Alternative Water-Policy Scenarios Using Integrated River-Basin Modeling: The Brantas River Basin, Indonesia

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Introduction

This paper describes the development of a water-resources optimization-simulation model of the Brantas basin in East Java, Indonesia. The Brantas basin is densely settled, and the water of the Brantas is used intensively for irrigation and, hydropower generation, and for municipal, industrial, domestic and other purposes. Water supply in the basin is now seasonally scarce in many years, and current and potential surface storage in the basin and groundwater are extremely limited. The Brantas is also home to a unique public corporation, Perum Jasa Tirta, which is a prototype River Basin Authority responsible for managing bulk water resources within the basin, maintaining and operating hydraulic infrastructure and helping manage riparian regions of the basin commons. These factors have identified the Brantas as an ideal laboratory in which to develop and test the integrated water-policy-simulation modeling approach we describe here. A map of the Brantas basin is attached as figure 1.

One of the challenges for water management, in the Brantas basin, as elsewhere in the water-scarce world, is to balance the claims of the community of existing water users against increasing new, and often competing, demands; and against the increasingly compelling requirements for water to serve environmental purposes. This model is intended as a tool to assist decision makers, including not only Perum Jasa Tirta but also national, provincial and basin water management councils, government agencies with water-management responsibilities, water users and other stakeholders, in performing this task efficiently and equitably. The goal of this modeling study, and the objective of policy simulation in general, is to provide decision makers with information, albeit "synthetic" information based on simulation models, that will allow them to anticipate the consequences of policies or actions (including the policy of "business as usual") before conducting these policy experiments within society at large, thereby maximizing the probability of successful implementation and minimizing the risk of unforeseen, possibly disastrous consequences.

The development of the integrated policy-simulation model is but one anticipated output of the project titled "Irrigation Investment, Fiscal Policy, and Water Resource Allocation in Indonesia and Vietnam," funded by the Asian Development Bank (ADB) and conducted by the International Food Policy Research Institute (IFPRI) and its Indonesian Directorate General

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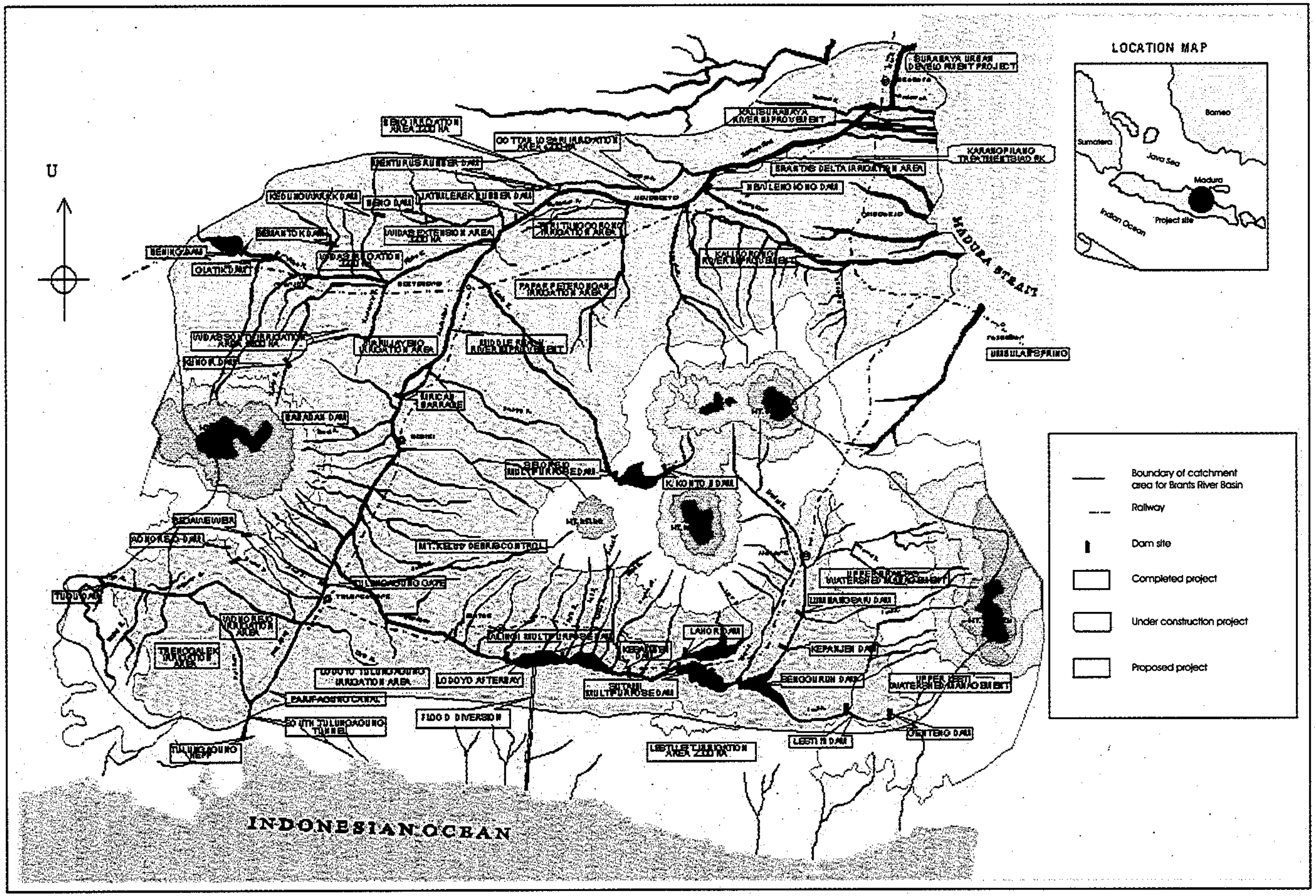
Figure 1. Map of the Brantas basin.



of Water Resources (DGWR). The project consists of three components: a) an assessment of water-allocation mechanisms and institutional structures for river-basin management and effects on irrigation management, b) an assessment of the effects of taxation, pricing policy, and irrigation investment on the incentives for irrigated farming, and c) the development and application of tools and integrated impact analysis to assess the effects of components a) and b). This paper will focus on the third component, although the relevance of policy-simulation output to the broader project goals should be obvious.

A river basin is an extraordinarily complicated system when viewed in purely physical terms; even more so when patterns of settlement, culture and economic activity are taken into consideration. Efforts to capture the richness and complexity of the physical-social-economic environment in model specification predictably encounter the limits posed by available data, and by computing power. A desirable model specification therefore embodies the principle of *Minimum Description Length* that asserts "the best model is the one that is smallest ... including the information to specify both the form of the model and the values of the parameters" (Gershenfeld 1999, 2). The "right" degree of complexity and physical realism is ultimately a subjective judgment, however, and the policy modeler must often strive for relevance at the expense of completeness. The modeler must determine if the marginal increase in the value of model output in policy analysis exceeds the marginal costs associated with increased model complexity, which include those associated with data collection, specification and execution time, and training, transfer and maintenance.

It is therefore reasonable to ask: What are the *essential* components of a useful policy simulation model of the Brantas, those objects or processes that *must* be explicit in the model to achieve relevance and credibility in policy analysis? Similarly, what features of the system can be safely ignored or excluded? A short list of defining attributes of the Brantas hydro-economic system includes the following:

Climatic seasonality. The Brantas experiences a climatic regime characterized by the annual progression of wet and dry seasons, and receives roughly 80 percent of its precipitation in the 5–6 months of the rainy season (December–May). The river discharge is similarly seasonal. As a consequence, the model must have a relatively high resolution in time, since the correspondence of supply to demand in time is a critical aspect of water management in the basin.

Limited storage. Current live reservoir storage in the Brantas is equivalent to around 3 percent of annual Brantas discharges only, suggesting that the potential to manage water crises through reservoir operating protocols alone is limited. However, the available storage is equivalent to 15 percent–20 percent of dry-season discharge, and water scarcity is a phenomenon of the dry season. The implication is that all storage must be represented accurately within the model, including the competing demands and constraints placed on multipurpose reservoirs.

Predominance of paddy cultivation. The agricultural economy of the basin is centered on the cultivation of paddy, nearly all of which is irrigated. Paddy cultivation differs substantially from the cultivation of alternative basin crops (maize, soybean, groundnut, sugarcane), principally in terms of water use. In addition to evapotranspirative demand, paddy requires substantial quantities of water for seedbed development, land preparation, weed suppression, temperature control and other uses. And, unlike many other irrigated crops, technological options for paddy irrigation are limited. Any useful model must be capable of simulating both the hydrology and agricultural economics of paddy cultivation with a fairly high accuracy.

Continuous cropping. A striking feature of irrigated agriculture in the Brantas, as throughout Java, is the continuous cropping calendar. Wet season (November–February) and first dry season (March–June) plantings are spread over 3–4 months each, for reasons relating to water management, labor availability and supply control among other factors. As a consequence, the model must include both crop choice and planting date as decision variables.

Other considerations apply to the model code itself, if it is to prove useful beyond the project time horizon. The code should be transparent: the model structure and parameters should be accessible both to the software engineers who must maintain and modify the model, and to policymakers and managers who require an understanding of the structure of, and assumptions underlying, the model if they are to use it effectively. The code should be flexible and modifiable: it should be possible to update the model in response to changing parameter values (prices, boundary conditions...) and in response to changes in the infrastructure of the hydrosystem itself. These and related factors have guided the development of the Brantas integrated model.

This paper is organized as follows. Section II contains an overview of the model conceptual structure, and of key specification issues related to model functional forms. Section III contains a description of key model components and equations. Section IV describes four model scenarios: baseline, 2020, dry year and increasing water charges to irrigated agriculture. The final section (V) describes some priority policy scenarios.

Some General Considerations Regarding Model Development and Application

Supply Augmentation versus Demand Management, and Distributional Efficiency

Efforts to address the problems of water scarcity or shortage are often conceptualized as falling within one of two broad approaches: supply augmentation and demand management. Supply augmentation includes the construction of reservoirs, tanks, and other regulated surface storage, development of groundwater resources, rainwater harvesting and related activities typically associated with water-resources engineering. Demand management, in contrast, emphasizes changes or modifications in people's behavior with respect to water, typically through the use of incentives and/or penalties. A suitably designed and implemented reward (penalty) structure can encourage efficiency in water use, thereby increasing the *effective* supply, that is, supply relative to demand, via reduction in the demand component. Demand management strategies serve to induce improvements in technical efficiency, including the development of new technologies and processes that require less water to achieve a given level of productivity; reduction of system leakages, and the development of improved water allocation rules, strategies and institutions, such as water markets and water banking.

This description of the integrated modeling approach will focus on demand management, specifically the use of economic instruments as policy tools. It must be emphasized, however, that this modeling approach is also potentially useful in simulating supply-augmentation strategies as well. The model language and structure easily accommodate additions and/or modifications to water-resources infrastructure, and thus the model can be useful in evaluating, for example, the relative effectiveness, in both physical and economic terms, of proposed investments in supply-augmentation infrastructure. The emphasis in policy simulation, however, is on demand-management strategies, and the discussion that follows will focus on the use of economic instruments. It will also focus on irrigated agriculture, but the arguments will be seen to apply to other categories of water demand with little or no loss of generality.

Embedded in the model specification are concepts of efficiency, both physical and economic. The two are closely related—technical efficiency refers to the physical quantity of output obtained per unit of physical input, while economic efficiency refers to the value of output obtained per unit value (or cost) of input. It is clear that the two are not identical, however, since there may be a wide range of physical input combinations that can be used to produce a unit of output in a technically efficient manner, but given differences in input and output costs, only one combination may be the most economically efficient, given market conditions.

There is a more specific definition of economic efficiency, one that is critical to water resources allocation decision making, called *distributional efficiency* or *Pareto efficiency*. Distributional efficiency is based on the fact that a particular resource (such as water) has both an average value and a marginal value in its various uses. The average value is the productive value averaged over the entire range of resource consumed. The marginal value is the productive value of the last (or the next) unit of the resource, evaluated at the current level of use. It is equivalent to the shadow price of the resource in a mathematical programming problem—the change in the objective function resulting from a one-unit change in the binding constraint. Average and marginal values typically differ because each additional or incremental unit of water used is not equally valuable to the firm or consumer—most production (consumption) relationships are characterized by declining marginal productivity (utility). For example, if an irrigated crop is at or near full water supply, any additional water application may have little or no impact on productivity and, hence, on farm income, so that the farmer would only be willing to pay very little for additional water at this point. Or, a household with restricted access to drinking water will be willing to pay considerably more per liter for additional water than a household already enjoying a high level of access and consumption. Differences in the marginal value of water between categories of use and across demand sites within the basin define the opportunities for the improvement of distributional efficiency, and it is fair to describe this integrated policy simulation model as marginal-value-driven, subject, of course, to a wide range of constraints, both physical and institutional.

Responses to Changes in Water Price (Quantity)—The Importance of Functional Form

Faced with an increase in the supply price of water, or an absolute change in the quantity of water available (as in a drought year), farmers have five basic strategies available for adapting to changing circumstances:

1. *They can use less water.* If water prices increase, farmers may choose to apply less than the full crop-water demand. This will result in a reduction of yield, but the farmer may be operating in a range of yields within which this yield reduction is proportionally less than the decrease in water use.
2. *They can switch to less-water-consumptive crops.* In the Brantas, for example, maize and paddy are roughly equally profitable at current input and output prices, but maize requires far less water per kilogram of yield. The price (or availability) of water may be the deciding factor.
3. *They can alter the time of planting* in an attempt to reduce irrigation demand, by exploiting seasonal variation in effective precipitation, evapotranspiration and possibly in the cyclic demand of competing water-using industries (e.g., sugar processing).
4. *They can substitute other inputs for water.* Increases in complementary inputs, including labor and fertilizer, can partially offset yield loss due to water reduction, although the range of substitution may be limited, particularly for crops such as paddy.
5. *They can increase the efficiency by which they use water.* This can include improved management, or investment in alternative, water-saving irrigation technologies.

Note that the first four adaptations can be implemented in the short run, in response to either unexpected or transient circumstances, while the fifth embodies adaptations that may occur in the short run (management) or the long run (investment).

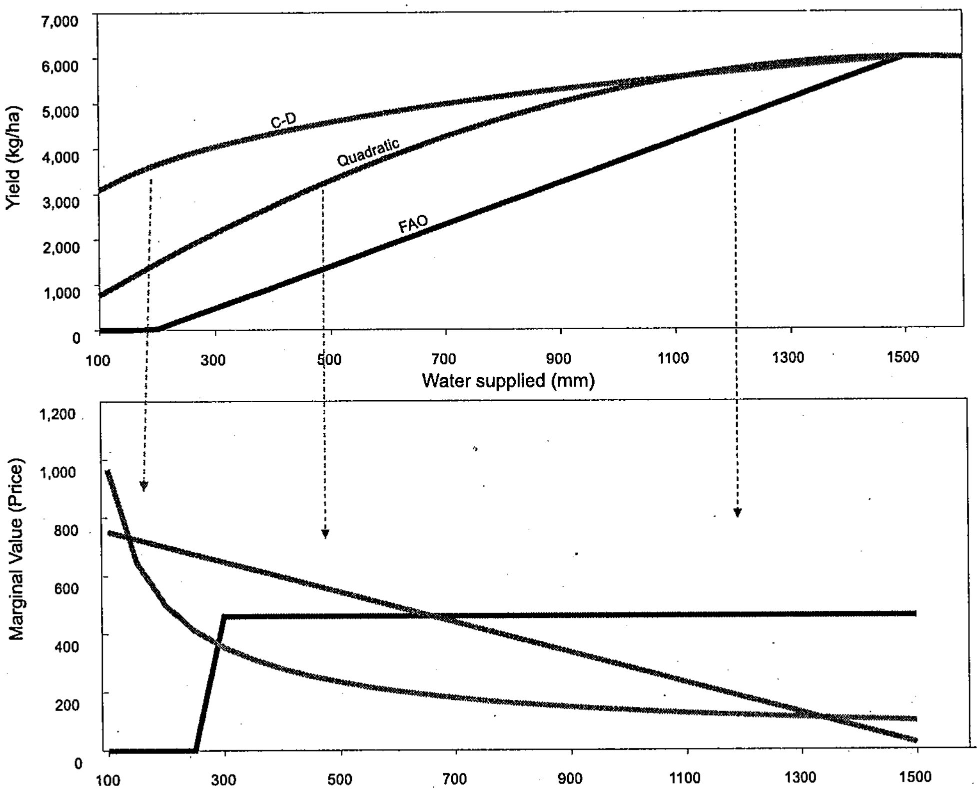
We would like to be able to simulate each of these types of responses within the model, to obtain maximum sensitivity both to economic policy instruments and to changes in environmental circumstances. This forces us to give careful consideration to the functional forms by which we represent water-production and consumption processes. When water is used as an intermediate input to a final output, as in agriculture and many industries, we employ a technical production function—a mathematical specification of the relationship between input and output quantities. When water is itself the final (consumed) product, as in domestic uses, we use an alternative approach based on willingness-to-pay functions and consumer surplus.

A variety of functional forms have been proposed to quantify the relationship between water as a quantitative input and resulting crop yield. Single-input (water)–single-output models include the FAO yield response coefficient method (Doorenbos and Kassam 1986), which specifies a linear relationship; and exponential models such as Bouman and Tuong (2001). Multi-input–single-output models include Cobb-Douglas and quadratic functions (Moore et al. 1993). In these and related models, water is one of multiple inputs, which can include land, labor, fertilizer and technology. Cobb-Douglas and quadratic forms are nonlinear. Other multi-input functions, such as Dinar-Lehey allow the simulation of the impacts of input water quality as well.

In evaluating the suitability of each functional form for simulating the (above) five responses, we offer the following observations. In regard to the substitution of other inputs for water (point 4), multi-input models are clearly superior, since rates of technical substitution are explicit and these relationships are estimated directly from observed data. It is possible to model substitution using single-input approaches, provided the "target" or maximum yield (corresponding to full water supply) is itself specified as a function of the other inputs, but in this case the rates of substitution have not been estimated directly. In regard to cultivation timing strategies (point 3), any of the approaches described above would appear suitable, since choice of planting time affects the water-demand level rather than output.

However, the evaluation of strategies 1 and 2 (reducing water supply, switching to alternative crops) requires particular care. All of the functional forms described will permit this kind of simulation, but the sensitivity with which they do so varies widely. To illustrate this point, consider figure 2, which depicts both output response to water application (upper) and corresponding marginal value of water (lower). Coefficients have been constructed such that a given quantum of water (1,500 mm) results in roughly the same maximum yield (6,000 kg/ha) in each production function for this hypothetical paddy crop.[4]

Figure 2. Output response to water application (upper) and corresponding marginal value of water (lower).



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[4] Other factors of production, such as labor, fertilizer and mechanical power are assumed implicit in these water-production relationships.

The lower portion of the graph depicts the marginal value of water in irrigated rice production, obtained by multiplying the derivatives of the production functions (upper graph) by the crop output price, which in this illustration has arbitrary units. We note that the FAO (linear) function has a constant derivative, the quadratic function a linear derivative and the Cobb-Douglas a convex derivative. Now, assume that a volumetric water charge is enforced, and consider an increase in this price (lower graph). Since an economically rational farmer will not purchase water past the point where the marginal value of the water equals its price, farmers facing both quadratic and Cobb-Douglas production relationships will reduce the amount of water purchased until the marginal value is again equal to the new (higher) price. The degree to which water use will be decreased is seen to depend on both the level and the shape of the marginal-value curve within the region determined by the price change. In this case, the price increase induced a larger response on the Cobb-Douglas, indicating that, in terms of this functional relationship, yield was originally in a region relatively insensitive to (small) changes in water supply.

For the quadratic, the quantity response to a price change of a given magnitude is invariant to location, since the derivative is linear. But, for the linear FAO-type function, the marginal value is a constant, and a farmer operating on a linear-production relationship has no incentive to reduce water use in response to a price increase, that is, until the price rises above his average value of water, at which point his response will be to switch to another crop rather than lose money. The full range of responses available under nonlinear production relationships is not available to him, at least within the context of this formal analysis.

This is not to argue that the water-production functional form should be determined on the basis of desired model behavior—functions are selected because they fit the data. However, experience has shown that, given the "signal-to-noise ratio" inherent in most production data sets, various alternative functional forms may fit the data equally well within the range of interests. We argue that, given a choice, a functional form that captures the declining marginal productivity of water should be used, since it is best suited to price-driven policy simulation.

Model Structure and Basic Equations

General Description of the Model

The policy-simulation model developed for the Brantas is the integration of a network-flow hydrologic model with physical-process simulation models of irrigated-agricultural production, hydropower generation, municipal (domestic) and industrial demand, and with economic relationships driven primarily by the relative prices and values of water in its respective uses. The resulting system of equations is linked to large-scale nonlinear optimization algorithms, which locate combinations of the decision variables that are mathematically optimal according to the structure of the objective function, the form of which is determined by the specific objectives of policy simulation. It is therefore described as a *river basin simulation-optimization model*. The integrated model differs from a conventional network-flow model in many key respects. Demand for water by sector and by location are endogenous to the model and represent the interaction of technical/economic water production or utility relationships in agriculture, industry and households with assumptions concerning the structure of water pricing, entitlements, public institutions, social custom and law.

The Brantas basin model has evolved from the prototype simulation-optimization model of the Maipo basin, Chile, described elsewhere. The conceptual and technical basis for integrated basin-scale modeling is described in the state-of-the-art review by McKinney et al. (1999). Additional background information on the Brantas basin physical setting and model development is found in Rodgers et al. 2001.

The model is coded in the high-level programming language GAMS (General Algebraic Modeling System), which was developed to provide an open, flexible architecture for mathematical-programming problems (Brooke et al. 1998). GAMS code is portable, self-documenting and readily modified. One can, for example, easily add a new irrigation system, reservoir, or hydropower plant to an existing model, or change the properties of such a model element, since the code is visible and accessible, and the structure of equations is independent of the number of set members, or where they spatially occur within the basin system. GAMS, in turn, is linked to one of two large-scale nonlinear optimization solvers, CONOPT2 or MINOS5. CONOPT2 is currently our solver of choice.

The model is organized around the water (or crop) year, beginning in October and ending in September. Model timesteps are 10-day periods, approximately: for each month, period 1 = 1:10 days, period 2 = 11:20 days and period 3 = 21: end of month (EOM). The model is "circular" in the sense that crops planted near or at the end of the crop year (period 36) are "wrapped around" to the beginning in a seamless cycle. In the following sections, individual model components are described in greater detail.

Network-Flow Model Structure and Inputs

The structure of the Brantas network-flow hydrologic model is based on the configurations of two reservoir operations models, WRMM and RBAM (Optimal Solutions Ltd. 2000), which are currently maintained at Perum Jasa Tirta. The network-flow model consists of reaches, which represent points of inflow to the system (reservoirs, river reaches, etc.), points of water storage, control, diversion and abstraction (dams, reservoirs, barrages, weirs, etc.), and demand sites (irrigation, municipal, industrial, hydropower, etc.). Each of these elements is linked via spatially permissible flow paths, which can represent natural or artificial channels. Inflows to the system, including precipitation, are model boundary conditions; and storage, channel and spillway capacities are model constraints. A schematic representation of the flow network is given in figure 3, and model elements are summarized in table 1.

Figure 3. Brantas river-basin modeling schematic.

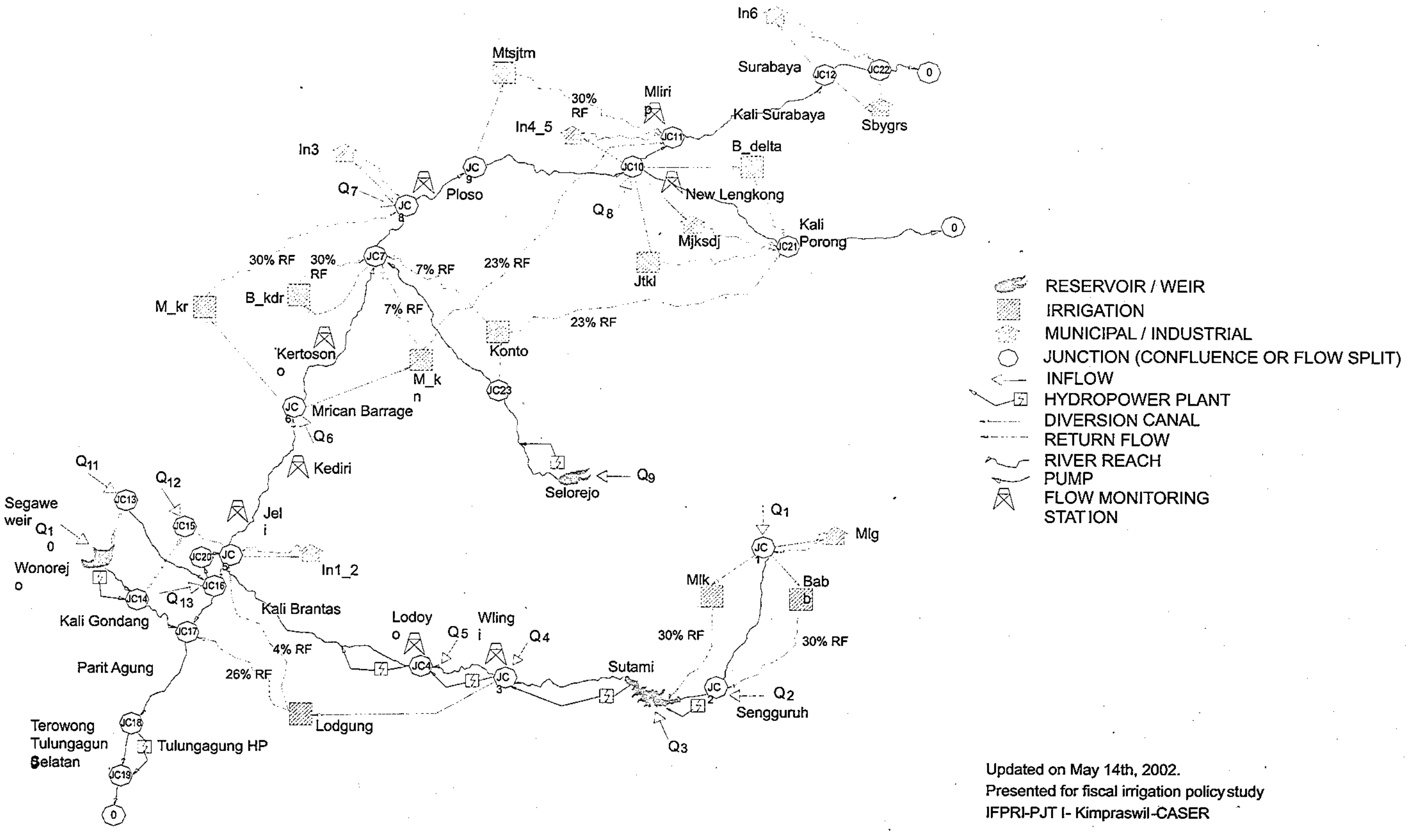

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Table 1. Integrated model components.

Model Component	Current	Planned	Comments
Reservoirs	3	5	320 MCM live storage
Reservoir hydropower plants	3	5	116 MW generating capacity
Run-of-river hydropower plants	4	4	124 MW generating capacity
Irrigation systems[a]	10 (14)	15 (20)	> 95,000 hectares
Municipal demand sites	3 (5)	na	Excludes groundwater, springs
Industrial demand sites	4 (7)	na	Excludes groundwater, unauthorized abstractions
River reaches	23		
Inflow records	13		MCM/year
Total network flow elements	63		
Total decision variables	>24,000		>90% in irrigated agriculture
Total equations	20,000		>90% in irrigated agriculture

Note: na = Data not available.

[a] Numbers in parentheses refer to the number of physical sites, as distinct from the number of model elements. When two or more sites abstract water from, and return flow to, a common model reach, they can be modeled as a single system.

The water balance on each network component (river reach, reservoir) can be generalized as:

$$\sum Q_{in} + I_i + \sum R = \sum Q_{out} + \sum A + \frac{\Delta S}{\Delta t} \tag{1}$$

where, Q_{in} inflow from upstream reaches, reservoirs, power plants
I diffuse inflow from runoff and groundwater discharge (may be negative)
R return flow from demand sites (irrigation, industry, etc.)
Q_{out} outflows to downstream reaches, reservoirs, power plants
A abstractions to demand sites
S storage (reservoirs only)
t model timestep

The integrated modeling approach as specified for the Brantas does not include an explicit rainfall-runoff component.[5] Inflows entering the system at reservoirs, channel reaches or aquifers are therefore one set of boundary conditions for the model, reflecting historical patterns of precipitation and discharge.[6] To provide these boundary conditions it is necessary to develop "natural" flows for each appropriate node or component comprising the model. Natural flows are those flows that would be observed in the absence of any artificial water regulation or manipulation, including storage, abstraction, discharge or redistribution outside of the natural-flow network. Natural flows are required for several reasons, perhaps the most important of which is to ascertain the true incremental flow contribution from each increment of drainage area as defined by the location of model nodes. Three discrete sets of estimated natural flows were made for numerous locations within the Brantas basin by JICA (1998), SRPCAPS (1999) and Optimal Solutions, Ltd. (2000), and they have been adapted selectively for the present study.

Natural flows evaluated at exterior nodes are simply measured discharges at these locations, since it is assumed that there is no significant regulation upstream of these points. For all interior nodes, natural flows must be reconstructed by water balance. For a generic node i (e.g., a weir location) connected upstream to a single node (i-1) the calculation for each timestep takes the general form (time subscripts implicit):

$$Q^{n}{}_{i} = Q^{n}{}_{i-1} + \sum_{i-1}^{i} A - \sum_{i-1}^{i} R + \sum_{i-1}^{i} \frac{\Delta S}{\Delta t} + Q^{in}{}_{i} \tag{2}$$

where,	Q^{n}_{i}	natural flows at node i	(m^3/sec)
	A	abstractions between nodes (i-1) and i	(m^3/sec)
	R	return flows	(m^3/sec)
	S	changes in storage	(m^3)
	t	model timestep	(sec)
	Q^{in}_{i}	inflow between nodes (i-1) and i, added to modeled flows at node I	

Natural flows are calculated recursively from upstream (exterior) nodes proceeding downstream. Where storage reservoirs are present, net evaporation must also be included in natural flow calculations.[7] SRPCAPS (1999) in addition calculated the implicit fraction of precipitation constituting inflow (Q^{in}) for each sub-catchment. A certain degree of consistency across sites is anticipated, and deviations from this pattern (roughly 50% of precipitation enters the flow system, varying by altitude, soil type, and ground cover) were used to identify and diagnose potential errors in the flow statistics.

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[5] Rainfall-runoff modeling may be eventually required to augment existing inflow data, particularly for tributary subsystems.

[6] Alternative climatic regimes can be modeled as well.

Calculating Irrigation System Efficiency, Return Flows and Depletions

We are interested in whole-basin efficiency, so that we must account for system offtakes, return flows, and depletions. It is therefore necessary to evaluate the relationships between diversion (abstraction) at the system level and the resulting supply available at the crop level; and between offtakes, return flow, and corresponding depletions. We consider three components of irrigation system efficiency and their relationship to return flows. Following Xie et al. (1993) we define:

Conveyance efficiency (Ec) as the ratio of the volume of water diverted to the main canals from all sources (Ws) to the volume delivered to the distribution network (Wd):
Ec = Wd/Ws

Distribution efficiency (Ed) as the ratio of the volume of water delivered to the field (Wf) to the volume delivered to the distribution network:
Ed = Wf/Wd

Field application efficiency (Ef) as the ratio of water beneficially used by crops (Wc) to the volume delivered to the field:
Ef = Wc/Wf

The SRPCAPS (1999) study team evaluated water-delivery records for the major Brantas irrigation schemes, and derived estimates of conveyance efficiency (Ec). SRPCAPS (1999) also recommended a value of 0.9 as appropriate for distribution efficiencies (Ed). We have estimated field efficiencies (Ef) based on a formalism suggested by Bernardo and Whittlesey (1989). This formalism is based on the observation that "...nonproductive losses generally increase as the point of maximum ET (evapotranspiration) is approached, leading to a diminishing return from water application" (p.2). There are other mechanisms at work as well, including the properties of soil-moisture release curves. We use an estimate of the form:

$$E_f = \exp^{\left\{-k\left(\frac{WS}{WD}\right)\right\}} \tag{3}$$

where,	WS	water supplied to crop for beneficial use, irrigation + precip
	WD	water demand at crop level
	k	an empirical parameter

The value of the parameter k is set such that the field application efficiency at supply equal to 100 percent of beneficial water demand is 0.9, indicating that one must supply approximately 1.1 mm of water for every 1 mm of beneficial demand at full supply. The resulting efficiencies used in the model baseline are summarized in table 2.

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[7] Brantas reservoir outflows are typically corrected for water-surface evaporation, so this step is redundant in the current model.

Table 2. Efficiencies of Brantas basin irrigation systems.

System name	Area (ha)	Conveyance efficiency (Ec)	Distribution efficiency (Ed)	Field application efficiency (Ef)	Project efficiency Ec*Ed*Ef
Brantas atlas + Bawah	3,130	0.65	0.90	0.90–1.0	0.53–0.59
Molek	3,984	0.63	0.90	0.90–1.0	0.51–0.57
Lodoyo-Tulungagung	12,298	0.56	0.90	0.90–1.0	0.45–0.50
Mrican Kanan	16,344	0.60	0.90	0.90–1.0	0.49–0.54
Mrican Kiri	12,546	0.72	0.90	0.90–1.0	0.58–0.65
Brantas Kiri-Kediri	534	0.62	0.90	0.90–1.0	0.50–0.56
Menturus-Jatimlerek	5,093	0.76	0.90	0.90–1.0	0.62–0.68
Jatikulon	619	0.65	0.90	0.90–1.0	0.53–0.59
Brantas delta	26,718	0.67	0.90	0.90–1.0	0.54–0.60
Konto systems	13,812	0.65	0.90	0.90–1.0	0.53–0.59

The Unified Economic Objective Function

The objective function of the integrated model is the combined, net water-generated revenue function for the basin. By expressing all objective-function linear components in a common metric (Rp per year), we avoid the need for the weighting schemes commonly used in multiobjective programming, which contains an unavoidable element of subjectivity. The unified objective function takes the generic form:

$$Max\{Z\} = \sum_{irr} Z_{irr} + \sum_{ind} Z_{ind} + \sum_{mun} Z_{mun} + \sum_{hydro} Z_{hydro} \qquad (4)$$

where, *irr, ind, mun, hydro* refer to net profits (benefits) over irrigated agricultural, industrial, municipal and hydroelectric demand sites, respectively. Currently, water-quality objectives or standards are also incorporated into the model directly as minimum flow constraints.

The terms in the objective function take the general forms of *profit functions* (used for irrigated agriculture and hydropower generation) emphasizing the contribution of water as a priced input in the production of an output with market value; and *benefit functions* (used for municipal and industrial demand[8]) which describe the value of water in uses such as domestic consumption where no output having market value is produced, but where use is nevertheless a valuable activity. The generic form of the profit function is:

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[8] The benefit function is used for industrial water demand because the specific forms of industrial water-production functions are not known.

$$Z_i = \left(y_i(w_i)\cdot Py_i - w_i \cdot Pw\right) \qquad (5)$$

where,	Py	price of output(s) y
	y(w)	output quantity y, a function of w
	w	quantity of water consumed
	Pw	unit price of water
	i	index of demand site

The generic form of the benefit function is:

$$Z_i = \left(\int_{W0}^{w} WTP(w) - w \cdot Pw\right) \qquad (6)$$

where, WTP(w) willingness-to-pay function for water
(other terms as above)

Calculating Irrigated Agricultural Output and Water Demand

Pursuant to the previous discussion of functional form, the following agricultural water production functions are understood to be provisional. We anticipate using either Cobb-Douglas or quadratic multi-input production functions once the data required to estimate functions of these forms has been fully processed and evaluated.

In the Brantas basin, paddy is the most important crop, from the perspectives of land use, water use, farm economy, and dietary composition. Bouman and Tuong (2000), on the basis of an analysis of over 30 studies of rice yields obtained under controlled conditions, have proposed a paddy water production function of the general form:

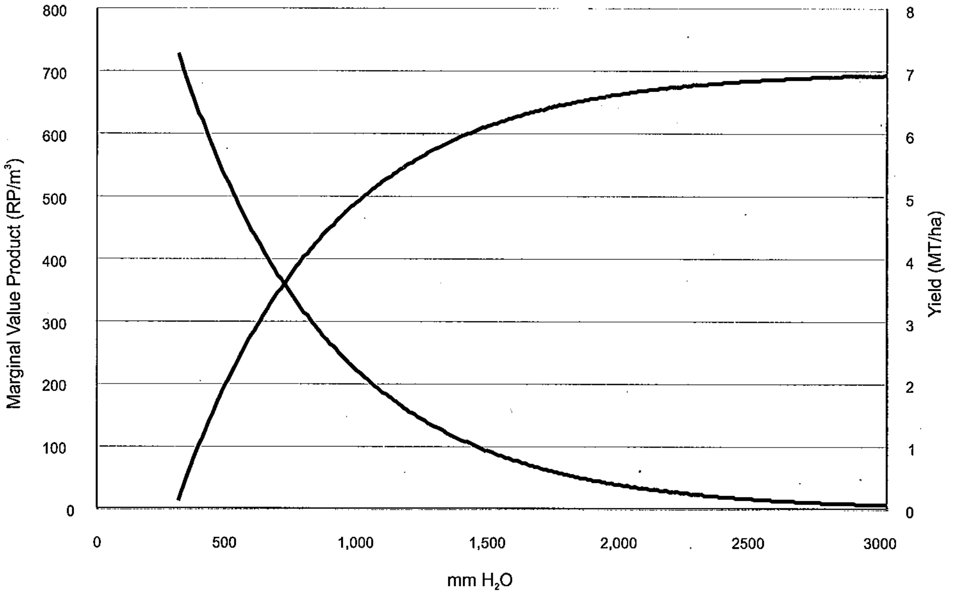
$$Y_A = Y_P \cdot \left(1 - e^{\{-\beta\cdot(W - W_0)\}}\right) \qquad (7)$$

where,	Y_A	actual yield	(kg/ha)
	Y_P	potential or non-water limited yield	(kg/ha)
	β	water-yield response coefficient	(parameter)
	W	water application	(mm)
	W_0	no-yield water application threshold	(mm)

The Bouman-Tuong function, and marginal value of water in paddy production are plotted in figure 4. We can see that there is an extensive region over which significant changes in water application have relatively little effect on yield, resulting in very low levels of marginal water value. This suggests that the demand for water for paddy irrigation will be highly sensitive to any price the farmers must pay for water, particularly within these ranges of application.

FAO methodology is based on the yield response coefficient (K_Y) method, described in FAO 33 1986. The K_Y method describes the fractional reduction in yield relative to its potential at full water supply (Y_P) resulting from a fractional reduction in actual evapotranspiration relative to reference crop evapotranspiration (ET_0):

Figure 4. Exponential water production function and marginal value of water.



$$\left(1-\frac{Y_A}{Y_P}\right)=K_Y\cdot\left(1-\frac{ET_A}{ET_0}\right) \tag{8}$$

where,			
	ET_A	actual evapotranspiration	(mm/day)
	ET_0	reference evapotranspiration	(mm/day)
	Y_A	actual yield	(kg/ha)
	Y_P	potential yield	(kg/ha)
	K_Y	crop yield coefficient	(unitless)

This functional form is linear, as noted above, which severely restricts the model as currently (provisionally) specified in evaluating the fine trade-offs resulting from modest changes in the (assumed) volumetric price of water that farmers face.

Calculating Hydropower Water Demand

The Brantas basin presently contains nine hydropower facilities, of which eight are currently operating. They are categorized either as reservoir facilities, for which effective head varies with the extent of reservoir storage, and run-of-river stations, for which head is essentially constant. Within the model, power generation is estimated using a standard approach based on effective hydraulic head, turbine-discharge volume, and efficiency. The general form of this equation is (Mays and Tung 1992) as follows:

$$P = C \cdot \gamma \cdot Q \cdot h \cdot \eta \qquad (9)$$

where,	P	power generated	(kWh)
	C	numerical coefficient to conserve units	
	γ	unit weight of fluid	(N/M^3)
	Q	rate of discharge	(M^3/sec)
	h	effective energy head	(M)
	η	turbine efficiency	

Q is a decision variable, and h is a state variable functionally related to reservoir storage. Power generation is a nonconsumptive use of water, and does not degrade water quality, although the extent and timing of power demand can, and does, conflict with the demand for water in various consumptive uses, at least during certain periods. Hydropower represents roughly 16 percent of the installed generation capacity in the Brantas basin.

Calculating Municipal (Domestic) Water Demand

The conceptual basis upon which municipal, or domestic demand is calculated is different from that of agricultural demand, since the water diverted and consumed by households is not an input to a production process as such, but rather an end use that serves a variety of needs, including drinking, cooking, washing and sanitation, which are not market transactions. The approach we use is to estimate the *consumer surplus* associated with each level of water use. This is the level of benefit or utility that a household receives from a given level of water consumption, which is in excess of what they must actually pay for the water. It is revealed through a stated *willingness to pay*, as recorded in a sample survey.

To obtain the consumer surplus estimate, first, we estimate a conventional log-linear demand function using data from a recent household survey of municipal water users: water demand (W) is found to be an increasing function of income and a decreasing function of price, as consistent with economic theory:

$$\ln(W) = \alpha + \beta \cdot \ln(Y) - \varepsilon \cdot \ln(P) \tag{10}$$

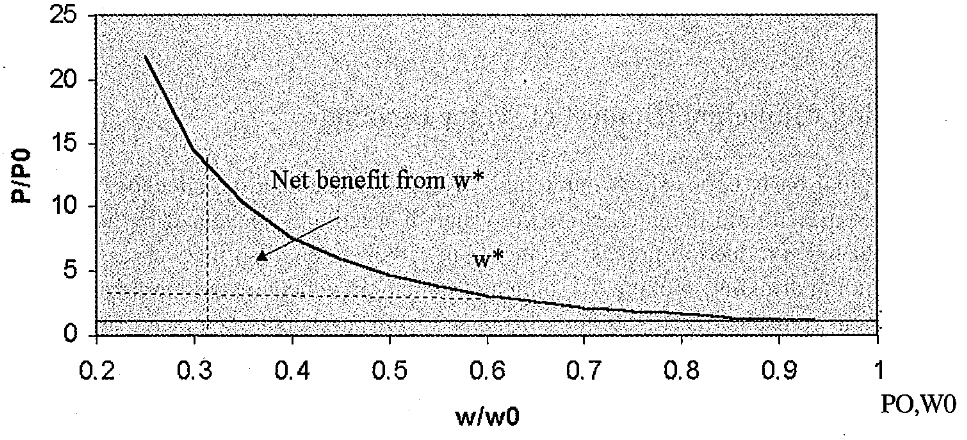
where, W = quantity of water demanded in M^3 per capita per 10-day period
Y = income in 1,000's Rp per capita per month
P = price of water in Rp per M^3

In our sample, **a** (intercept) = -1.067, **b** (elasticity with respect to income) = 0.4817 and **e** (elasticity with respect to price) = 0.478.[9] Next, we invert the equation to obtain price as a function of quantity: this is the *inverse demand or willingness-to-pay curve* which in real-space takes the form:

$$P = e^{\left(\alpha/\varepsilon\right)} \cdot Y^{\left(\beta/\varepsilon\right)} \cdot W^{\left(-1/\varepsilon\right)} \tag{11}$$

The next stage is to identify a minimum acceptable level of consumption, W_0. This can be done either on the basis of the household sample-survey results, or on the basis of internationally accepted norms. We can now estimate per capita consumer surplus as a function of water consumption (w) by integrating the inverse demand function between w_0 and w, and subtracting the price actually paid. The estimation of consumer surplus is illustrated in figure 5.

Figure 5. The estimation of consumer surplus.



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[9] ε is actually negative, since quantity demanded falls as price increases, but we report the absolute value of the coefficient.

$$CS(w) = \frac{e^{(\alpha/\varepsilon)} \cdot Y^{(\beta/\varepsilon)}}{\left(1 - 1/\varepsilon\right)} \cdot \left\{w^{(1-1/\varepsilon)} - w_0^{(1-1/\varepsilon)}\right\} - w \cdot Pw \qquad (12)$$

It is important to recognize that this estimate of consumer surplus is not directly comparable to the value of water in agricultural production, since the conceptual bases for estimation differ. In particular, the base level W_0 is more a mathematical necessity than a measurable quantity. However, water reallocation within the model is driven not by consumer surplus itself, but by the marginal willingness to pay for water, which is more directly comparable to the marginal-value productivity of water in an agricultural-production function.

Calculating Industrial Demand

The calculation of economic demand for water by industrial users in the Brantas is complicated by several factors. First, we have no reliable information on the internal economics of water use by Brantas industries. In addition, commercial water users in the Brantas consist of many discrete industries—sugar processing, paper, leather and food processing—each of which uses water as a productive input in unique ways. A production-function approach to water demand (which is the conceptually correct approach given that water is an input to a marketed end product) is therefore impracticable, at least in the absence of new data. Second, we do not have survey or other data revealing willingness to pay by industry for various increments of water delivery, as we do for domestic use. In addition, the price at which Perum Jasa Tirta provides water to industrial users has changed very little over the last decade; thus the empirical relationship between price and quantity provides very little information on the underlying economic-demand relationships.

We have taken a provisional approach to the estimation of industrial water demand, which rests upon several pieces of information that we do possess. The first is the estimated average value-added associated with each cubic meter of water used in industry, for a recent year (1996). JICA calculated water's share of total input costs, and assumed that the share of value-added was proportional. The resulting estimate of water's average net productivity in industry is Rp 176/m^3 in 1996, or Rp 360/m^3 in 2000 (adjusted using the industrial deflator). We also know that Brantas industries have improved their water use efficiency in recent years, and have consequently reduced their purchases of water from PJT (internal communication). It appears reasonable to assume that current levels of water use are therefore demand-constrained. This would suggest, in principle, that industries are using water roughly to the point where the marginal value product of water equals the price they pay for water, P_W, currently Rp 51/m^3. Finally, we know how much water is actually being abstracted by industries at various locations throughout the basin.

Given the observed level of water use, and of average and marginal values, we can develop a synthetic willingness-to-pay curve in the following way: first, we reasonably assume that the demand for water is inversely related to price, reflecting declining marginal productivity:

$$\ln(W)=\alpha-\varepsilon\cdot\ln(P_W) \tag{13}$$

Since this curve, by assumption, will pass through the point (W, P_W), where W refers to the current level of use, there will be a unique value of **a** for each value of **e**. A review of some recent literature on industrial demand for water (Wang and Lall 1999; Renzetti 1992) suggests that ?, the demand elasticity of water with respect to price has an absolute value in the range 0.5 to 1.0. It is likely to be higher in regions where industries are relatively inefficient in water use; and relatively inelastic where they are highly efficient. Since Brantas industries have recently improved their water use efficiency, it was assumed that elasticities are in the range 0.5 to 0.75 in absolute value. For a given value of **e**, the log intercept (**a**) is easily obtained from equation (14) given the known or assumed values of W and P_W.

The final stage is to find the base water use, W_0, below which no benefits occur. The appropriate value of W_0 is that which corresponds to an average surplus value equal to the JICA 1997 estimate of 360 Rp/m^3:

$$\left[\frac{e^{(\alpha/\varepsilon)}}{\left(1-\frac{1}{\varepsilon}\right)}\cdot\left(W^{(1-1/\varepsilon)}-W_0^{(1-1/\varepsilon)}\right)-W\cdot P_W\right]\cdot\left(\frac{1}{W}\right)=360 \tag{14}$$

This expression can be rearranged to show that W_0 is always a constant fraction of W for a given value of **e**. This allows the synthetic demand curve to be scaled to varying levels of water use while preserving the marginal and average productivity of water. Values of (W_0/W) for typical values of elasticity (e) are: **e** = -0.5, W_0/W = 0.1104; **e** = -0.6, W_0/W = 0.02617; **e** = -0.75, W_0/W = 0.0076. In current model runs, we use an elasticity (e) of –0.5.

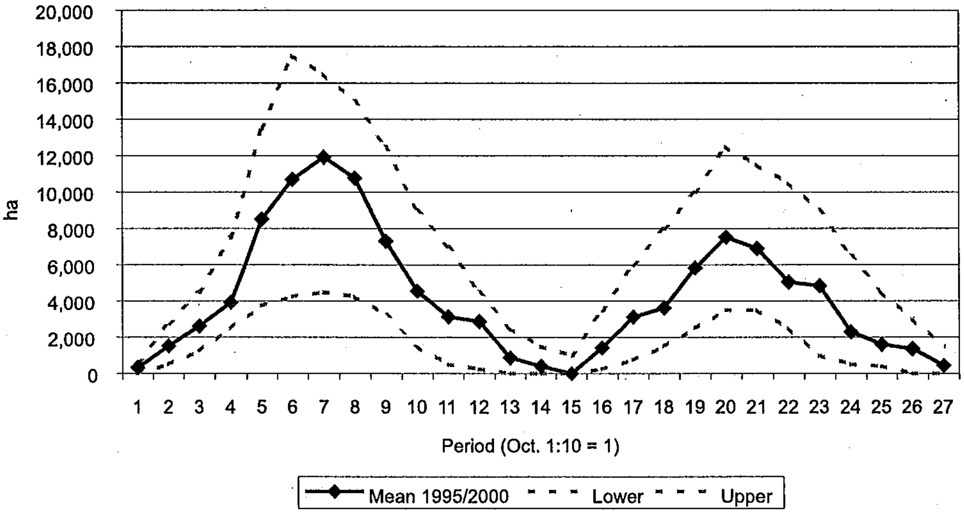
Constraining the Model

There are many classes of constraints in the model, reflecting the physical capacities of infrastructure, such as the live storage capacity of dams, the conveyance of channels, and the design irrigated area within a system. Even within these constraints, found primarily in the network-flow portion of the model, the solution space (set of feasible combinations of decision variables) is unmanageably large. The largest numbers of free (decision) variables occur within the irrigation modules. These include area by crop and planting date (> 1,500) and water supplied to each crop in each period (> 22,000). To reduce this sample space, we enforce two sets of constraints, one set at the system level and another at the basin level.

The system-level constraints require that for each major crop type, there are minimum and maximum planting requirements by season. Minimum requirements are intended to ensure that at least a fraction of the historical level of cultivation is maintained through the range of scenarios. This is understood to reflect the nature of traditional preferences, acquired expertise in cultivation and risk aversion that often lie outside the realm of purely price-driven calculation. These constraints are set at around 40 percent of average cultivation levels. Maximum constraints, in contrast, serve two functions. The first is land suitability: all land within a given irrigation system may not be simultaneously suitable, e.g., for paddy cultivation, which requires (or prefers) soils of high clay content to minimize percolation, and root crops that require more well-drained soils for optimal yields. The second function is supply control: there is an inverse relationship between aggregate supply and market (farm-gate) price, so that overproduction of crops would lead to the depression of prices. As the current configuration of the model does not specify farm-gate prices endogenously, planting limits provide alternative constraints against oversupply.[10]

The basin-level constraints are designed primarily as supply control as well. These constraints stipulate that the sum of all crops (by type) established within each of the 36 model periods falls within bounds defined by historical patterns of cultivation. The levels of these constraints, plotted with historical levels of cultivation, appear in figure 6.[11] It is seen that these constraints are not overly restrictive. It is also important to note that both sets of constraints apply to linear combinations of individual decision variables, thereby retaining many degrees of freedom—no individual variables are subject to *ad hoc* constraints within the model.

Figure 6. Global planting constraints on paddy.



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[10] We have run versions of the integrated model with endogenous price specifications, which achieve the desired objective of supply control effectively, but the addition of the endogenous price equations increases execution time by a full order of magnitude.

[11] Sugarcane is similarly constrained.

Solving the Model

Optimization modelers will typically initialize the values of decision variables before attempting an optimization, in order to move the optimization search immediately to a subregion of the solution space within which the optimal solution is believed to lie. This will reduce the time required for computation, which can be considerable, but it may also bias the model solution toward a particular local (as opposed to global) value. We have discovered that, due to the extremely large number of decision variables (24,000) and equations (20,000), and due to the numerous nonlinearities in the model equations, GAMS will typically fail to find a feasible solution when initialized and run in this manner. We have developed an alternative solution method based on a four-stage optimization, where an increasing number of decision variables are solved in each stage. No initializing values are used; all decision variables start at system defaults. The step-wise procedure is as follows:

1. Optimize the network-flow components (including hydropower, municipal and industrial demand as active decision variables) while holding irrigation water abstractions by system to fixed, historical levels. This gives us initial values of all decision variables associated with the flow network, but excluding cropping and irrigation decisions.

2. Optimize crop-planting decisions across all irrigation systems, again holding total water abstractions to the same constant value as in phase 1, which require full water supply to each crop. This gives us initial values of crop area allocations by planting date, an important decision variable.

3. Re-optimize irrigation system output, again holding system abstractions constant, but now allowing decisions on field-level water allocation by crop and period. This is by far the largest class of decision variables in the integrated model, containing roughly 22,000 of the 24,000 total decision variables.

4. Finally, link the network-flow and irrigation system equations and solve the entire system, with all decision variables subject only to the model physical and institutional constraints.

The technique is time-consuming, with an average run cycle requiring between 7 and 24 hours on a standard PC (Pentium III, 1 GHZ). However, the solutions have the desirable property of not being biased by the initial values selected by the modeler.

Some Preliminary Model Results

In this section, we describe the results from some preliminary model runs. These runs are primarily diagnostic. That is, while we may obtain some useful insights relevant to policy design from these runs, we have performed them primarily to diagnose model performance and sensitivity relative to changes in parameter values. In addition, the final model specification used for policy analysis will contain updated specifications of crop water production functions, for reasons discussed earlier, which are likely to have a substantial influence on the model response to changes in relative price. We will also improve our specification of industrial demand, although the form of this modification will depend on the data subsequently available.

Scenarios and Data

The following scenarios were run. Details are summarized in table 3.

Baseline. Most boundary conditions at 1995–2000 values; water-charge prices at current (PJT) levels; municipal demand based on estimated demand model parameters, with an upper limit of 500/l*ca*day; industrial demand by synthetic WTP as described above.

2020. This scenario is based largely on projections made by SRPCAPS (1999) except as noted: climatic boundary conditions at baseline levels; irrigation-system areas adjusted downward due to urban infringement, which is anticipated to affect the Brantas delta irrigation systems most profoundly; increases in municipal demand driven by population growth and increase in service coverage; industrial demand growth as estimated by SRPCAPS; and loss of reservoir capacity as estimated by JICA (1998).

Dry year. This scenario is based on crop year Oct. 1996–Sept. 1997, which was one of the driest in the last 20 years. Precipitation and system inflows are the historical flows for this period. All other conditions are as in the baseline scenario.

ISF. A series of scenarios using the baseline values of all parameters and boundary conditions, to which a volumetric water charge (ISF) was introduced, and systematically increased from 0 Rp/m^3 to 35 Rp/m^3 in 5 Rp/m^3 increments. The 35 Rp/m^3 ceiling was chosen because it corresponds to the JICA (1998) estimate of full capital and O&M cost-recovery level, approximately.

In all scenarios, the following crop types and durations were used. Durations were based on an analysis of cropping patterns in the Brantas irrigation systems during five recent crop years (1995/96–1999/00), and verified on the basis of the 1999/2000 farm sample survey (given below):

Crops	Paddy	120 days	(20 days nursery, 100 after transplant)
	Maize	90 days	
	Soybean	90 days	
	Groundnut	110 days	
	Sugarcane	365 days	(does not include initial land preparation)

Other parameters related to irrigated cropping—including mean and maximum yields, input and output prices, intensity of fertilizer and pesticide application, labor intensity, use of machinery, and water use—are based on plot-level data collected by field teams from the Center for Agricultural and Socioeconomic Research (CASER) during late 2000–early 2001. The sample consisted of 160 farm households from each of four irrigation systems chosen to represent

Table 3. Summary of model scenario assumptions.

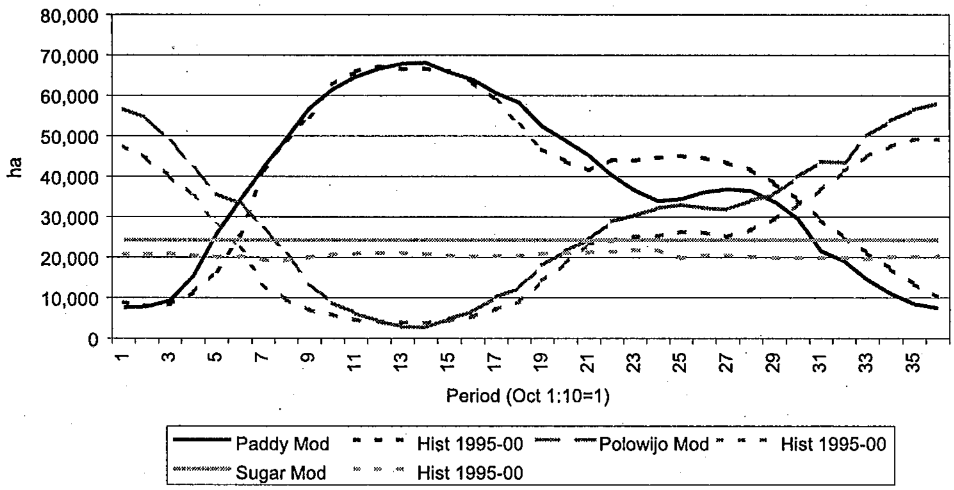
Parameter	Baseline	2020	Dry year	Water charge
Precipitation	Effective, 80% exceedance probability, 1970-1999	Effective, 80% exceedance probability, 1970-1999	Effective, crop year 1995-1996	Effective, 80% exceedance probability, 1970-1999
Inflows	8,030*10^6 m^3	8,030*10^6 m^3	6,200*10^6 m^3	8,030*10^6 m^3
Irrigated area	95,038 ha net	82,087 ha net	95,038 ha net	95,038 ha net
Municipal demand	1,200,000 served	3,100,000 served	1,200,000 served	1,200,000 served
Industrial demand	121.5*10^6 m^3 base	231.3*10^6 m^3 base	121.5*10^6 m^3 base	121.5*10^6 m^3 base
Reservoir capacity (active storage)	320*10^6 m^3	308*10^6 m^3	320*10^6 m^3	320*10^6 m^3
Water charges	Irrigation 0 Rp/m^3 Municipal 35 Rp/m^3 Industrial 51 Rp/m^3 Hydro13.6 Rp/kKWhH	Same as base	Same as base	Irrigation fees: 0:5:35 Rp per cubic meter
Water entitlement	200 literes per day per ca, domestic	Same as base	Same as base	Same as base

different agro-ecological settings within the basin: Lodo Agung in the upper region, Mrican Kiri and Kanan in the middle and Porong canal in the Brantas delta. In each system, 3 tertiary blocks were chosen on the basis of water-delivery infrastructure and composition of cropping, and 40 farm households were selected from within each tertiary block, for a total sample size of 480.[12] It should be noted that values of most parameters differ across irrigation systems, contributing in turn to differences in profitability, and in the marginal value of water across systems.

Baseline, Dry Year and 2020 Scenarios

Given a proper model specification, the baseline scenario should *resemble* current conditions within the basin, but not necessarily duplicate them. This is because we do not anticipate that water use in the basin is currently optimized. Figure 7 depicts area under cultivation, modeled and historical, by period beginning with Period 1 = Oct. 1:10 through Period 36 = September 21:30. Three crop types are depicted: paddy, polowijo crops and sugarcane. Polowijo crops are dry-footed, irrigated crops, including maize, soybean, and groundnut. We can see that the historical pattern is well approximated. We have observed that our model has a tendency to grow slightly less paddy in the first dry season (March–June) than has actually been grown, and somewhat more polowijo during the first and second dry seasons. We suspect that this is because paddy and maize (the dominant polowijo crop) are close economic competitors, and because we have allowed the cultivation of high-yielding hybrid maize, as consistent with

Figure 7. Area under cultivation, model and historical, 1995–2000.



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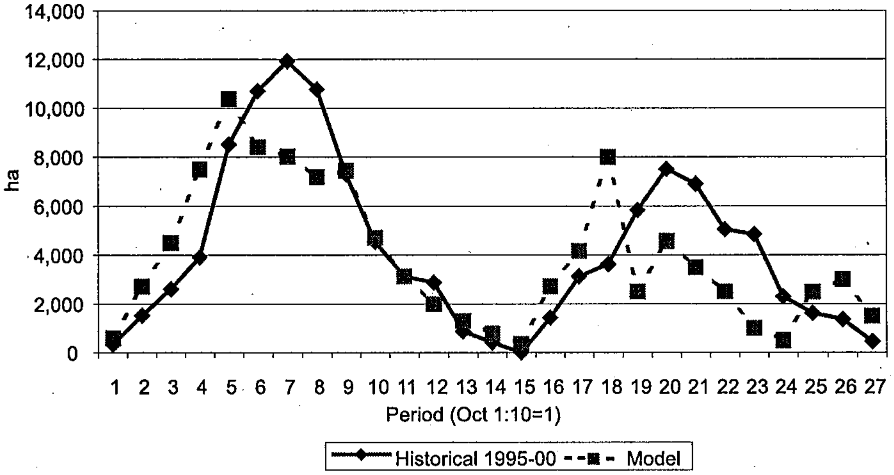
[12] The tertiary block is the most disaggregated unit for which irrigation delivery records are available.

our sample survey findings.[13] The model also grows slightly more sugar than is grown historically, possibly because we have specified sugar rendering rates of up to 8 percent during the irrigated sugarcane season (May–September) as compared to the 6.7 percent–7 percent rates more commonly observed throughout the year.[14]

Figures 8a (paddy) and 8b (polowijo) depict newly established crops, modeled and historical, by period. (Figure 7 differs from figure 8 in that the former depicts the standing crop during each time period, which embodies crop durations as well as dates of establishment, while the latter depicts only the hectares of newly established crop in each period). This is a more sensitive indicator of model performance. We observe that modeled paddy and polowijo planting schedules adhere closely to historical patterns, but with a tendency toward earlier planting, particularly of paddy, in both seasons. We believe that this may be because the model "knows" when the rain is coming, and how much, while in reality farmers do not, so they tend to be conservative in their planting decisions rather than risk losing a nursery crop to drought.

Figure 8a. New plantings, paddy, model and historical, 1995–2000.



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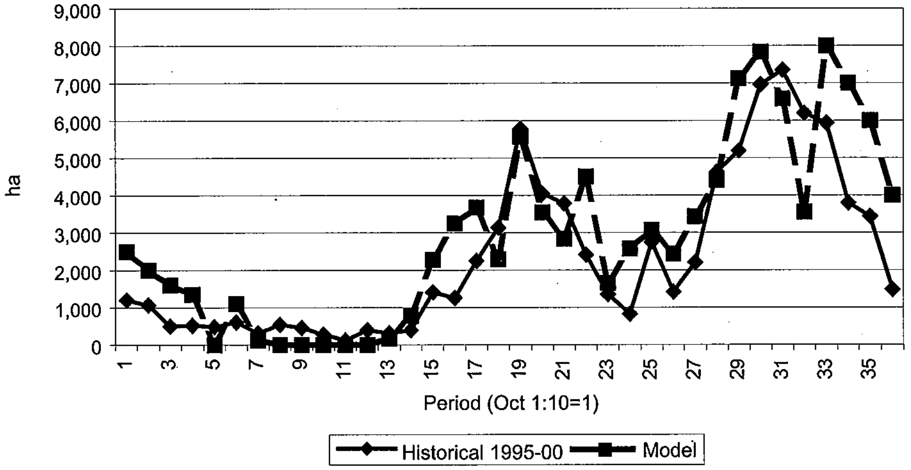
[13] Hybrid maize produces higher yields, but has higher associated input costs, which are also represented within the model.

[14] In the model, sugarcane gross yields and sugar extraction rates are seasonally variable.

Figure 8b. New plantings, paddy, maize, model and historical, 1999–2000.



Figures 9a (baseline, 2020) and 9b (dry year) depict the basin inflows and outflows by period, for the Brantas main stem. The difference between these curves is the disappearance within the system, which consists of consumptive use and non-beneficial losses, such as reservoir and canal evaporation, and losses to unrecoverable groundwater. In each figure, a minimum flow constraint is indicated. This corresponds to a minimum flushing flow requirement in the Surabaya river. It is observed that during years of normal climatic conditions, roughly one-third of system inflows are depleted on an annual basis, and the majority of dry-season flows (June–November) depleted. The water-quality constraint is only occasionally binding, during August-October. In the dry year (Oct. 1996–Sept. 1997, measured inflows), depletion rates are higher at around 40 percent of annual flows, and the water quality (minimum flow) constraint is seen to be binding almost continuously during the dry season (May–September).

Figures 10a and 10b depict the stages of two of the three storage reservoirs within the Brantas, Sutami, and Selorejo, respectively.[15] In the model, Sutami storage is the combined storage of Sutami and Lahor reservoirs, which are connected by an ungated tunnel. Numerical simulation determined that, given the model timestep of 10 days, the two reservoirs could be modeled as a single unit except under extremely unusual (hypothetical) circumstances. The only constraints applied to reservoir operations were the seasonal requirements for flood pool in the wet season and minimum reserve storage in the dry season. In both cases, the model chooses solutions that involve more aggressive use of stored water. The relatively "flat" pattern in Sutami-Lahor arises due to the model's attempt to maximize hydropower production. Baseline and 2020 patterns differ very little, in spite of the shift in demand away from agriculture and toward municipal and industrial demand, which are less seasonal, over this period. Reservoirs are drawn down more aggressively during the dry year, particularly in the period July–September, as expected.

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[15] No historical data exist for Wonorejo, which began operation in 2001.

Figure 9a. System inflows, outflows and flow constraint, baseline.

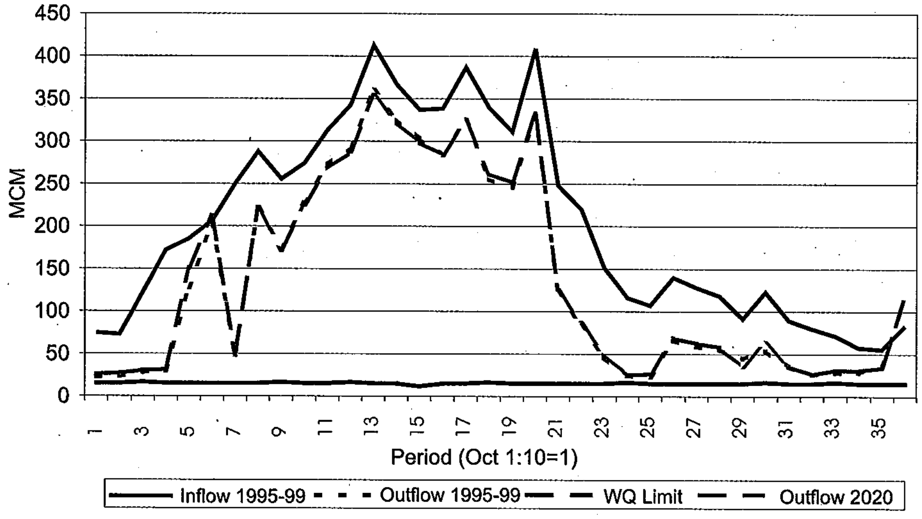


Figure 9b. System inflows, outflows and flow constraint, dry year (1996–1997).

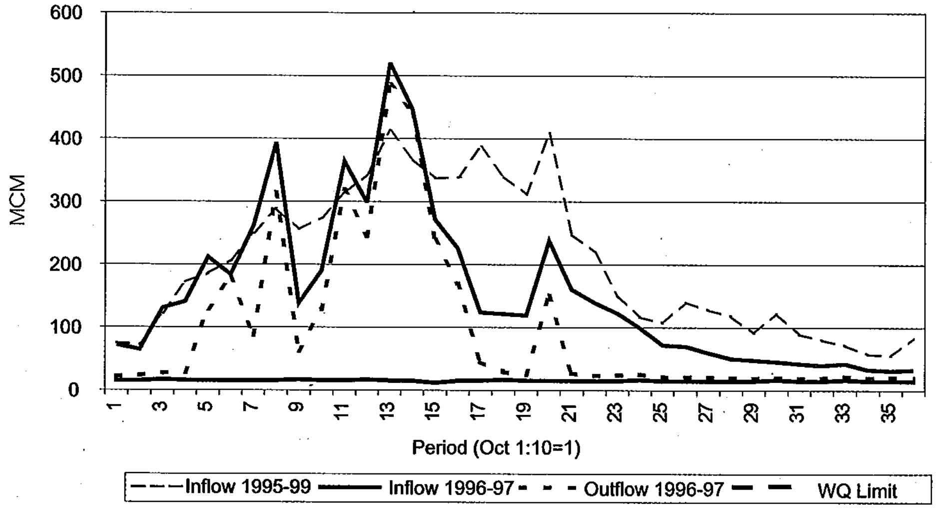


Figure 10a. Sutami-Lahor reservoir levels, modeled and historical.

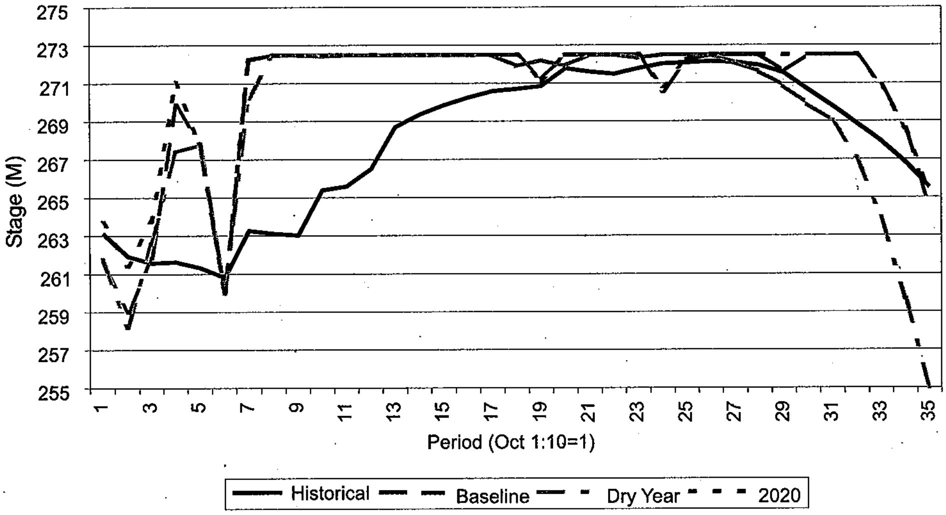
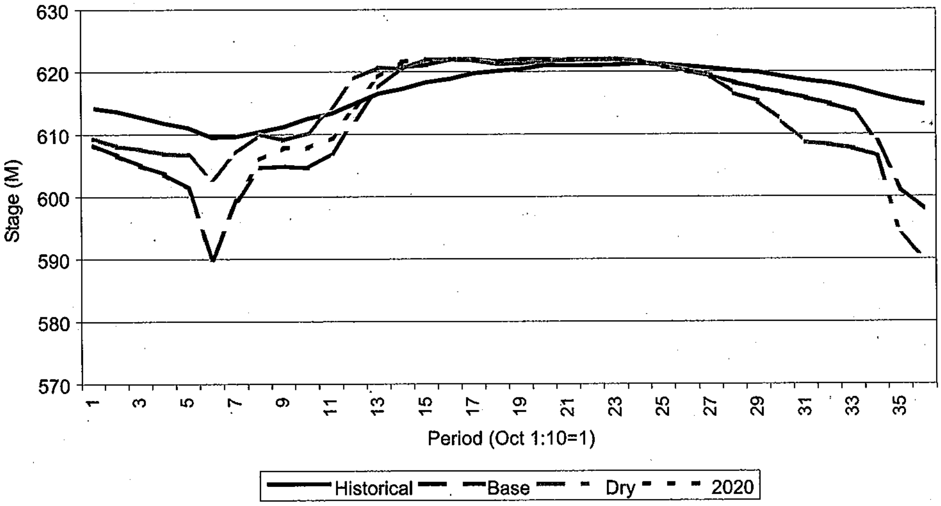


Figure 10b. Selorejo reservoir levels, modeled and historical.



Irrigated agricultural area and yield under each model scenario, and relative to historical levels, are summarized in table 4. A distinguishing feature of the scenarios is a reduction in the overall paddy planting, and a corresponding increase in the dry-footed irrigated (polowijo) crops. The model shows a preference for sugarcane relative to historical practice, although the model shifts sugarcane planting almost entirely to the irrigated season, May–August. Yields in general change very little, reflecting a tendency of the model to make adjustments in crop area and composition while maintaining full or near-full water supply.

In summary, the baseline and alternative scenarios provide evidence that the model is capable of recreating the overall dynamics of irrigated agriculture within the basin, and responds in a consistent manner to alterations in the boundary conditions. Model performance will almost certainly improve when all agricultural production functions have been respecified using forms that reflect the declining marginal value of water, as consistent with physical evidence.

Increasing Volumetric Water Charges

This set of scenarios was intended to evaluate the sensitivity of the model to changes in the level of a hypothetical volumetric water charge to irrigated agriculture. The analysis focuses on agriculture, and all parameters related to municipal, industrial and hydropower demand are constant throughout these scenarios, although these sectors are still competing with agriculture for available supplies. A primary objective was to discover how the model solutions embodied the various strategic responses described earlier—water saving, crop substitution, and shifting cropping calendars. In its present form, the model cannot simulate input substitution, as all inputs to crop production are parameters rather than decision variables in the current model specification.

The comparative model output appears in table 5. Figure 11 displays the change in cropping composition resulting from increasing water charges. Less paddy is planted, as anticipated, since paddy is a water-consumptive crop, requiring water for nursery, soil saturation, water-layer development, percolation, temperature and weed control, in addition to evapotranspirative demand. Planting shifts to polowijo crops, primarily maize, and sugarcane to a lesser extent. The extent of the area reallocation is small, however—on the order of 1–2 percent. Shifts in production mirror those of planted area, reflecting negligible changes in yield. The timing of planting shows very little response to increased charges as well. Figure 12 displays the planting schedule associated with each level of water charge for paddy. Only minor adjustments occur, and these are primarily within-season as distinct from across-season.

The primary adjustments relative to historical cropping patterns were already evident in the baseline scenario, in which farmers planted paddy earlier in both seasons, and reallocated land from paddy to polowijo during the dry season. The reasons that further changes of a non-marginal nature did not accompany increasing water charges again relate to marginal conditions—even water charges of 35 Rp/m^3 lie below the marginal value of water for each of these crops at full use, at least according to the current specifications of production functions.

The strategy of accommodation to increasing water charges is only one output of interest, however. We are also interested in the net impact of such charges on the farm economy. Table 6 summarizes the structure of costs and revenues by crop and by water charge. Table 7 summarizes the per-hectare costs for each crop and price scenario, and water's corresponding

Table 4. *Summary of model output, irrigated agriculture.*

	Historical	Baseline	% Change	Dry year	% Change	2020	% Change
Planted area (in ha)							
Paddy							
Wet season	69,452	69,061	-0.6	68,681	-1.1	57,060	-17.8
Dry season 1	44,036	36,447	-20.8	31,831	-27.7	30,065	-31.7
Total	113,487	105,508	-7.6	100,512	-11.4	87,125	-23.2
Polowijo							
Wet season	8,593	11,906	27.8	11,894	38.4	10,945	27.4
Dry season 1	31,218	38,828	19.6	39,000	24.9	32,617	4.5
Dry season 2	44,973	54,503	17.5	51,827	15.2	42,529	-5.4
Total	84,785	105,237	19.4	102,721	21.2	86,092	1.5
Sugarcane	19,499	24,250	19.6	24,694	26.6	24,075	23.5
Total planting	217,771	234,995	7.3	227,927	4.7	197,292	-9.4
Cropping intensity	2.29	2.47	-	2.40	-	2.40	-
Yields (in mt/h)							
Paddy	5.48	5.63	2.7	5.53	1.0	5.74	4.7
Maize	3.42	5.37	36.3	5.36	56.6	5.45	59.4
Soybean	1.21	1.36	11.1	1.25	3.2	1.45	20.0
Groundnut	1.09	1.13	3.4	1.12	3.2	1.20	10.2
Sugarcane	na	6.11	-	6.08	-	6.12	-

Note: Historical values are based on crop years 1995/96–1999/00; Percent changes relative to historical; mt/ha = metric tons per hectare; na = data not available. Percent changes relative to historical.

Table 5. *Planted area, production and yield impacts of water charge.*

	Rp 00	Rp 05	Rp 10	Rp 15	Rp 20	Rp 25	Rp 30	Rp 35
Planted area (ha)								
Paddy	105,508	105,272	104,828	104,522	103,996	103,711	103,540	103,265
WS paddy	69,061	68,936	68,786	68,624	68,394	68,300	68,161	67,984
DS1 paddy	36,447	36,336	36,042	35,898	35,602	35,410	35,379	35,281
Polowijo	105,237	105,339	105,654	105,628	105,881	105,975	106,055	106,097
Maize	88,497	88,545	88,671	88,572	88,731	88,724	88,860	88,989
Soybean	11,083	11,095	11,207	11,240	11,320	11,435	11,443	11,402
Groundnut	5,657	5,699	5,776	5,815	5,830	5,815	5,751	5,706
Sugarcane	24,250	24,313	24,400	24,541	24,690	24,784	24,851	24,956
Production (mt)								
Paddy	594,089	592,820	590,379	588,605	585,625	584,100	583,056	581,474
WS paddy	397,246	396,515	395,636	394,681	393,372	392,835	392,050	391,051
DS1 paddy	196,842	196,305	194,743	193,924	192,253	191,265	191,006	190,423
Polowijo	496,418	496,831	497,633	497,199	498,192	498,442	499,136	499,745
Maize	474,953	475,308	475,882	475,362	476,229	476,340	477,097	477,840
Soybean	15,080	15,094	15,227	15,256	15,359	15,514	15,515	15,425
Groundnut	6,385	6,428	6,524	6,582	6,604	6,588	6,524	6,479
Sugarcane	148,135	148,445	148,870	149,565	150,293	150,754	151,085	151,599
Yield (mt/ha)								
Paddy	5.631	5.631	5.632	5.631	5.631	5.632	5.631	5.631
WS paddy	5.752	5.752	5.752	5.751	5.752	5.752	5.752	5.752
DS1 paddy	5.401	5.403	5.403	5.402	5.400	5.401	5.399	5.397
Polowijo	4.717	4.716	4.710	4.707	4.705	4.703	4.706	4.710
Maize	5.367	5.368	5.367	5.367	5.367	5.369	5.369	5.370
Soybean	1.361	1.360	1.359	1.357	1.357	1.357	1.356	1.353
Groundnut	1.129	1.128	1.130	1.132	1.133	1.133	1.134	1.135
Sugarcane	6.109	6.106	6.101	6.094	6.087	6.083	6.080	6.075

Note: mt = metric tons; ha = hectare.

Figure 11. Changes in area by crop in response to increasing water charges.

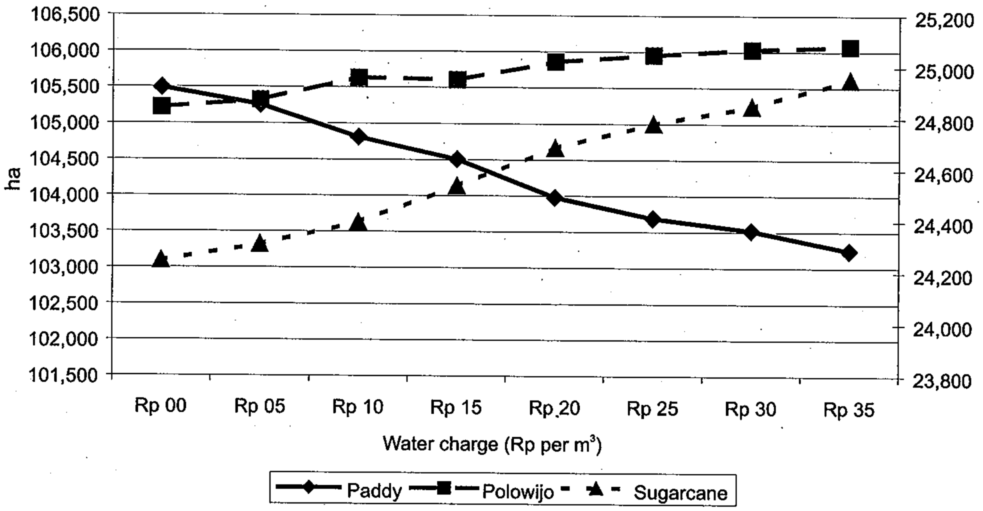


Figure 12. Changes in planting date in response to increasing water charges.

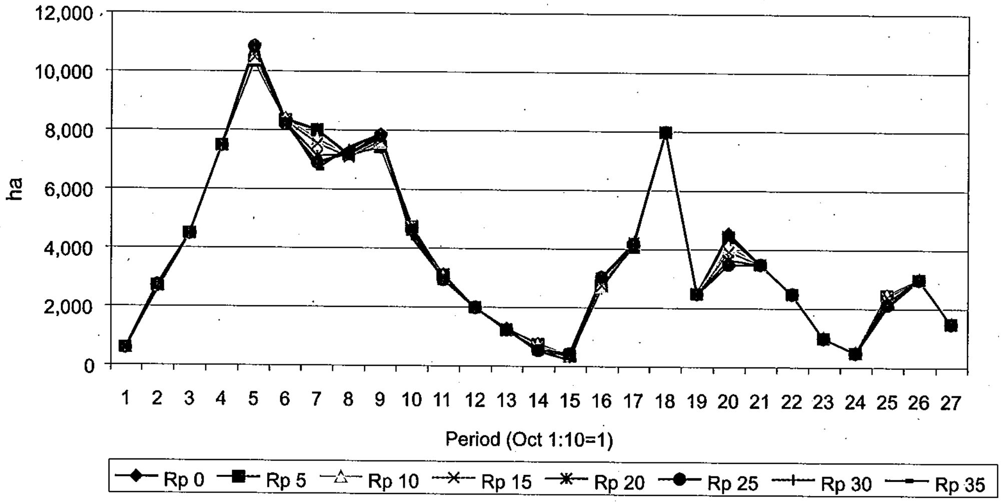


Table 6. Structure of costs and revenues, water charge.

	Rp 00	Rp 05	Rp 10	Rp 15	Rp 20	Rp 25	Rp 30	Rp 35
Gross revenue in Rp million								
Paddy	592,994	591,730	589,307	587,497	584,498	582,925	581,847	580,250
WS paddy	396,448	395,723	394,846	393,869	392,529	391,952	391,146	390,135
DS1 paddy	196,547	196,007	194,461	193,628	191,969	190,973	190,701	190,115
Polowijo	442,540	442,906	443,990	443,782	444,724	444,905	445,292	445,548
Maize	396,278	396,481	397,028	396,584	397,273	397,240	397,830	398,380
Soybean	25,829	25,856	26,085	26,136	26,317	26,585	26,586	26,435
Groundnut	20,432	20,570	20,877	21,062	21,134	21,080	20,877	20,733
Sugarcane	546,615	547,760	549,327	551,892	554,579	556,278	557,501	559,396
Costs of cultivation (excluding water) in Rp million								
Paddy	296,119	295,457	294,198	293,375	291,909	291,153	290,688	289,918
WS paddy	193,937	193,578	193,143	192,707	192,081	191,846	191,473	190,989
DS1 paddy	102,182	101,879	101,055	100,668	99,828	99,306	99,215	98,928
Polowijo	207,328	207,544	208,095	207,924	208,444	208,506	208,796	209,021
Maize	184,774	184,916	185,266	185,011	185,456	185,437	185,817	186,185
Soybean	13,027	13,037	13,123	13,147	13,200	13,303	13,309	13,234
Groundnut	9,527	9,591	9,706	9,766	9,788	9,766	9,670	9,602
Sugarcane	266,750	267,446	268,398	269,956	271,589	272,621	273,364	274,515

Continued

Table 6. Continued.

	Rp 00	Rp 05	Rp 10	Rp 15	Rp 20	Rp 25	Rp 30	Rp 35
Water charges (Rp million)								
Paddy	0	3,869	7,700	11,511	15,244	18,991	22,726	26,410
WS paddy	0	1,896	3,784	5,663	7,526	9,396	11,233	13,046
DS1 paddy	0	1,974	3,916	5,848	7,718	9,595	11,492	13,364
Polowijo	0	1,701	3,411	5,115	6,833	8,550	10,269	11,994
Maize	0	1,395	2,790	4,179	5,574	6,964	8,374	9,788
Soybean	0	214	432	649	871	1,102	1,322	1,544
Groundnut	0	92	189	288	388	484	573	662
Sugarcane	0	1,243	2,495	3,762	5,043	6,324	7,606	8,909
Net crop value (Rp million)								
Paddy	296,876	292,403	287,409	282,611	277,345	272,781	268,433	263,922
WS paddy	202,511	200,249	197,918	195,498	192,922	190,709	188,439	186,100
DS1 paddy	94,365	92,154	89,491	87,112	84,423	82,072	79,994	77,822
Polowijo	235,212	233,661	232,484	230,743	229,447	227,849	226,227	224,533
Maize	211,504	210,169	208,973	207,394	206,243	204,839	203,639	202,407
Soybean	12,803	12,605	12,530	12,341	12,245	12,180	11,955	11,657
Groundnut	10,905	10,887	10,981	11,009	10,958	10,830	10,633	10,469
Sugarcane	279,865	279,071	278,435	278,174	277,947	277,333	276,530	275,971

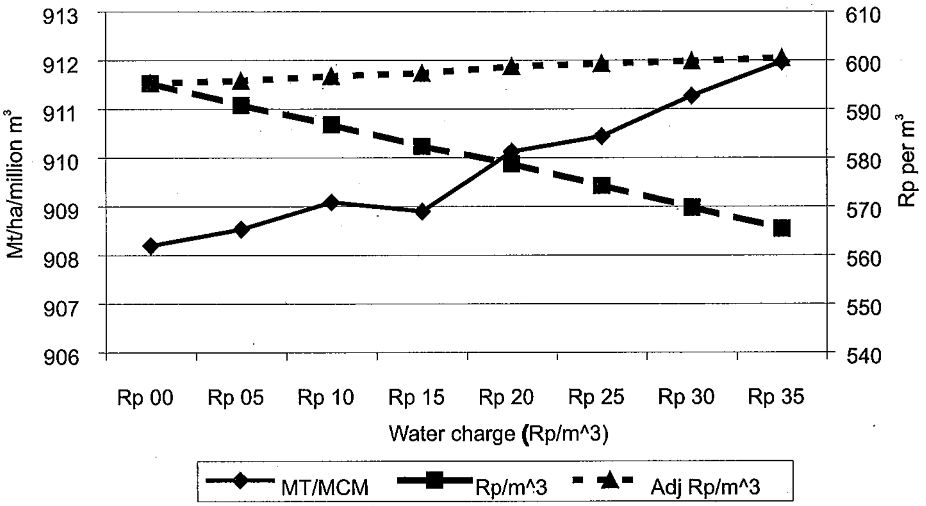
Table 7. *Water as a cost of production.*

	Rp 00	Rp 05	Rp 10	Rp 15	Rp 20	Rp 25	Rp 30	Rp 35
Water costs in (Rp/ha)								
Paddy	0	36,756	73,454	110,129	146,583	183,114	219,488	255,752
WS paddy	0	27,501	55,018	82,522	110,035	137,573	164,807	191,896
DS1 paddy	0	54,314	108,639	162,903	216,794	270,954	324,836	378,799
Polowijo	0	16,150	32,285	48,428	64,532	80,682	96,823	113,051
Maize	0	15,756	31,463	47,181	62,814	78,495	94,236	109,989
Soybean	0	19,263	38,535	57,702	76,958	96,351	115,497	135,455
Groundnut	0	16,207	32,787	49,487	66,555	83,231	99,648	116,032
Sugarcane	0	51,131	102,242	153,283	204,249	255,180	306,076	356,997
Water costs as % of total costs of cultivation								
Paddy	0.0	1.3	2.6	3.8	5.0%	6.1%	7.3%	8.3%
WS paddy	0.0	1.0	1.9	2.9	3.8%	4.7%	5.5%	6.4%
DS1 paddy	0.0	1.9	3.7	5.5	7.2%	8.8%	10.4%	11.9%
Polowijo	0.0	0.8	1.6	2.4	3.2%	3.9%	4.7%	5.4%
Maize	0.0	0.7	1.5	2.2	2.9%	3.6%	4.3%	5.0%
Soybean	0.0	1.6	3.2	4.7	6.2%	7.6%	9.0%	10.5%
Groundnut	0.0	1.0	1.9	2.9	3.8%	4.7%	5.6%	6.5%
Sugarcane	0.0	0.5	0.9	1.4	1.8%	2.3%	2.7%	3.1%

fraction of input costs. These numbers embody the attempts farmers make to minimize the burden of increasing water charges, however limited in this case.

We are finally interested in water use efficiency. Figure 13 depicts the physical output in metric tons per hectare per million cubic meters delivered to the field, which is the basis of the hypothetical water charge in this model, as a function of water charge. This is seen to increase, as a consequence of improved physical efficiency induced by the water charge. Figure 13 also depicts the net returns in rupiah per cubic meter, also aggregated over all crops. This is seen to decline, reflecting the water charge as an increasing cost of production. However, when water charges are added to net income, reflecting the fact that these fees are essentially transfers of wealth from one party (farmer) to another (some institution), we see a modest increase in the implicit value of water in irrigated agriculture induced by the increasing cost of the resource.

Figure 13. Water-use efficiency and net returns as affected by water price.



Conclusion: Policy Modeling Scenarios

The development of the integrated model of the Brantas basin is not an end in itself, but rather provides a tool by which to accomplish the broader objectives of the project. The value of the policy-simulation model output will be highest when it is used to explore scenarios for which a conventional, pro forma benefit-cost analysis is either unfeasible or likely to yield biased results through failure to anticipate the situation dynamics correctly. The benefits of scenario-driven policy simulation are not limited to the public agencies responsible for planning and implementing basin-scale water-resources strategies. Policy modeling offers, in addition, a means by which each community of stakeholders can anticipate how their interests are likely to be affected by proposed policies, and an opportunity for these communities to participate in strategic water-resources planning, through the participatory development of these scenarios.

There are four items on our current policy-simulation agenda. They are a) an evaluation of the relationship between water-charge and cost-recovery policy and the economic health of the irrigated agriculture sector, b) an analysis of the impact of varying levels of expenditures on the operation and maintenance (O&M) of hydraulic infrastructure, c) a cost-benefit analysis of the construction of two proposed new dams in the Brantas, and d) an evaluation of proposed institutional reforms, including the establishment of property rights in water and the creation of water markets. These items are seen to be extensively interrelated. A brief justification for each follows.

The first analysis, an evaluation of the relationship between water-pricing policy and the economic health of the irrigated agriculture sector, is a primary objective of IFPRI/ADB RETA 5866. The technical assistance is predicated on the observations that within many regions of East and South Asia, and in the Brantas, demand is increasing for both agricultural commodities and freshwater resources, competition is increasing between the agriculture and nonagriculture sectors for available freshwater, the performance of irrigation infrastructure is in decline, new irrigated area is increasingly expensive to develop, and foreign direct assistance will not continue at historical levels. All of these developments represent implicit or explicit threats to the economic well-being of the agricultural community. While it is clear to many that the long-term interests of the agricultural community are not well served by the ongoing, heavy subsidy of water, it is equally clear that farmers cannot outbid new industrial and municipal users (and possible others) for increasingly scarce supplies. We can use policy simulation to explore a range of water-charge structures and cost-recovery mechanisms, in terms of overall efficiency and with particular emphasis on the well-being of the irrigation sector.

The second objective, an analysis of the impact of varying levels of expenditures on the O&M of hydraulic infrastructure is, in many respects, a specific component of the first. The link between the progressive underfunding of irrigation system O&M and the subsequent deterioration of system performance relative to design standards have been recognized for over a decade (see, e.g., Easter 1999). Nevertheless, we still have too little internally consistent data on the two processes to perform a conventional benefit-cost analysis, which would allow the design of financing arrangements that are optimal jointly to farmers and public agencies, and which reflect a long-term commitment to financial self-sufficiency in the irrigation sector. Pioneering simulation work on evaluating system maintenance versus early rehabilitation strategies has been done by Skutsch (1998, 1999), but this study has greatly simplified the relationship between maintenance investment, system efficiency and overall system productivity. We intend to perform an analysis at the river-basin level, in which the relationship between levels of investment and efficiency over time can be made explicit. This approach will allow farmers to respond to varying levels of irrigation-service quality, and will help them to determine which level of maintenance is optimal, and how it can be financed.

The model's ability to simulate the addition of new infrastructure within the basin hydrosystem will permit us to perform an ex ante analysis of the benefits associated with constructing two new dams and power plants within the Brantas. JICA (1998) has identified two proposed projects, Beng and Kedung Warak, as potentially cost-effective. These multipurpose structures would contribute an additional 150-200 MCM of usable storage to the basin. They are pump-and-store systems, however, and the anticipated economic viability of these projects is highly sensitive to estimates of growth in demand and willingness to pay for water, primarily by domestic and industrial users. We will simulate the economic performance of these proposed structures under a range of scenarios concerning both demand and climatic input.

Finally, we can use policy simulation to investigate the feasibility of several institutional reforms proposed under the World Bank-supported WATSAL (Water Resources Sector Adjustment Loan) process, initiated in 1999 (World Bank 1999) to support water-sector reforms in Indonesia. The proposed reforms associated with WATSAL are sweeping, but two in particular would benefit strongly from ex ante policy simulation and analysis. Under objective b), "Strengthening of the institutional and regulatory framework for integrated and equitable river basin management," a specific adjustment outcome is "Establishing a national framework for an enforceable water use rights system for surface and groundwater allocation, and a uniform framework of water abstraction licensing by provincial governments." Under objective d), "Improving the performance and sustainability of irrigation systems," outcomes include "Adopting a national framework for the establishment by district governments of autonomous and self-financing water user associations (WUAs) and water user association federations (WUAFs) to manage irrigation networks" and "Implementing a nation-wide Irrigation Service Fee framework for sustainable financing of operation, maintenance and asset amortization of irrigation schemes by the local government, WUAs and WUAFs" (1999, ii). During this period of water-sector reform, the value of information is extremely high, and policy simulation can be a tool of great value.

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