the amount of water available for the SS season, taking into account the FW releases, the accumulated inflows, and the evaporation losses. In turn, stock of water in storage as of April 1 and its corresponding releases rule determine if the SS season will be carried out. If carried out, the SS plantings response function is used to compute the number of hectares planted. At the end of the year, two computations are carried out. First, the annual plantings are computed by adding the FW and SS plantings. Second, the end-of-the-year stock of water is computed, by adding inflows received and deducting releases and evaporation losses during the SS season. Consequently, the end-of-the-year stock is the starting stock for the planning period. Please refer to figure 9 for a depiction of the process.

V. Tailoring the Inflow-Based Derivative

There are six elements in the design of a weather derivative: the underlying variable, the accumulation period, the location of measurement, the tick size, the trigger, and the indemnity rules. Each element requires careful choices that ultimately determine the effectiveness of this hedging mechanism.

The underlying variable used in this research is reservoir inflows. Alternatively, one could have used reservoir storage. The problem with reservoir storage is that it is the result of a combination of management and random events. One of the most basic principles of insurance is not insuring management. In contrast, reservoir inflows are a purely random variable and no manipulation can be exercised over it. In addition, just like reservoir storage and with the help of well-understood reservoir operation policies, inflows convey all the information about the scarcity of water to the irrigator and the consequences of major shortfalls.

In terms of the accumulation period, we have designed a contract that takes into account two periods. The first period runs through the entire agricultural year, thus it takes into account the inflows accumulated throughout the 12-month period corresponding from October 1 to September 30. From the point of view of the irrigator, this 12-month period determines the availability of water for the FW season. The second period is more related to the particular characteristics of inflows in the Mayo Valley. We have observed that in the period corresponding to October 1 to March 30, there are events that bring more than expected inflows. We term this event the “bonus.” This event is beneficial for irrigators because it replenishes the reservoir previous to the beginning of the SS season. Thus, when the “bonus” occurs, irrigators are more likely to grow crops in the SS season. The importance of this event is that it partially decreases the need for insurance. Therefore, any contract that aims to protect the income of irrigators has to take this event into account to both make premiums more feasible and to correctly price the contract.

The location where the inflows are measured is the reservoir itself. Fortunately, even before the reservoir was built, CNA measured the potential inflows generated by the Mayo River. Therefore, we obtained monthly observations of the inflows dating back to 1943. More importantly, irrigators and CNA trust in the quality of these measurements, which are essential for the decision-making process.

Since we are going to be using a per-hectare equivalent to measure the net returns to irrigators, the tick size will also be in hectares. Specifically, the contract pays 100 ha for each million m^3 below the strike level.

The choice of the strike level is based on the notion that operators follow a safety first approach. Based on the observation that plantings in the most recent years have been around 80,000 hectares, we propose that objective of the reservoir operator is to guarantee irrigation for at least 70,000 hectares (77% of the land in the irrigation district). Therefore, we propose a put contract that has two strikes and two indemnity rules. The first strike relates to the first measurement period (the annual inflows). It states that if the accumulation of inflows is inferior to a strike inflow level, I_c, an indemnity payment, P, will occur in April 1 of the next year (18 moths after purchasing the contract). However, this payment will be reduced if the "bonus" occurs. Thus a second component of the contract is the reduction rule. In particular, the contract states that the payment will not be discounted if the "bonus" falls short of a minimum level, denoted by I_{min}. But, if the "bonus" is greater than this strike, the payment will be reduced according to a linear rule. The maximum discount occurs when inflows surpass the upper level or I_{max}. The use of some equations might further clarify the design of the rules. The maximum payment that the irrigator can get at any given time is calculated according to equation 1.

(1) $$\overline{P}_t = TIC \times \begin{cases} 0 & if\ I_{t-1} > I_C \\ \left(I_C - I_{t-1}\right) & if\ I_{t-1} < I_C \end{cases}$$

Where I_{t-1} is the accumulation of inflows from October to September in the previous cycle; TIC is the hectare-equivalent income paid for each unit below the strike; P is the maximum expected payment if no discount is applied. However, this payment might be reduced according to the following rule:

(2) $$P = \overline{P}_t * D$$

Where D is a discount factor calculated according to the following rule:

(3) $$D = 1 - \begin{cases} 1 & if\ I_{1,t} \geq I_{\max} \\ \left(\dfrac{1}{I_{\min} - I_{\max}}\right) \times \left(I_{\min} - I_{1,t}\right) & if\ \ I_{\min} < I_{1,t} < I_{\max} \\ 0 & if\ I_{1,t} \leq I_{\min} \end{cases}$$

and $I_{1,t}$ represents the inflows accumulated from October to March in the cycle.

For example, assume the following parameters: $I_c = 725$, TIC = 100 ha. Then, if the inflows corresponding to the period agricultural year 2005-2006 were 550 million m^3, then maximum payment would be 17, 500 ha.[8] However, if inflows of 300 million m^3 were registered in the period October 2006 to March 2007, then the payment would have to be discounted[9] to 50% of the maximum payment, which is 8,750 ha.

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[8] $\overline{P} = \left(725 - 550\right) \times 100 ha = 17{,}500$

[9] $D = \left(1 - (-0.0025) \times (-200)\right) = 0.5$, supposing $I_{\min} = 100$ and $I_{\max} = 500$.

VI. Results and Discussion

The results of the derivative contract will be assessed for the following: affordability, value for the irrigator, and risk reduction effectiveness. The affordability will be assessed according to the risk premium. The risk premium rate carries two components: the pure premium and a load. The pure premium rate is equal to the average indemnities paid by the irrigator divided by the average income of the producer. In a world with no transaction costs and more uncertainty about the distribution function of inflows, the irrigator would expect that in the long run the premium payments would be offset by the mean indemnities. However, due to administration costs and uncertainty, the insurer usually charges a "loaded" premium. For this application, we assume the load is 2.5% over the pure premium. The best design should afford enough protection with a relatively small premium.

The risk reduction of the instrument is examined using the value-at-risk (VaR) and coefficient of variation (CV) measures of risk. According to the financial literature, VaR is a measure of the maximum financial loss for a given confidence level in a specific time horizon. For example, for a specified probability level b , VaR is simply the loss that is exceeded over the time period with probability $1-b$. In our empirical application, we consider VaR in terms of reduction in hectare equivalent income. However, in a slight diversion from the financial literature, our approach consists of finding the probability that the lowest level of hectare-equivalent income exceeds a desired threshold. The level of threshold we have chosen is 70,000 hectares. We assume that the reservoir operator follows an operation policy that aims at guaranteeing this level of plantings. Shortfalls below this level impose severe hardship for the irrigators. This is the ultimate risk irrigators will try to hedge against by using the inflow-based derivative.

While VaR provides information about the probability of experiencing reductions beyond 70,000 ha, it does not provide information about the magnitude of those extreme reductions. Therefore, we use the notion of conditional value at risk (CVaR) to measure these expected reductions. In the financial literature CVaR is a currency-denominated measure of the significant unfavorable changes in the value of a portfolio. For example, for the confidence level b , there is a VaR that can be computed. CVaR is the expected loss that occurs in excess to the VaR threshold with $1-b$ probability. In our application, CVaR measures the average potential reduction in hectare equivalents that occur beyond the 70,000 threshold with a given level of probability.

We further develop a valuation of this instrument from the irrigator's point of view by using the CVaR measures. In particular, we propose that the value of this derivative can be inferred by comparing the mean expected reduction in plantings beyond the critical threshold of 70,000 ha. In other words, we compare the CVaR with and without risk-sharing. The difference between both measures provides a good indication of what the expected plantings reductions would be in the worst case scenario, which is what irrigators would like to avoid. We conjecture that a proxy for the willingness to pay for this instrument exists when CVaR without the derivative is greater than the CVaR with the derivative.

First, we discuss the necessity of introducing a double-trigger contract to hedge the inflows risk, as opposed to a single trigger. In order to make this necessity clear, we compare the effectiveness of the contract with and without the discounting rule. A single-trigger contract would be simpler to implement as it could be sold at the beginning of the agricultural year (October) and the indemnity payment would be received at the end of the year (September). The put contract would pay only if inflows fall short of the strike level. However, with this design the irrigator would not take advantage of the natural hedging mechanism offered by the reservoir and the inflows during the FW season. If the "bonus" inflows are sufficiently large, irrigators have the ability to carry out productive activities during the SS season, which increases their annual income. The results from the base case scenario (no derivative) are presented in table 6.

In table 7, we present the different criteria to demonstrate the superiority of a double-trigger contract. We compare three strike levels: 500, 600 and 700. The results demonstrate that the best design for the single-trigger contract is achieved by setting the strike level at 500 units. By paying a premium of 1%, irrigators can expect the following risk reduction measures. First, they can expect a slight decrease in the CV from 17.1% to 16.6%. This relative risk reduction is accompanied by a downside risk reduction as measured by VaR, which indicates that the probability of obtaining levels of income below the 70,000 threshold is reduced from 10.2% without the derivative to 9.1% with the derivative. The value of the derivative for the irrigator is approximately 657 units, which is the difference between the expected losses with and without the insurance below the 70,000 threshold.

On the other hand, the contract with the double trigger yields better risk reduction results at the expense of a slightly higher premium, except for the case in which the October 1 strike is set at 500. For illustration only, consider a contract that pays whenever inflows fall short of the 700 units strike in October 1, but that linearly discounts the payment for inflows above 100 units in the FW. The discount increases linearly to the point that no payment is made whenever these seasonal inflows accumulate to more than 500 units. In this case, the premium to be paid by the irrigator is higher, namely 5.6%. In addition, the contract reduces the probability of falling below the VaR threshold to 3.6%. Moreover, the value of protection increases from 657 units to 4103 units. Compare the columns 2 and 7 in table 7.

We conclude that if irrigators are interested in protecting the tail of the distribution, the double-trigger contract yields better coverage. Although the premium associated with the double-trigger contact seems a bit higher, it actually is not too high in terms of affordability.[10] Actually, the higher premium is an indication of the increased protection that can be gained by a slightly higher premium. In summary, if the inflow-based derivative is designed with a double trigger, it can better serve the objective of protecting against the downside risk associated with reduced income due to water shortages.

Once we have established that the double-trigger is superior to the single trigger contract, the next question to be addressed is: which among the double trigger designs yields the best contract? Fixing the tick size at 100 ha, there are two choice variables to arrive at the "optimal" design. The first choice concerns the trigger to be used to compute the maximum possible payment as of October 1. The second choice variable is the parameter mix in the rule that discounts the maximum payment when "bonus" inflows occur during the FW season. Please refer to table 8 for a comparison of different hedging strategies (i.e. selection of strikes and discounting rules) available to irrigators in the Rio Mayo district. Equipped with this information, irrigators possess an array of information

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[10] Premium rates below 10% are considered affordable.

that characterizes different hedging strategies and return distributions associated with each strategy.

For instance, irrigators can compare the benefits and costs between strategies. For instance, consider the choice between strategy A (payments are completely discounted if FW inflows exceed 500 million m^3) and strategy B (payments are completely discounted if FW inflows exceed 400 million m^3) for a particular strike level, say 700. While under strategy A the irrigator receives a lower expected profit and pays a higher premium, the level of protection afforded with strategy A is superior as reflected in a lower probability of exceeding the VaR threshold, and a lower expected loss beyond VaR.

The superiority of the different designs changes across different strike levels. For example, at the strike level of 600, strategy A is the superior in terms of risk reduction and valuation. However, at the strike level of 800, strategy B is the superior one. Furthermore, in the last column of table 8 we report the strike level with the highest value of protection. For strategy A, the value of protection is maximized at a strike level of 708, for strategy B at 740, and for strategy C at 730. The results show that strategy C is the least effective in reducing risk at all strike levels. Therefore, it is likely irrigators would choose hedging strategies A or B depending on their risk attitudes.

Upon comparison of three most feasible combinations of choice variables, it seems that the best contract is that which sets the first strike at 740 units and stops paying after 400 units in the FW season. Using this contract, irrigators are able to reduce the probability of exceeding the VaR threshold from 10.2% to 3.4%. Similarly, the CV is reduced from 17.1% to 14%. Moreover, the value of the contract as computed by the CVaR measures is 4,253 units. All these protection is affordable at a premium of 6.5%. Please refer to figure 8 for a depicting of the CDF of the hectare-equivalent income.

VII. Conclusion

We have studied the risk environment of the Rio Mayo irrigation district in Sonora and developed a stochastic dynamic simulation model of the ARC reservoir. In order to accomplish this objective we have fitted empirical distributions to inflows and to plantings response functions. With this framework we designed an inflow-based derivative that mitigates the adverse impact of uncertain availability of irrigation supplies. The results indicate that for this particular reservoir the best design is a double trigger contract that discounts payments for occurrence of “bonus” inflows in each FW season. We have shown that this design is feasible because it takes advantage of the natural hedging provided by the FW inflows. Furthermore, the contract is feasible as loaded premiums remain below the 10% benchmark.

Although we have modeled the irrigation district under the assumption that it is a single production unit, we know that in reality the district is a collection of decision units. However, the institutional characteristics of the SRL as a collective group indicate that the implementation of a contract of this type could be feasible. The SRL could be used as an intermediary between the irrigators and the insurance company that sells the contract. In this sense, the role of the SRL would be to collect the premium from the individual contribution of its members and distribute the indemnities accordingly. Since the SRL is a group of the same farmers, it already possesses informational advantages in terms of the impact of water shortages on each individual. For instance, we know that farms that are located closer see their supply see water curtailed at a lower proportion than marginal farms located in the most distant areas from the canal. The SRL could implement rules that differentiate the relative size of the premium to be paid or the indemnities to be received.

In the same line of thought, one could conceive that indemnity payments during water scarcity periods would provide additional liquidity to the system that would spur water market transactions. Those farmers willing to buy water will now have more cash to confront the incremented marginal price of water due to its relative scarcity. Thus, in some fashion we can see that this contract would not only mitigate the losses to the irrigation district as a whole, but also would encourage the development of water markets that lead to an efficient use of the resource. Further research on this aspect is suggested.

Since this is a work in progress, the next steps are to design contracts such that the irrigator does not have to wait for 18 months to receive the payments. This could be accomplished by introducing two beginning-of-season triggers: one for October 1 and another one for April 1. In this manner, the irrigator would receive a partial payment in October if the year-around inflows fall short of the first trigger, and a second payment in

April if the “bonus” inflows do not occur. In addition, one could design contracts for each of the 16 modules in the case that irrigators prefer to use the module as the collective group rather than the SRL.

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Table 1: Descriptive Statistics of Hydrologic and Production Data From the Rio Mayo Irrigation District

	Inflows[a]	Ag Release[a]	Storage[a,b]	Production[c]
Mean	1,034	832	743	103,644
StDev	451	198	227	19,229
95 % LCI	905	776	680	97,083
95 % UCI	1,163	889	807	110,204
CV	44	24	30	19
Min	455	441	315	70,202
Median	932	827	685	103,230
Max	2,511	1,240	1,206	142,465
Count	47	48	49	33
Autocorrelation Coefficient	0.13	0.3	0.24	0.08

Source: CNA, SRL

a: inflows, releases and storage is measured in million m^3 (1 cubic meter = 0.0008107 acre foot = 35.315 cubic foot).

b: storage as of October 1 (beginning of agricultural cycle).

c: production measured in hectares (1 hectare = 2.47 acre).

Table 2: OLS Regression Results Dependent Variable: Annual Releases (Mean[a] 877)

Variable	Coefficient	t-ratio	Mean[a]
Constant	245.89	4.45	
October Storage	0.55	8.22	741
Fall-Winter Inflows	1.07	7.12	375
$(\text{Fall-Winter Inflows})^2$	(0.007)	(5.021)	
Adjusted R^2	0.85		
F-statistic	62.63		
Durbin-Watson statistic	2.15		
Observations	33		

Source: Own computations

a: measured in million m^3.

Table 3: Parameters for Seasonal Plantings Response Functions

	Fall-Winter hectares	Spring-Summer hectares
Constant	(19000)	(12,000)
Fall-Winter Release	380	
$(\text{Fall-Winter Release})^{1.5}$	(8.8)	
Spring-Summer Release		245
$(\text{Spring-Summer Release})^{1.5}$		(5.6)

Source: own computations

Table 4: Water Conveyance Efficiency Ratios From the Rio Mayo Irrigation District

	Fall-Winter	Spring-Summer
From Reservoir to SRL	90%	77%
From SRL to Module	83%	75%
From Module to Farm	73%	67%
Overall (Reservoir to Farm)	55%	39%

Source: CNA, SRL

Table 5: Parameters for the Seasonal Operation Policies for the ARC Reservoir

	Fall-Winter Release	Spring-Summer Release
Constant	187	
Storage as of October 1	(0.0005)	
$(\text{Storage as of October})^{1.5}$	0.02	
Storage as of April 1		0.6

Source: own computations

Table 6: Base Case Scenario Simulation Results (No Hedging)

VaR[a] (percent)	10.2
CV (percent)	17.1
CVaR[a,b]	6,421
Expected Annual Income[b]	92,523

Source: own computations

a: Evaluated at the 70,000 threshold.

b: Measured in hectare equivalent income.

Table 7: Comparison of Simulation Results: Single Vs. Double Trigger Design

	Base	Single Trigger Contract			Double Trigger Contract[a]		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Strike Levels	-	500	600	700	500	600	700
Premium (percent)	0	1	3.9	10.1	0.7	2.4	5.6
VaR[b] (percent)	10.2	9.1	9.3	10.4	9.5	6.9	3.6
CV (percent)	17.1	16.6	15.7	14.9	16.7	15.7	14.3
CVaR[b,c]	6,421	5,764	6,074	6,795	6,056	4,496	2,318
Expected Annual Income[b]	92,523	92,041	90,636	87,338	92,079	91,256	89,626

Source: own computations

a: Double trigger applies in the FW season inflows according to the following discount rule: $I_{max} = 500$; $I_{min} = 100$.

b: Evaluated at the 70,000 threshold.

c: Measured in hectare equivalent income.

Table 8: Comparison of Simulation Results: Three Double Trigger Designs

	Base	Discounting Design			
		Strategy A $I_{max} = 500; I_{min} = 100$			
Strike Levels	-	600	700	800	708
Premium (percent)	-	2.4	5.6	10.1	5.9
VaR[b] (percent)	10.2	6.9	3.6	5	3.6
CV (percent)	17.1	15.7	14.3	12.9	14.2
CVaR[b,c]	6,421	4,496	2,318	3,225	2,316
Expected Annual Income[b]	92,523	91,256	89,626	87,309	89,457
Value	-	1,925	4,103	3,196	4,105
		Strategy B $I_{max} = 400; I_{min} = 100$			
Strike Levels	-	600	700	800	740
Premium (percent)	-	2.2	5.1	9.1	6.5
VaR[a] (percent)	10.2	7	3.7	4.6	3.4
CV (percent)	17.1	15.8	14.5	13.2	14
CVaR[a,b]	6,421	4,570	2,393	2,958	2,168
Expected Annual Income[b]	92,523	91,360	89,896	87,800	89,131
Value[b]	-	1,850	4,028	3,463	4,253
		Strategy C $I_{max} = 500; I_{min} = 100$			
Strike Levels	-	600	700	800	730
Premium (percent)	-	2	4.5	8	5.4
VaR[b] (percent)	10.2	7.3	3.9	4.7	3.4
CV (percent)	17.1	15.9	14.7	13.5	14.3
CVaR[a,b]	6,421	4,781	6,421	3,043	2,180
Expected Annual Income[b]	92,523	91,469	90,193	88,420	89,706
Value[b]	-	1,640	3,882	3,378	4,241

Source: own computations

a: Evaluated at the 70,000 threshold.

b: Measured in hectare equivalent income.

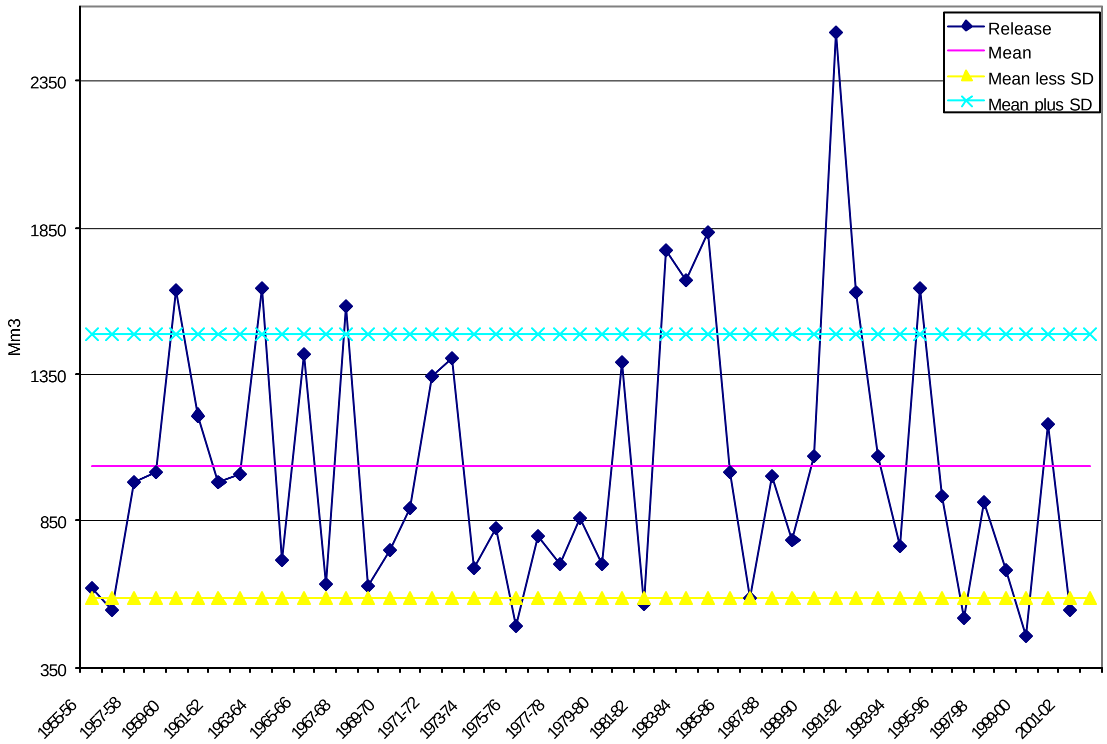

Figure 1. Time Series for Reservoir Releases (1955-2001)

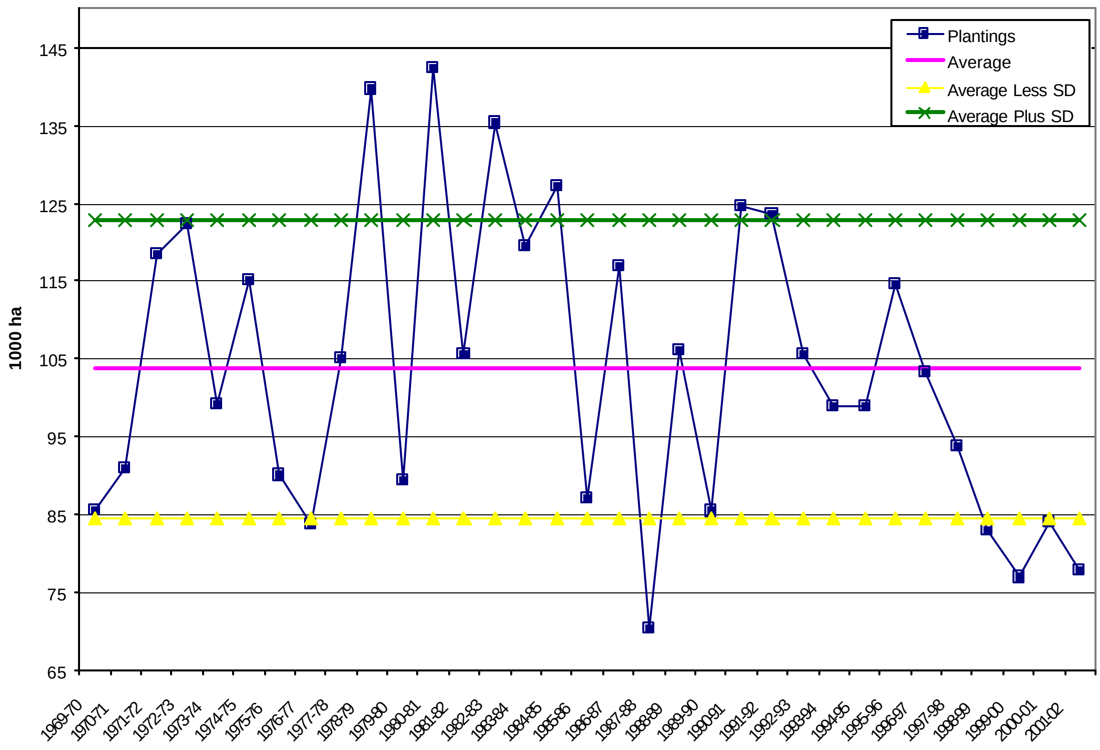

Figure 2. Time Series for Plantings (1969-2001)

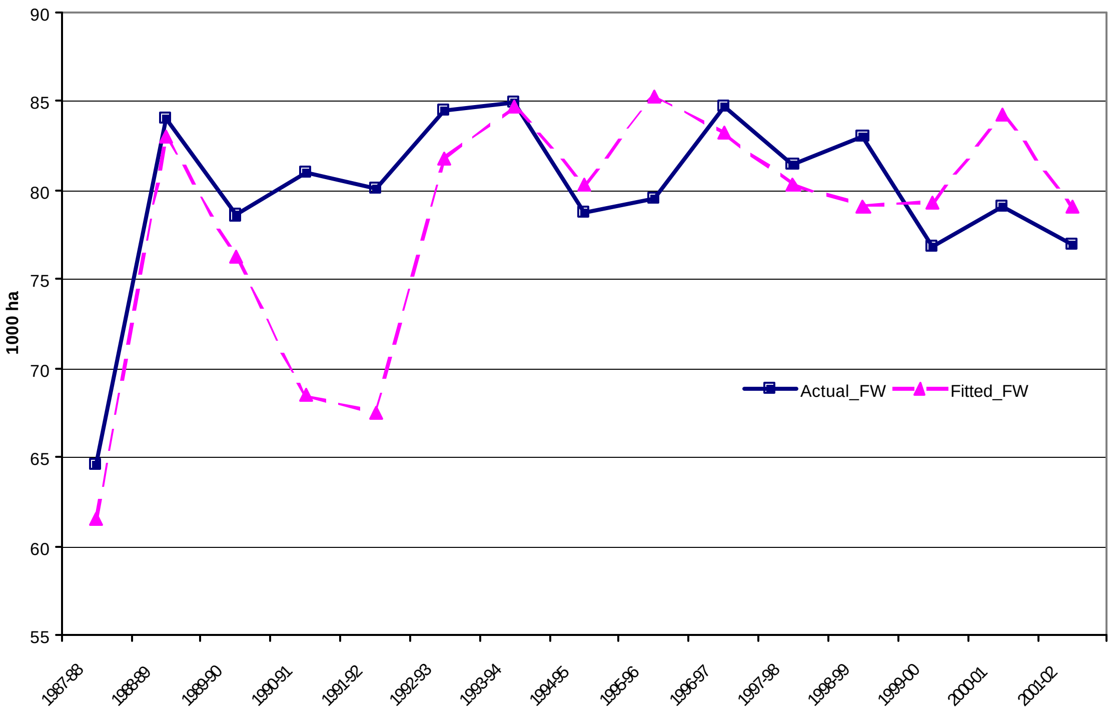

Figure 3. Actual vs. Fitted FW Plantings (1987-2002)

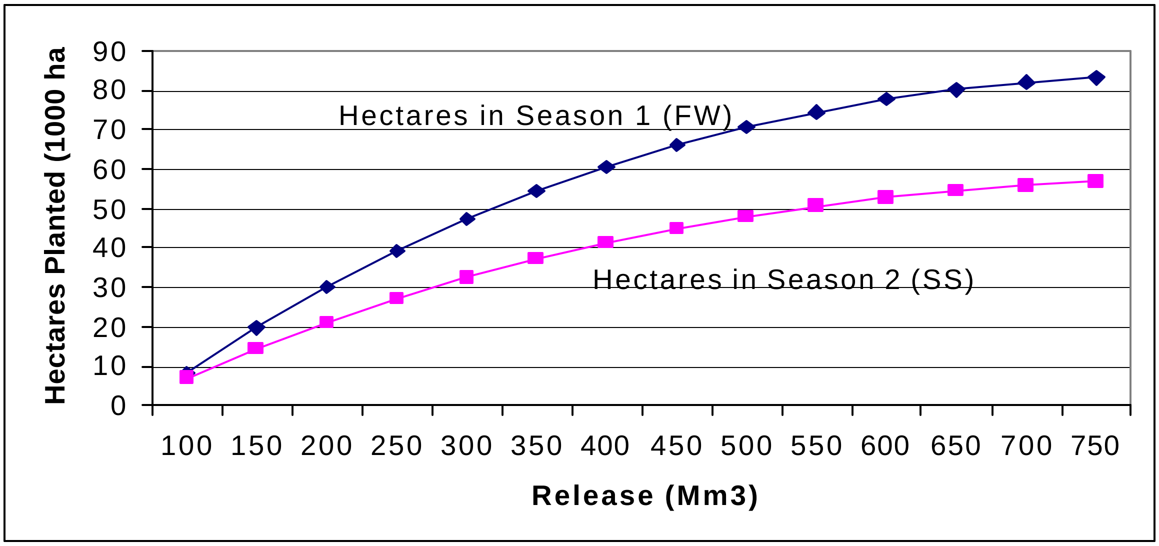

Figure 4. Planting Response Functions

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Time series identification for CAN
Box-Pierce Statistic =     8.9038      Box-Ljung Statistic  =    9.7904
Degrees of freedom   =         10      Degrees of freedom   =        10
Significance level   =      .5413      Significance level   =     .4591
* => |coefficient| > 2/sqrt(N) or > 95% significant.
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
Lag |  Autocorrelation Function     |Box/Prc|  Partial Autocorrelations
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
  1 | .360*|           |****        |  6.36*| .360*|            |****
  2 | .094 |           |*           |  6.80*| .063 |            |*
  3 |-.026 |          *|            |  6.83 |-.097 |          * |
  4 | .110 |           |*           |  7.42 | .226 |            |**
  5 |-.029 |          *|            |  7.47 |-.131 |          * |
  6 | .063 |           |*           |  7.66 | .175 |            |**
  7 | .069 |           |*           |  7.89 | .121 |            |*
  8 |-.047 |          *|            |  8.00 |-.220 |         ** |
  9 |-.131 |          *|            |  8.84 |-.125 |          * |
 10 | .035 |           |*           |  8.90 | .209 |            |**
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Figure 5. Correlogram for Inflows Times Series

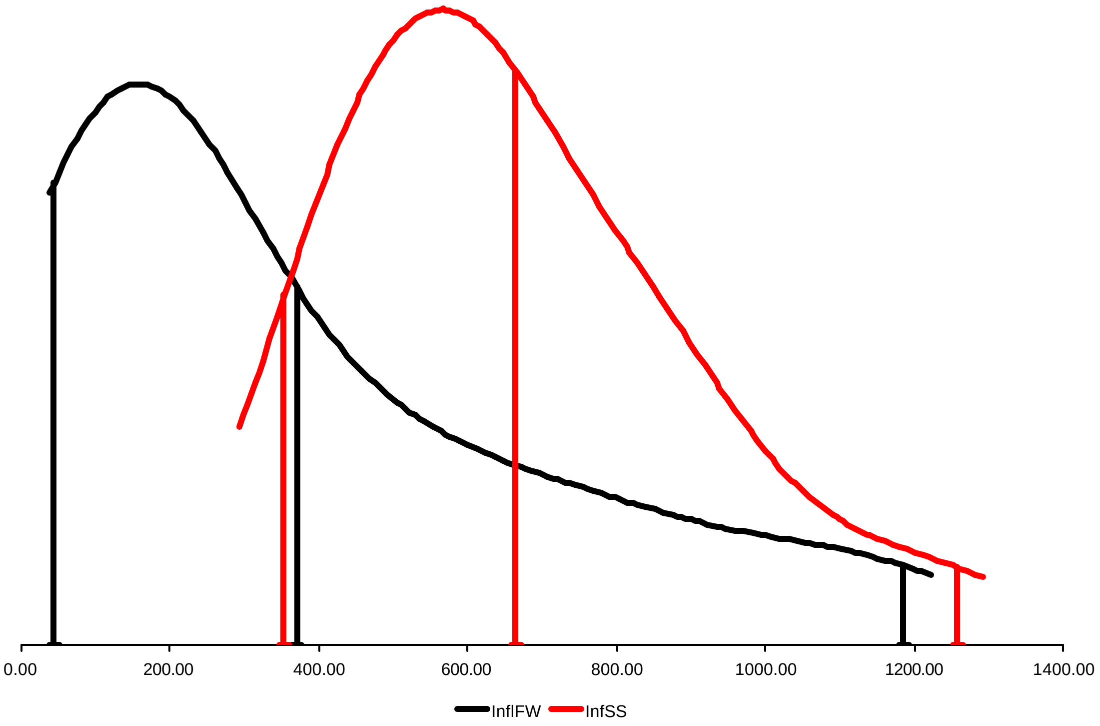


Figure 6. Empirical PDF for FW and SS Inflows

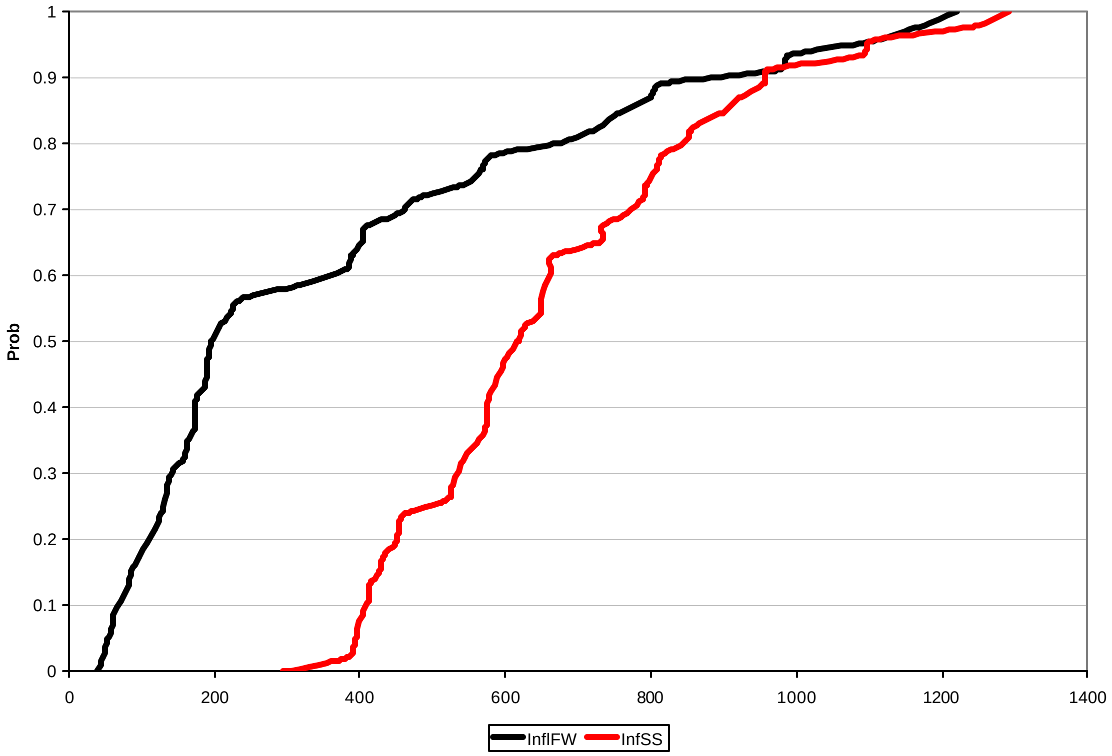


Figure 7. Empirical CDF for FW and SS Inflows

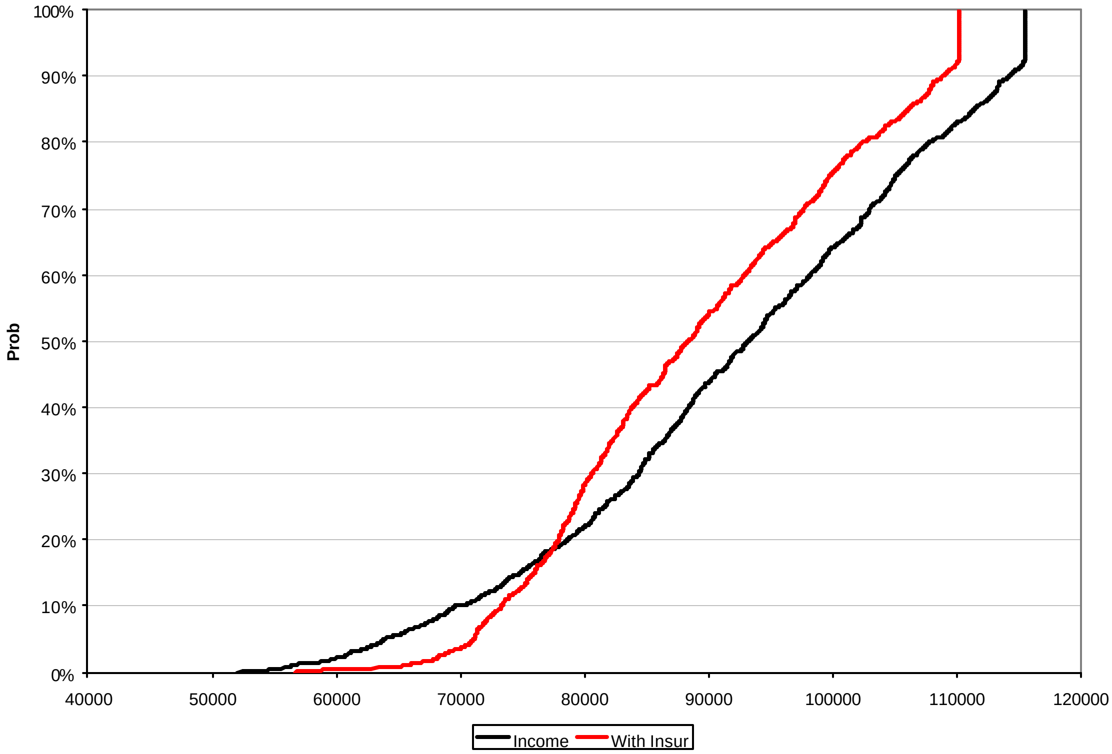
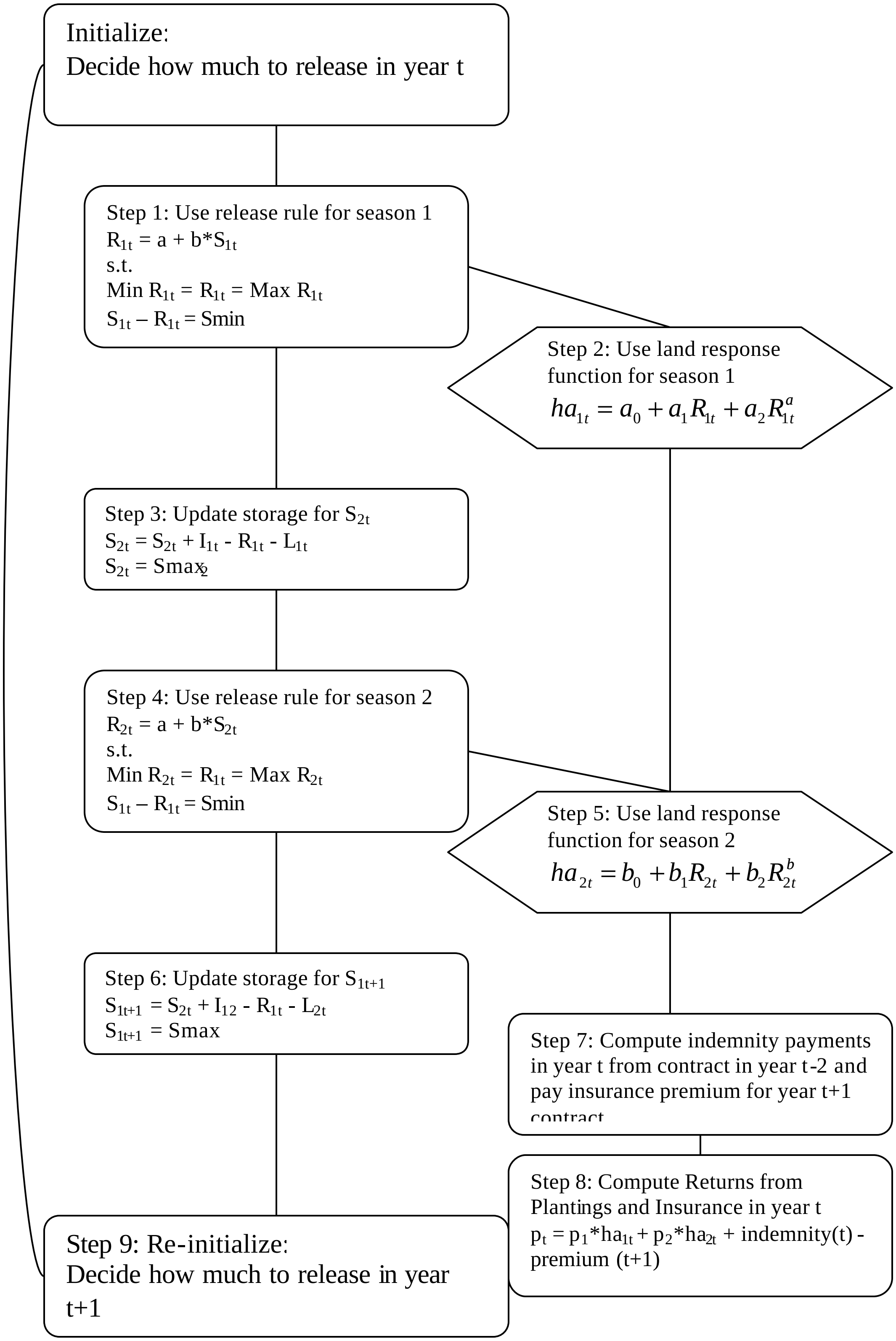


Figure 8. Hectare-Equivalent Income with Hedging and without Hedging

Figure 9. Reservoir Operation Model



Notation:

ha_{it} = total plantings of the crop portfolio in the ith season of year t (hectares).

S_{it} = reservoir storage level at the beginning of ith season in year t (million m^3).

$S\max$ = Maximum capacity of the reservoir (million m^3).

$S\min$ = Minimum (dead) capacity of the reservoir (million m^3).

$S\max_2$ = Maximum storage level at the beginning of season 2 for flood control (million m^3).

I_{it} = reservoir inflows during year t in season i (million m^3).

R_{it} = reservoir releases during year t in season i (million m^3).

L_{it} = evaporation and other losses in year t in season i (million m^3).

p_i = average (weighted) net return per hectare from portfolio ($).

p_t = total per-hectare net return in year t ($).