**Modeling the Economic Benefits of Supplemental Irrigation**

Marcelo Torres

*Department of Economics*

*University of Brasília, Brazil*

Richard Howitt

*University of California, Davis, USA*

Lineu Rodrigues

*Embrapa Cerrados, Brazil*

**RESUMO:** Modeloshidroeconômicos existentes na literatura são geralmente aplicados a áreas áridas ou semi-áridas do mundo onde precipiração é muito baixa e as culturas agrícolas são 100% irrigadas. Nesses modelos, a água disponível para os agricultores é resultado da agregação dos volumes de água de superfície e subterrânea em reservatórios contruídos ou naturais como rios, lagos e aquíferos. Nesse modelos, precipitação é implicitamente considerada como uma das fontes de água somente via seus efeitos nos volumes dos reservatórios. Contudo, na maioria das áreas agricultáveis do mundo, uma significante parcela da água aplicada pelos agricultores vem de precipitação que cai diretamente sobre as culturas e os sistemas de irrigação são usados como fontes supplementares de água no caso de secas. Neste caso, precipitação e água dos reservatórios não são perfeitamente substituíveis. Ao usar dados primários referentes à atividade agrícola de uma subbacia hidrográfica no centro-oeste brasileiro onde precipitação e o uso suplementar de água ocorrem, esse artigo demonstra que modelos hidroeconômicos padrão tendem a subestimar os impactos das secas sobre a atividade agrícola. Isso é explorado através da construção de dois modelos alternativos de produção agrícola acoplados a um modelo hidrológico, onde o objetivo é a maximização da receita líquida regional. No primeiro modelo de produção, a substituição entre precipitação e água de superfície estocada em reservatórios é explicitamente formalizada e essas duas fontes de água são consideradas separadamente mas interconectadas. No segundo, elas são simplesmente agregadas em uma fonte única de água. Ambos modelos são utilizados para simulações de efeitos de secas sobre o uso do solo e da água, preços sombra da água e a renda agrícola. Resultados demonstram que no primeiro modelo não somente os retornos esperados para os agricultores são consistentemente menores como, talvez mais importante, a variabilidade dos retornos é maior.

**Palavras-chave**: microeconomia aplicada, recursos hídricos, renda agrícola, modelos hidroeconômicos.

Área ANPEC: 11.

JEL: Q25, Q18, Q15.

**ABSTRACT:** Standard hydroeconomic policy models are usually applied to areas in the world where precipitation is very low and crops are fully irrigated. As such, these models pool the total annual stored precipitation plus other water supplies and assume that this total water supply can be allocated by time and place. This water pooling approach treats seasonal precipitation and irrigation water as fully substitutable. In many irrigated areas, however, a significant amount of water used by crops comes from seasonal precipitation. In fact the majority of the global irrigation systems are supplemental to seasonal rainfall and, in this context, precipitation and water stored in reservoirs are not fully substitutable. By using primary data from a sub watershed in Brazil, where precipitation and supplemental water use occur, this paper shows that standard models are likely to under-estimate the predicted drought impacts. The paper investigates this issue by setting up two alternative economic models of regional net-revenue maximization based on a calibrated economic programming model integrated with a mass balance hydrologic model. In one model the substitution between precipitation and irrigation water is explicitly formalized and in the other precipitation and irrigation water are aggregated together in a single water supply. The models are used to estimate and predict the short-run impacts of precipitation cuts on irrigation reservoir levels and the impacts of lower irrigation water supply on farmers’ agricultural income. In comparing the results, we find that the expected returns to farmers are lower under the former model and the variability of returns is higher.

**Keywords**:Applied microeconomics, water resources, agricultural income, supplementary irrigation, positive mathematical programming, hydroeconomic model.

**INTRODUCTION**

Farmers are the dominant water users worldwide and compete for water resources which are heterogeneously distributed across time and space. Changes in water availability may affect agricultural income, productivity and cropping strategies and have potential environmental effects for the hydrologic system as a whole. Therefore, an accurate evaluation of how farmers may react to different water resource policies or environmental scenarios (e.g.: temperature, water supply, precipitation regimes etc) is important for policy makers and can help to shed light on ways to increase farmers’ income and to alleviate poverty in many parts of the rural world. This paper questions whether the simpler hydroeconomic models that treat seasonal precipitation as part of the total irrigation water supply are sufficiently accurate for policy analysis in regions where irrigation is supplemental to seasonal precipitation.

Empirical modeling of the effects of alternative water allocation regimes on agricultural communities and farmers’ reactions is complex and by definition interdisciplinary. Several surveys of studies that develop models involving economics, hydrology, ecology and agronomy have been published (Harou et al. 2009 and Booker et al (2012)). Although all the studies attempt to integrate different disciplines, each one focuses on a particular issue. For example, Rosegrant et al. (2000) , Cai et al. (2003) focus on salinity and water availability for irrigation; Cai (2008) on the optimal strategies for water allocation among competing sectors and Harou and Lund (2008) on water pricing, irrigation and institutional constraints; Loucks (2006) focuses on the integration of economics and ecology and Guan and Hubacek (2007) on the relationship between economic activity and water quality; and finally Krol et al. (2006), Medellín-Azuara et al. (2008, 2010) and Harou et al. (2006) focus on the estimation of drought and climate change impacts on water availability for agriculture.

One of the aspects these studies have in common is that their models are applied to arid or semi-arid regions of the world where rainfall during the growing season is minimal or absent. Water available for irrigation in an arid or semi-arid region predominantly comes from out of season precipitation, or is imported from regions where precipitation occurs through a system of man-made channels, rivers, groundwater aquifers. For example, water from Northern California and the Sierras is used to irrigate Central Valley and Southern California regions. Similar transfers are found in Spain, Chile, Israel and Australia.

In many areas of the world, however, precipitation occurs during the growing season, and a significant amount of water used for crop production comes from precipitation that falls directly onto the crops. Rost et al (2009) in figure 3 show regions of the world where there is a significant increase in net primary productivity due to irrigation. The largest areas under irrigation are located in monsoon climates and Central American regions where irrigation systems are supplemental to seasonal rainfall. During the rainy season in these areas, it is common for farmers to experience several days without rainfall. Water storage in surface reservoirs or underground aquifers provides a supply of irrigation water in the event of a drought. When precipitation is lower than expected, farmers will, *ceteris-paribus*, react by taking more water from surface or groundwater sources to irrigate their crops. That is, precipitation and surface (or groundwater) water are substitute agricultural inputs.

Our point is that the predicted drought impacts from models that ignore the restrictions implicit in precipitation and the surface (or groundwater) substitution relationship for seasonal rainfall are likely to under estimate the severity of drought. For instance, if the impacts of a reduction in precipitation on farmers' income are estimated considering only the changes in the volume of the reservoirs or other water bodies, the impacts may appear to be minimal if the amount of water in the reservoir is not a binding constraint on deliveries. If however, the model allows for the fact that a reduction in precipitation may induce famers to replace rainfall with water from reservoirs, the impacts of drought on income may be significant even if the reservoirs´ volume is not binding, since access to irrigation water from the reservoirs is costly due to water fees, pumping costs, and system maintenance costs.

One way to deal with this issue is to include precipitation as an explicit input in the production system as in Maneta et al. 2009 and Torres et al. 2012. Although these two studies have made important contributions to the literature, gaps remain. In particular, the integration of uncertain rainfall with irrigation supplies in a formal production function. The models used in this study build and improve on these earlier models in that the calibration of water use is now exact, and the stochastic nature of precipitation and its effect on income risk is explicitly modeled. In this context, this paper measures the importance of correctly specifying precipitation by setting up two alternative simulation models of regional agricultural production. One where the substitution between precipitation and surface water is explicitly formalized and another where precipitation and irrigation water are lumped together in a single water supply quantity, as is generally done in the models applied to arid and semi-arid regions cited above.

Both models are integrated with a hydrological model which estimates the amount of water available for irrigation and precipitation in time and space. The agricultural production models and the hydrological model are externally coupled and the resulting hydroeconomic models are used to estimate and predict the short-run impacts of precipitation cuts on irrigation reservoir levels and the impacts of lower irrigation water supply on farmers’ agricultural income. As in Maneta et al., 2009, the focus is on the Buriti Vermelho river sub-basin, situated in the Federal District, near Brasília. The database is based on primary data collected from interviews performed during the dry and wet seasons of the 2007/2008 agricultural year. More details are provided throughout the paper sections below.

**METHODOLOGY**

In this paper, we develop an agricultural production model (hereinafter termed the economic model) using a mathematical programming approach and apply it, using primary data from the farm community of Buriti Vermelho located in a sub-watershed in the São Francisco River Basin in Brazil. The model is calibrated to reflect the coexistence of irrigated and rainfed agriculture in the region. Moreover, it takes into account seasonal precipitation levels as one of the arguments of the crop specific multi-input, multi-output production functions. In this model, water is introduced through two sources: from the surface water storage system and from seasonal precipitation that falls directly onto the crops. The model is specified so that farmers adjust their product mix, production technology, area under cultivation, and water use in response to economic and physical changes. Specifically we model the changes in relative input and product prices, the availability of surface water for irrigation, for different levels of precipitation. The amount of water available to farmers and the relationship between precipitation and the level of water in reservoirs is estimated with a hydrologic model that follows a water balance approach and yields water availability estimates on a monthly basis at the farm level.

**Economic Model**

The economic model is based on a class of models called *Positive Mathematical Programming* or *PMP,* (Howitt 1995) and largely used in applied economics (House, 1987; Howitt and Gardner, 1986; Kasnakoglu and Bauer, 1988; Lance and Miller, 1998; Chatterjee et al, 1998; Paris and Howitt, 1998; Maneta et al 2009, Medellín-Azuara et al. (2010), Torres et al. 2012, Howitt et al. 2012).

Each farmer *g*’s goal in a given agricultural year is to choose *Xhi*  and *Xhj*, the amounts of input *h* to be applied on rainfed crop *i* and on irrigated crop *j* respectively, in order to maximize net agricultural income. More formally, the farmer´s problem is

The first two terms inside the brackets represent gross income where *pi* and *pj* are the unit selling prices of rainfed crop *i* and irrigated crop *j* faced by farmer *g*. Rainfed and irrigated crops are produced respectively with a rainfed production function  and an irrigated production function. The superscript *r* denotes rainfed and *ir*, irrigated.Both production functions are discussed in more detail below. The third term in equation (1) represents total cash costs with rainfed and irrigated crops, in which *ph* is the price of input *h*. The inputs considered are land (*land*), applied water (*aw*), hired labor (*lb*), family labor (*flabor*) and materials (*mat*). This last category of inputs is an aggregate cost that includes the expenditures on machinery, fertilizers, pesticides, seeds and any other input used in the production of irrigated and rainfed crops. The last two terms, in parenthesis, represent the implicit cost of land used in rainfed and irrigated crops. Both terms have an exponential functional form, with parameters , , and and capture costs related to the farmer *g*’s land allocation process that are not directly observed by the researcher. Such non-linearity in costs may arise, for example, from managerial constraints, heterogeneity in land quality and spatially non-uniform access to water on farms.[[1]](#footnote-1)

The irrigated and rainfed production functions follow a CES (*Constant Elasticity of Substitution*) functional form. More formally, for rainfed crops, production is represented by

. (2)

Where *Ai* , *bhi* ,  and are parameters. When producing rainfed crops farmers can use all inputs except surface water. So *h* in (2) refers to land, labor, family labor and materials only. The parameter  is defined as , in which σ is the elasticity of input substitution. *εi* is the parameter associated with returns to scale. If equals 1, greater than 1 or smaller than 1, we have constant returns, decreasing returns or increasing returns respectively. , where is the precipitation that is expected to fall onto crop *i* and  is the actual amount of precipitation that falls onto crop *i*. *Precipi* is a measure of the realized annual water stress in rainfed crop production. We note that the dryland model is calibrated to data on the expected rainfall in the region, which is an exogenous parameter that the farmer has to assess, and thus is not directly part of the farmer’s economic allocation decisions, though as an external parameter, it does modify the input allocation first order conditions. As such, the levels of inputs such as fertilizer and labor must also reflect the farmer’s level of risk aversion, and so we do not add an explicit risk aversion term in the objective function, as it is already implicit in the individual famer data used to calibrate the production function and the crop specific land cost function

For irrigated crops (superscript *ir*) production is represented by

 . (3)

Where the arguments and parameters are defined as above with the difference that famers may use applied water (a*w*) to irrigate crop *j*. Applied water used on crop *j* by farmer *g* (*Xawj*) is defined as the sum of the amount of water used from surface water (*sw*) on crop *j* by farmer *g* (*Xswj*) and actual precipitation (). That is,

 (4)

Note that equation (4) implies that surface water based irrigation and seasonal precipitation are perfect substitutes, and that the quantity of irrigation water applied in any period and location is a function of the precipitation. In the irrigation production function, total water use is now a control variable and is subject to the same set of first order conditions and substitution conditions as the other inputs. A comparison of equations (2) and (3) shows that in the dryland model stochastic rainfall modifies the scale parameter *Ai*, but in the irrigated production function total water use is a fully controllable input.

An important distinction of this paper is that within the irrigation production function specification there are two different and important ways of defining how precipitation enters into the crop water supply. We will term these two models the “precipitation model” and the “model with pooled constraints”. The key difference is that while irrigation water is an allocatable resource in both time and location, precipitation is not allocatable in either time or location, but falls evenly over all crop areas and varies stochastically within the growing season. In the precipitation model the farmer is able to allocate only their irrigation water within the seasonal constraints in response to changing precipitation. In the pooled model the monthly precipitation is added to the irrigation supplies and the total water supply is allocated optimally over crops and time. This widely used specification of pooled water supplies allows a greater level of water substitution than the farmer actually faces, and thus under-estimates the impacts of drought on the expected returns and variability of farm income.

Before we proceed, a brief note on the input prices. The prices of land and hired labor are unit prices (per hectare and man-hour respectively) paid by each farmer. For materials, prices are not modeled as separate from quantities, so the expenditures (unitary price paid times input quantity used) with each input in the materials category are summed up by crop. The price of applied water () is the average cost with surface water constructed as the sum of the costs of hired labor used in irrigation, pumping electricity, and irrigation capital divided by the total amount of surface water used by farmer *g* on irrigated crop *j*.

*Parameter Estimation of the Production and Implicit Cost of Land Functions*

The parameters of the production function and the land implicit cost terms are derived analytically based on a system of equations that result from the first order conditions for net-revenue maximization (FOC’s) and are subject to assumptions on the returns to scale and the elasticity of input substitution and the land supply elasticity. The FOC’s state that farmers maximize their net revenue by choosing an amount of input applied to crops *i* and *j* such that the value of the input marginal product equals its marginal cost. This marginal cost is composed of the sum of the market input price, if the input is traded in a market, and the shadow price in the case of inputs with limited binding supply. Land, family labor, and applied water are defined as subject to maximum supply constraints.

In the case of the land input, besides the market price and the limiting supply shadow price, the *PMP* approach considers a third component of the marginal cost of land. This component is the value of the Lagrange multiplier associated with a calibration constraint that restricts the maximum amount of land that can be applied to a given crop to be equal to the amount actually allocated in the base year. This Lagrange multiplier measures the marginal implicit cost of land and is crop and farmer specific. All shadow prices and the Lagrange multipliers are calculated through a regional linear programming model of land allocation setup with the mathematical optimization software *GAMs*.

Farmers are assumed to operate under constant returns to scale () and subject to an elasticity of input substitution (*σ*) of 0.25 and a supply-land elasticity 0.7 for all crops. An explicit exercise that shows how all the parameters are calculated may be seen in Maneta et al. 2009 and on Torres et al. 2012.

*Regional Net-Revenue Model*

Once the crop and farmer specific parameters are calculated, their values are re-introduced in (1) and a non-linear regional annual net-revenue maximization problem is set as:



The regional model chooses andsuch that the regional annual net-income is maximized.  and are respectively the rainfed and irrigation production functions, specified in (2) and (3), and parameterized with , ,,, ,, , .

This regional maximization problem is subject to the following set of constraints.

*Resource constraints*

 (6)

 (7)

 (8)

 (9)

 (10)

*Water Stress Constraint*

 (11)

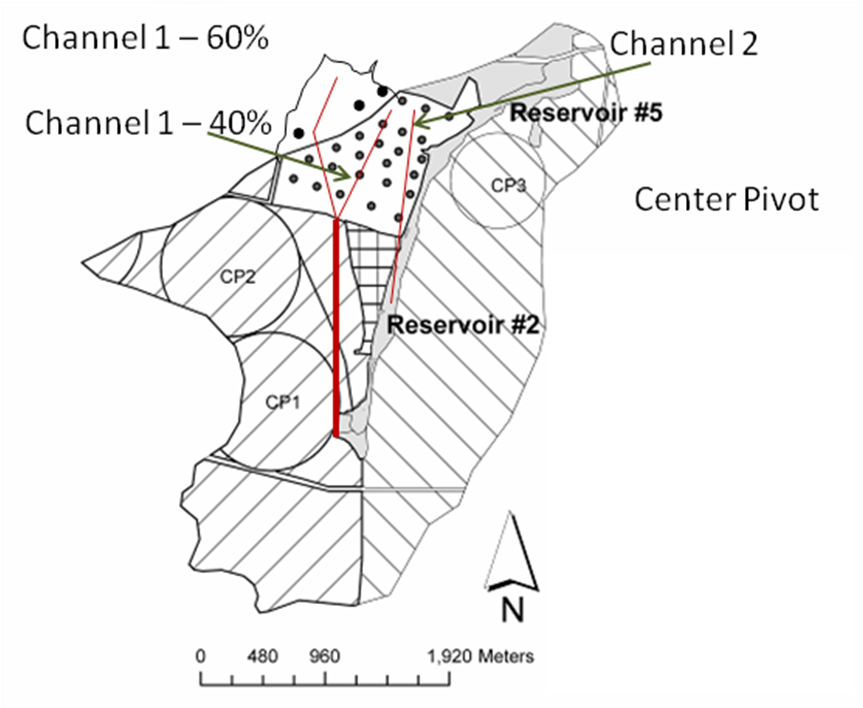
Constraints (6) and (7) establish that the total annual amount of land and family labor that farmer *g* can use in the production of crops *i* and *j* throughout the agricultural year must be less or equal to the annual total amount of land and family labor available,and  respectively. Constraint (8) shows that the total amount of water used by crop *j* throughout the agricultural year () must be equal to the annual amount of surface water farmer *g* decides to apply, plus the total annual amount of water used from the precipitation that falls over the land area where crop *j* is grown, . *m* refers to the 12 months of the year. Constraint (10) says that the annual amount of surface water farmer *g* can use to irrigate all irrigated crops, , must be less than or equal to the annual amount of surface water available, . Lastly, constraint (11) establishes that the annual ratio of applied water to a hectare of land cannot fall below a certain threshold,, where *k* is a parameter ranging from 0% to a 100% and is the applied water to hectare of land ratio normally used by farmer *g* on crop *j.* In this study *k* is assumed to be 0.85 . Essentially, this constraint puts an upper limit on the amount of water stress that can be applied to a given crop.

**Hydrological Model**

The Buriti Vermelho River has five small reservoirs, two of which (reservoirs #2 and #5) are shown in figure 1, and are used for irrigation by the small farmers. Each of the two reservoirs has one channel that serves different parts of the watershed. Farmers that capture water from the sub-watershed are represented by a black dot and the center pivot – CP3 in Figure 1 below. The upstream channel (thicker red line) that comes from the mouth of the Buriti Vermelho creek that splits into two channels by the time it reaches the farmers. Farmers on Channel 1a and on Channel 1b –get 60% and 40% of the diverted water respectively. Farmers on Channel 2 get surface water from the Midstream Reservoir 2 and the center pivot (CP3) gets water from the downstream Reservoir 5. Center pivots 1 and 2 (CP 1 and CP2) are located within the basin, but withdraw water from outside the watershed so they are not considered in the model. In terms of access to surface water, farmers withdraw water in a cascading manner. Farmers at channels 1a and 1b get water first from a reservoir near the creek mouth. After the diversion, the water flow that remains in the creek goes to reservoir 2 that supplies water to the farmers at channel 2. The remaining water flows to reservoir number 5 which then is used to irrigate the center pivot.

A hydrologic model was developed to calculate water flows in the channels. Since the channels are not monitored, the estimation was performed by simulating discharge as a function of the water height above the pipeline. The hydrologic model is based on Thornthwaite and Mather, 1955, and uses the procedure developed in Liebe et al., 2009. Simulations were done daily and the results were aggregated monthly to populate the economic model. More specifically, the hydrologic model provides estimates of the amount of surface water from the creek that is available monthly to each farm in the community and the owner of the center pivot. That is, the hydrologic model provides estimates of  in equation (10). It also provides estimates of daily millimeters of precipitation which is aggregated to a monthly estimate which are then used as the basis for the calculation of the amount of precipitation the falls onto the crop *j* and *i* by farmer *g*.

**Figure 1 – Buriti Vermelho sub-watershed**



**Channel 1a**

•

**Channel 2**

**Buriti Vermelho**

**Creek Mouth**

•

•

•

**Channel 1b**

•

•

•

•

**SITE OF STUDY AND DATA**

The area of study, the Buriti Vermelho sub watershed as shown in figure 1, is located about 100 kms from Brasília, Brazil. The primary data were collected in situ through a survey of all 25 famers located in the basin who used water from the basin during the agronomic year 2007/2008 (October 2007 through September 2008). The survey was administered in two phases: one immediately after the wet season (October 2007 – March 2008) and another immediately after the dry season (April – September of 2008). For each farmer and crop produced during the agronomic year, data was collected on outputs (prices received and quantity produced) and inputs (prices paid and quantity used). The amount of surface water used monthly by crop and by farmer, , was estimated with information collected on the frequency and duration of irrigation, the type of irrigation technology used and the type of pump by crop and farmer. A planting and harvesting calendar for each crop and each farmer plus the area allocated to each crop was then used to estimate the monthly precipitation that fell on the crops,  and .

Tables 1and 2 below show the monthly surface water demand as a percentage of total surface water supply and farmers’ descriptive statistics according to their relative position across the basin. Considering the baseline year as a typical year, Table 1 shows that in general farmers use a small percentage of the total surface water available (20% on average for farmers at the channels and 16% for the center pivot ). Farmers at Channel 1b face the highest percentages and as a consequence are closer to a surface water binding situation. Table 2 shows that Farmers at channel 1a have on average higher annual net revenues than farmers on channel 1b. Farmers at channel 2 are the lowest income farmers on average and the center-pivot farmer (CP3) earns the highest net-income. Farmers at the channels use on average 3 to 4 hectares of cropping land yearly, while the center pivot uses 44 hectares.[[2]](#footnote-2) Farmers at Channels 1a and 1b have higher net-revenue per hectare, a slightly higher reliance on rainfed crops and have a much higher rate of water per irrigated land than farmers at Channel 2. Farmers at the channels plant vegetables and fruits and are more diversified than the center pivot farmer who mostly relies on grains (corn, beans, wheat and soybeans). Lastly, although most of the land is irrigated, at least at some point in time, for the farmers at the channels, 25% of the total water used (precipitation and surface water) is supplemental. This percentage increases to 64% in the case of the center pivot.

**Table 1 – Monthly percentage of surface water demand over monthly total water**

**supply at the baseline year Conditions**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Months* | *Channel 1a* | *Channel 1b* | *Channel 2* | *Center Pivot* |
| January | 12.4 | 35.5 | 12.1 | 0.0 |
| February | 21.8 | 40.4 | 19.4 | 0.0 |
| March | 28.3 | 24.7 | 17.8 | 25.4 |
| April | 28.1 | 28.1 | 25.4 | 16.9 |
| May | 19.2 | 24.2 | 22.4 | 18.9 |
| June | 5.7 | 23.7 | 24.8 | 18.1 |
| July | 7.0 | 16.4 | 22.9 | 9.4 |
| August | 9.4 | 16.5 | 11.7 | 10.5 |
| September | 7.9 | 17.3 | 12.4 | 0.0 |
| October | 20.7 | 5.6 | 24.9 | 15.8 |
| November | 23.3 | 9.3 | 19.9 | 14.8 |
| December | 16.1 | 28.3 | 18.2 | 0.0 |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| *Farmers* | *Annual Average*  *Net-Revenue*  (*Brazilian Reais*) | *Average Cropping Land*  (*hectares*) | *Annual Water Use*  *per Irrigated Land*  (*m3 ̸ hectare*) | *Irrigated*  *Land*  (*%*) | *# of crops* |
| Channel 1a | 30,036.00 | 3.22 | 1722 | 85 | 18 |
| Channel 1b | 22,635.00 | 4.10 | 2066 | 70 | 11 |
| Channel 2 | 15,171.00 | 3.40 | 1097 | 94 | 20 |
| CP3 | 432,208.00 | 44.00 | 4412 | 62 | 4 |
| *Farmers* | *# of Farmers* | *Average Annual Net-Revenue per Hectare*  (*BrazilianReais*) | *Target Crops* | *Supplemental water use* ***(a)***  (*%*) | |
| Channel 1a | 7 | 9,340.00 | Vegetables and Fruits | 24  29  22  64 | |
| Channel 1b | 5 | 5,518.00 | Vegetables and Fruits |
| Channel 2 | 10 | 4,459.00 | Vegetables and Fruits |
| CP3 | 1 | 2,098.00 | Grains |

**Table 2 – Descriptive statistics across basins**

1. Percentage of surface water from the reservoirs used to irrigation over the total amount of water

used (direct precipitation over the crops + surface water from the reservoirs).

**CALIBRATION, VALIDATION AND SIMULATION**

*Calibration and Validation*

The basic model used for calibration is the one formed by equations 5 through 11 and called Precipitation Model (MP). By calibration it is meant that the optimized output and input mix for each farmer *g*, resulting from the net revenue maximization problem, is sufficiently close to the values observed in the base year. That is within the range of plus or minus 5% compared to the observed base year values.

Besides the fact that the basic model calibrates closely to the base year data, other important features of the model are important to validate the model´s prediction capability. An agricultural production model that includes precipitation and stored surface water as inputs should show that progressive cuts in precipitation are ceteris-paribus translated into more surface water pumping. Also it should show that increasing cuts in surface water availability, given the level of precipitation, are translated into increasing net-revenue losses. Effects across the basin should also be heterogeneous as farmers´ reliability on water and access vary across the basin. These results, based on the basic MP model, are corroborated by Figures 2, 3 and 4 below.

Figure 2 shows that cuts in precipitation from 5 to 90% will induce farmers to substitute surface water for precipitation by increasing the amount of pumped surface water up to 70%, given surface water costs and volume are kept at the baseline year levels. This farmer response to dry conditions is common the world over, but is sometimes not formally modeled, or is modeled with the two water sources being perfectly and costlessly substituted.

**Figure 2 – Impacts on Surface Water Use**

**Due to Cuts in Precipitation**



In terms of the impacts of cuts in surface water availability on the regional net-revenue, Figure 3 shows that given different levels of precipitation, the higher the cut in precipitation, the higher is the impact on net-revenue of a given cut in surface water availability. That is, the shadow price of surface water increases with increased cuts in precipitation. At the baseline precipitation level, impacts on net revenue start to become apparent only at 50% or higher cuts in surface water. For reductions in precipitation by 30% and 50%, however, impacts on net-revenue starts at much lower cuts in surface water. Similar patterns can be seen in Figure 3 with successive cuts in surface water availability.

**Figure 3 – Impacts on regional net revenue due to cuts in surface**

**water availability**



Across the basin, drought impacts on water supply and net revenue are shown to be heterogeneous. Assuming a 50% and a 30% cut in precipitation, the hydrological model estimates the corresponding impacts of these precipitation cuts on the reservoir levels (Table 3). As expected, a 30% cut in precipitation will cause a lower impact on surface water supply than a 50% cut but these impacts are not homogenous. Farmers at the end of the stream are hit harder successively in terms of access to water in the reservoirs. Figure 4 below shows, for example, that farmers at Channel 1b face a higher impact compared to farmers at Channel 1a. This is likely because they have less access to water due to their channel having a lower conveyance capacity. Table 3 shows that farmers at Channel 1a are much more effective in compensating for the loss in precipitation by pumping more surface water then farmers at channel 1b. The relatively higher reliance on purely rainfed crops by farmers at Channel 1b might also help in explaining this pattern (Table 2). The unfavorable position of farmers at Channel 2 and the center pivot 3 at the middle and end of the stream explains, in great part, the result that they are hit hardest in terms of water supply for both the 30 or 50% cuts in precipitation (Table 3). All farmers compensate for the 30% cut in precipitation by supplementing with more surface water. At the 50% cut, farmers at the channels repeat the supplemental water use pattern, in some cases, more than doubling amount of supplemental water use (Channel 1b), but the center-pivot farmer ends up reducing the amount of supplemental water used by 34%. This is likely due to the fact that water supply becomes more strongly binding since it drops 92% in volume.

**Table 3 – Changes in surface water supply and surface water use**

**across the basin after the 30 and 50% precipitation cuts**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Farmers* | *30%* | | *50%* | |
| *Change in Surface Water Supply*  *(%)* | *Change in Surface Water Use*  *(%)* | *Change in Surface Water*  *Supply*  *(%)* | *Change in Surface Water Use*  *(%)* |
| Channel 1a | -26 | 93 | -46 | 132 |
| Channel 1b | -33 | 48 | -49 | 44 |
| Channel 2 | -54 | 67 | -71 | 41 |
| CP3 | -75 | 17 | -92 | -34 |

Impacts on farmers’ revenue from cuts in precipitation and corresponding changes in the surface water supply estimated by the hydrological model may be seen in Figure 4 below. In general, an increase in drought severity from having a 30% and a 50% cut in precipitation causes an average decrease in expected revenue of 14% and a 23% respectively. As expected, the cost of cuts increases nonlinearly with the severity of drought. Also on average, costs due to a 50% cut in precipitation are 64% higher than for the 30% cut scenario.

The farmers’ position across the basin, access to surface water and reliance on irrigation or rainfed crops explain the range of drought impacts on net-revenue. Farmers at Channel 1b suffer more than farmers at Channel 1a either at a 30 or 50% cut in precipitation (see Fig. 4 below) since Channel 1b has a lower capacity (in fact Table 2 shows that water supply drops relatively more for farmers at Channel 1a than on Channel 1b) and its farmers rely more on rainfed crops than the ones on Channel 1a. Relatively to farmers at Channels 1a and 1b, farmers at Channel 2 suffers more despite their relatively more extensive use of irrigation (94% of their land is irrigated) and lower rate of irrigation water per hectare on irrigated land (Table 1). Their downstream position and relatively higher decrease in surface water supply (-54 and -71% ) due to the cuts in precipitation likely explain their net-revenue patterns. The Center pivot relies more on supplemental water, but its water supply decreases, relatively to other farmers, the most (75 and 92% , Table 2) due to its downstream position. As a consequence the drop in its net revenue is the highest. Also the fact that the center pivot farmer has a relatively high percentage of rainfed crops may also help to explain the pattern of drought impacts on its net-revenue.

**Figure 4 – Drought impacts on net revenue across the basin**

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*Simulation*

Besides the Precipitation Model (MP) as defined by equations 5 through 11 we construct an alternative model (called hereafter Model with Pooled Constraint or MPC) in which the maximization is subject to a simpler set of constraints. The MPC uses the same equation 5 and constraints (6), (7), (8) and (11) as used in the MP model, but constraints (9) and (10) are substituted by a pooled water constraint such as

 (12)

Constraint (12) states that for each farmer *g* the total annual amount of water applied to irrigated crops, , must be less or equal to the annual amount of surface water available () plus the total annual amount of rain that falls onto irrigated crops ().

In the MP model, substitution between precipitation and surface water is explicitly formalized and restricted to reflect the distribution of precipitation. In the MPC model, precipitation and irrigation water are aggregated together in a single water supply amount as is generally done in the models applied to arid and semi-arid regions cited in the introduction. For both of these versions two drought scenarios are simulated: a 30% and a 50% reduction in precipitation over all months of the year.

**RESULTS**

**Pooling Versus Non-Pooling**

Figure 5 below shows the net-revenue impacts under a 30% cut in precipitation predicted by the precipitation basic model (MP), in red bars, and the model with pooled water constraint (MPC) in grey bars. In here as in Table 3, we use the hydrological model estimates of the corresponding impacts of a 30% cut in precipitation on reservoir levels. In general, by showing a larger net-revenue across the basin, the traditional MPC pooled model underestimates the expected net-revenue losses compared to the more accurately specified MP precipitation model. This underestimation pattern is more evident for farmers at Channel 2 and the Center Pivot (CP3). In terms of the average impacts on regional production, the MPC model may underestimate by as much as 53% at the baseline precipitation and surface water supply conditions and by 22% under the 30% precipitation cut.

**Figure 5. Net revenue under the effects of a 30% cut in**

**precipitation. MP and MPC models**



**Stochastic MP and MPC models.**

Stochastic versions of the PM and MPC model were developed using the synthetic hydrologic precipitation records for the region to generate a series of stochastic precipitation values. We fitted a log-normal distribution for the precipitation with parameters of 4.6 and 0.5 as the mean and standard deviation respectively. This same distribution is used to generate a series of stochastic surface water supply values. [[3]](#footnote-3) The purpose in this section is to use both model versions as a tool to perform a risk analysis based on the variability of net returns and on the use of supplemental surface water to mitigate short run drought effects. The two models were solved for each of the 50 precipitation and surface water supply realizations and the results were used to calculate the difference in the revenue risk between the two model specifications.

**Table 4: Average net income variation by farm size**(a)

|  |  |  |  |
| --- | --- | --- | --- |
|  | *Average Net Income per Hectare* | | |
|  | *Large* | *Medium* | *Small* |
| *Precipitation Model* |  |  |  |
| Mean | 2124.3 | 8885.7 | 5631.0 |
| Standard deviation | 297.3 | 8952.2 | 8510.6 |
| Coefficient of Variation | 0.14 | 1.01 | 1.51 |
| Percent Supplemental | 64.9 | 29.8 | 25.4 |
| *Pooled Model* |  |  |  |
| Mean | 2970.1 | 10695.9 | 7244.5 |
| Standard deviation | 381.7 | 8702.0 | 8611.8 |
| Coefficient of Variation | 0.13 | 0.81 | 1.19 |
| Percent Supplemental | 0 | 0 | 0 |

1. Large, one farm with 206 hectares of annual area under plow; medium,

7 farms with 4 to 7 hectares of land area under plow; small, 15 farms

with area under plow below 4 hectares.

Table 4 shows the difference in farm income risk measured by the two model specifications. Not only does the pooled model underestimate the expected loss due to stochastic rainfall but for all farm sizes, the risk as summarized by the coefficient of variation is also downplayed by the water pooling model. Under both model specifications, net income risk is reduced by larger farm sizes and a greater proportion of supplemental water used by the farmers. For each farm, there are 50 realization values of net-revenue per hectare. The mean values and standard deviation are calculated considering all farms within each type (large, medium and small) over all 50 realizations. Percent supplemental is the average percentage of surface water used over total applied water (surface water + precipitation), considering all farms within each type (large, medium and small) over all 50 realizations. Percent supplemental in the MPC model is zero since surface water is pooled with precipitation, which is costless.

The results suggest that the variability of net returns decreases with increased farm size and that supplemental water use reduces income variability. Moving from large to medium farms, the coefficient of variation sharply increases by seven and six fold in the MP and MPC models respectively. The difference is even larger if we compare large with small farms. From medium to small, the coefficient of variation increases around 50% in both versions. At the same time (based on the MP model) the percentage of supplemental water used decreases by half from large to medium farms and by 15% from medium to small. [[4]](#footnote-4) The coefficient of variation estimates for the pooled MPC model are consistently lower compared to the MP model values. In addition, the underestimation gets more evident for the cases of medium and small farmers. In general, Table 4 shows that 1) revenue risk is greater for small farmers, 2) supplementary irrigation reduces risk, and 3) pooling water sources in a single and undistinguishable source results in underestimation of the revenue risk..

**Figure 6: Stochastic Precipitation-Net Income Distribution- Small Farms- PM and MPC Models**



Figure 6 shows the frequency distribution of net income for small farms as generated by the MP and MPC model specifications. From the deterministic results we know that the mean income is higher for the MPC model. In addition figure 6 shows that the income distribution under the pooled MPC model has a positive skew on the upside. This skewedness reflects the ability of optimizing farmers to make better use of the total water resources when they are plentiful if they are, unrealistically, assumed to be completely flexible and substitutable across crops and growing seasons.

**CONCLUSION**

This paper shows that for many irrigation systems that provide supplemental water to seasonal precipitation, the specification of substitution between irrigation and precipitation has a significant impact on model results. In short, models that assume a fully substitutable pooled water supply underestimate the net income cost of drought and the value of supplemental water, in addition, the pooled model introduces a positive upward bias in net income. In areas where the water access rule is a first-come, first-serve basis and farmers are located in a cascading series along a river with farmers situated downstream are more likely to be inflicted with the greatest cuts in supply. For a given drought situation, they get the remaining water after it has been diverted to satisfy the demands of farmers located upstream. This paper shows this effect using a fully integrated modeling approach that combines hydrology and economics and can be used for the estimation and quantification of the drought impacts on agricultural income. It also shows that the use of modeling approaches that do not explicitly consider the substitution relationship between surface water and precipitation will underestimate the average drought impacts and the risk implied by stochastic precipitation. While the current empirical example is too small to generalize, it does show that modelling situations, where irrigation is supplemental to precipitation, using conventional arid region pooled water models will introduce bias into both the estimates of expected net revenue and their variance. Clearly, the importance of this bias will depend on the relative importance of expected precipitation to the total seasonal water requirement. In many irrigated systems the contribution of precipitation is substantial, and with it the potential for bias from incorrectly specified models.

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1. For a more detailled discution on the functional form and the definition of the implicit land cost term please see Medellín-Azzuara 2010. [↑](#footnote-ref-1)
2. After planting and harvesting a given crop, the plot of land may be re-used for cropping more than once in a single agricultural year. [↑](#footnote-ref-2)
3. Ideally, for a given distribution assumed for precipitation, the hydrological model should generate the corresponding distribution of values of the surface water volume in the reservoirs. Although it is likely that the water volume follows the same distribution assumed for precipitation, it is not likely they share the same parameters (mean and standard deviation). We assume here, however, they share the same parameters. [↑](#footnote-ref-3)
4. We should bear in mind that medium and small farmers are more comparable because they share similar irrigation technologies and product mixes (vegetables and fruits). The large farm operation in the sample uses center-pivot technology and grows grains. [↑](#footnote-ref-4)