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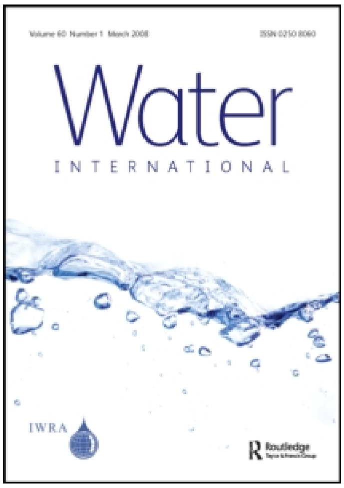

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Assessing agriculture–water links at the basin scale: hydrologic and economic models of the São Francisco River Basin, Brazil

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

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This article uses a basin-wide hydrologic model to assess the hydrologic and economic effects of expanding agriculture in the São Francisco River Basin, Brazil. It then uses a basin-wide economic model of agriculture to examine the effects of implementing water use regulations. Preliminary results suggest that substantially expanding agriculture would put pressure on some of the river's environmental flows. Agricultural output and rural employment would increase, though not in spatially uniform ways. The economic model demonstrates how cropping area, crop mix and production technology respond simultaneously to water shortages. While farmers can adjust, the costs of doing so may be beyond the reach of resource-poor farmers.

Keywords: hydrologic modelling; 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 São Francisco 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, whereas 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 over 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, Law 9433 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

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policy instruments, some of which remain to be developed. Although significant progress has been made in the planning process (e.g., Braga and Lotufo 2008), formidable challenges confront implementation. Two of the challenges this research seeks to address in the context of the São Francisco River Basin (SFRB) are as follows:

- 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.
- 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 enhance livelihoods and the environment.

For addressing these issues a basin-wide hydrologic model (ideally one capable of dealing with stochastic weather events) and an economic model of agriculture (ideally capable of capturing farmer adjustments to weather and other shocks) at the same spatial scale are required; to date, neither of these exist for the SFRB (World Bank 2004, Braga and Lotufo 2008). This article 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. The next sections demonstrate the usefulness of the hydrologic model for examining the hydrologic consequences of expansions of the agricultural frontier in the SFRB and then use the basin-wide hydrologic model to assess some of the economic and environmental consequences of such an expansion. We then describe the economic model of agriculture and demonstrate its usefulness for predicting the effects of water use regulation on agricultural activities for a subset of municípios (Brazilian equivalent of US counties) in the SFRB. Section 6 summarizes the article and concludes with some observations related to rural poverty.

The basic hydrologic model

MIKE Basin is a 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 run-off 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 (Madsen 2000).

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

For the purposes of this project, the SFRB is divided into several areas in order to calculate water budgets 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 allow for the calculation of water budgets in the reservoirs, which mainly supply water for agricultural, industrial and urban sectors; also, due to the strategic importance of reservoirs, discharge records of high quality, reliability and temporal

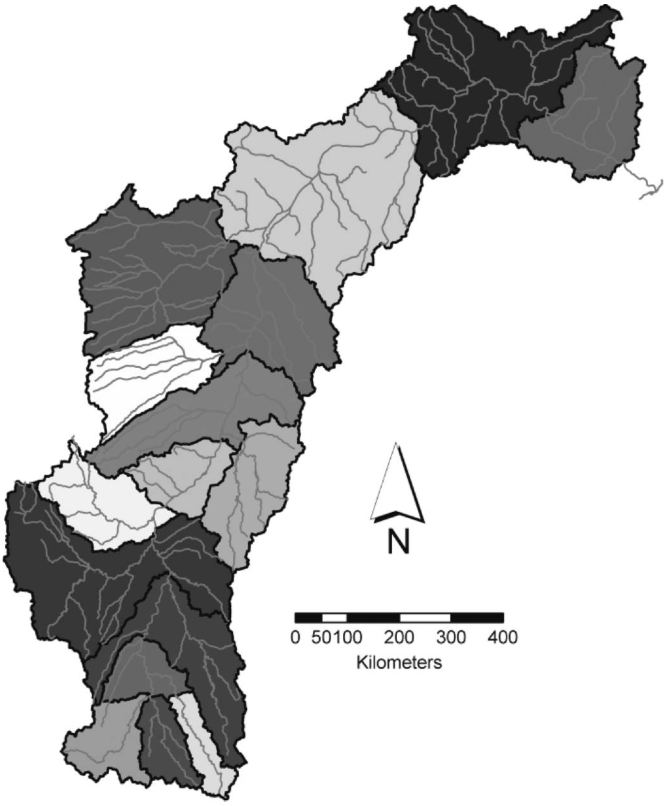

Figure 1. The São Francisco River Basin (SFRB) watershed configuration used in MIKE Basin.
Source: Authors' calculations.

resolution exist at these points. The spatial configuration of the basin was determined by the discharge stations for which data were available. The entire SFRB was divided into 16 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 16 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 southern hemisphere winter. In general, the contrast between the wet and dry seasons is more dramatic in the wetter areas in the south and west. In the central north and northeast parts of the basin the precipitation is much lower, whereas the atmospheric demand is high and constant throughout the year. This produces a climate with strong semi-arid characteristics. Near the mouth of the São Francisco River, the climate has strong oceanic influences and the rainfall pattern reverses, that is, the southern winter months tend to be the wettest.

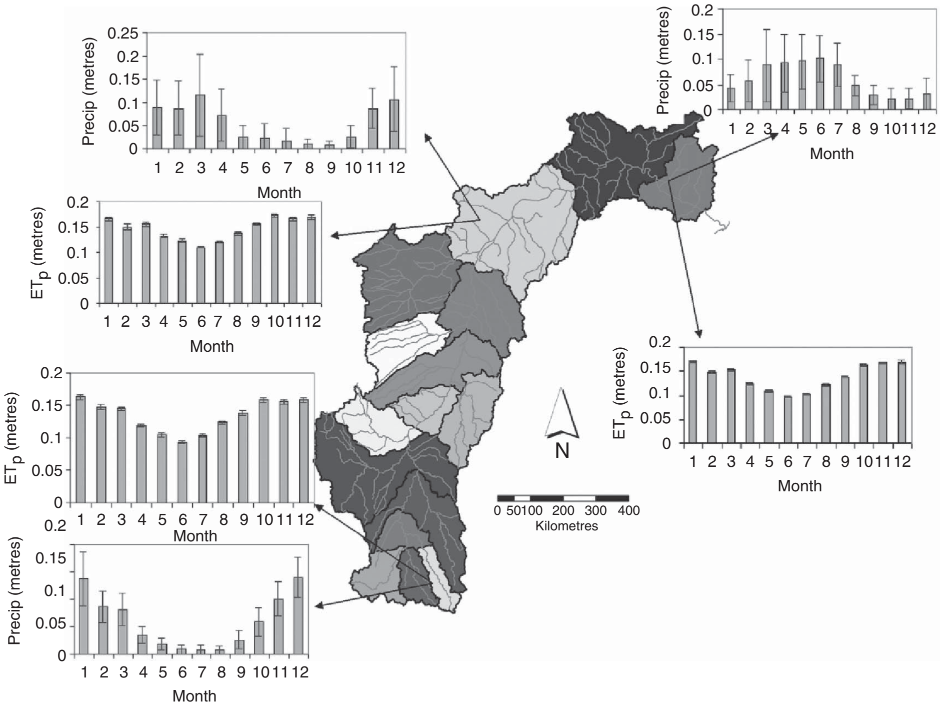

Figure 2. Mean monthly precipitation and potential evapotranspiration and their standard deviations for the São Francisco River Basin (SFRB). Bars represent mean monthly averages for precipitation (precip) and potential evapotranspiration (ET_p). Whiskers represent standard deviations of precipitation or ET_p for the month. January is month number 1.

Source: Authors' calculations.

Although the precipitation regime shows large differences for different parts of the basin, the evapotranspiration pattern is stable for the entire basin, with evapotranspiration being high for all months, but slightly lower during the cooler winter months, especially in the south of the basin.

The most unpredictable month in terms of precipitation is March. In general, the expected monthly variability in rainfall is proportional to the monthly average, so that months with a large mean amount of 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 semi-arid and oceanic climates than for those in the southern or western parts of the basin. Conversely, the dry months are the most "reliable". During these months, there is very little precipitation and there is rarely a year during which the precipitation is much higher than the monthly mean. Evapotranspiration is high and relatively constant.

Discharge is one of the basin responses to precipitation and therefore reflects patterns similar to those for precipitation (Figure 3). January through April is the period with the highest 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 rivers and their tributaries have the lowest discharge. In general, the monthly pattern shows the integrated effects of the climates of the basin (plus the regulating effect of the

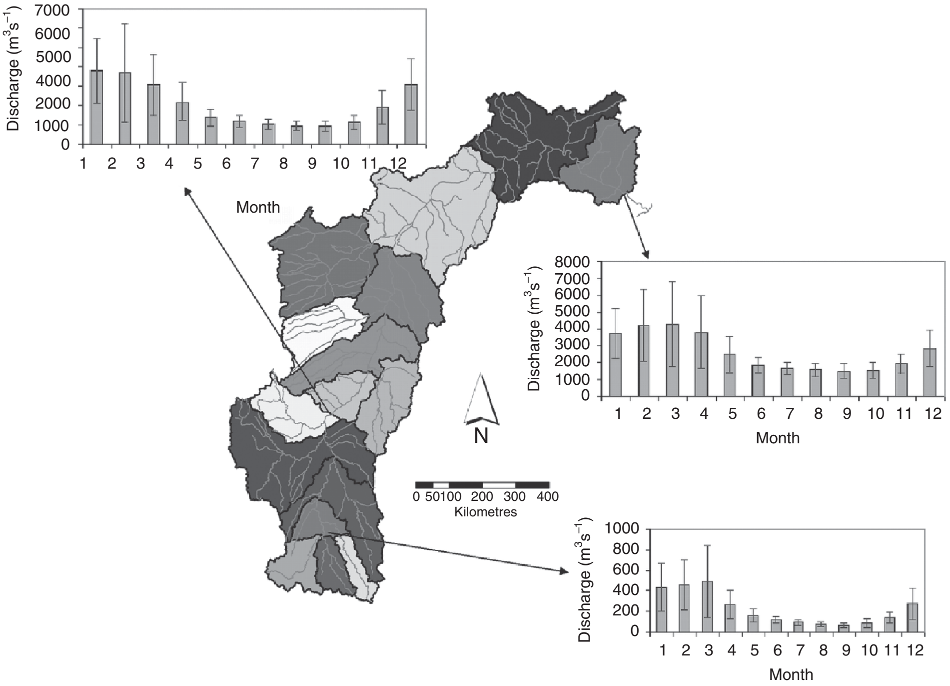

Figure 3. Monthly river discharge and standard deviations in the São Francisco River Basin (SFRB). Bars represent mean monthly averages for discharge. Whiskers represent standard deviation of discharge for the month. January is month number 1.

Source: Authors' calculations.

multiple reservoirs); for example, at the mouth of the São Francisco River the highest precipitation occurs during the winter months, but the highest discharge occurs during the summer months.

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. By calculating the covariance structure of these three variables, assuming they follow a multi-normal distribution, the probability density function, which contains information about the likelihood of different rainfall run-off scenarios, can be obtained. Monthly precipitation, potential evapotranspiration and discharge can be calculated by using this joint probability function.

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

If 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 are known, we can estimate irrigation water demand as follows:

$$\text{Water demand}\,[L^3T^{-1}] = \frac{\text{ET}_\text{p}[L^3T^{-1}] * K_\text{c} - P[L^3T^{-1}]}{I_\text{eff}} \qquad (1)$$

where ET_p is potential evapotranspiration, K_c is an effective crop coefficient for a given crop mix, P is precipitation and I_{eff} is a dimensionless irrigation efficiency factor ($0 > I_{eff} \geq 1$) that represents the irrigation technology used.

For the model simulations reported below, we used $K_c = 1$ and $I_{eff} = 0.8$ as representing average values for the crop coefficient and the irrigation efficiency throughout the SFRB. In this study we assume that farmers make one-time decisions on the irrigation technology investments, which are reflected in the irrigation efficiency coefficients and therefore remain constant throughout the simulation (see the economic model of agriculture below). We further assume that soil moisture remains constant (via applied water) and that at the end of the year soils are left with the same amount of water they began with. Precipitation in excess of the evapotranspiration demand is assumed to be lost either to deep percolation or to run-off.

Because we statistically characterized the hydrologic inputs and responses of the system and agricultural water demand, we can statistically evaluate the probability that a given amount of water will be required by using Equation (1). To do so we use the Monte Carlo method in which the model is run multiple times and a joint probability distribution of precipitation, evapotranspiration and discharge is obtained. In doing so, we obtain a set of possible outcomes regarding surface water stocks, including the minimum and maximum levels expected given the worst and best climatic conditions. We also obtain the set of possible water demands for each of the 16 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 area under irrigation has been increased by 22,000 ha (holding constant the area-specific crop mix) in 15 of the catchment areas identified in the current configuration of MIKE Basin and by 2000 ha in one small município in the southern SFRB (an additional 332,000 ha under irrigation in the entire basin). Assuming that irrigation efficiency is 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 precipitation is high, the average increase in water demand is low. There are important increases in water demand by water users further north in the semi-arid region of the basin.

For most users, especially those in the semi-arid areas of the basin, winter (dry season) is the season 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 in identifying areas of drought risk and in measuring the extent of risk for rainfed agriculturalists, as well as in measuring 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 20 $m^3 s^{-1}$ 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 capable of supplying 5 $m^3 s^{-1}$ during the wet season may be problematic because in 20% of the years (20% of the cases lie above the 0.8 percentile line) water demand would be higher than the amount of water available, in some cases by up to two or three times. This characterization can be used to produce a map for assessment of risk analysis.

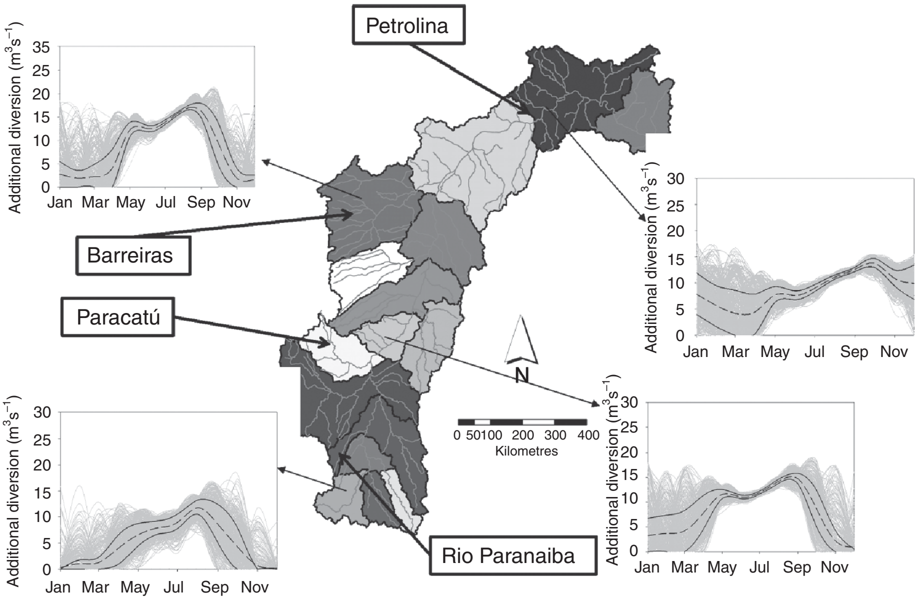

Figure 4. The effects of expanding agriculture on water demand in the São Francisco River Basin (SFRB). Side figures contain calculated additional water diversions from the river necessary to meet the simulated irrigation expansion in some areas in the SFRB. The dashed line indicates average water demand and solid black lines depict the 0.2 and 0.8 percentiles of the calculated discharge distribution; grey lines are the results of specific Monte Carlo experiments.

Source: Authors' calculations.

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 (World Bank 2004). One easy way to predict these marginal benefits is to assume that as the 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 and so on are chiefly responsible for observed land use patterns, so, for small changes in cultivated land, using existing patterns as a guide seems reasonable.

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 chiefly due to the differences in product mix, though area expansion in the Rio Paranaiba município was smaller than in the other municípios due to agroecological constraints. In the case of Petrolina, in particular, area expansion occurred primarily in irrigated, high-value, high-employment fruit/vegetable production, which make intensive use of hired labour.

Once water demand associated with simulated agricultural expansion has been characterized, the impact on the river system (river discharge and the dynamics of above-ground water stocks) can also be evaluated. Figure 5 provides estimates of river discharge for

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/year)
Barreiras	36,524	2,350
Petrolina	192,854	14,300
Paracatú	41,989	7,400
Rio Paranaiba	3,676	190

Note: R$ = Brazilian reais.

Source: Authors' calculations based on IBGE data. Estimates are based on a roughly 22,000-ha increase in cultivated area in Barreiras, Petrolina and Paracatú (but much less in the land-constrained Rio Paranaiba município), taking the production mix and production technology existing in the base year (2006) as a point of departure, and valuing additional output at 2006 prices. Labour use data used to generate employment estimates are derived from the most recent Brazilian agricultural census (1995/1996).

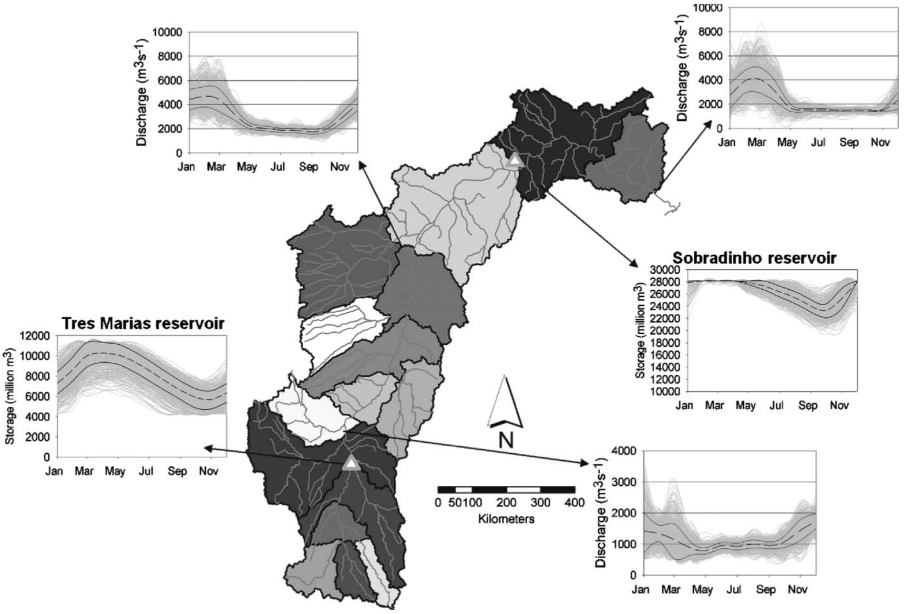

Figure 5. The effects of expanding agriculture on above-ground water storage in the São Francisco River Basin (SFRB). Side figures contain calculated discharge and reservoir storage for some locations in the SFRB. The dashed line indicates average water demand and solid black lines depict the 0.2 and 0.8 percentiles of the calculated discharge distribution; grey lines are the results of specific Monte Carlo experiments.

Source: Authors' calculations.

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 the water stocks in either dam be expected to fall below the levels required to maintain (assumed) environmental flows. However, the effects of the simulated agricultural expansion on flows could be quite substantial. For instance, average flows upstream of the Sobradinho dam decrease more than 116 $m^3 s^{-1}$ during September and October and decrease more than 66 $m^3 s^{-1}$ in January. Downstream of the Sobradinho dam the impact during the dry months is less evident due to the regulatory effects of the dam, but during the wet season (December and January) releases are on average between 300 and 450 $m^3 s^{-1}$ smaller than before the agricultural expansion.

Although the large capacity of the reservoirs reduces the impact of climatic conditions and the expansion of cultivated area on water storage, the discharge in rivers is more variable; hence farmers and others depending on these discharges are more vulnerable. The rivers in the northern part of the basin have a distinct 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 (see graph in upper-left 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 climatic variability. Although rivers in the semi-arid regions are highly variable with respect to discharge rates during the high-flow months, in the wetter parts of the basin discharge rates vary less throughout the year.

Perhaps most important, the simulated expansion of the agricultural frontier throughout the SFRB brought about important reductions in average seasonal flows as discussed above, especially during the dry season in areas away from the regulatory effect of large reservoirs. This may have negative implications for ecosystem services to which these flows may contribute (e.g., aquatic life, waste removal).

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 and so on (Braga and Lotufo 2008). 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 the 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 on 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 the availability of surface water for irrigation. The model also considers how policies might independently and jointly affect cropping patterns, agricultural productivity and profitability, employment, 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 greater detail in Howitt (1995, 2005) and widely used in applied research and policy analysis by Howitt and Gardner (1986), House (1987), Kasnakoglu and Bauer (1988), Lence and Miller (1988), Arfini and Paris (1995), Chatterjee *et al.* 1998, Heckelei and Britz (2000) and Helming *et al.* (2000). Other modelling approaches addressing similar sets of issues include Prechel *et al.* (2002), Röhm and Dabbert (2003), Cai *et al.* (2006) and Medellín-Azuara *et al.* (2008).

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. In this study, we introduce resource constraints on the availability of land, water for irrigation and family labour. The net income from agricultural activities (NI) is divided into two parts: (1) revenue, defined as the price of crops, *p*, multiplied by the quantity of crops produced *q*, which is assumed to be a function of the quantities of inputs used, *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 follows:

$$\mathrm{NI}_s = \sum_i \left[p_i q_i(x_{ij}) - c_i(x_{ij}, w_{ij}) \right], \quad \text{for } s = 1,\ldots,S \text{ municípios,} \tag{2}$$

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 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. We also assume that the production process is represented by a constant elasticity of substitution (CES) technology. Under these assumptions, the production function for the model is represented by the following equation:

$$q_i = A_i \left(\sum_j \beta_{ij} x_{ij}^{\gamma} \right)^{\frac{1}{\gamma}}, \tag{3}$$

where q_i is the quantity of output for crop *i*, x_{ij} is the quantity of input *j* used in the production of crop *i*; A_i and β_{ij} are parameters to be estimated, and $\gamma = \frac{\sigma - 1}{\sigma}$, where σ represents the elasticity of substitution among inputs in the production process.

For the cost function we assume the following specification:

$$c_i = \sum_j w_j x_{ij} + \alpha_i x_{il} + \psi_i x_{il}^2 \tag{4}$$

where w_j is the market price associated with input *j* used in crop *i*, x_{ij} is 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 remaining two terms form the implicit cost associated with land allocation. It has a quadratic form with parameters α_i and ψ_i and incorporates the increasing marginal costs associated with allocating more land to a particular crop. This quadratic form may be interpreted as the result of a farmer's land allocation process, which is not directly observed by the researcher, that associates rapidly increasing costs with extending acreage for given crops. Such non-linearity in costs may arise, for example, from heterogeneity in land quality, spatially non-uniform access to water on farms and so on.

For this exercise, we use data from the most recent Brazilian Agricultural Census (1995/1996) to estimate the model (Paris and Howitt 1998, Torres *et al.* 2006). We assume a value of 0.4 for σ. The parameters A_i and β_{ij} in Equation (3) are calculated analytically using the first-order optimality conditions for the maximization of Equation (2): value of marginal product associated with each input is set to be equal to its market price (if existent) plus its shadow value in the case of restricted supply inputs. These shadow values were calculated using a linear programming net revenue model of land allocation subject to water, land and family labour availability constraints. For the estimation of the parameters α_i and ψ_i in Equation (4), additional prior information on the elasticity of output supply is required. For this exercise we used a value of 2.5 for this elasticity.

A common level of geopolitical aggregation in Brazil is the município; this is the spatial unit of observation used in this exercise. For the demonstration version of this model we have chosen the six municípios that comprise the Rio Preto River Basin, a sub-watershed of the SFRB (Figure 6).

We now use the model sketched out above to examine the effects of mandated reductions in water use in agriculture (e.g.) 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.

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

By incorporating the calculated parameters A_i, β_{ij}, α_i and ψ_i in Equation (2), we are able to set up a non-linear maximization problem of net income subject to availability constraints on land, water and family labour. This non-linear model is then used for simulations based on variations in water supplied 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. 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 three municípios even with a 10% reduction. However, as water becomes scarcer (i.e., as availability is reduced by 20, 30 and 40%), there are 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, respectively, show the changes in crop mix and water use per crop associated with a 10% reduction in water availability. Note, once again, that the highly varied responses across municípios to a uniform increase in water scarcity; different soils, access to markets and so on can greatly influence the marginal contribution of applied water to overall profits and hence the incentives to alter agricultural activities in the face of increasing water scarcity. For example, in rice, which is among the most water-sensitive crops, there are reductions in area across all municípios, whereas the same is not true for (say) citrus. Perhaps most important, the model suggests that increased water scarcity induces a broad array of responses in terms of crop mix: area under some crops (e.g., orchard fruits) might expand, whereas the area dedicated to other crops such as rice and corn might decrease. 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 use in terms of profitability.

Figure 6. Municípios that make up the Rio Preto River Basin and their location in the São Francisco River Basin (SFRB).

Discussion and policy implications

This article described a basin-wide hydrologic model that was designed to calculate site-specific water budgets for surface water flows and storage within the SFRB, and to stochastically simulate the effects of weather on these key hydrologic variables. The results of this basin-wide hydrologic model alone could be important in identifying the types and characteristics of water conveyance and irrigation infrastructure; for example, knowing how frequently water delivery systems will fail to meet agricultural demand

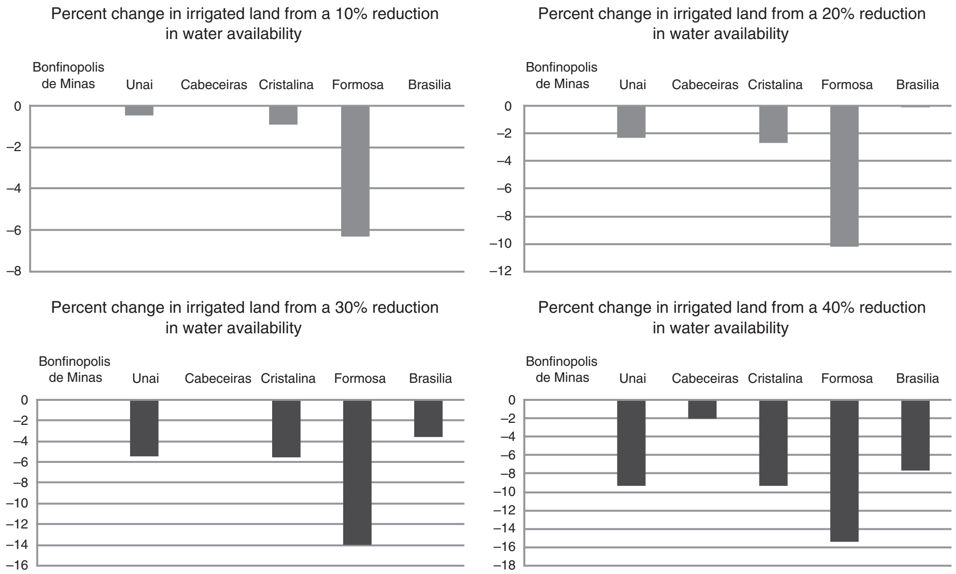

Figure 7. Effects of reduced water availability (10%, 20%, 30% and 40%) on irrigated area, percent change from baseline, by município.

Source: Authors' calculations.

could be important to farmers and to the policymakers who may need to intervene under such circumstances.

The basin-wide hydrologic model was then used to assess the effects of an expansion of the agricultural frontier in each of the 16 sub-catchment areas identified in the model. As one might expect, the hydrologic effects were very site-specific, for example, the high-rainfall areas in the southern SFRB reacted very differently than did the semi-arid northeast, and the several very large reservoirs along the river course acted as buffers to many of the effects of the simulated increases in cultivated area. But the hydrologic effects of the agricultural expansion were evident throughout the SFRB, especially during dry years.

A simple economic model of agriculture was used alongside the basin-wide hydrologic model to estimate the economic and employment effects of the agricultural expansion. These effects, too, were very site-specific and depended on the product mix and production technology in place prior to the expansion. In all areas agricultural gross domestic product (GDP) increased, and in some areas rural employment increased substantially. Hence, even in this simple model, policymakers can begin to explore the site-specific economic and employment effects of promoting agriculture, and the site-specific and downstream hydrologic consequences of doing so.

Next, a more complex economic model of agriculture was described and used in a subset of contiguous municípios in the central western part of the SFRB to assess the effects of (hypothetical) reductions in the availability of surface water for irrigation. The model demonstrated the very substantial adjustments in product mix, area under plough and irrigated area in response to water shortages; farmers' actions were driven by differences in the marginal productivity of water across products and buffered the negative effects on farm profits that reductions in available water can cause. Policymakers concerned with minimizing the effects of water use regulations on rural incomes will benefit from such knowledge.

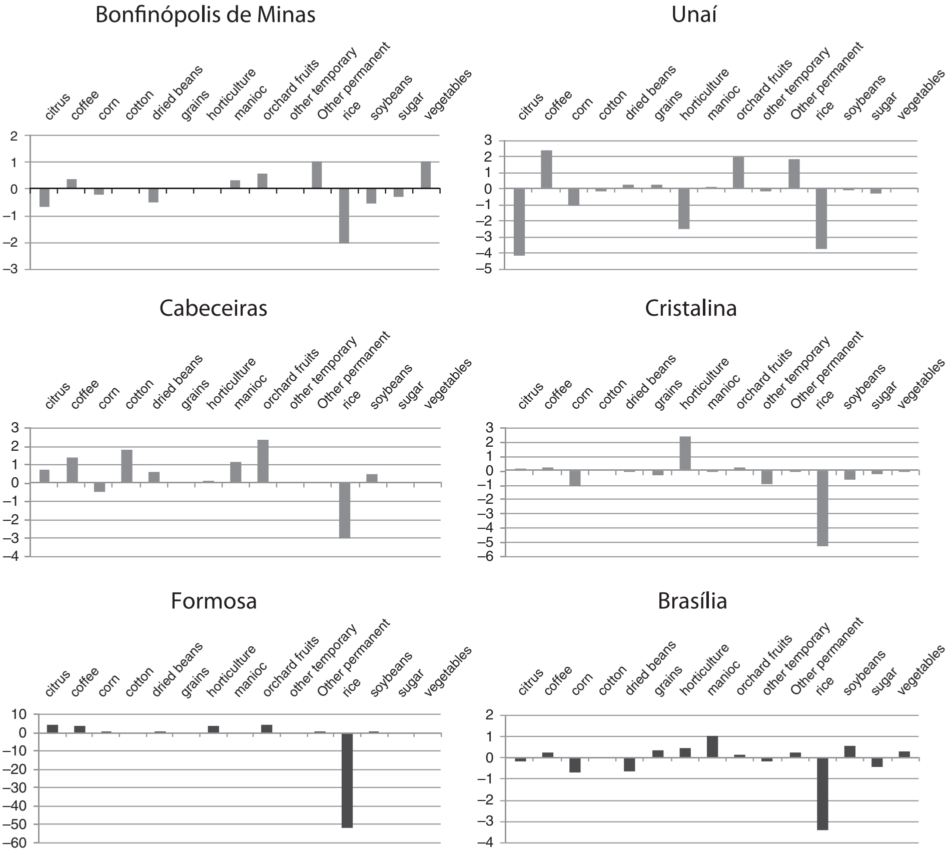

Figure 8. Effects on *crop allocation* associated with a 10% reduction in water availability, % change from baseline, by município.

Source: Authors' calculations.

Finally, protecting and enhancing the situations of the rural poor in the SFRB are fundamental concerns of this research; this article contains some insights that will be useful to policymakers in achieving these objectives. First, most small-scale farmers in the SFRB depend on rainfed agriculture for their food and their livelihoods and hence remain exposed to drought risk. The stochastic version of the basin-wide hydrologic model can be used to identify high-risk areas as regards the likelihood and severity of drought, and the economic model predicts its direct and indirect (via farm employment) economic consequences. This information can help policymakers prepare for and mitigate the economic effects of unavoidable weather shocks. 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 predict the location, frequency, intensity and duration of such unmet water demand. This information, too, is useful in planning irrigation schemes and in preparing for weather shocks. Third, although the economic model of agriculture demonstrates the ability of farmers to adjust to changes in water availability, these 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, small-scale farmers need: reliable information (e.g., on weather); access to credit (e.g., to cover the costs of on-farm

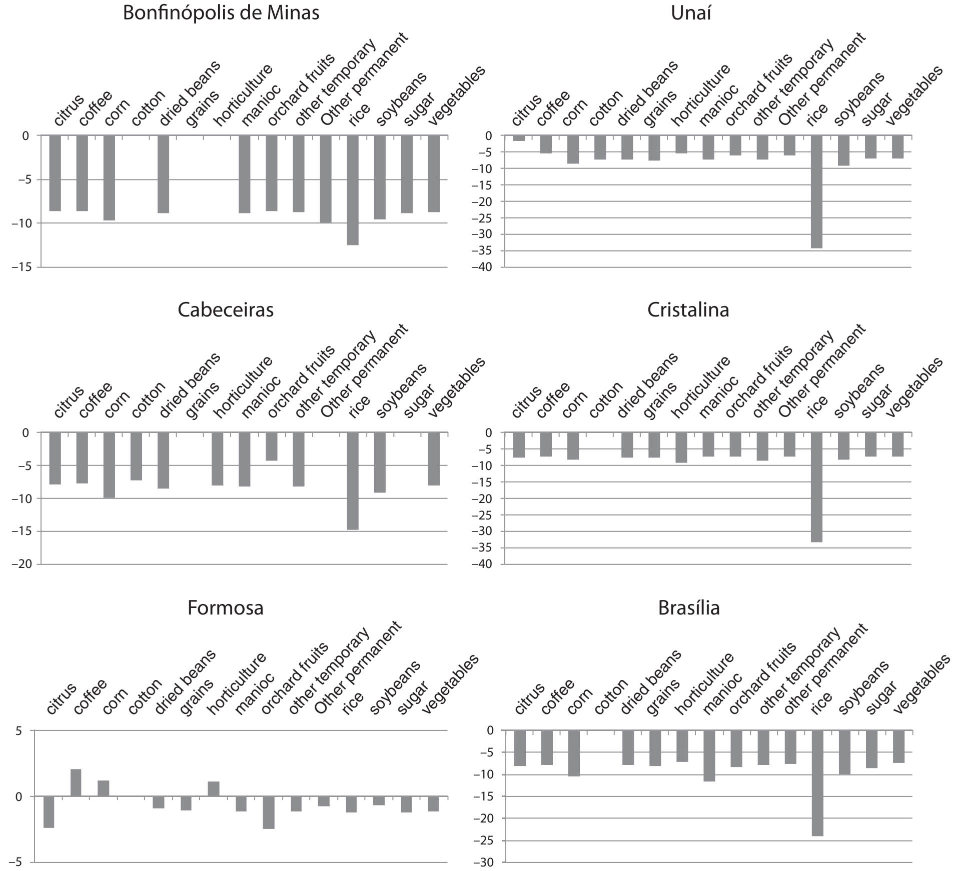

Figure 9. Effects on *applied water* associated with a 10% reduction in water availability, % change from baseline, by município.

Source: Authors' calculations.

water conveyance and irrigation infrastructure); 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 an important role to play in helping to provide each of these.

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References

Arfini, F. and Paris, Q., 1995. A positive mathematical programming model for regional analysis of agricultural policies. *In*: E. Sotte, ed. *The regional dimension in agricultural economics and policies. Proceedings of the 40th EAAE seminar, 26–28 June 1995* Ancona: University of Ancona, 17–35.

Agência Nacional de Águas (ANA), Global Environmental Facility, United Nations Environment Programme, and the Organization of American States, 2004. *Strategic action program for the integrated management of the São Francisco River Basin and its Coastal Zone: Final Report*. Brasília, Brazil: Agência Nacional de Águas.

Bodo, B.A., 2001. *Annotations for Monthly Discharge Data for World Rivers (Excluding Former Soviet Union)*. Available from: http://dss.ucar.edu/datasets/ds552.1 [Accessed June 2008].

Braga, B.P.F, and Lotufo, J.G., 2008. Integrated river basin plan in practice: the São Francisco River Basin. *Water Resources Development*, 24 (1), 37–60.

Cai, Ximing, C. Ringler, and M. W. Rosegrant, 2006. *Modeling water resources management at the basin level: methodology and application to the Maipo River Basin*. Washington, DC: International Food Policy Research Institute, Research Report 149.

Chambers, R.G. and Just, R.E., 1989. Estimating multioutput technologies. *American Journal of Agricultural Economics*, 71, 980–995.

Chatterjee, B., Howitt, R.E. and Sexton, R.J., 1998. The optimal joint provision of water for irrigation and hydropower. *Journal of Environmental Economics and Management*, 36 (3), 295–313.

Heckelei, T., and Britz, W., 2000. Positive mathematical programming with multiple data points: a cross-sectional estimation procedure. *Cahiers d'Economie et Sociologie Rurales*, 57, 28–50.

Helming, J.F.M., Peeters, L., and Veendendaal, P.J.J., 2000. Assessing the consequences of environmental policy scenarios in Flemish agriculture. *In*: T. Heckelei, H.P. Witzke, and W. Henrichsmeyer, eds. *Agricultural sector modeling and policy information systems. Proceedings of the 65th EAAE seminar, 29–31 March 2000*. Kiel: Wissenschaftsverlag Vauk, 237–245.

House, R.M., 1987. *USMP regional agricultural model*. National Economics Division Report, ERS 30. Washington, DC: USDA.

Howitt, R.E., 1995. A calibration method for agricultural economic production models. *Journal of Agricultural Economics*, 46, 147–159.

Howitt, R.E., 2005. *Agricultural and environmental policy models: calibration, estimation and optimization*. Unpublished.

Howitt, R.E. and Gardner, D.B., 1986. Cropping production and resource interrelationships among California crops in response to the 1985 Food Security Act. *In*: H.O. Carter, ed. *Impacts of farm policy and technical change on US and Californian agriculture, 1986*. Davis: University of California. 271–290.

Instituto Brasileiro de Geografía e Estatística (IBGE). *Censo Agropecuário 1995/1996*. Brasília, Brazil: IBEE.

Kasnakoglu, H. and Bauer, S., 1988. Concept and application of an agricultural sector model for policy analysis in Turkey. *In*: S. Bauer and W. Henrichsmeyer, eds. *Agricultural Sector Modelling*. Kiel: Wissenschaftsverlag Vauk.

Lence, H.L. and Miller, D., 1998. Estimation of multi-output production functions with incomplete data: a generalized maximum entropy approach. *European Review of Agricultural Economics*, 25, 188–209.

Madsen, H., 2000. Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. *Journal of Hydrology*, 235, 276–288.

Medellín-Azuara, J., *et al.*, 2008. Adaptability and adaptations of California's water supply system to dry climate warming. *Climate Change* 87 (Suppl. 1), S75–S90.

Mitchell, T.D. and Jones, P.D., 2005. An improved method for constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology*, 25, 693–712.

Paris, Q. and Howitt, R.E., 1998. An analysis of ill-posed production problems using maximum entropy. *American Journal of Agricultural Economics*, 80, 124–138.

Preckel, P.V., Harrington, D., and Durman, R., 2002. Primal/Dual positive math programming: illustrated through and evaluation of the impacts of market resistance to genetically modified grains. *American Journal of Agricultural Economics,* 84, 679–690.

Röhm, O. and Dabbert, S., 2003. Integrating agri-environmental programs into regional production models: an extension of positive mathematical programming. *American Journal of Agricultural Economics*, 85, 254–265.

Torres, M., *et al.*, 2006. *A demonstration economic model for the São Francisco River Basin: Specification, calibration, and preliminary simulations*. São Francisco River Basin Research Team Working Paper. Revised: September 30, 2006

World Bank, 2004. Brazil – irrigated agriculture in the Brazilian semi-arid region: social impacts and externalities. Main Report. Report No. 28785-BR. 26 April 2004.