Assessing agriculture-water links at basin scale: A hydro-economic model of the São Francisco River basin, Brazil.

Marco Maneta[1], Marcelo Torres[1], Stephen A. Vosti[1*], Wesley W. Wallender[1], Summer Allen[1], Luís H. Bassoi[2], Lisa Bennett[1], Richard Howitt[1], Lineu Rodrigues[3] and Julie Young[1]

[1] *University of California (UCD), Davis, USA.*
[2] *Embrapa Semi-Arid Tropics, Petrolina, Brazil.*
[3] *Embrapa Cerrados, Planaltina, Brazil.*
[*] *Corresponding author: S.A. Vosti, Dept. of Agricultural and Resource Economics, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA.. Tel 1 530 752 8097. Email: vosti@primal.ucdavis.edu*

Abstract

The São Francisco River provides about 70% of the surface water in Northeast Brazil, and like much of Brazil the basin includes communities characterized by a broad range of incomes, including persistent poverty. The basin's agricultural systems cover a wide range between capitalized export-focused enterprises and subsistence farms, and the basin also hosts several important water-dependent ecological zones. Increasingly, the complex web linking water availability, water quality, water productivity, economic growth, poverty alleviation and community and ecosystem health is coming into focus. Brazilian federal law requires that public policymakers promote and guide water management so as to improve overall social welfare. However, knowledge gaps hamper implementation:

- We do not know how decisions on water use are taken by important water-use groups, and once taken, how these decisions affect the water-use options available in other parts of the basin, now and in the future; and
- We lack information for assessing scale-dependent, freshwater dynamics and using these dynamics to predict the effects of alternative water policies designed to promote increased water productivity, and enhancement of livelihoods and the environment.

This paper describes a basin-wide hydrologic model and a basin-wide economic model of agriculture. When the models are linked, they are used to assess the effects of access to and the cost of irrigation water on agricultural change, and the effects of agricultural change (perhaps promoted using water policies) on water resources. Two separate basin-wide models are developed. The first is MIKE Basin, a model used to calculate water budgets for large watersheds. Data are aggregated to the level of user-defined sub-basins within the main watershed. MIKE Basin uses a conceptual rainfall-runoff model (NAM model) based on a multiple-tanks concept that simulates the release of water from the different storage units in each sub-basin. Runoff from each user-defined sub-basin is accumulated or routed down the river network; stage-discharge and rule curves are used to operate the reservoirs. The second is a positive mathematical programming model developed at município (county) level. The model uses observed farmer behavior to identify factors influencing the extent of agriculture, crop mix and production technology, and then uses these relationships to predict the effects of changes in economic, policy or hydrologic circumstances. These two models are then 'linked' to assess the effects of agricultural change in water use (and hence on water resources), and the effects of water and other economic policies on agriculture.

Preliminary results suggest that although the water resources of the SFRB are generally under-utilized, substantially expanding agriculture in the basin could put major pressure on some of the river's environmental flows, even at the river's mouth. Increases in cultivated area would, however, increase agricultural GDP and rural employment, both of which would help reduce rural poverty. Results also demonstate the potentially uneven economic effects of

water-use regulations across farmer types; poor farmers are less affected than non-poor farmers under some circumstances.

Given the array of hydrologically inter-related water-scarce and water-surplus areas within the SFRB, a basin-wide approach to water management is clearly called for. In some areas water is scarce (or will become scarce very soon) and policy action to identify water rights and manage water resources should be put into place. In other areas, water use in agriculture can be greatly expanded; in these areas, market access and capital constraints are the factors limiting agricultural expansion and modernization.

Keywords
Hydrologic modeling, economic model of agriculture, water policy, Brazil, basin-wide water management.

Introduction

The São Francisco River provides about 70% of the surface water in Northeast Brazil and, like much of Brazil, the basin includes communities characterized by a broad range of incomes, some of which have very high rates of persistent poverty. The basin's agricultural systems cover a similar range between highly capitalized, export-focused enterprises and subsistence farms. Major corporations and cottage industries comprise the industrial water-use sector while cities and towns tap the basin for municipal supplies. The basin also hosts several important water-dependent ecological zones. Increasingly, the complex web linking water availability, water quality, water productivity, economic growth, poverty alleviation, and community and ecosystem health is coming into focus. Conflict for water among various water user communities and sectors is becoming common, often with negative consequences for resource-poor stakeholders (ANA 2004).

Brazilian federal law requires that public policymakers promote and guide water management so as to improve overall social welfare. More specifically, the law clearly places hydrological resources in the public domain. It charges policymakers with the wise and sustainable management of these resources via the use of water price policy and other policy instruments, some of which remain to be developed. However, formidable challenges confront implementation. Two of the challenges this research seeks to address in the context of the São Francisco River Basin (SFRB) are:

- Incomplete understanding of how water-use decisions are taken by important water-use groups, and once taken, how these decisions affect the water-use options available in other parts of the basin, now and in the future; and
- Incomplete information for assessing scale-dependent, freshwater dynamics and using these dynamics to predict the effects of alternative water policies designed to promote increased water productivity, and enhancement of livelihoods and the environment.

This paper describes a basin-wide hydrologic model and a basin-wide economic model that are being developed and linked to address policy issues related to agriculture, rural poverty, and inter-sectoral and inter-basin trade-offs regarding water use. The next section briefly describes the hydrologic model. Section 2 demonstrates the usefulness of the hydrologic model for examining the hydrologic consequences of expansions of the agricultural frontier in the SFRB; Section 3 uses the basin-wide hydrologic model to assess some of the economic and environmental consequences of such an expansion. Sections 4 and 5, respectively, describe the economic model of agriculture and demonstrate its usefulness for predicting the effects of water use regulation on agricultural activities. Section 6 ends the paper with some preliminary observations related to rural poverty.

1. The basic hydrologic model

MIKE Basin is a simple model used to calculate water budgets for large watersheds where hydrologic data are scarce. The data needed to run the model are minimal, but the information it provides is also limited. This information is aggregated to the level of user-defined sub-basins within the main watershed. Input data on runoff from each user-defined sub-basin are accumulated or routed down the river network to calculate output discharges for each sub-basin; stage-discharge and rule curves are used to operate the reservoirs.

Depending on the complexity of the simulation, the user will need hydrologic information, which typically includes runoff, precipitation, evapotranspiration, and water management data from groundwater and reservoirs (pumped water from groundwater and water withdrawals from reservoirs and rivers).

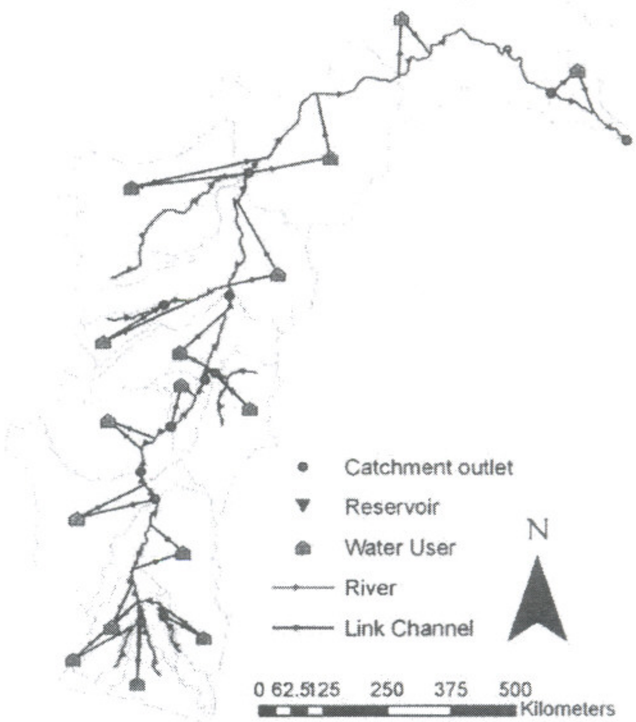
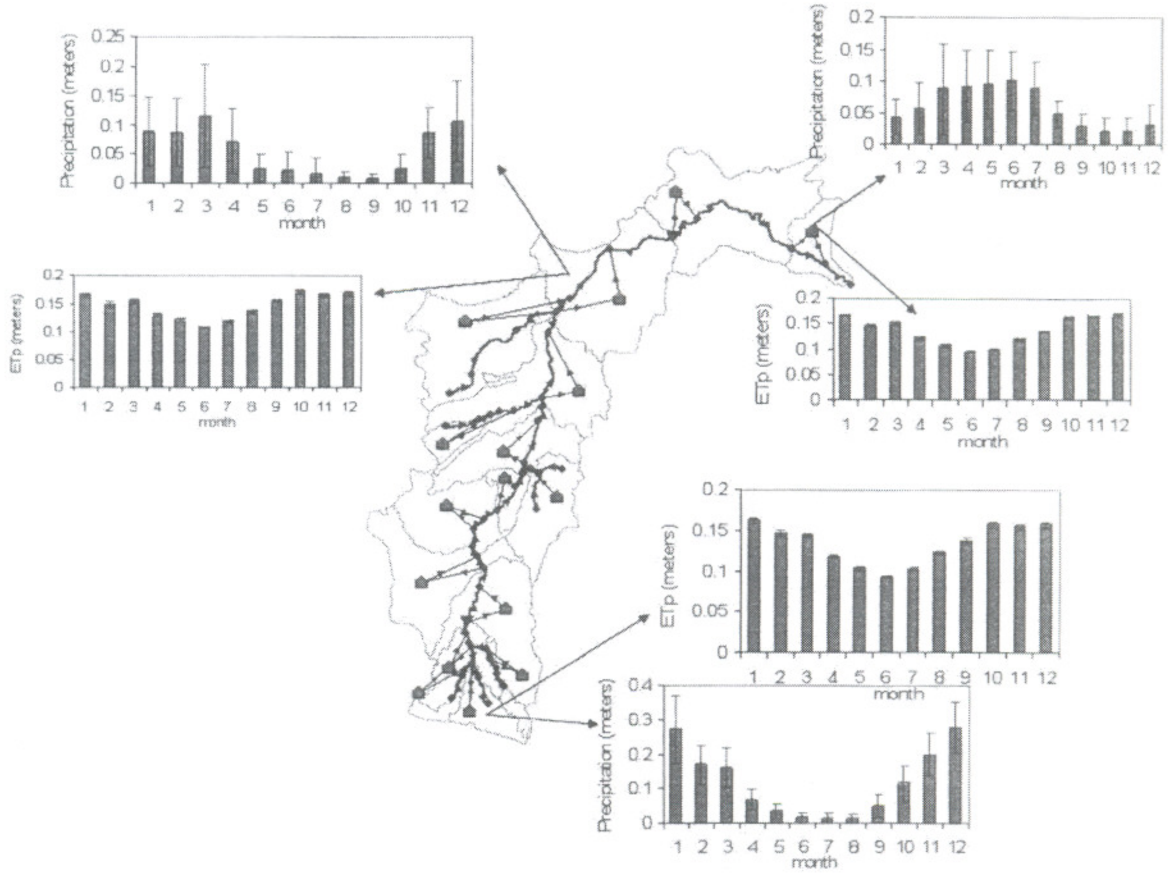


Figure 1. The São Francisco River Basin configuration in MIKE Basin. Source: Authors' calculations.

For the purposes of this project, the SFRB is divided into several areas in order to calculate the water budget and the water availability at key points in the basin. The key areas chosen are those formed mainly by the drainage areas (sub catchments) of the main reservoirs in the watershed plus several support nodes at main known river gauges. These extra support nodes: i) allow for the calculation of the water budget in the reservoirs, which are the main water suppliers to satisfy irrigation, industrial, and urban water demands; and ii) due to the strategic importance of reservoirs, discharge records of high quality, reliability, and temporal resolution should exist for those points. The spatial configuration of the basin was determined by the discharge stations for which data were available. The entire SFRB was divided into 15 watersheds indicating the drainage areas of each station (Figure 1). A water user representing agricultural water demand was assigned to each watershed. The simulations are run using a monthly time step.

For each watershed, monthly data on precipitation and evapotranspiration are available from the CRU_TS_2.10 dataset (Mitchell and Jones, 2005) and discharge is available from the DSS522.1 dataset (Bodo, 2001). It is therefore possible to construct a simple characterization of the climate of each of the 15 zones in terms of their mean conditions each month and the expected variability (Figure 2). The southern and western parts of the basin have climates that can be classified as tropical with a dry season in the central months of the calendar year. In general, the dry season is more contrasting as we move to wetter areas in the south and west. In the central north and northeast parts of the basin the amount of precipitation is much lower, while the atmospheric demand is high and constant throughout the year. This produces a climate with strong semiarid characteristics. Near the outlet of the São Francisco River, the climate has strong oceanic influences and the rainfall pattern reverses, i.e., the central months of the year tend to be the wettest months.



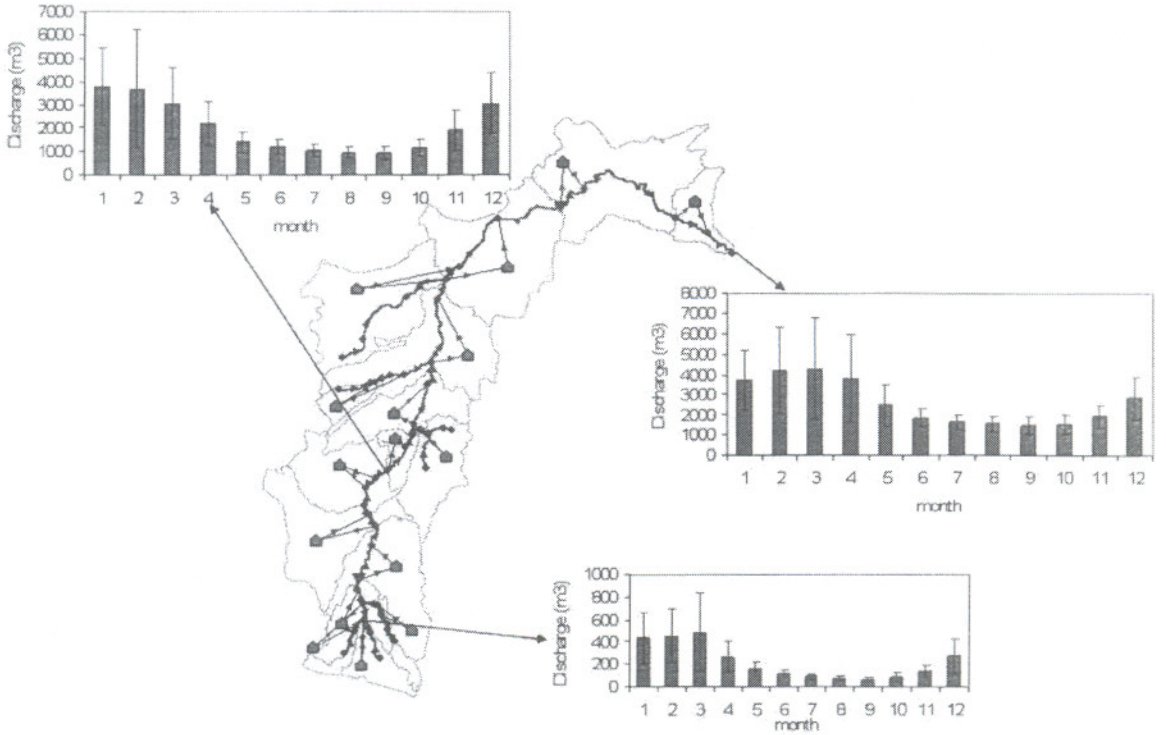
Note: Blue bars are mean monthly averages for precipitation and potential evapotranspiration (ETp). Red whiskers are standard deviation of precipitation or ETp for the month. January is month number 1.

Figure 2. Mean monthly precipitation and potential evapotranspiration and their standard deviations for the SFRB. Source: CRU_TS_2.10 dataset (Mitchell and Jones, 2005) and Marco Maneta.

While the precipitation regime shows important differences for different parts of the basin, the evapotranspiration pattern is stable for the entire basin, showing high evapotranspiration demand for all the months but slightly lower during the cooler winter months. This winter recession is more contrasting as we move south in the basin.

The most unpredictable month in terms of precipitation is March. In general, the expected variability in rainfall is proportional to the average, so that months with a large mean precipitation tend to have the most months with precipitation well above or well below the long-term average. Furthermore, the variability in monthly precipitation is typically larger for the areas with semiarid and oceanic climates than for those in the southern or western parts of the basin. Conversely, the dry months are the most 'reliable.' During those months, there is very little precipitation and there is rarely a year during which the amount of precipitation is much larger than the mean. Evapotranspiration is high and relatively constant.

Discharge, the basin response to precipitation, reflects patterns similar to those for precipitation (Figure 3). January through April is the period with the largest river discharge, as one would expect, and the months with highest discharge are also the months with the largest standard deviations for discharge. The most predictable rates of monthly discharge occur during the winter (dry) months, when river and its tributaries see their lowest discharge. In general, the monthly pattern shows the integrated effects of the climates of the basin (plus the regulating effect of the multiple reservoirs), for example, at the mouth of the São Francisco River the highest precipitation occurs during the winter months but the highest discharge rates occur during the summer months.



Note: Blue bars are mean monthly averages for precipitation and potential evapotranspiration (ETp). Red whiskers are standard deviation of precipitation or ETp for the month. Source: DSS522.1 dataset (Bodo, 2001) and Marco Maneta.

Figure 3. Monthly river discharge and standard deviations in the SFRB

Precipitation, evapotranspiration, and discharge are clearly interdependent in the SFRB. Typically, years with above-average monthly precipitation will have above-average monthly discharges and (slightly) lower monthly potential evapotranspiration. Calculating the covariance structure of the three variables and assuming they follow a multinormal distribution, we can obtain the probability density function, which gives us information about the likelihood of different scenarios. With this joint probability function, we can calculate the probability of a given month having a given precipitation, a given potential evapotranspiration, and with these calculate discharge.

2. Using the hydrologic model to assess the effects of an expansion of cultivated area

If we know the irrigated area in each of the polygons that comprise the entire basin, the monthly crop-specific water requirements throughout the year, and irrigation efficiency, we can estimate irrigation water demand as follows:

(1) Water demand (L3T-1) = (ETp[L3T-1] * Kc – P[L3T-1])/Ieff

Where ETp is potential evapotranspiration;

Kc is an effective crop coefficient for a given crop mix;

P is precipitation; and

Ieff is a dimensionless irrigation efficiency factor (0>Ieff<=1) that represents the irrigation technology used.

We obtained climate data from the above-mentioned databases. For the model simulations reported below we used KC =1 and Ieff = 0.8 as representative average values for the crop coefficient and the irrigation efficiency through the SFRB.

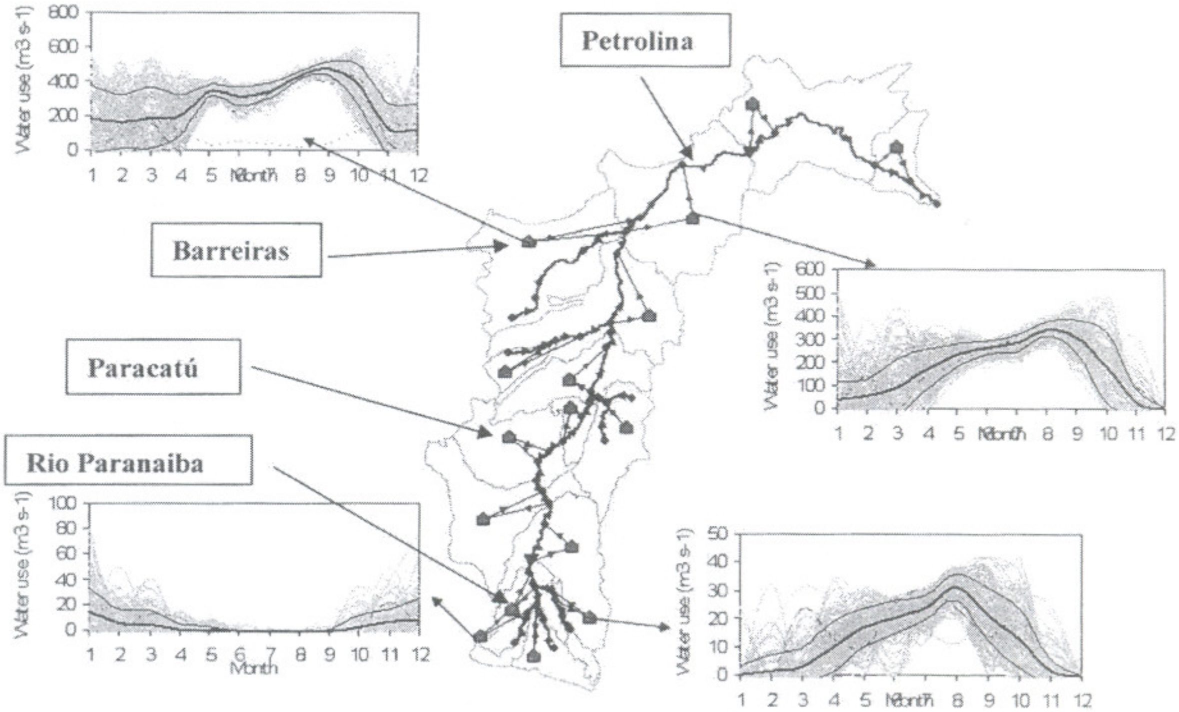
Because we characterized statistically the hydrologic inputs and responses of the system and agricultural water demand, we can evaluate statistically the probability that a given amount of water will be required. To do so we use a Monte Carlo method in which the model is run multiple times drawing from a joint probability distribution of precipitation, evapotranspiration, and discharge. In doing so, we obtain a set of possible outcomes regarding surface water stocks, including the maximum and minimum levels expected given the worse and best climatic conditions. , We also obtain the set of possible water demands for each of the 15 agricultural 'water users' that comprise the SFRB.

We demonstrate the usefulness of this approach by assessing the effects of an expansion of the agricultural frontier in the SFRB. Let us imagine that the irrigated area were increased by 22,000 hectares (holding constant the area-specific crop mix) in each of the catchment areas identified in the current configuration of MIKE Basin. Assuming that irrigation efficiency was equal to 0.8; we can simulate the effects of this expansion of agricultural activities on average water demand per month, and its knock-on effects on the water resources throughout the basin.

Figure 4 presents the results of this agricultural expansion on water demand for a subset of water users in the basin (the four water use graphs measure increases in water demand vis-à-vis the baseline). As expected, the results reflect the climatic features of each area. In the southern region where the amount of precipitation is large, the average increase in water demand is low. There are important increases in water demand by water users further north in the semiarid region of the basin.

For most users, especially those in the semiarid areas of the basin, the central months of the year (dry season) are the months with the highest average demand. It is interesting to note that while demand during the June-September period is quite consistent (narrow standard deviation); demand during the wet season is more variable because frequently the 'wet' months are drier than usual. This type of analysis helps identify areas of drought risk and measure the extent of risk for rain-fed agriculturalists, as well as measure the frequency with which and the extent to which water needs will not be met for irrigated agriculture.

For example, in the Boqueirão area (upper left graph in Figure 4) an irrigation system designed to guarantee about 400 $m^3 s^{-1}$ to irrigate the entire cultivated area during the dry season would likely be sufficient to meet irrigation water needs even in the driest years. This is because there is very little variability in dry-season rainfall patterns. However, in that same area, designing a system able to supply 200 $m^3 s^{-1}$ during the wet season may be problematic since in 34% of the years (approximately 68% of the cases bound by ±1 standard deviation) water demand would be almost 400 $m^3 s^{-1}$, twice what the system could supply. This characterization can be used to produce a map for assessment of risk analysis.



Note: Red lines indicate average water demand and blue lines depict standard deviations; grey lines are the results of specific Monte Carlo experiments. Source: Marco Maneta, MIKE Basin model simulations.

Figure 4. The effects of expanding agriculture on water demand in the SFRB

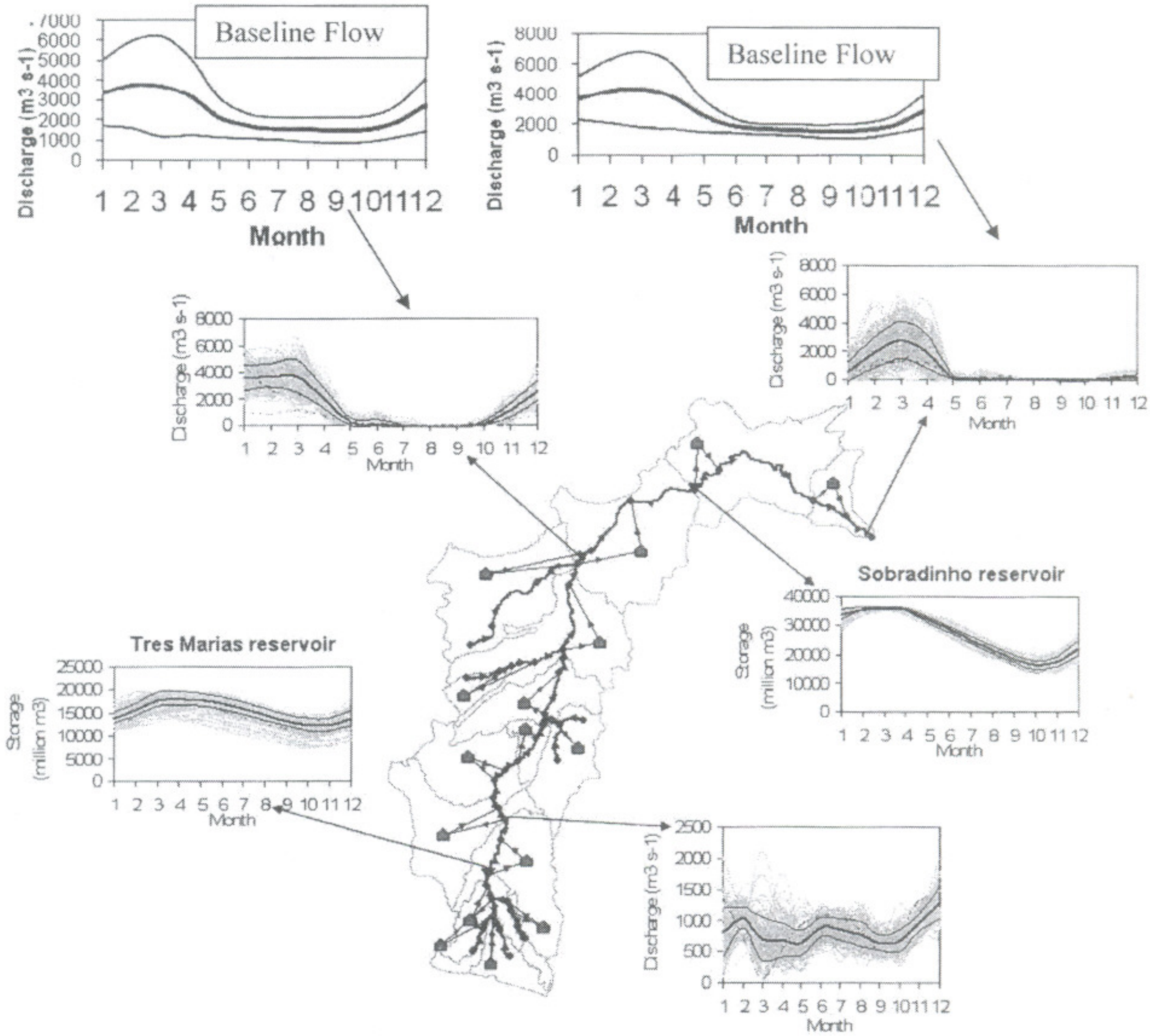
3. An assessment of the economic benefits and environmental costs of agricultural expansion
Aside from using additional water resources, area expansion in agriculture also generates benefits in terms of increased income flows and increases in rural employment. One easy way to predict these marginal benefits is to assume that as cultivated area in each município is expanded, the current (2006) município-specific proportional land use patterns are retained, and the site-specific gains are (hence) proportional to those generated by existing agricultural activities. Market forces, agroecological characteristics, etc. are chiefly responsible for observed land use patterns, so, for small changes in cultivated land, using existing patterns as our guide seems reasonable.

Table 1. Income and employment benefits of agricultural expansion

Selected municípios	Gross value of total additional agricultural output (thousands 2006 R$)	Total increase in employment (person-months/yr)
Barreiras	36,524	2,350
Petrolina	192,854	14,300
Paracatú	41,989	7,400
Rio Paranaiba	3,676	190

Source: Authors' calculations based on IBGE data.

Table 1 presents estimates of what these marginal benefits might be for four municípios in the SFRB (see Figure 4 for their location). The very large differences in the values of output and employment benefits attributable to the simulated agricultural expansion are due chiefly to the differences in product mix, though area expansion in the Rio Paranaiba município was smaller than in the other municípios. In the case of Petrolina, in particular, area expansion occurred primarily in irrigated, high-value, high-employment fruit/vegetable production.



Note: Side figures contain estimates of discharge and reservoir storage for some locations in the SFRB. Red lines represent averages, blue lines are the standard deviations, and grey lines represent the results of Monte Carlo experiments. Source: Marco Maneta, MIKE Basin model simulations.

Figure 5. The effects of expanding agriculture on above-ground water storage in the SFRB

Once water demand associated with the simulated agricultural expansion has been characterized, the impacts on the river system (river discharge and the dynamics of above-ground water stocks) can be also evaluated. Figure 5 depicts estimates of river discharge for selected locations in the river system and the storage dynamics of two reservoirs (the Três Marías and Sobradinho dams). It is clear from the simulations that even in the worst-case rainfall scenario the effects on water storage in the two reservoirs are very limited. In no case can we expect the water stocks in either dam to be depleted below the levels required to maintain (assumed) environmental flows. However, the effects of the simulated agricultural expansion on environmental flows could be quite substantial, e.g., the final discharge of the São Francisco River could be zero during several months (compare the two right-hand graphs of Figure 5).

While the large capacity of the reservoirs reduces the impact of the climatic conditions and the expansion of cultivated area on the water storage, the discharge in rivers is more variable, hence the farmers and others depending on these discharges are more vulnerable. The rivers in the northern part of the basin have a clear dry season during which flow rates are generally low, but during the wet season these rivers may experience highly variable flow rates depending on weather conditions during the specific year (see graph in upper-right portion of Figure 5). River discharge in the southern part of the basin (see graph in the lower-right portion of Figure 5) shows a more regular discharge regime, but inter-annual variability of this discharge is also important indicating high sensitivity to the climatic variability. While rivers in the semiarid regions show larger variability in discharge rates during the high-flow months, in the wetter parts of the basin this variability is very similar throughout the year.

Perhaps most important, the simulated expansion of the agricultural frontier thoughout the SFRB brought about dramatic reductions in seasonal flows, with potential negative implications for ecosystem services to which these flows may contribute (e.g., aquatic life, waste removal, etc.). At the top of Figure 5, two nested figures show the baseline flows of two selected points along the SFRB. Note that in both cases the baseline flows never reached zero, but in both cases area expansion in agriculture caused flows to dry up and remain dry, in one case for several months.

4. An economic model of agriculture

Water allocation and water use decisions are influenced by public policy and other factors both within and beyond the basin. Within the basin, public policy can take the form of investments in water conveyance infrastructure (e.g., canal systems), the establishment of water-user associations, the establishment (and enforcement) of water- or land-use regulations, the establishment of water pricing schemes, etc. Outside the basin, policies such as national tax policies relating to irrigation development, operations, and maintenance; agricultural input and output pricing policies; and inter-basin water transfer schemes can act either to reinforce or to mitigate effects of policies at the basin or sub-basin levels.

To identify the effects of alternative water management options, we are developing a basin-wide, município-level economic model that focuses agriculture. The model incorporates the optimizing behavior of farmers and takes into consideration the ability of farmers to respond to changes in economic incentives, among them changes in the cost of applied water. In developing this model, we paid particular attention to policies that regulate surface water use, and those that establish basin-wide and sub-basin water prices. We also considered how such policies might independently and jointly affect cropping patterns, agricultural productivity and profitability, employment, and poverty, and water use efficiency in the basin.

The economic model of agriculture for the SFRB described here is based on a class of models called Positive Mathematical Programming (PMP), described in more detail in Howitt (1995a), and widely used in applied research and policy analysis by Howitt and Gardner (1986), House (1987), Kasnakoglu and Bauer (1988), Arfini and Paris (1995), Lence and Miller (1988), Heckelei and Britz (2000) and Helming et al. (2000).

The model considers municípios as economic agents who manage multi-output, multi-input production operations with a specific objective in mind (net-income maximization) and subject to an array of biophysical and socioeconomic constraints. The net income (NI) is divided in two parts: 1) revenue, defined as the price of crops, p, multiplied by the quantity of crop produced q, which is assumed to be a function of the quantities of input, x; and 2) cost, c, which is a function of input prices, w, and input quantities, x. Input and output prices are given, that is, production decisions at the município level do not affect market prices. In this context, the net-revenue equation for município s can be written as:

(2) $$NI_s = \sum_i p_i q_i(x_{ij}) - c_i(x_{ij}, w_{ij}), \text{ for } s = 1,\ldots, S \text{ municípios},$$

Where $q_i(x_{ij})$ is the production function for $i = 1,\ldots, I$ crops;

x_{ij} is the quantity of input j, for $j = 1,\ldots, J$ inputs, used in the production of crop i;

$c_i(x_{ij}, w_{ij})$ is the cost function associated with crop I;

x_{ij} is defined as above; and

w_{ij} is the price of input j used in the production of crop i.

We assume also that there are constant returns to scale. That is, for a given level of land quality, if farmers double the amount of all inputs used, crop production will also double. Under these assumptions, the production function for the model is represented by:

(3) $$q_i = \alpha_i (\sum \beta_{ij} x_{ij}^{\gamma})^{\frac{1}{\gamma}},$$

Where q_i is the quantity of output for crop i, and, x_{ij} is the quantity of input j used in the production of crop i;

α_i, and β_{ij} are parameters to be calculated;

$\gamma = \dfrac{\sigma - 1}{\sigma}$; and

σ is the elasticity of substitution among inputs in the production process.

For the cost function we assume the following specification:

(4) $$c_i = w_j x_{ij} + \psi_i x_{il}^2,$$

Where w_j is the market price associated with input j used in crop I;

x_{ij} as the quantity of the input j used in production of crop I; and

x_{il} is the number of hectares allocated to crop i.

Thus, the cost to produce crop i is defined by two terms: the first term on the right-hand side is the market price of the inputs, w_j, multiplied by the quantity of inputs used, x_{ij}; and the second term is the implicit cost associated with land allocation. It has a quadratic specification with parameter ψ_i and incorporates the increasing marginal costs associated with allocating increasing amounts of land to a particular crop. The rationale for including such implicit land allocation costs are based on land quality heterogeneity and risk. It is important to stress that, at least for this version of the model, we do not intend explicitly to model risk and/or land heterogeneity. We only assume instead that there is an implicit cost associated with land allocation to a particular crop, which may take the form of risk, land heterogeneity or both, and that this cost has a quadratic functional form associated with land.

For this exercise, we use data from the most recent Brazilian Agricultural Census (1995/96) to estimate the model. The lowest level of geopolitical aggregation in Brazil is the município (Brazilian counties); this is the spatial unit of observation used in this exercise. For the demonstration version of this model we have chosen the 6 municípios that comprise to the Rio Preto River Basin, a sub-watershed of the São Francisco River Basin (Figure 6).

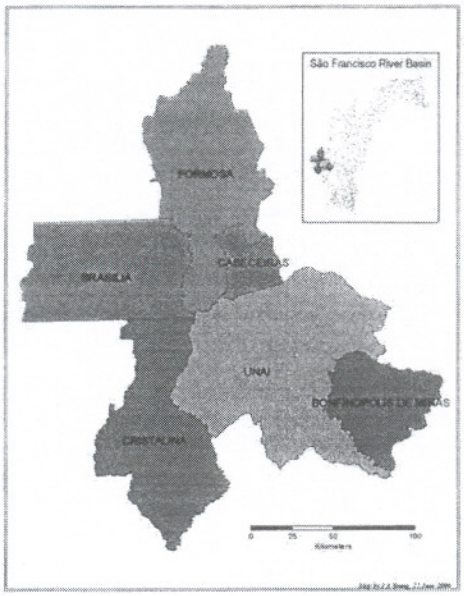


Figure 6. Municípios that make up the Rio Preto River Basin.

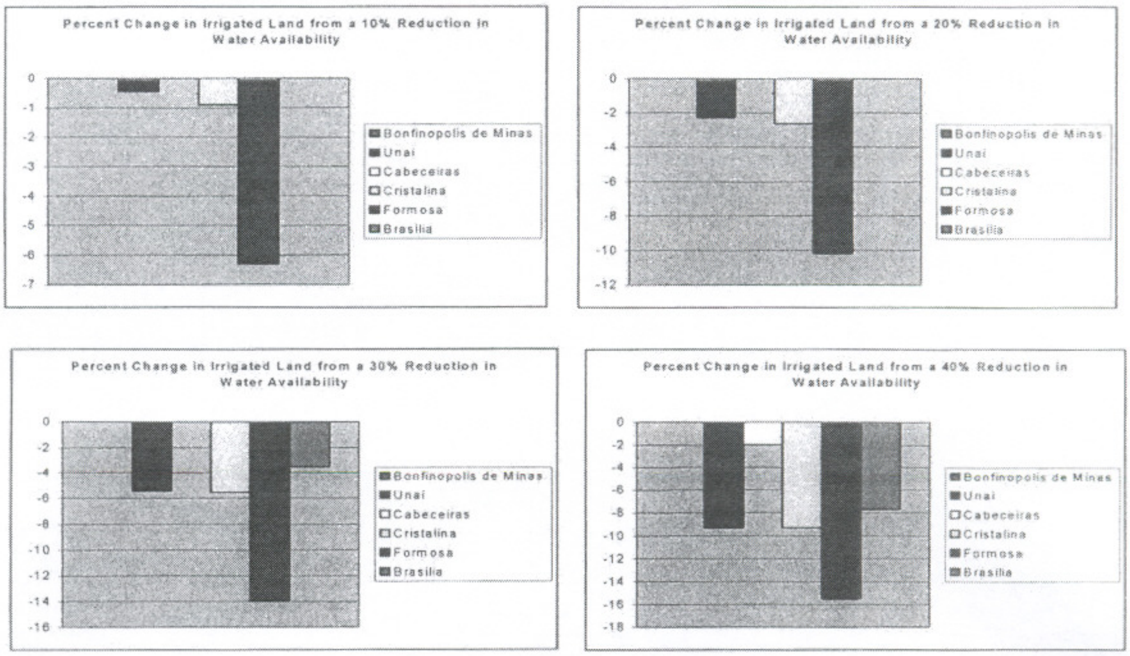


Figure 7. Effects of reduced water availability (10/%, 20%, 30% and 40%) on irrigated area, by município. Source: Authors' calculations.

We now use the model sketched out above to examine the effects of mandated reductions in water use in agriculture to restore seasonal surface water flows; we highlight the effects on irrigated area, crop allocation, and applied water. Note that all results are presented in terms of deviations from an established agricultural baseline.

5. Using the economic model to predict the effects of reduced supplies of water to agriculture

Figure 7 depicts the effects on the amount of area under irrigation of a series of decreases (10, 20, 30 and 40% decrease) in water availability (as mandated by water management policy). A 10% reduction in water availability is enough to induce reductions in irrigated land in Formosa, Unaí, and Cristalina. Notice that there is no change in irrigated area in Bonfinópolis de Minas, Cabeceiras and Brasília, which is due to the fact that water is not a constraint in these 3 municípios even with a 10% reduction. However, as water becomes more scarce (i.e., as availability is reduced by 20, 30, and 40%) we begin to see major reductions in the area under irrigation in almost all municípios.

Farmers also react to reductions in water availability by changing what they produce and how much water they apply. Figures 8 and 9 show the changes in crop mix and water use per crop (again, by by município) associated with a 10% reduction in water availability. Note once again, the highly varied responses across municípios to a uniform increase in water scarcity; different soils, access to market, etc., can greatly influence the marginal contribution of applied water to overall profits. For example, in rice, which is among the most water-sensitive crops, there are reductions in area across all municípios, while the same is not true for (say) citrus. Perhaps most important, the model suggests that increased water scarcity generates a broad array of responses in terms of crop mix, area in some crops will expand (e.g., orchard fruits) while the area dedicated to other crops such as rice and corn will likely fall. This reshuffling of crop mix in response to water scarcity is a result of the non-uniform marginal contribution of water to output across crops, and of farmers' efforts to allocate increasingly scarce resources (in this case, water) to their best uses in terms of profitability.

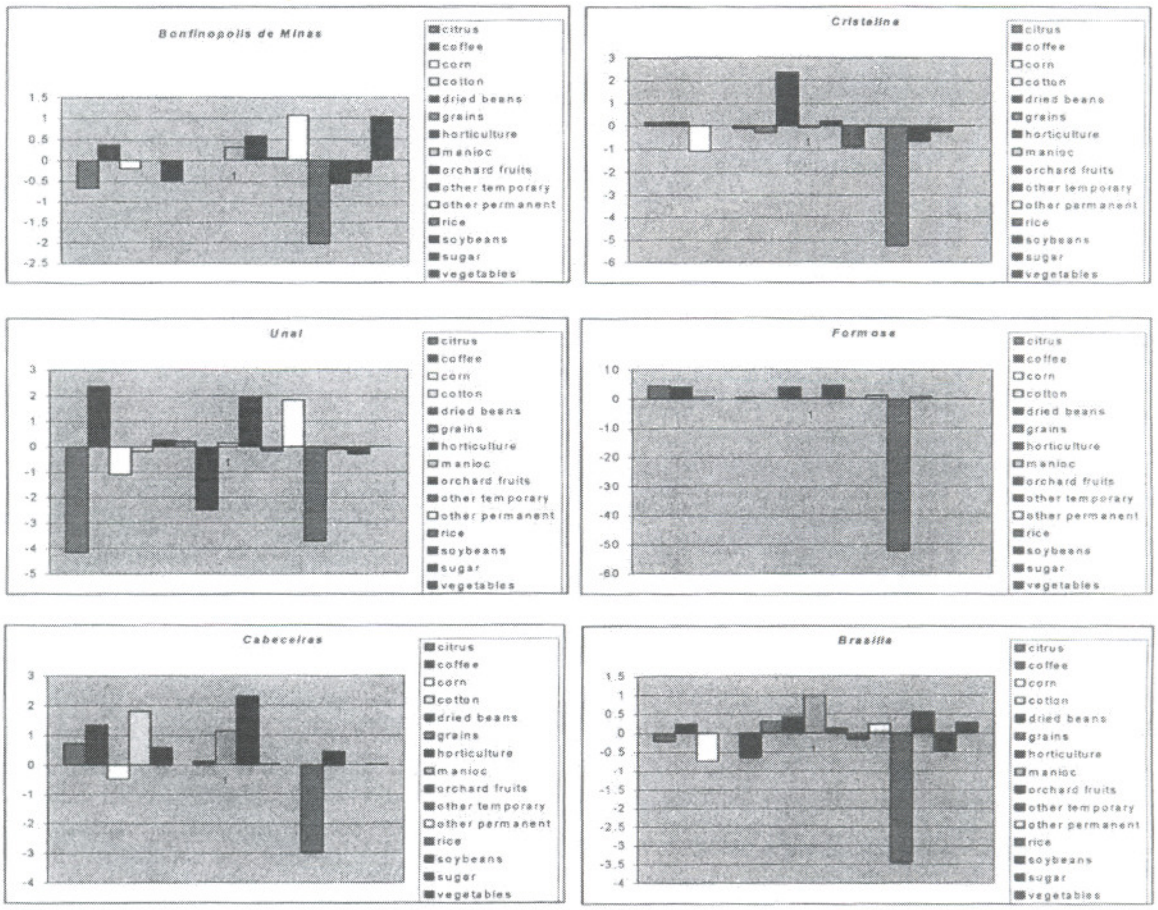


Figure 8. Percent change in crop allocation associated with a 10% reduction in water availability. Source: Authors' calculations.

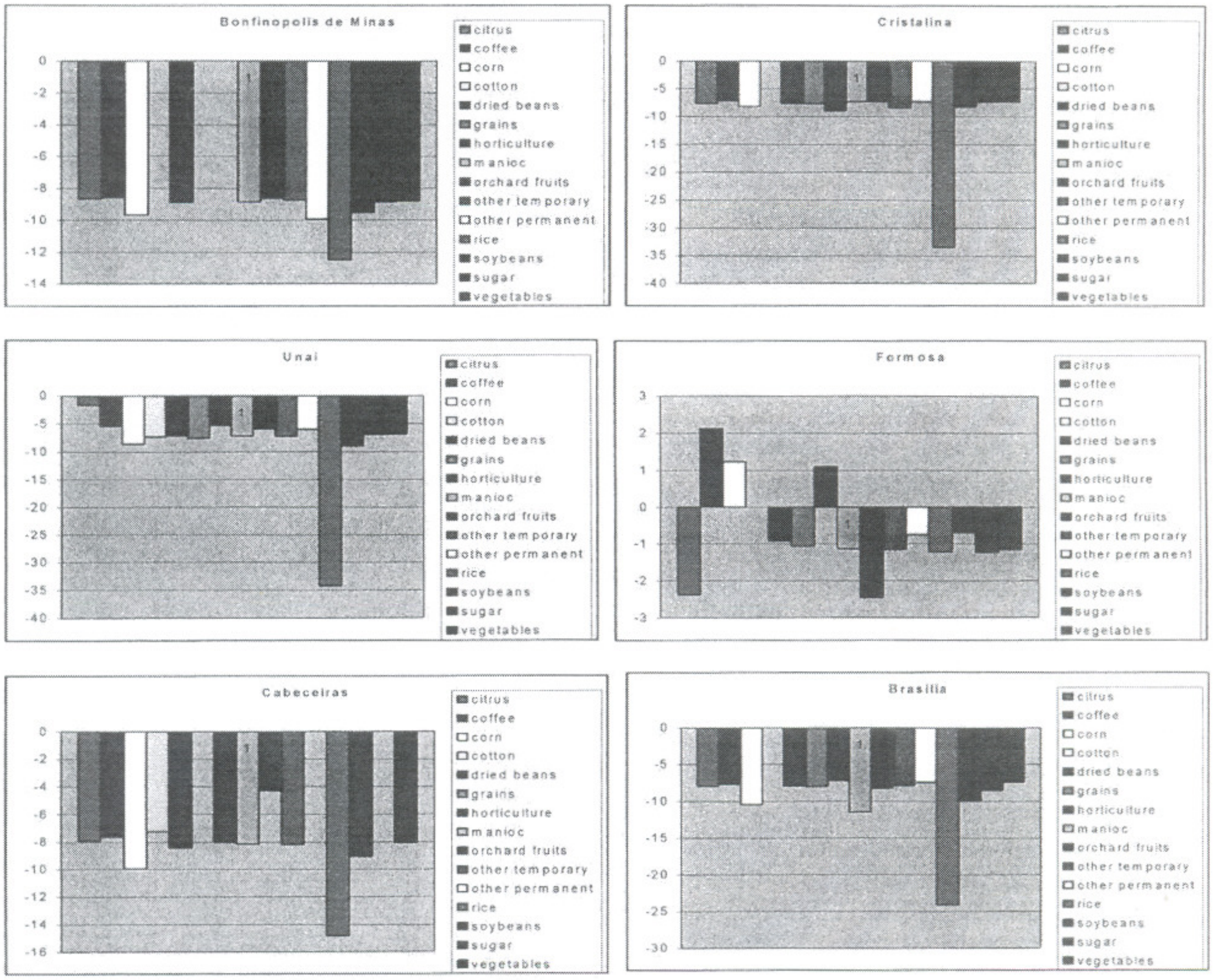


Figure 9. Percent change in applied water associated with a 10% reduction in water availability. Source: Authors' calculations.

6. Rural Poverty

The basin-wide hydrologic and economic models presented above can be used to examine the effects of weather and policy actions on agriculture and hence on rural poverty. We highlight several important examples here.

First, although the proportion of irrigated area is increasing throughout the SFRB, most agriculture in the SFRB is rainfed and hence remains exposed to drought risk, though this drought risk is not uniform across the basin. The stochastic version of the basin-wide hydrologic model can be used to identify high-risk areas as regards drought and the economic model can predict the final effects of droughts on agriculturalists, once their profit-maximizing adjustments have been taken into account. If the direct effects (via income declines) or the indirect effects (via employment declines) of droughts on rural poverty merit policy action, these models can suggest where interventions will be most needed and what types of interventions will be most effective.

Second, even in irrigated areas, inter-annual variations in rainfall can lead to unmet water demand, with implications for farm income and employment. Both models can be used to predict where such unmet water demand will occur and how frequently it is likely to occur and how large unmet demand will be. It can also suggest upstream and water storage management changes to reduce the likelihood or intensity of such shortfalls.

Third, while the economic model of agriculture demonstrates the ability of farmers to adjust to changes in water availability and to changes in water prices, not shown here. Field observations confirm the direction and extent of such adjustments, however, the adjustments are not costless and some may be beyond the reach of resource-poor farmers. To adjust optimally to changing water availability and other situations, farmers need:

- Reliable information (on weather, for example);
- Access to credit (to cover the costs of on-farm water conveyance and irrigation infrastructure, for example):
- Advice on how to grow, process, and transport the broader array of products that irrigation can make available; and
- Access to markets for these products.

The public sector has important roles to play in helping to provide each of these.

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