CHAPTER 9

Integrated Economic-Hydrologic Modeling of the Brantas Basin, East Java, Indonesia: Issues and Challenges

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Introduction: Motivation for the Modeling Study

This paper describes the integration of economics, hydrology and policy simulation in a unified, basin-scale model applied to the Brantas basin, East Java, Indonesia. The paper has four primary objectives. The first objective is to provide a context and a justification for integrated model development within the broader framework and objectives of the Indonesian component of the project titled "Irrigation Investment, Fiscal Policy, and Water Resource Allocation in Indonesia and Vietnam." This study is funded by the Asian Development Bank (ADB) and conducted by the International Food Policy Research Institute (IFPRI) and its Indonesian partners: Perum Jasa Tirta, the Center for Agricultural and Socioeconomic Research (CASER), and the Directorate General of Water Resources Development (DGWRD). The second objective of the paper is to describe current conditions in the water sector within the Brantas basin, and to relate these conditions to project objectives. The third is to provide a summary description of the integrated approach to basin-scale modeling. The fourth, and most important, is to describe the development, structure and application of such an integrated economic-hydrologic-policy simulation model for the Brantas basin. As the project is still in its early stages, there can be no discussion of results except to give a description of the process.

In describing the development of this model, we will highlight several issues and challenges we have encountered to date that will be, hopefully, broadly relevant to practitioners of integrated watershed modeling in other locations as well. This paper is intended to complement the paper by Sunaryo (2000), included in these proceedings. Sunaryo (2000) describes the history of water resources development in the Brantas basin, as well as the legal and institutional framework and guiding principles.

The IFPRI/ADB study is motivated by several critical and interrelated factors currently affecting many emerging economies of South and East Asia, and the Brantas basin specifically.

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These include: a) increasing demand for both agricultural commodities and freshwater resources; b) increasing competition between the agricultural and nonagricultural sectors for available freshwater; c) deterioration of irrigation infrastructure and escalating costs of developing new irrigation capacity; and d) deterioration of water quality as a consequence of both agricultural and nonagricultural activities. Effective physical limits to freshwater resources in many Asian basins, as in the Brantas, dictate that institutional reform and alternative economic incentives and policy strategies are required to cope with increasing scarcity and competing inter-sectoral demand. The project is designed to assist national and regional policy makers and river basin authorities to make appropriate policy decisions for the development and allocation of water resources, and to establish priorities for the reform of institutions and incentives that affect water resource allocation, particularly the irrigation sector.

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). The focus of this paper is on the third component, although it must be emphasized that the integrated basin model is a tool to accomplish the broader objectives of the project, and not an end in itself.

The basin-level component a) consists of technical and institutional analyses of alternative water allocation mechanisms and their impacts on agricultural productivity, growth and sustainability, and on environmental quality within the basins. Basins selected for detailed study are the Brantas in East Java, Indonesia, described in this document, and the Dong Nai basin in southern Vietnam, described in a companion paper prepared for this workshop (Ringler et al. 2000). The specification, testing and application of formal (mathematical) models integrating basin hydrology, economics and policy scenarios are key components of the basin-level studies. The national-level component b) consists of a complementary analysis of national tax policies that influence irrigation development, operations and maintenance; of agricultural input and output pricing policies; and of trends in public expenditures for irrigation and water resources. The structure and approach of the project are predicated on the observation that national fiscal policies can act to either reinforce or mitigate effects of policies at the basin level. An integrated approach is believed to be particularly relevant in evaluating the feasibility of using direct water charges to recover irrigation costs. If irrigated farmers are heavily taxed through general fiscal and price policies, effective irrigation cost recovery through direct water charges will be much more difficult to achieve.

Two points deserve emphasis. First, that the modeling approach is explicitly predicated on principles adopted at the 1992 United Nations Conference on Environment and Development held in Dublin, specifically that *Water development and management should be based on a participatory approach, involving users, planners, and policymakers at all levels* for which the river basin provides the appropriate framework, and that *Water has an economic value in all its competing uses and should be recognized as an economic good* (Calder 1999, 52). The comparative evaluation of policy instruments is correspondingly based on the collective economic benefit generated under each policy scenario, appropriately

constrained to reflect social norms and the statutory environment. Second, that the viability of the irrigated agriculture sector is of paramount importance to the authors and sponsors of this study, as consistent with the mission of IFPRI and the CGIAR: to increase agricultural productivity, protect the environment and alleviate poverty.

Basin Profile and Description of Major Water-Sector Issues and Challenges

Physical Setting and Description of the Brantas Basin

The Brantas basin lies entirely within the Province of East Java, Indonesia between east longitudes 110^0 30' and 112^0 55' and between south latitudes 7^0 01' and 8^0 15'. The basin, approximately 12,000 km^2 in area, is bracketed by volcanic massifs, and contains two active volcanoes: Mt. Semeru to the east, and Mt. Kelud near the basin center. Mt. Semeru is continuously active, although eruptions are not cataclysmic and most ash falls outside of the Brantas basin. Mt. Kelud has been active in approximately 15–year cycles in recent decades, most recently in 1990, and eruptions have had catastrophic consequences on occasion. Risk of civil disaster from volcanic eruptions is a major concern in the basin. Volcanic ash is both a major source of soil fertility and a primary cause of reservoir sedimentation. Basin geology consists of tertiary formations including basalts and andesites in the volcanic uplands, marine limestone underlying the plains and deltaic areas and consolidated volcanic ash throughout. The plains and the delta consist of alluvial soils (silt, clay loams) well suited for paddy cultivation.

The basin lies within the Intertropical Convergence Zone, in which the semiannual reversal of prevailing winds results in distinct wet (November–April) and dry (May–October) seasons. During the wet season, there are around 25 rainy days per month, compared to 7 or fewer during the dry season. Annual precipitation is around 2,000 mm on average, with roughly 80 percent occurring in the wet season. The mean annual temperatures range from 24.2 ^{0}C at Malang (elevation 450 m asl) to 26.6 ^{0}C at Porong in the delta, and relative humidity varies seasonally from 55 percent to 95 percent.

Figure 1 shows the Brantas basin and its primary topographic and hydrologic features. The Brantas river is approximately 320 km long, and has its headwaters in the Arjuno volcanic massif, a major topographic feature dominating the southeast-central portion of the basin. It courses clockwise around the massif, first south through the Malang plateau (elevation 400 m asl), then west through the major dam and reservoir complex consisting of Sengguruh, Sutami/ Lahor, Wlingi, and Lodoyo, respectively. At the confluence with the Ngrowo river in the Southwestern portion of the basin, the Brantas turns north through the agriculturally productive plains region and finally east through the delta, also an important paddy-growing area, where it discharges into the Madura Strait. Primary tributaries above the delta include the Lesti (southeast), Ngrowo (southwest), Konto (central), and Widas (northwest) rivers. The Upper Brantas channel slopes are relatively steep (>0.005); and much more gentle lower in the system ($\leq$0.001).

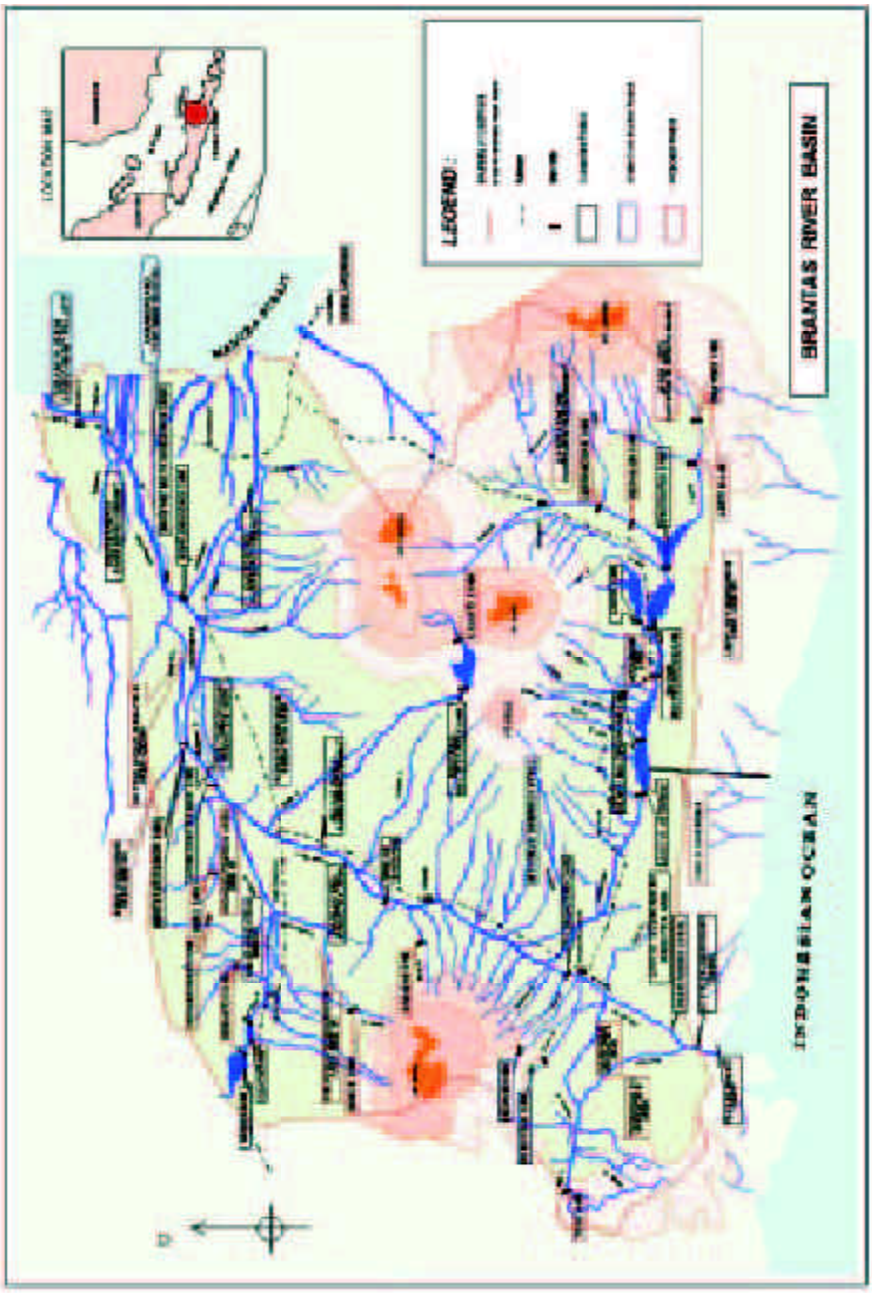

Figure 1. Map of the Brantas basin showing key features.

The Brantas enters the delta downstream (east) of Mojokerto, where it is regulated by the New Lengkong barrage (NLB). The barrage, reconstructed in 1973 on the site of a structure of the colonial era, partitions the Brantas into four major channels: the Surabaya and Porong rivers and the Porong and Mangetan canals. The canals provide irrigation for the extensive agriculture in the deltaic region. The Porong river essentially serves as a floodway and the Surabaya river serves as the primary water supply to the major port city of Surabaya. Within the Surabaya city, the Surabaya river further bifurcates into the Mas and Wonokromo rivers. Discharge at NLB is entirely controlled by gated structures, and the barrage is the lowest point on the Brantas system at which the main stem discharge can be measured directly. Annual discharge at NLB averages around 250 m^3/s, with a strong seasonal cycle reflecting the seasonality of precipitation. Measured, reconstructed and estimated discharges at NLB are summarized in table 1.

The agricultural economy of the basin is centered on the cultivation of paddy, nearly all of which is irrigated. Other important food and cash crops include maize, cassava, soybean, peanut, tobacco, coffee and sugarcane. Dry-footed crops grown primarily in the dry season, including maize, soybean and peanut, are collectively known as polowijo. Prevalent rotations include paddy-paddy-polowijo, paddy-paddy-fallow, and paddy-polowijo-other. Table 2 summarizes the harvested area, production and value of agricultural produce within the Brantas basin for 1995.

Table 1. Mean annual discharge, specific discharge and basin yield ratios, Brantas river at NLB (8,444 km^2).

Study	Mean Annual Discharge (Q) m^3/sec.	Specific Q m^3/sec. per 100 km^2	Equivalent Depth mm	Yield Ratio Runoff/ Precipitation	Period of Data Gathering
SRPCAPS					
Natural, 1999	257	3.04	960	0.52	1970–1996
JICA II Natural 1998	238	2.82	889	0.48	1977–1996
Van der Weert 1994	163	1.93	721	0.39	na
SRPCAPS					
Measured 1999	233	2.76	870	0.47	1971–1997

Major Water Management Issues and Challenges in the Brantas Basin

Irrigated agriculture is by far the largest consumptive use of water in the Brantas, currently consuming around 19 percent of the total annual discharges and 72 percent of annual discharges utilized consumptively or nonconsumptively. Other significant withdrawals are made by municipal and industrial users. Aquaculture in the delta utilizes residual and return flows. A significant quantity of hydropower is generated within the basin, and flushing flows are required to maintain standards of water quality, particularly in the region below the NLB. Brantas water is used recreationally as well. Summaries of water use by sector appear in table 3. Recent major studies of water management in the basin, particularly the Master Plan IV (JICA 1998) and the SRPCAPS (Binnie and Partners 1999) have identified several issues as the

Table 2. Harvested area, production, yield, and value at wholesale of important crops, Brantas basin.

Commodity	Harvested Area (ha)	Production (MT)	Yield (MT/ha)	Wholesale Price (Rp/MT)	Value at Wholesale (M Rp)	Percent of Total
Total paddy	433,703	2,260,670	5.21	455,229	1,029,123	55.35
Wetland paddy	422,471	2,223,495	5.26			
Dryland paddy	11,232	37,175	3.31			
Maize	239,039	945,198	3.95	377,735	357,034	19.20
Cassava	55,170	884,947	16.04	157,437	139,323	7.49
Sweet potato	5,310	71,251	13.42	227,954	16,242	0.87
Peanut	19,104	20,606	1.08	1,450,000	29,879	1.61
Soybean	67,659	82,408	1.22	1,136,130	93,626	5.04
Mung bean	8,423	8,030	0.95	280,000	2,248	0.12
Cashew	8,781	1,543	0.18	7,500,000	11,570	0.62
Coconut	85,030	87,948	1.03	314,694	27,677	1.49
Coffee	19,095	8,439	0.44	4,640,000	39,157	2.11
Clove	16,550	4,407	0.27	2,950,000	13,001	0.70
Kapok	19,648	6,897	0.35	400,000	2,759	0.15
Cotton	90	51	0.57	320,000	16	0.00
Tobacco	9,913	21,003	2.12	3,430,000	72,039	3.87
Tea	342	539	1.58	2,800,000	1,510	0.08
Sugarcane	94,630	592,627	6.26	40,000	23,705	1.27
Cacao	2,297	246	0.11	1,340,000	330	0.02
Total	1,084,784	4,996,810			1,859,240	

Notes: 1. Basin totals have been defined in terms of the 9 Kabupaten and 5 Kotamadya located totally or partially within the Brantas basin. Of these, Kabupaten Trenggalek lies partially outside the basin so that numbers appearing in the table are biased upward.
2. Source of production figures: Province of East Java (1999) Jawa Timur Dalam Angka 1998; for year 1998.
3. Source of wholesale prices: www.fao.org, market wholesale prices for year 1995 (latest available).

Table 3. Summary of water withdrawal estimates, million m^3/year.

Category of Use	JICA	JICA[a]	SRPCAPS	WRMM	GSAS
Irrigation	2,138.0	1,943.2	1,929.57	2,067.0	3,192.7
Domestic	470.6	108.0	421.40	207.0[b]	421.1
Industrial	215.0	104.0	255.00	118.0	142.8
Fisheries	16.7	40.8	NA	NA	NA
Flow augmentation	0.0	0.0	236.52	315.0	272.5
Total abstractions	2,840.4	2,196.0	2,842.5	2,707.0	4,029.1

[a]Direct surface abstractions only; excludes groundwater use and transfers.
[b]PDAM only; excludes non-PDAM rural withdrawals.

primary challenges currently facing water-resources managers in the Brantas, as discussed in the following sections.

Water quantity

The quantity of water available in the dry season is currently barely sufficient to meet existing demand, particularly when in-stream water quality objectives are considered. This is particularly (but not exclusively) a concern in the high-consumption region below the NLB, which includes the Brantas deltaic irrigation systems, the Greater Surabaya municipal area and a high percentage of the Brantas basin industries. In dry years such as 1997, fully 100 percent of Brantas flows reaching the NLB are utilized. This current level of dry-season utilization also fails to reflect the large percentage of the existing population that is currently not served, or served poorly by the PDAMs (municipal water supply companies). According to SRPCAPS 1999, in 1995 only around 2 million of the basin's 14 million residents were served directly by the PDAMs via either house connections or standpipes. Demand is increasing as a function of growth in both population and income, and the potential for recycling return flows below the NLB is limited. On an annual basis, however, the Brantas is not fully allocated, a substantial amount of the wet season flow entering the Madura Strait unused. This reflects both the strongly seasonal distribution of runoff and the limited extent of reservoir storage within the basin. Active storage within the basin's eight reservoirs is currently around 360 million m^3, equivalent to only 3–4 percent of the annual discharge.[2]

Water quality

Water quality in the Brantas-Surabaya is often poor, leading to adverse impacts on both public health and economic development. Zones of particularly poor quality of water include the reach immediately downstream of Malang and the Lower Brantas-Surabaya area. Problems of water quality are currently primarily related to biochemical oxygen demand (BOD) from domestic waste and industry. Problems are not limited to dry-season flows. Significant elevations in BOD have been observed during wet-season runoff, suggesting that animal and other wastes accumulate during the dry season and are mobilized during the wet season. Mobilization of contaminated sediments by wet-season flushing flows is also suspected.

Sedimentation of reservoirs

Volcanic activity occurs both continuously (Mt. Semeru) and episodically (Mt. Kelud) in and around the Brantas basin, resulting in the deposition of large quantities of ash. Volcanic sediment is a primary source of reservoir sedimentation, with Mt. Kelud deposits adversely

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[2]One m^3/sec. per year is equal to 31.5 million m^3 of storage. Thus, 360 million m3 is equivalent to roughly 11.4 m^3/sec. continuous discharge on an annual basis, or 23 m^3/sec. flow continuous augmentation over the dry season.

affecting Wlingi and Lodoyo reservoirs, and Mt. Semeru deposits affecting Sengguruh and Sutami, respectively. It has been estimated that the Sutami reservoir has lost nearly 50 percent of its gross storage and 40 percent of its active storage since its construction in 1972 due to sedimentation. The Sengguruh reservoir, which was completed in 1988 primarily to serve as a sediment trap for Sutami, has lost over 80 percent of its original gross storage (JICA 1998). New storage is considerably more difficult and expensive to develop than were existing reservoirs.[3] Solutions to the ongoing problem of reservoir sedimentation involve expanded upland conservation efforts, such as the Sabo (check-dam) development and rehabilitation occurring on Mt. Kelud.

Low water-use efficiency

In 1999, SRPCAPS estimated that overall efficiency of irrigation water use is quite low in the Brantas delta, around 27 percent, and this inefficiency contributes to the frequently observed water shortages in this region. Overall efficiency is defined as the combined effect or product of intake efficiency, system operating efficiency and on-farm (tertiary unit) efficiency. Return flows in the delta cannot in general be reused, although they may provide flushing flows to the brackish fishponds. Inefficiencies for irrigation systems above the NLB have less-profound consequences, since most return flows from upstream systems can be recycled in the delta and Surabaya. Primary factors contributing to inefficiency include poor timing of deliveries and deteriorating infrastructure. Domestic water use efficiency is also low, with system losses in the Surabaya area estimated to be 30–45 percent of gross deliveries.

Poor cost recovery in irrigation

Indonesian farmers do not pay directly for irrigation water, as domestic (PDAM) and industrial users do. Ramu (1999) notes the fact that PJT's revenues are largely derived from the sale of water to nonagricultural users creates an allocation bias against agricultural users. Although an irrigation service fee (ISF) system exists, collections are sporadic and insufficient to cover irrigation-related operation and maintenance (O&M). Under current ISF, farmers are charged a fixed amount per hectare per season depending on the crop grown (US$1=Rp 9,450), so that no incentive exists for increased efficiency. JICA (1998) has estimated that PJT would need to levy a volumetric water charge of Rp 25/m^3 to recover both irrigation investment and recurring O&M costs, an amount only slightly below the corresponding municipal water charge (Rp 30/m^3).[4] The observation that many farmers within the Brantas surface irrigation systems invest in powered pump sets to augment surface water deliveries demonstrates that they are not unwilling to pay for irrigation water, however, provided that the timing and quantity correspond to their cropping requirements.

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[3]JICA (1998) estimated the unit water costs for five proposed dams, which range from Rp. 890 to Rp. 2,200 per cubic meter at current June 1997 prices, assuming a 12% discount rate.

[4]Prices ca. June 1997.

Conflicting and overlapping institutional responsibilities

Numerous State, Provincial, *Kabupaten/Kotamadya* (district/municipal), and local agencies are involved in planning and managing water and related land resources in the Brantas basin. The theoretical guiding principle of *One River, One Plan and One Integrated Management* is thus violated to some extent in practice. For example, while PJT provides bulk water to irrigation systems located on the Brantas and main tributaries, it does not operate or manage these systems; this is done by the Provincial or District Water Resources Service (under Public Works, now KIMPRASWIL). JICA (1998) describes a number of additional cases where tasks are duplicated, or where a given agency's mandate is obscure. In addition, the Republic of Indonesia is in the process of implementing an ambitious program of decentralization (regional autonomy). The consequences of decentralization on basin water management are not yet clear, but some PJT staff members have voiced concern over the potential for conflict and inconsistency in water allocation and management practices.

Availability and consistency of data

The quantity and coverage of hydrologic and socioeconomic data for the Brantas basin is, at first inspection, reasonably complete and extensive. However, there are indications that certain important variables, including reservoir inflows and channel discharges, are subject to bias due to changes in stage-storage relationships or channel cross-sectional profiles, both due to sedimentation and/or scour. Low-flow discharge measurements are, in many cases, known to be poor or nonexistent due to the location and elevation of stilling wells. Irrigation return flows are not measured, and must be reconstructed using water balance accounting.

Integrated Economic-Hydrologic Modeling and Policy Analysis

Overview of the Integrated Economic-Hydrologic Model

The integration of economics and hydrology within a common, holistic modeling framework is justified by several factors. First, multi-objective optimization modeling, often integrated with simulation modeling, is a tool of established value to both water engineers and agricultural economists, and the language of mathematics is common to both. Second, advances in computing power, along with the development of increasingly powerful and efficient optimization algorithms, permit the solution of increasingly complex models. Third, the river basin provides a natural framework for the analysis of both hydro-systems and water-based economies. Fourth, the two disciplines are extensively interpenetrated, as water enters as a factor of production in many economic processes, and economic factors are primary drivers of design and decision making in water resources engineering. Finally, the need to anticipate the impacts of new economic policies in the water sector requires integrated modeling, given that policy experiments, if actually implemented on a broad scale, would require years to yield meaningful interpretation, and might involve considerable political risk. A state-of-the-art review of integrated economic-hydrologic modeling at the basin scale is

provided by McKinney et al. (1999) and will not be duplicated here. Interested readers can find this document on-line at IWMI's website as SWIM Paper No. 6. An application of the integrated model to the Maipo basin in Chile is described in Rosegrant et al. 2000, which is also available on-line at IFPRI's website as EPTD Discussion Paper No. 63. An additional application of the modeling approach in the Aral Sea region is described in McKinney and Cai 1997.

The integrated economic-hydrologic-policy analysis model (henceforth called "integrated model") being developed for the Brantas basin is based on the Maipo model (Rosegrant et al. 2000), but it is anticipated to differ in many respects, reflecting differences in the respective hydrosystems and agricultural economies. The model structure outwardly resembles a conventional network flow optimization model, such as WRMM (Binnie and Partners 1999). Model nodes, which represent sources 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.) are linked via spatially permissible flow paths, which can represent natural or artificial channel reaches. Inflows to the system, including effective precipitation, are model boundary conditions, and storage, channel and spillway capacities are model constraints.

The integrated model differs from a standard network flow model in many key respects, however. Demand for water by sector and by location is endogenous to the integrated model, and it represents the interaction of technical/economic water production or utility relationships in agriculture, industry and households with the costs of delivering water to each potential consumer under assumptions concerning the structure of water pricing, entitlements, public institutions, social custom and law. Thus, for example, decisions concerning the type and area of crops planted in an irrigation system during a particular season are decision variables within the integrated model, and not simply assigned ex ante. In addition, surface-water-groundwater interactions are made explicit, and aquifers are included as points of inflow, storage, recharge and abstraction. In the Maipo version of the integrated model (Rosegrant et al. 2000), water quality (specifically salinity) and its impact on agricultural productivity were also included, although the role of water-quality simulation in the Brantas basin model has yet to be determined. The integrated model is structured and intended to go well beyond the customary approach of optimization models, which tend to focus on traditional engineering ("hard") solutions such as the reoperation of reservoir facilities. It is designed to evaluate nonstructural-, noncontrol-based ("soft") approaches to the optimization of benefits as well, including the pricing of water, establishment of water use rights and related policy and institutional changes.

The objective function of the integrated model is the combined, net water-generated revenue function for the basin. This unified objective function takes the generic form:

$$Max\{Z\} = \sum_{irr} Z_{irr} + \sum_{ind} Z_{ind} + \sum_{mun} Z_{mun} + \sum_{hydro} Z_{hydro} + \sum_{fish} Z_{fish} \qquad (1)$$

where, *irr, ind, mun, hydro,* and *fish* refer to net benefits (profits) over irrigated agricultural, industrial, municipal, hydroelectric, and aquacultural demand sites, respectively. The negative

impacts of degraded water quality are assumed to enter into the net benefits functions as costs of treatment and/or production losses. Alternatively, water-quality objectives or standards can be incorporated directly as model constraints.

Each term in the objective function takes the general form of a profit function (Chambers 1988), emphasizing the contribution of water as a priced input: net revenue (benefit) equals gross revenue less variable costs associated with water:

$$Z_i = (y_i \cdot Py_i - w_i \cdot Pw_i) \tag{2}$$

where,

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

In equation (2), y may be a vector of outputs, and is assumed to be a function of multiple inputs of which water is always represented explicitly. The preliminary functional forms of several of the respective benefit (profit) functions are discussed subsequently.

Table 4 provides a summary classification of the integrated model in standard terminology (Singh 1995). The model is coded in the high-level language GAMS (General Algebraic Modeling System), which is coupled with the large-scale nonlinear optimization solvers MINOS and CONOPT (Brooke et al. 1998.) Model development is expected to follow a recursive process in which specification, testing, application and subsequent refinement take place concurrently. The process is depicted in figure 2, adopted from McKinney et al. 1999. The first stage of model development consists of the specification of a relatively simple network flow optimization model, which is intended primarily to verify hydrologic water balance. Validation at this stage consists of comparing integrated model output with the output of the existing WRMM (Binnie and Partners 1999) and RBAM (Optimal Solutions Ltd. 2000) network flow models of the Brantas basin, which are currently maintained by the PJT staff; and with historically observed reservoir levels and discharges. Subsequent versions will incorporate endogenous production decisions, surface-water-groundwater interactions, important tributary systems and water quality.

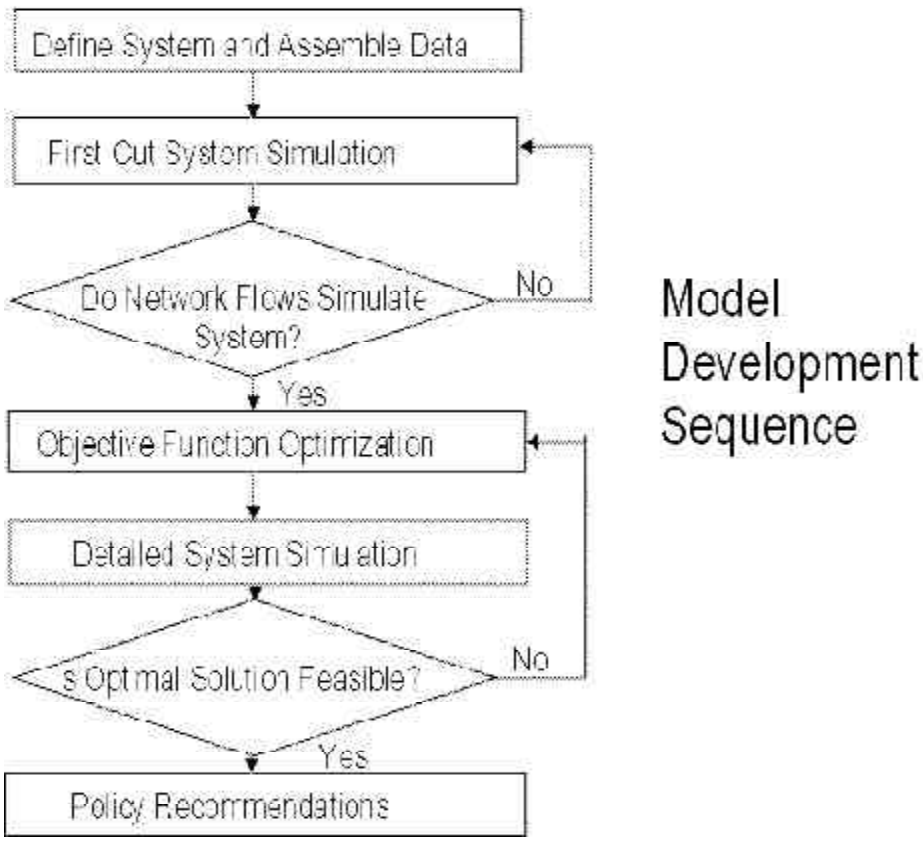
In the following sections, specific components of the integrated model will be described in some detail. Particular emphasis is given to the irrigated agriculture sector, which is of central importance in the study. In the first section, we discuss the representation of the physical system. The physical system is understood to consist of physical entities with explicit locations, including dams, reservoirs, power plants and demand sites; and physical relationships such as water balance, hydropower and water-production functions. The second section describes the economic aspects of the model, which consist primarily of benefit (profit) functions and attending parameters and assumptions describing economic behavior. The third section contains a brief discussion of economic incentives and policy strategies, and the means by which they are implemented within the model.

Table 4. Important attributes of the Brantas basin integrated model.

Model Attributes:	
Model type	Optimization + Simulation
Model structure	Modular, spatially distributed processes
Degree of integration	Holistic
Process description	Deterministic [a]
Spatial domain	Basin (12,000 km^2) + groundwater
Time domain	Multi-year planning horizon [b]
Time step	10–day
Governing equations	Algebraic
Objective function	Maximize net basin income derived from water [c]
Solution algorithm	Numerical, NLP
Language	GAMS/CONOPT/MINOS

[a]Possible to structure as chance-constrained.
[b]Single-year operational version also under development.
[c]Appropriate social and legal constraints apply.

Figure 2. Stages of integrated model development



Physical Components of the Model

The preliminary framework for the Brantas basin integrated model has been adapted from the existing WRMM and RBAM network flow models developed by Binnie and Partners as part of the SRPCAPS 1999 and by Optimal Solutions, Ltd. (2000). In this initial framework, only the Brantas main stem and the Ngrowo subbasin are included, surface- water-groundwater interactions are not included, water demand is exogenous, and economic relationships are not specified (the objective function is based on social priority weighting). Figure 3 depicts the schematic for this simplified model. The use of a simplified basin representation is predicated both on the need to establish a preliminary baseline calibration, and on the ready availability of hydrologic data consistent with the simplified system as assembled for the WRMM and RBAM projects. It must be emphasized that the final policy simulation model will be greatly expanded relative to the preliminary version.

Calculation of Natural Flows

The integrated modeling approach described here 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 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 time step takes the general form (time subscripts implicit):

$$Q^{n}{}_{i} = Q^{n}{}_{i-1} + \sum_{i-1}^{i} A - \sum_{i-1}^{i} R + \sum_{i-1}^{i} \frac{\Delta S}{\Delta t} + Q^{in}{}_{i} \qquad (3)$$

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

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

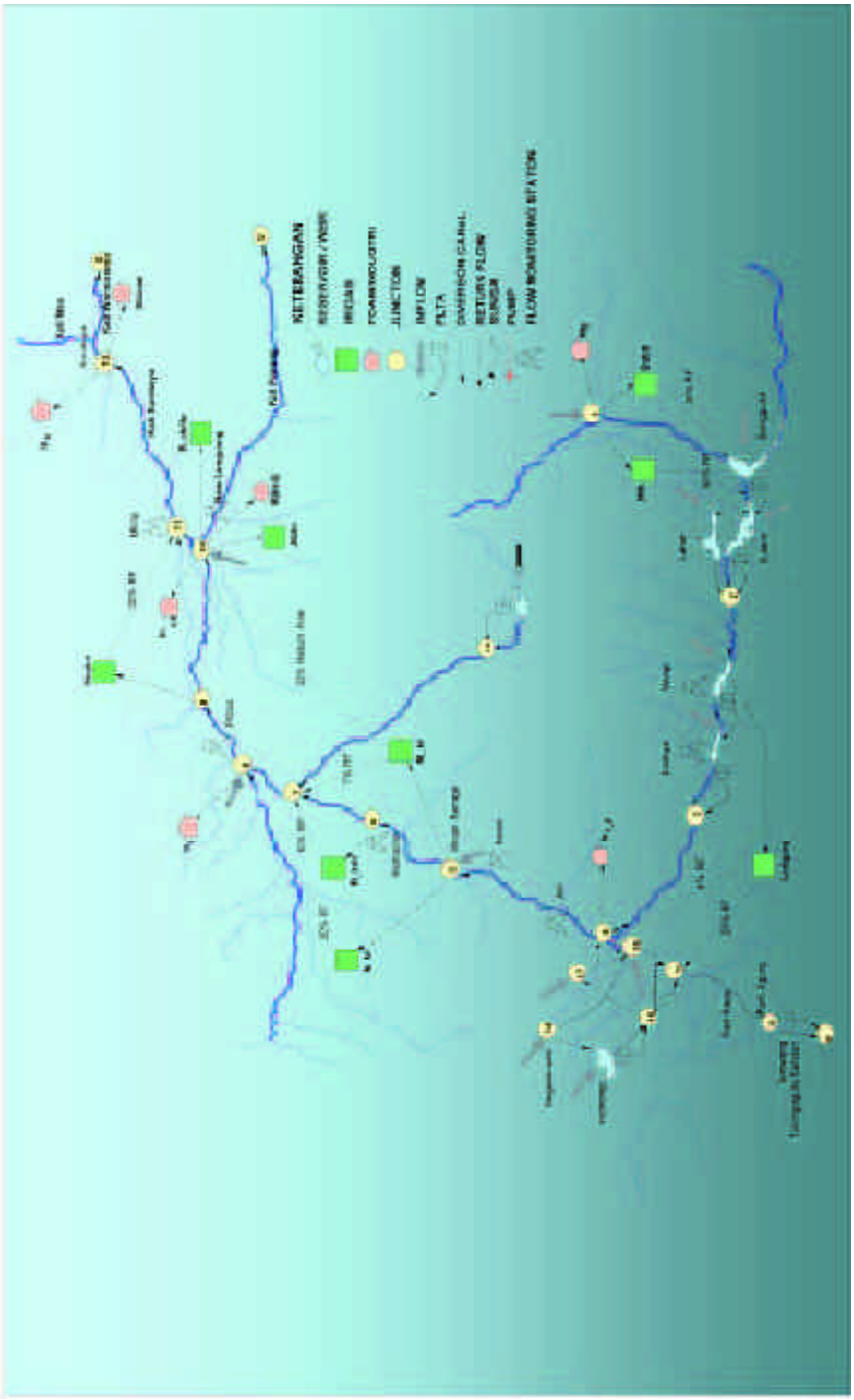


Figure 3. Model schematic of the Brantas main stem.

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 between nodes (i-l) and i	(m^3/sec.)
	ΔS	changes in storage between nodes (i-l) and i	(m^3)
	Δt	model time-step	(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] In addition, in 1999 SRPCAPS 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.

Reservoirs

The Brantas basin contains eight reservoirs or barrages having significant storage capacity (table 5). Total current active storage is approximately 350 million m^3, which is only around 3 percent of the total annual discharge of the Brantas, and 17–18 percent of dry-season flows. These are multipurpose facilities, providing flood control in the wet season, water supply and power generation. Operating rules differ by season and by forecast hydrologic regime (normal, low-, high-flow years) as determined by the Provincial Water Management Committee. Five of these reservoirs (Sengguruh, Sutami, Lahor, Wlingi and Lodoyo) are located in series on the Brantas Main Stem; Wonorejo is within the Ngrowo sub-catchment, Selorejo is in the Konto sub-catchment and Bening is within the Widas sub-catchment. The simplified model includes all reservoirs except Bening, so that less than 10 percent of the total basin storage is excluded from this first-cut model. In the context of the integrated model, reservoirs are described in terms of their respective water balances, stage-volume, and stage-area relationships, hydropower generating capacity and spillway constraints; and direct precipitation and evaporation are accounted for.

One hypothesis following from the relatively small volume of active storage in the basin relative to annual flows is that strategies to optimize the productivity of water will not depend to any great extent on reservoir reoperation, since the scope for reoperation is simply too limited. In the long run, effective storage within the basin will probably have to be increased, although very few suitable (low-cost) sites remain. JICA (1998) evaluated several proposed dam and reservoir construction projects, and concluded that three of these are financially justifiable given current and projected economic conditions. These projects (Beng, Genteng 1 and Kedungwarak dams), when completed, would add around 270 million m^3 to available collective storage within the basin (JICA 1998). This is a significant increase over current storage but the resulting collective storage would still be less than 10 percent of annual flows.

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

Table 5. Storage reservoirs in the Brantas basin in operation or under construction in 2000 (million m³).

Reservoir Name	Year Completed	Design Gross Storage	Design Effective Storage	Current Gross Storage	Current Effective Storage (SRPCA Estimate)	Year of Survey
Sengguruh	1988	21.50	2.50	3.37	1.17 (1.24)	1996
Sutami	1972	343.00	253.00	183.42	146.63 (153.1)	1997
Lahor	1977	36.10	29.40	32.88	26.54(26.85)	1995
Wlingi	1977	24.00	5.20	4.97	1.41(0.94)	1996
Lodoyo	1980	5.80	4.20	2.35	2.35(2.35)	1996
Selorejo	1970	62.30	50.10	48.76	44.51(44.5)	1993
Bening	1981	32.90	28.40	31.70	28.05(26.0)	1993
Wonorejo[a]	2001				106.00(83.0)	
Total [b]					356.66(337.98)	

[a]Effective=Design storage for Wonorejo is variously given as 106 Mm^3 and 89.4 Mm^3 in JICA II. The reservoir is currently filling and is expected to contribute to dry-season flows commencing 2001.

[b]Total includes Wonorejo.

Hydropower generation

The Brantas basin presently contains nine hydropower facilities, eight of which are currently operating. The location and capacity of these facilities are summarized in figure 3 and table 6. They are categorized 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):

$$P = C \cdot g \cdot Q \cdot h \cdot h \tag{4}$$

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. In practice, the design maximum generator output and corresponding head and discharge are known for each hydropower facility, and power generation can be calculated using the ratios of actual head and discharge to design values.

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 (1993).

Table 6. Hydropower generation capacity and annual output, Brantas basin.

Hydropower Facility	Peak Generating Capacity (kW)	Annual Power Output (Million kWh)
Sutami [a]	70,000	213.2
Tulungagung	36,000	184.0
Wlingi	54,000	164.98
Sengguruh	29,000	98.56
Lahor [b]	35,000	75.8
Wonorejo	6,500	31.7
Lodoyo	4,500	31.7
Selorejo	4,500	20.0
Bening [c]	650	1.9
Total	240,150	821.84

Source: Annex 1 in JICA.
[a]Sutami contribution to combined Sutami-Lahor output.
[b]Lahor contribution to combined Sutami-Lahor output.
[c]Annual output for Bening based on assumption of 8 hours per day at maximum output. Members of the PJT staff report that Bening is not currently producing power.

Municipal demand sites

Municipal water demand included in the integrated model is associated with the regional water supply companies, or *Perusahan Daerah Air Minum* (PDAM). There are 14 PDAMs in the Brantas basin, corresponding to districts (*kabupaten*) and municipalities (*kotamadya*). Some individual PDAMs such as Surabaya Kota operate multiple withdrawal and treatment plants. The majority of domestic water supply within the Brantas basin is obtained from sources other than PDAMs; however, only around 12 to 14 percent of the basin's residents are serviced directly by PDAMs (JICA 1998; SRPCAPS 1999). The rest of the residents obtain their domestic water supply from wells, irrigation canals and directly from the river.

Only PDAM abstractions will be included in the preliminary version of the model, however, and only those which are taken from the Brantas, as distinct from springs, wells and other sources not subject to administration by the river basin authority. The locations of these abstraction sites (Surabaya, Sidoarjo and Malang Kota) appear in figure 3.

Industrial demand sites

Approximately 215 million m^3 of water are used in industrial production (1996) of which around 130 million m^3 are abstracted directly from the Brantas, and the remainder obtained from groundwater, PDAMs and other sources. Around 95 industries abstract significant quantities of water, with sugar and paper industries using the largest quantities (58% and 22%, respectively) and degrading the quality of return flows. In the simplified specification of the

integrated model, these industrial users are grouped into four abstraction sites (figure 3), all in the lower portion of the basin.

Irrigation systems

Classification of irrigated area. Irrigated agriculture is the primary consumptive use of water in the Brantas, and the irrigation sector will be described in somewhat greater detail. Irrigated area in the basin can be characterized in two ways. The first distinction is made on the basis of extent of administrative control over water and the type and extent of physical infrastructure. The categories are a) *technical irrigation areas*, which have relatively well-developed physical infrastructure, and in which water distribution up to the tertiary canal head is controlled by the DPU Pengairan (Irrigation Department); b) *semi-technical areas*, which are also government-managed, but in which physical infrastructure is less well developed; and c) *simple*, village or nontechnical areas, including user-constructed schemes and systems transferred from the government to *HIPPAs* (Water Users Associations). Simple areas tend to have relatively less-developed physical infrastructure, and water may not be available in the dry season, depending on location. Cropping intensity is correspondingly highest (> = 2.0) on technical areas, and lowest (> = 1.0) on nontechnical areas. Table 7 summarizes the Brantas basin irrigated area by type according to administrative units (districts, municipalities.) The total net irrigated area in the Brantas basin was estimated at 309,000 hectares in 1996; of which 242,000 hectares are classified as technical, 32,000 hectares as semitechnical, and 35,000 hectares as nontechnical.

A second distinction can be made between areas irrigated directly from the Brantas via one of the 12 primary schemes, and all other irrigated areas. The distinction is significant from the perspective of model development, since only systems which are physically linked to modeled portions of the Brantas hydrosystem and over which administrative control can be exercised can justifiably be included. Net area on direct schemes of Brantas is around 83,200 hectares (1996), nearly all of which are technical. Annual cropping intensities on Brantas direct systems typically exceed 2.0. Direct systems of Brantas included in the integrated model are identified in table 8, along with the cropping pattern for 1995/96. Table 9 presents estimates of system-level efficiency. System or conveyance efficiency is defined as the ratio of the sum of measured flows at tertiary offtakes to the measured system intake volume. Losses in efficiency result from seepage in primary, secondary and tertiary canals, and illegal diversions.

Calculation of evapotranspiration. In the integrated model, water demand is endogenous, and variables describing the composition of cropping in each system (area by crop, planting dates, rotations, etc.) are correspondingly decision variables. Therefore, it is necessary to specify the model such that crop water requirements for an arbitrary cropping pattern in each system can be calculated internally, based on localized coefficient values. The approach used in the current version of the model is based on reference crop evapotranspiration estimates calculated using the FAO Penman-Monteith equation combined with crop and crop-stage coefficients. The method is described in detail in FAO Irrigation and Drainage Papers No. 33 (1986) and No. 56 (2000).

The minimum climatic data needed to calculate ET_0 using the FAO Penman-Monteith are a) daily maximum and minimum temperature (^{0}C), b) daily mean relative humidity (%)

Table 7. Irrigated area in the Brantas basin, 1996.

Branch Irrigation Service Office	Technical (ha)	Semitechnical (ha)	Nontechnical (ha)	Total (ha)
Malang	13,623	1,433	745	15,801
Kepanjen	16,493	5,420	5,303	27,216
Kediri	20,547	2,060	7,680	30,287
Tulungagung	15,585	6,072	1,747	23,404
Trenggalek I	6,257	2,395	3,721	12,373
Blitar	23,984	2,880	6,086	32,950
Jombang	22,785	0	810	23,595
Mojoagung	22,070	0	1,509	23,579
Pare	18,700	0	1,072	19,772
Nganjuk	33,725	2,864	2,079	38,668
Mojokerto	20,877	7,353	3,315	31,545
Sidoarjo	27,073	765	602	28,440
Wonokromo/ Surabaya	744	725	0	1,469
Total	242,463	31,967	34,669	309,099

Source: DPU Pengairan, in JICA II, table A4-1 p. A4-56, Volume III.

Table 8. Seasonal cropping patterns, direct systems of Brantas (mean 1994/95 and 1995/96).

Irrigation Scheme	Wet Season Paddy (ha)	Dry Season Paddy[a] (ha)	Sugarcane (12 mo.) (ha)	Polowijo Wet Season (ha)	Polowijo Dry[b] Season (ha)	Other Crops[c] (ha)	Gross Irrigated Area (ha)
Brantas Atas	223	248	0	570	1,190	421	2,652
Brantas Bawah	1,069	1,055	183	14	84	0	2,405
Molek	3,347	2,152	279	279	3,745	40	9,842
LodoAgung	6,900	5,668	3,080	1,725	9,980	616	27,969
Mrican Kanan	12,414	8,494	4,247	1,797	9,310	0	36,262
Warujay-Kerto	10,307	8,170	2,263	377	11,690	0	32,807
Brantas Kediri	422	363	85	0	90	0	960
Jatimlerek[d]	1,456	820	574	21	821	349	4,041
Menturus	848	238	2,476	170	1,390	0	5,122
Jatikulon	563	564	31	0	111	0	1,269
Brantas delta	18,333	13,955	8,482	1,094	7,935	0	49,799
Surabaya	984	749	455	59	426	0	2,673
Total	56,866	42,476	22,155	6,106	46,772	1,426	175,801

Source: JICA table A4-2, p. A4-57 in Vol. III.

[a]Includes both “with permission” and “without permission.”

[b]Includes first and second dry seasons.

[c]Includes cotton, tobacco, apples.

[d]Includes Bunder I and II.

Table 9. Estimated system efficiency of irrigation schemes in the Brantas basin.

Scheme	Net Area (ha)	Wet Crop Efficiency (%)	Dry Crop I Efficiency (%)	Dry Crop II Efficiency (%)	Cropping Intensity Gross/Net	Weighted Efficiency (%)
Brantas Atas	1,222	60	55	50	2.30	57
Brantas Bawah	1,901	70	70	50	1.94	70
Molek	3,984	63	62	62	2.07	62
Lodoyo-Tulungagung	12,232	58	54	54	2.34	56
Warujayeng Kertosono	12,546	75	69	69	2.06	72
Brantas Kiri-Nganjuk	534	65	60	55	1.84	63
Mrican Kanan	16,334	65	54	54	2.45	58
Bunder I & II	334	70	70	50	2.30	67
Jatimlerek	1,716	92	80	80	2.43	85
Menturus	3,392	65	78	78	1.44	69
Jatikulon	619	70	60	50	1.96	65
Brantas Delta	27,762	68	67	55	1.88	68
Surabaya	955	70	70	50	1.10	70
Total	83,531					64[a]

Source: Based on Table 4.11, SRPCA Main Report, p. 4–44.

[a]Area and season-weighted mean of schemes assuming that for a cropping intensity of, e.g., 2.30, weights were 1/(2.3) for each of wet crop and dry crop I, and 0.3 (2.3) for dry crop II.

or alternative measure of atmospheric moisture content, such as dewpoint, c) daily mean wind or sunshine hours, which are more easily measured. These data are routinely collected at ten climatic stations within the Brantas basin. Note that the Penman-Monteith itself need not be solved within the integrated model, once location and period-specific values of ET_0 have been calculated by Penman-Monteith, they are attached to the model as parameters.

Potential evaporation for specific crops (ET_C) differs from reference crop evapotranspiration (ET_0) since various crops differ in physiology, height, degree of development, degree of ground cover, and other factors. In the single-crop coefficient approach, reference crop evapotranspiration is multiplied by the appropriate crop and crop-stage-specific coefficients to obtain evapotranspiration demand by crop for each 10-day period.

Crop production functions. The calculation of crop-specific ET values is only a preliminary step towards the calculation of effective crop water demand, since it cannot be assumed that crop development will take place under conditions of full water supply. The critical trade-off between water delivery and irrigated agricultural output must be made explicit using water production functions, several of which are described in the literature. 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 (Y_P) resulting from a fractional reduction in actual evapotranspiration relative to reference crop evapotranspiration (ET_0):

$$\left(1-\frac{Y_A}{Y_P}\right)=K_Y\cdot\left(1-\frac{ET_A}{ET_0}\right) \tag{5}$$

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	

Although the yield response coefficient method is widely used, the functional form may not be suitable for paddy, the most important irrigated crop in the Brantas basin. On the basis of a meta-analysis of over 30 studies of rice yields obtained under controlled conditions, Bouman and Tuong (2000) have proposed a paddy water production function of the following form:

$$Y_A = Y_P\cdot\left(1-e^{\{-b\cdot(W-W_0)\}}\right) \tag{6}$$

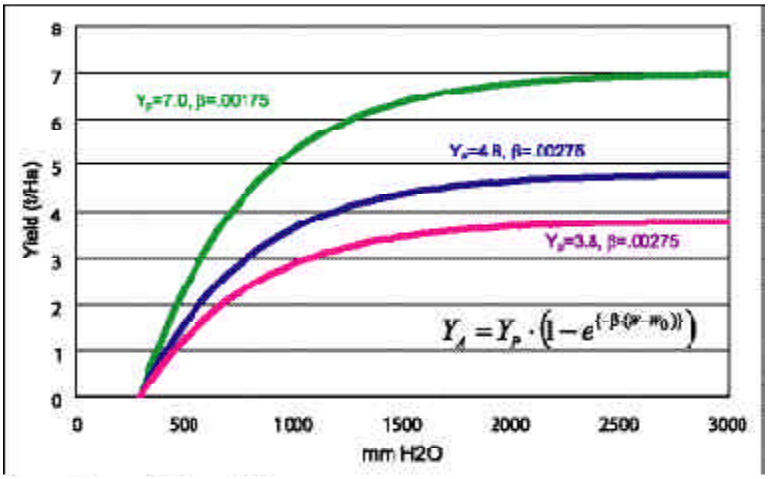
where,	Y_A	actual yield	(kg/ha)
	Y_P	potential or non-water limited yield	(kg/ha)
	β	initial water use efficiency	
	W	water application	(mm)
	W_0	no-yield water application threshold	(mm)

In plotting equation (6) it is observed (figure 4) that there is an extensive region over which significant changes in water application have relatively little effect on yield. This has obvious and important implications for the economic analysis of paddy cultivation when water is a priced input. It is important to note that the level of water demand associated with Yp is not identical to ET_{Paddy}, since optimal paddy production occurs under ponded conditions, which require additional water for land preparation, percolation losses, and maintenance of the water layer (Bouman and Tuong 2000). In equations (5) and (6), it is assumed that Y_P is itself a function of other factors, fixed and variable, which determine and constrain yield:

$$Y_P = Y_P\left(Cl, S, ... \mid Cr, K, L, F, M, ...\right) \tag{7}$$

where,	Cl	climatic factors	(units as appropriate)
	S	soil quality	
	Cr	crop variety	
	K	capital (technology)	
	L	labor	
	F	fertilizer	
	M	managerial expertise	

Figure 4. Bouman and Tuong water yield response curves.



Source: Bouman & Tuong 2000

The functional form of (7) is not known ex ante, and will be explored using data collected from the farm survey, described under "Economic Components of the Model, with Emphasis on Irrigated Agriculture," and aggregate output and water delivery data.

An additional general form of the water production function is described by Dinar and Letey (1996), which is used in the Maipo study (Rosegrant et al. 2000.) The Dinar-Letey relationship is intended to represent the combined impacts of water delivery and salinity on crop yields. It takes the form:

(7) $$Y_A = Y_P\left[a_0 + a_1\left(\frac{w_i}{E_{\max}}\right) + a_2 \cdot \ln\left(\frac{w_i}{E_{\max}}\right)\right] \quad (8)$$

where, w_i infiltrated water
E_{max} maximum evapotranspiration
a_0, a_1, a_2 estimated coefficients

In the Brantas basin, soil salinity is not believed to have a significant negative influence on crop productivity, and extensive analysis will be required to determine the functional form most appropriate for describing water-yield relationships in the Brantas.

A limitation in most water-production function approaches to estimation of yield is that the distribution of water deliveries in time is seldom explicit. Yet, seasonal yield may largely reflect the period of greatest water stress, as distinct from overall seasonal delivery. FAO 33 (1986) describes a penalty adjustment intended to capture this phenomenon, used in the Maipo study:

$$Y' = Y_A \cdot \sum_t \left(D_{MAX} - D_{AVG} \right) \tag{9}$$

where,	Y'	stress-reduced yield	(kg/ha)
	Y_A	Yield predicted by water-production function	(kg/ha)
	D_{MAX}	maximum deficit within the crop growth season	(ratio)
	D_{AVG}	mean deficit within the crop growth season	(ratio)

Equation (9) is assumed to be location- and crop-specific.

Deficits themselves are calculated as:

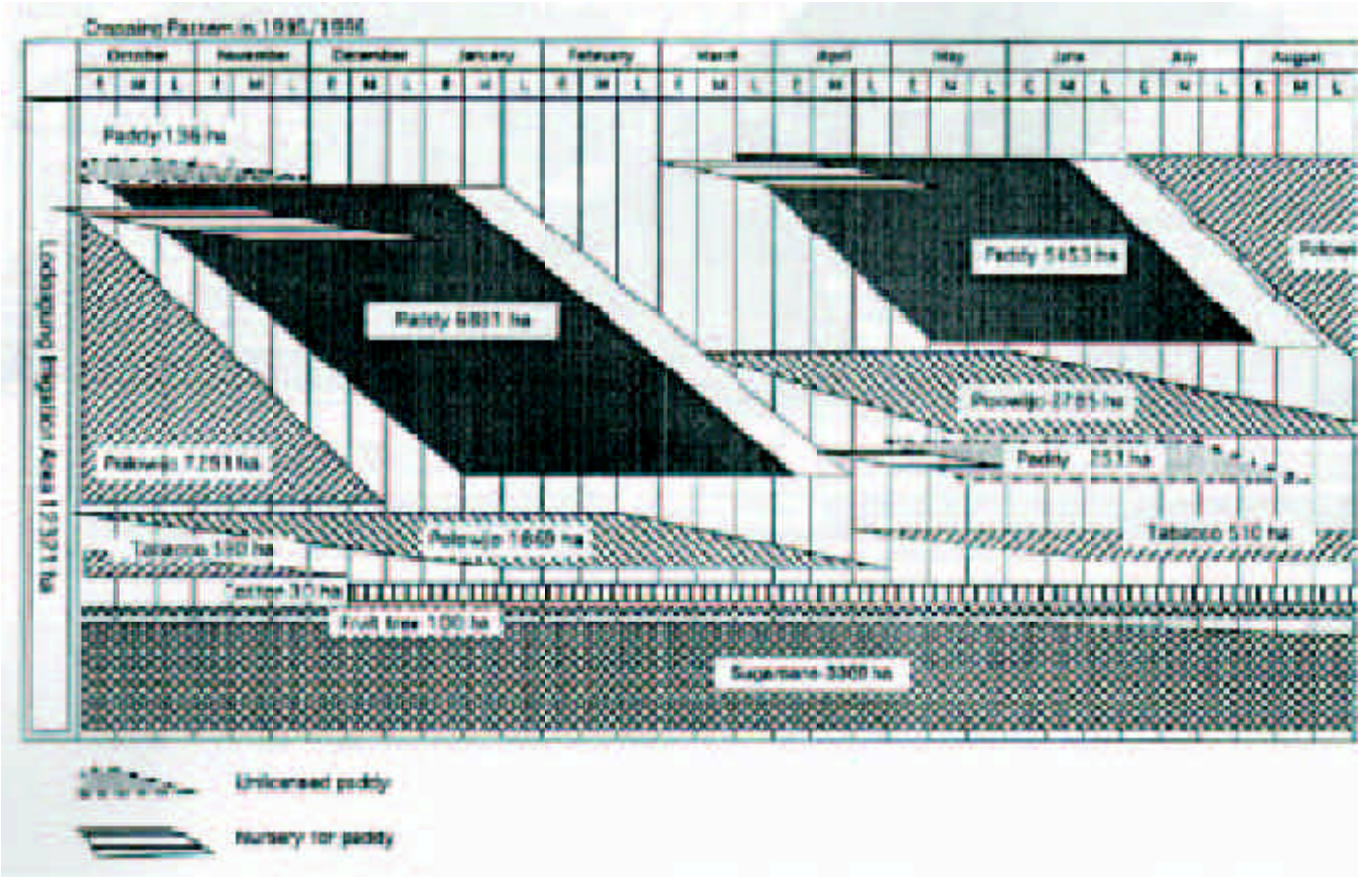
$$D = K_Y \cdot \left(1 - \frac{E_A}{E_{MAX}} \right) \tag{10}$$

where, K_Y is as above and E_A and E_{MAX} are actual and maximum rates of evaporation, respectively.

Cropping patterns and calendars. Given water production and other physical relationships, potential water savings in irrigated agriculture can, in principle, be realized via several mechanisms. These include improved system operation, repair and upgrading of physical infrastructure, more carefully calibrated cropping calendars, substitution of other inputs for water, alternative irrigation technologies, and a shift in cropping composition to less water-intensive crops. The substitution of imports for domestic production ("virtual water") is also an option. The extent to which any of these can produce significant water savings in a given irrigation system will depend critically upon the current status of that system and, in many cases, the water savings obtainable in theory prove extremely difficult to realize in practice.

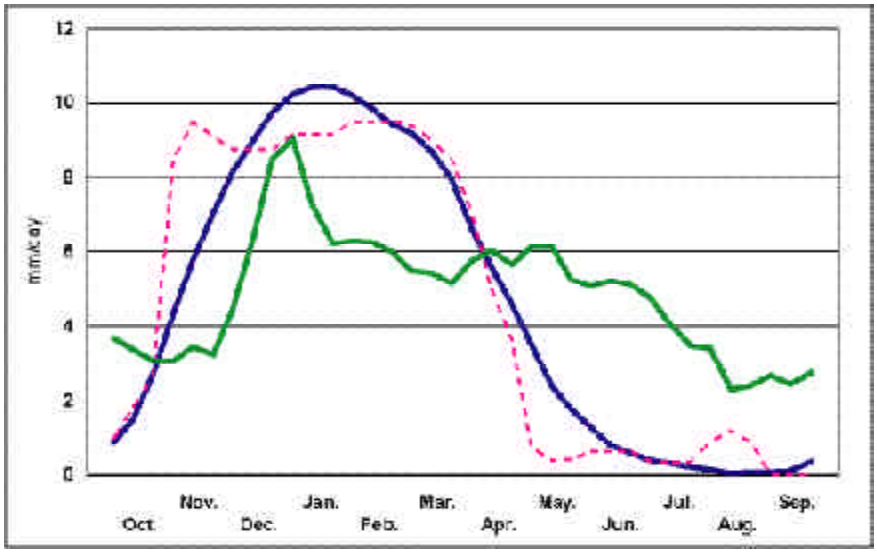
Figure 5 depicts the cropping pattern in Lodoyo-Tulungagung (LodoAgung,) a 12,300-hectare irrigation system in the upper Brantas basin, in 1995–96. The system is cropped intensively year-round, and a mix of short- and long-duration crops is present. It is observed that the paddy and polowijo cropping seasons are extremely attenuated, with certain operations, including nursery, land preparation, and transplanting, extended over 90 days. This attenuation of field operations is understood to reflect constraints posed by labor and water, and by economic factors discussed under "Economic Components of the Model, with Emphasis on Irrigated Agriculture." Figure 6 depicts the corresponding distribution, in time, of system crop-water demand in LodoAgung, inclusive of paddy-land preparation and percolation requirements but excluding conveyance losses and nonutilized (return) flows, calculated using the methodology described above. Demand is compared with direct precipitation, both 50-percent probability values derived from 27 years of data, and data for 1995/96. It appears obvious that by compressing the paddy cultivation cycle, significant water savings will result. A cursory analysis comparing water demand net of precipitation between existing and compressed cropping calendars (maintaining cropping composition) indicates a reduction in ET + percolation demand of roughly 20 percent relative to the observed cropping calendar. However, the desirability of such a shift can be questioned on economic grounds,

Figure 5. Schematic of cropping in Lodoyo-Tulungagung, 1995–96.



Source: Keadaan Irigasi; analyzed by JICA Study Team.

Figure 6. Time variation in water demand and direct precipitation, Lodoyo-Tulungagung.



since the income effects of such a shift depend critically upon the economics of both water and local commodity price response, as discussed subsequently.

Percolation rates and system efficiency. Strategies to improve agricultural water productivity often focus on irrigation system efficiency, typically defined as the ratio of quantity demanded to quantity supplied (e.g., Xie et al. 1993). To estimate the potential range of water savings obtainable from hypothetical improvements in efficiency, it is necessary to possess defensible estimates of system efficiencies under the *status quo*. Supply is measured, with the appearance of reasonable accuracy, at the tertiary block level for 10-day periods in many technical irrigation systems of Brantas, using calibrated flumes or similar structures.[8] By contrast, crop-water demand, essentially beneficial ET and percolation (for paddy) less effective precipitation, must be estimated. The FAO Penman-Monteith equation used here has been found to provide the most accurate estimates of ET_0 from among all approaches evaluated by comparison with field measurement, providing estimates within 5 percent of "true" ET in both arid and humid climates (Smith et al. 1992).

Percolation rates are more problematic. References on rice cultivation often recommend the use of percolation rates in the range of 2 to 6 mm/day for puddled alluvial soils, depending on soil conditions (FAO CROPWAT, DeDatta 1981). However, as a component of this study, PJT engineers measured percolation from puddled, flooded paddies at eight locations within the Brantas basin in December 2000 (wet season) using a double-

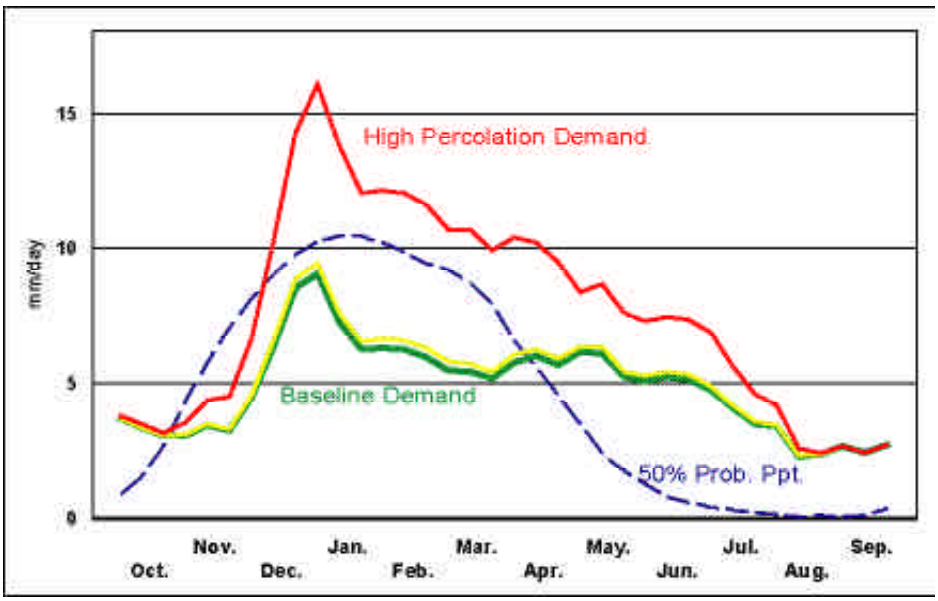
[8]Flumes and weirs were examined at several locations during the process of selecting farm survey samples. Most were well-maintained, although several others were damaged, or occasionally completely absent. All blocks included in the sample survey were required to have well-maintained gates.

ring infiltrometer over 24 hours (Suprapto and Hendradjaja 2000). Observed values ranged from 5 mm/day (2 sites in LodoAgung) to 210 mm/day (Mrican Kiri), with a mean value of 77 mm/day. These are consistent with Armitage (1999) who measured percolation rates of 26 mm/day (wet season) and 103 mm/day (dry season) in the Brantas delta using a single-ring infiltrometer. In similar vein, Bouman and Tuong (2000) report that although land preparation requirements for paddy cultivation are, in theory, around 150–200 mm, amounts as high as 650–900 mm are observed under field conditions, and seepage and percolation account for 50–80 percent of total water inputs to the field. Given that paddy cultivation is by far the most prevalent pattern of cultivation within the irrigation systems of the Brantas basin (table 8), the systematic underrepresentation of percolation rates will lead to nontrivial biases in estimates of crop-water demand and, hence, of current system efficiency and scope for its improvement. While system-wide percolation rates are judged unlikely to equal or exceed 77 mm/day, rates in the 2–5 mm/day range may also be unrealistically low. Figure 7 depicts the increase in crop-water demand for LodoAgung (1995/96) if dry- and wet-season rates are increased to 7.5 mm/day and 15 mm/day, respectively, from the recommended 2.6 mm/day and 4.4 mm/day used in the original calculations.

Interactions between groundwater and surface water

In the Maipo model, groundwater aquifers are fully defined by five coefficients: over-surface area (m^2), bottom elevation (m), maximum elevation (m), saturated hydraulic conductivity (m/sec.) and effective yield (m/m). This describes an unconfined, homogenous and isotropic

Figure 7. Impact of differing percolation rates on water demand in Lodoyo-Tulungagung.



aquifer, characteristic of an extensive alluvial formation.[9] Water balance is calculated in the same way as for a reservoir. For any time period, net change in storage equals the net flux across the aquifer boundary, implicitly vertically (only). Water can be abstracted via pump or recharged via percolation. The upper boundary is flexible, reflecting the extent of storage, and permits the modeling of groundwater overdraft scenarios when combined with information on well depth.

Groundwater data currently available for the Brantas basin include maps of geology and groundwater potential, and detailed data on public irrigation wells, including location, depth of penetration and pump capacities.

Issues and challenges in representing and modeling the physical system

The preceding discussion has identified several issues that represent challenges in the representation of the physical system and the utilization of the integrated model for policy analysis. Several of the most important are summarized below:

Limited reservoir storage. The combined effective reservoir storage in the Brantas is small, relative to both annual discharges and agricultural demand. In addition, most of the storage is in series (Sengguruh, Sutami/Lahor, Wlingi and Lodoyo reservoirs) on the Brantas main stem, thereby limiting the flexibility and independence of operating rules. Reservoir reoperation is, therefore, not likely to play a major role in strategies to increase water productivity at the basin scale, at least given the current infrastructure. This places a disproportionately heavy burden on the agriculture sector to accommodate increasing demand, presumably through increased efficiency and reallocation. The model may prove useful in establishing the economic viability of new storage, since new infrastructure is easily added to the model.

Appropriate level of detail in system representation. We are presently working with a relatively simple representation of the Brantas hydrosystem, which will be modified and expanded as we obtain additional data and experience. In determining what the final model looks like, we need to consider the appropriate balance between the accuracy (or the *appearance* of accuracy) that results from a detailed, highly disaggregated system representation, and the clarity of interpretation and computational efficiency associated with a simplified model. To illustrate, first consider the issue of irrigated area to be included in the Brantas model. The basin contains around 310,000 hectares of irrigated area of which 242,000 are technical. Yet, the 12 systems connected directly to the Brantas and subject to allocation decisions made by the basin authority constitute 83,000 hectares, or only 33 percent of the technical irrigated area within the basin. Can a basin model, particularly one in which the agriculture sector is of central importance, be considered adequately

[9]Definitions of terms relating to groundwater hydrology can be found in Smith and Wheatcraft 1993 and Heath 1991.

specified if two-thirds of the irrigated area subject to regulation is excluded?[10] Or, consider connectivity: if reallocation of water within a tributary does not result in a net change in the discharge to the main stem, it may be more efficient to exclude that subsystem from the integrated model, and possibly to model it separately. The Widas tributary subbasin currently supplies no net inflow to the Brantas main stem during the dry season and, as a consequence, this subbasin has been excluded from PJT's WRMM and RBAM network flow models. It seems relevant to ask whether this would necessarily be the case under an alternative water allocation scenario.

Appropriate level of physical detail in irrigation system modules. An analogous question can be asked concerning the desirable level of physical realism in the simulation of relationships concerning system water supply and agricultural output. Extremely detailed hydrologic-biophysiological models of crop-soil-water relationships have been developed (e.g., Ali et al. 2000; Wopereis et al. 1996) but would the use of detailed physical process models improve the value or accuracy of policy analysis based on integrated model output at the basin scale? In practice, their use would present nearly insurmountable difficulties due to both data availability and computational demand. Moreover, basic principles of error propagation dictate that the highest-variance components of a complex model will dominate the variance of model output. As a result, any putative improvements in accuracy derived from increasingly rigorous specification of individual system components may have little or no real effect on overall model accuracy or the validity of results, unless all components could be upgraded to a comparable level of detail. The challenge here is to balance the level of detail across sectoral simulation modules so that no individual sector dominates the model error or monopolizes computational resources.

Appropriate values for percolation and related parameters. The potential consequences of parameterizing an agricultural water production model with improper percolation values, which can vary by orders of magnitude, are troubling. Field measurement is essential, at the very least for establishing the magnitude of uncertainty. We may choose to develop a stand-alone model at the irrigation system level, and use historical deliveries and sensitivity analyses to arrive at the most plausible range of values for each system.

Groundwater. The specification of groundwater in the integrated model is crude by hydrologic standards, but relative simplicity is required for computational reasons and by virtue of restricted data. Still, we must consider what might be gained by linking the integrated model to an established groundwater flow model (e.g., MODFLOW) to generate improved long-term policy scenarios.

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[10]If the four major Brantas tributaries—Amprong, Ngrowo, Konto and Widas—are included in the model specification, the percentage of total technical irrigated area of the Brantas basin increases to 50 percent.

Economic Components of the Model, with Emphasis on Irrigated Agriculture

In certain respects, the specification of the economic components of the integrated model presents a greater challenge than the hydrologic specification. The primary reason is an absence of conservation laws analogous to those that govern the behavior of the physical system. Using continuity, we can anticipate how the hydrologic system will behave under a wide range of conditions, including conditions outside of historical observation. In anticipating the economic consequences of hypothetical modifications in policy, however, we must make use of economic models that have been calibrated using data observed under specific historical conditions, and it is never clear how robust the observed (calibrated) relationships are to modifications in policy.

In some sectors, such as power generation, the specification of the benefit (profit) function is straightforward, and rests entirely on published cost and price data. In others, such as the municipal and industrial sectors, further information is required in the form of the demand schedules for water, which may be difficult to derive from existing data, particularly if water has been sold at regulated or subsidized prices. The greatest challenge is faced in the irrigated agriculture sector. Since water has been heavily subsidized (if not free), an explicit water production function approach is used, and the sector is characterized by multiple-input, multiple-output production relationships. The following descriptions of the hydropower and M&I benefit functions are correspondingly brief, and the discussion of the agricultural economy more extensive.

Net benefit function for hydropower generation

Net benefit from the generation of hydroelectric power is simply the gross revenue less costs of production, aggregated over all hydropower plants:

$$Z_{hydro} = \sum_i P_i \cdot \left(PP_i - PC_i \right) \tag{11}$$

where,	Z_{hydro}	net benefit from hydropower production	(Rp)
	i	index of sites	
	P_i	power produced at site i	(kWh)
	PP_i	marketed price of power	(Rp/kWh)
	PC	variable cost of power generation	(Rp/kWh)

The current selling price for hydropower in the Brantas is Rp 13.61 per kWh.

Net benefit function for municipal and industrial water consumption

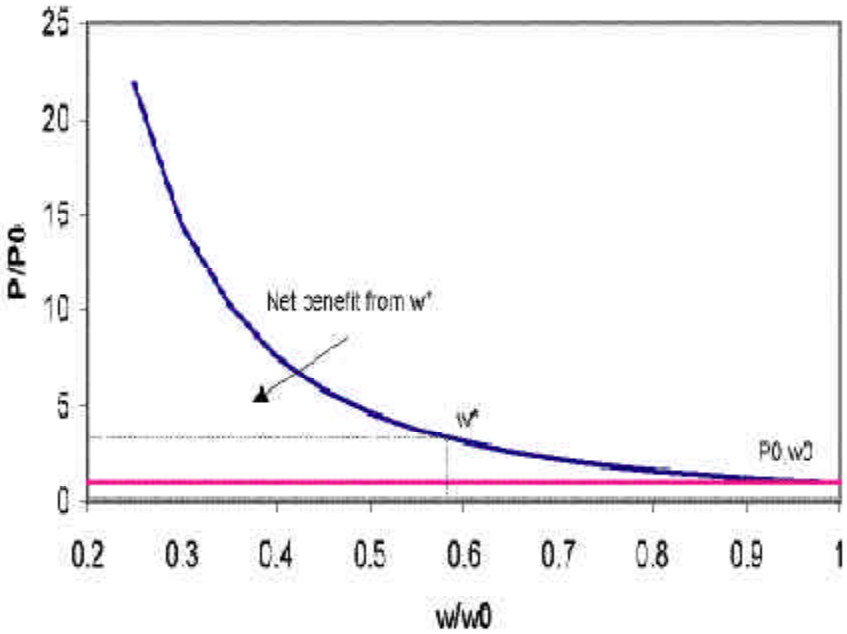
The net benefit function for municipal and industrial users is somewhat less straightforward, since it requires an estimate of the price elasticity of demand in each sector and at each location. The benefit function is an inverse demand function of the form:

$$Z_{mun,ind} = \sum_{m,i} \left[\frac{w_0 \cdot p_0}{(1+a)} \left\{ \left(\frac{w}{w_0} \right)^a + 2a + 1 \right\} - w \cdot wp \right] \qquad (12)$$

where,	Z_{mun}	net benefits to municipal (industrial) consumers	(Rp)
	m,i	indices of municipal and industrial demand sites	
	w_0	maximum withdrawal of water	(m^3)
	wp	price of water	(Rp/m^3)
	p_0	willingness to pay at full use	(Rp/m^3)
	a	reciprocal of the elasticity of demand	

The estimation of benefits is illustrated in figure 8.

Figure 8. Inverse demand curve for M&I demand sites.



Net benefit function for irrigated agriculture

Model calibration and constraint. In the agriculture sector module, choice of crop, area by crop, planting dates and level of input use are all potential decision (endogenous) variables at the irrigation system level, resulting in virtually unlimited degrees of freedom. This can pose an extraordinary challenge to optimization solvers, especially in a model containing multiple irrigation systems, and the established practice is to impose constraints, thereby greatly reducing the feasible solution set. Actual, physical constraints are already established by the availability of land and water and the suitability of land to specific crops, and implicit

constraints by labor, capital (e.g., hand tractors), and by the ability of farmers to purchase inputs. While the use of mathematical programming in the agriculture sector policy modeling has an extensive history, characteristic problems associated with calibration and constraint predictably arise:

Programming models should calibrate against a base year or an average over several years. Policy analysis based on normative models that show a wide divergence between base period model outcomes and actual production patterns is generally unacceptable. However, models that are tightly constrained can only produce that subset of normative results that the calibration constraints dictate. The policy conclusions are thus bounded by a set of constraints that are expedient for the base year, but often inappropriate under policy changes. This problem is exacerbated when the model is on a regional basis with very few empirical constraints, but with a wide variety of crop productions (Howitt 1995a).

In the Maipo study (Rosegrant et al. 2000), area by crop was constrained on the basis of historical cropping data. At least two other options are available, although the application of either within the integrated model framework appears at this point to be problematic. The first is to make output prices endogenous, so that any tendency towards overspecialization is countered by the resulting depression of output prices due to oversupply. Additional justification for making output prices endogenous is discussed below. The endogenous price approach has the appeal of theoretical rigor but, in practice, it makes heavy demands of the optimization solver. The second option is to explore the use of Positive Mathematical Programming (PMP). The PMP approach assumes that observed cropping patterns and input use are economically rational given prices, policies, and attitudes toward risk, and uses these observations to infer marginal cost conditions. The method is described by Howitt (1995a, b) and will not be discussed in detail here, beyond noting that certain restrictions are placed on the forms of the production and constraint functions. However, as PMP involves a three-stage estimation procedure,[11] it is not yet clear how the method would be integrated within the existing basin model framework.

All of these methods require historical data on cropping patterns, resource use and prices. Data on cropped area by season (by 10-day periods) is archived at the district-level offices of the DPU Pengairan (Irrigation Service) and data at the tertiary-block level are being assembled for several recent years (1995–2000) by PJT staff on the basis of these records. Additional data are required on input use at the farm level, including labor, fertilizer and water, and on input and output (sale) prices. These were collected in a farm-sample survey, described below.

Farm economy-sample survey. To properly specify the physical production and economic benefit functions at the irrigation system level, a farm sample survey was conducted by CASER in October and November 2000. The sample consisted of 160 farm households from each of four irrigation systems chosen to represent different agro-ecological settings within the basin: LodoAgung in the upper region, Mrican Kiri and Kanan in the middle and Porong canal in the Brantas delta. In each system, three tertiary blocks were chosen on the basis of

[11]In addition, Howitt's most recent work involves the use of maximum entropy estimators.

water delivery infrastructure and composition of cropping, and 40 farm households were selected from within each tertiary block, stratified by location and size of holding, for a total sample size of 480. The tertiary block is the most disaggregated level at which water deliveries are physically measured in Brantas irrigation systems.[12] The sample was further stratified on the basis of the size of landholdings.

The scope of the data collected from sample farm households included a) household characteristics, b) landownership and holding, c) cropping pattern, d) input use, production, price of output, and inputs used, revenue (per crop, per season, per plot of land cultivated), e) irrigation technique and estimated water use, f) further uses of water resources, g) employment and income from other sources (farm income from parcels of land outside of sample blocks, off-farm activities, non-agriculture, others), and h) household expenditures, including food consumption. The data collected from this survey, currently being processed, should permit wide flexibility in the choice of economic models, from simple water production functions to agriculture-sector input-output models.

The survey was additionally structured to learn about the factors that farmers considered important in managing and allocating water. The individual (farm household) interviews were augmented by group interviews with Water User Organizations (WUOs or *HIPPA*) and Farmer's Groups, as well as with local officials from the Irrigation Service. These interviews have provided valuable insight into the formal and informal relationships between individual farmers and local institutions, and between local institutions and district- or basin-level institutions.

Choice of technology. The Maipo basin study (Rosegrant et al. 2000) examined, among other things, the interaction between choice of irrigation technology and price of water. Water application technologies included flood, furrow, sprinkler and drip irrigation, each characterized by the extent of uniformity in application, which is an important dimension of application efficiency. The net benefits component for this study was, therefore, specified as:

$$Z_{irr} = \sum_{cr} A_{cr} \cdot Y_{cr} \cdot PC_{cr} - \sum_{cr} A_{cr}\left(Cf_{cr} + Ct_{cr}\right) - \sum_{t} w_t \cdot PW_t \quad (13)$$

where,	irr	index of irrigation site (implicit on right-hand terms)	
	cr	crop type	
	A	area planted in each crop	(ha)
	Y^{cr}	crop yield	(Mt/ha)
	PC^{cr}	crop price	(Rp/Mt)
	Cf^{cr}	fixed costs	(Rp/ha)
	Ct	technology costs	(Rp/ha)
	w	quantity of water used in period t	(m^3)
	PW	unit price of water	(Rp/m^3)

[12]The quality of water delivery measurement is uneven, and depends on the condition of physical infrastructure. Sample blocks all possess relatively recent, properly functioning flumes or weirs, so that water use as reported by farmers can be compared to deliveries as recorded by the Irrigation Service gate tenders.

A distinct feature of this net benefits function is the inclusion of a technology cost associated with each method of irrigation. In general, the more uniform the water application, the higher the technology cost. In specifying the Brantas basin model, it is not yet clear whether such a range of technologies will be included. The cultivation of paddy, the dominant crop in the Brantas basin, requires ponded water for at least part of the growing season and water redistribution occurs field-to-field, largely driven by gravity, thus mooting the primary justification for high-efficiency application technologies. The choices of crop rotational sequence and planting dates, by contrast, emerge as significant management decisions in the Brantas.

Endogeneity of output prices. In a world of open borders and absence of distorting macroeconomic policies, producers everywhere should, in principle, face the same (world) market prices for generic commodities, adjusted for inland transport and associated marketing and related costs. In practice, there are nearly always distorting interventions, and always spatial and temporal variations in the farm-gate and wholesale prices of agricultural commodities, reflecting corresponding variations in supply. In Indonesia, the primary intervenor in the rice market is BULOG, which has operated a classic buffer stock scheme since the late 1960s, arguably successfully—it is one of several factors that led Indonesia to achieve self-sufficiency in rice in the 1980s—albeit at a high cost (Ismet et al. 1998).

Returning to the observed cropping pattern in LodoAgung for 1995/96 (figure 5), the attenuation of field operations (land preparation, transplanting) are understood to reflect the relative scarcity of labor and water (SRPCAPS 1999). In addition, however, the staggering of plantings appears to be a deliberate strategy to stabilize prices, ensuring that a given season's harvest does not all enter the market in a brief period.[13] Thus, well-meaning attempts to compress cropping calendars as a water-saving strategy may actually work against price stability and farm income. Consequently, there are two arguments for structuring the integrated model to solve output prices endogenously: the desire to avoid artificial over-constraint of the sector model, and the desire to capture a potentially important component of the set of economic incentives faced by farmers.

Output prices can be treated endogenously by evaluating an additional inverse- demand function appropriate to each site and each commodity, of the general form:

$$\ln(Py) = a + b \cdot \left(\frac{1}{z}\right) \cdot \ln(Y) \tag{14}$$

where,	Py	output price	(Rp/kg)
	Y	output quantity	(kg)
	β	market share of crop Y	(fraction)
	ζ	price elasticity of demand	(ratio)
	α	estimated coefficient	

[13]Personal conversations with CASER staff. Ismet et al. (1998) note that "In the absence of intervention, prices drop steeply during the main harvests, level off during the second season harvest and rise during the lean season." (p. 284).

The primary disadvantage of endogenous output pricing is, once again, the demand placed on computing resources.

Issues and challenges in representing and modeling the economic system

The following appear as the major challenges facing us in specifying the economic components of the integrated model:

Availability of data on water demand. The calculation of elasticities requires at least some form of a demand schedule based on observed, historical behavior. While PJT has priced water delivered to municipal (PDAM) and industrial customers, water charges are not necessarily based on marginal productivity values, and it remains to be seen whether existing data are sufficient to estimate proper demand elasticities for these sectors. In the irrigated agriculture sector, it is clear that water has been a free, or at least a heavily subsidized, good. Much analysis will be required using our sample survey data, but it should be possible to construct the appropriate agricultural water demand curves, given what is known about physical water-production relationships.

Model calibration and constraint. Available aggregate data on area, output and prices appear sufficient to permit the calibration of an agriculture-sector model, applicable, at least, to the irrigation systems in the Brantas basin. Questions remain as to how we properly constrain the model. The unconstrained model possesses unacceptably large degrees of freedom, while over-constraint restricts the ability of the model to generate policy analysis. Howitt's PMP approach appears promising, and has been used in both agriculture- and water-sector models, but it will require further investigation and testing in the context of our integrated model.

Endogenous prices. The endogenous specification of agricultural output prices within the model has great theoretical and aesthetic appeal and, indeed, given what we know about the influence of commodity prices on cropping calendar decisions, it could be argued that they are required to generate a truly useful policy simulator. However, the endogenous specification introduces an additional, substantial degree of computational complexity, and only experience will tell us if it can be justified in the present study.

Economic Incentives and Policy Scenarios

A primary focus of the IFPRI study and accompanying modeling effort is the evaluation of various economic incentives and institutional reforms with regard to their impact on water use efficiency and allocation within the Brantas basin. Tiwari and Dinar (2000) define economic incentives as "signal mechanisms that affect the decision-making process and motivate water users to use water more efficiently." Economic incentives include prices, subsidies and taxes, and quotas combined with market allocation mechanisms. Institutional reform includes the creation, strengthening or redefining of property rights and entitlements, decentralization of authority, privatization and turnover of irrigation systems, and the strengthening of local institutions, among others. A substantial recent literature exists

concerning the use of economic incentives in the water sector, as summarized by Dinar and Subramanian (1997), Dinar (2000), Johansson (forthcoming), and Tiwari and Dinar (2000). No attempt will be made here to review this extensive literature or to cite individual case studies, only to summarize key attributes of several instruments and to describe how they can be implemented within the model framework.

Water pricing

Water pricing "denotes any charge or levy that farmers have to pay in order to obtain access to water in their fields, ... and is based on the users' pay principle (UPP) that those who benefit from the use of scarce resources should pay." (Tiwari and Dinar 2000:3) The treatment of water as a priced commodity can, in principle, accomplish several distinct purposes: It can directly generate revenues for water management authorities, which are available for reinvestment in the water sector as new capital expenditure and O&M, thereby reducing water sector dependence on general revenues. It can assist in the prioritization of water allocation. It can provide an objective means of resolving conflicts, and it can make the value of environmental services and amenities explicit. Most significant in the context of this study, the pricing of water can regulate demand by providing strong incentives for the efficient use of water. Note that the level of prices, along with the price elasticity of demand, will determine the extent to which these purposes are accomplished. It is possible, for example, to price water at a level that is successful in generating revenue but is ineffective in modifying demand.

Water pricing can take many forms, each of which can be represented explicitly in the integrated model framework. The most straightforward is volumetric pricing, which can be structured to reflect spatial and temporal variation in the scarcity of water, or to discriminate between sources of supply (groundwater, canals and natural channels) if desired. While volumetric pricing, in principle, provides the clearest incentive for efficient water use, in practice, it requires metering, which is difficult and expensive if not entirely impractical at the farm level.[14] It also creates an incentive for the illegal diversion of water.

Alternative, nonvolumetric water charge mechanisms include output-based fees, area-based fees and levies based on both area and crop. Water charges based on output are easier to assess (no metering is required) and, in principle, reflect not only quantity but also quality of water delivery. The strength of the incentive is not as great as that of volumetric pricing, however, and output-based fees may simply penalize efficient farmers. Area-based fees are easy to implement, as neither metering nor assessment of output is required. However, if the same fee is assessed irrespective of quality of delivery (e.g., to both head enders and tail enders) and/or cropping pattern, the efficiency incentive can be undermined, and the equity of the pricing system called into question. An improvement is to base the fee on area and crop.[15]

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[14]Water measurement can and does occur at the tertiary block level in many Brantas irrigation schemes, although the accuracy of such measurements depends both on the condition of the physical infrastructure and on the skill and commitment of the gate tender.

[15]H. Lofgren of IFPRI concludes that charges based on crop and area are largely equivalent to volumetric charges in terms of incentive value, subject to assumptions concerning reliability and timing of deliveries. Personal conversation with Ruth Meinzen-Dick, December 2000.

The water charge mechanism in any of its manifestations is represented in the model directly within the net benefit function (equation 2). The appropriate level of prices is determined by repeated simulation over a range of hypothetical water charges, observing the resulting impact on cropping pattern, farm sector income and welfare, and overall water use.

Subsidies and taxes

Subsidy-based policies can provide incentives by both removal and creation. Water delivered to consumers in any sector at below-the-cost-of-supply (with or without capital cost recovery) is subsidized, and a baseline scenario involves the removal of this incentive by the use of O&M-based charges as the basis for water pricing policy. In the Brantas basin, these prices, inclusive of capital cost recovery, are currently estimated at around Rp 25/m^3 for irrigation, Rp 10/m^3 for municipal supply and Rp 30/m^3 for industrial supply given investment through 1997 (JICA 1998; current 1997 prices). A broader objective of this study is to determine how the removal of current subsidies and other distorting factors, if implemented, would affect farm incomes and the welfare of the rural sector.

Subsidy as proactive policy can also be used to promote water-efficient technologies in a variety of ways. Farmer or WUO investment in water-saving technologies, including system repairs and upgrading (e.g., lining of tertiary canals) can be directly subsidized via cost-sharing incentives, subsidized via concessionary credit, or indirectly via knowledge transfer, including training and extension. It can also take the form of institutional strengthening, or via the writing down of outstanding capital costs when state assets, such as irrigation infrastructure, are transferred to WUOs.

Other forms of subsidy to promote water savings can be envisioned, based on the use of targeted price supports to encourage the use of less water-consumptive crops (the inverse strategy involves taxing highly water-consumptive crops). The cost of such programs is minimized if the extent of such support is fixed, and farmers (or WUOs) submit bids to participate.[15] A variation is cross-compliance: if farmers agree to use less water, they become eligible for participation in other subsidy or price-support programs.

Corresponding tax policies can be direct or indirect as well. Direct taxation policies include abstraction taxes, which like water charges can be targeted by type of abstraction (groundwater v surface water) or by season and location. Abstraction taxes, unlike water delivery charges, can be applied to resources, such as groundwater, that are developed by the farmer rather than provided by the government. Direct taxes can also take the form of levies on excess consumption, i.e., withdrawals in excess of the quantity deemed sufficient for the successful cultivation of a particular crop. Indirect taxes can be levied on inputs, such as energy or fertilizer that enter the production process and co-vary with water use.

The implementation of taxes and subsidies within the integrated model is only slightly more complicated than direct water charges, and involves modifying the functional forms of profit functions. In general, for the purposes of policy simulation, taxation and subsidy are less advantageous than direct water charge mechanisms, since the economic incentive effect is often less direct and, hence, more difficult to characterize.

Quotas and rights

Quotas are simply allocation rules or entitlements, enforceable by legal or administrative authority and like water charges they can be made subject to variation in time, space, source and type of use. Quotas can be constructed to ensure that total abstraction within a region (e.g., basin or tributary) or within economic sector remains within limits determined to be environmentally sound or consistent with conservation or other objectives.

It is generally agreed that quotas function as effective tools for demand management when associated rights are established and when all or parts of these quotas (and possibly associated rights) are transferable via market mechanisms. Under these conditions, allocative efficiency can be achieved at a relatively low cost to water-management authorities, and possibly at lower political risk as well. Markets for water and water rights are also subject to a range of economic and physical failures including monopoly power, imprecise information (high transaction costs) and physical losses due to transmission; and water markets must typically be regulated to prevent abuse.

To simulate water trading, based on quotas within the model, the marginal value-water withdrawal relationship is determined for each demand site (aggregated over all crops) over a range of water withdrawal levels. The result is a fitted demand curve for that site, which can be used to evaluate system-wide gains/losses from water trading (Rosegrant et al. 2000). The quotas in the context of the model take the general form of constraints and can be assigned on the basis of landownership or historical levels of withdrawal with transactions costs included. Revenues and costs associated with the sale or purchase of water enter the net benefit function.

Policy simulation v policy advocacy

In Indonesia, as in most regions, there is a history of politically sanctioned subsidy in the irrigation sector, and cheap water has naturally come to be viewed as an entitlement. The discussion of alternative policies, particularly those based explicitly on economic incentives, invariably generates controversy, among those who (correctly or otherwise) perceive themselves as beneficiaries under a “cheap water” policy and those concerned more broadly with distributional justice and the welfare of low-income farmers.

The objective of policy simulation is *not* to advocate for a given set of policy strategies but rather to provide a positive analysis of the likely, relative impacts of proposed policy regimes on total benefits, benefits by sector and location and, ideally, on the distribution of benefits by economic class. A concern for the welfare of the irrigated agriculture sector, currently under stress, is one of the primary motivations for the ADB/IFPRI study, and the analysis of net subsidy/taxation described under “Introduction: Motivation for the Modeling Study” is designed in part to address concerns of distributional equity. We believe that decisions concerning the sustainable, efficient, and just distribution of water resources should be derived on the basis of informed discourse in the social, political and legal arenas, and that the quality of this debate can only be improved by a careful, objective analysis of the likely economic consequences of proposed policies.

Summary of Key Points and Concluding Observations

This paper describes the Brantas basin in East Java, Indonesia. It is a region of major geographic, demographic and economic significance, and one which is subject to the mismatch of water supply with demand, both spatially and temporally, which is a defining characteristic of many river basins in Asia. Specific features of the Brantas, which have significant implications for water management within the basin and policy design include the following:

- Rapid growth in population, economic activity and corresponding water demand
- Strongly seasonal distribution of precipitation and resulting discharge
- Limited surface water storage, ongoing threats to this storage and limited potential for the development of new surface storage
- High cropping intensities, particularly in irrigated areas
- Dominance of paddy cultivation, a highly water-consumptive crop for economic, historical, social and ecological reasons
- History of heavily subsidized water in the agriculture sector
- History of centralized water administration at the river-basin level

Given the current status of hydraulic infrastructure within the basin, it appears evident to the authors of this study that only limited gains in efficiency can be achieved through the reoperation of existing facilities, although significant improvements in system efficiency may be possible to realize through upgrading, repair and maintenance of existing irrigation infrastructure. Barring, or even allowing for expansion of hydraulic infrastructure, it is equally evident that significant changes in practice within the irrigated agriculture sector will be required to meet the challenges of escalating demand for water within the basin. Potential nonstructural strategies include improved system operation, more carefully calibrated cropping calendars, substitution of other inputs for water, a shift in cropping composition to less water-intensive crops, and the substitution of imports for domestic production.

Three related, but distinct, challenges to the irrigated agriculture sector can be identified (Bouman and Tuong 2000): a) to save water, b) to increase water productivity, and c) to produce more output with less water. The first challenge is easily met, for example, by reducing the cropped area, growing less rice, and importing more foodgrain, but we find this approach unacceptable. If many nations in the region followed a similar strategy, the production base would erode and the putative cost savings from imports would be eventually neutralized. It is also possible to meet the second challenge, for example, by the redesign of cropping calendars, as illustrated in this paper. However, it is only by producing more food with less water that food security, economic growth, inter-sectoral equity and the economic health of the agriculture sector can be promoted in the long run.

In the long run, hard or structural solutions will be required as well. Although present and foreseeable storage, within the basin, in the soil, in reservoirs, and groundwater, is limited

relative to current and projected demand, the careful, joint management of this storage can increase the quantity of water available to meet new demand (Keller et al. 2000).

This paper has also described the development of an integrated economic-hydrologic-policy simulation model, which is intended to serve as a tool to investigate means by which the water resources within the Brantas basin can be managed more productively, equitably and sustainably, given the defining basin characteristics noted above. The use of such integrated models represents a relatively recent approach to water policy evaluation, and the present application to the Brantas basin is, in many ways, an experiment.

However, the results of previous applications of the integrated modeling approach (McKinney and Cai 1997; Rosegrant et al. 2000) are promising. The use of an integrated modeling approach permits the exploration of both “hard” and “soft” solutions to the problem of growing water scarcity, and their interaction, within a single framework.

Literature Cited

Ali, M. H.; L. T. Shui; K. C. Yan; A. F. Eloubaidy; and K. C. Foong. 2000. Modeling water balance components and irrigation efficiencies in relation to water requirements for double-cropping systems. *Agricultural Water Management* 46:167–182.

Armitage, Stuart. 1999. A study of on-farm water use and irrigation performance in the Brantas delta, East Java, Indonesia. M.Sc. diss.: University of Southampton, Department of Civil and Environmental Engineering.

Binnie and Partners (Overseas) Ltd. 1999. *Surabaya River Pollution Control Action Plan Study (SRPCAPS)* (Surabaya Urban Development Project, Technical Assistance from IBRD Loan No. 3726-IND). In association with P T. Indra Karya; PT. Multi Tehniktama Prakarsa; PT. Exsa International Co. Ltd. 5 volumes.

Bouman, B. A. M.; and T. P. Tuong. 2000. Field water management to save water and increase its productivity in irrigated rice. Submitted for publication.

Brooke, A.; D. Kendrick; A. Meeraus; and R. Raman. 1998. *GAMS: A user's guide*. Washington, D.C.: GAMS Development Corp.

Chambers, R. G. 1988. *Applied production analysis: The dual approach*. Cambridge: Cambridge University Press.

Calder, Ian R. 1999. *The blue revolution: Land use and integrated water resources management.* London: EarthScan.

De Datta, S. K. 1981. *Principles and practices of rice production.* Los Banos, Philippines: International Rice Research Institute.

Dinar, A.; and J. Letey. 1996. *Modeling economic management and policy issues of water in irrigated agriculture*. Westport, Connecticut: Praeger.

Dinar, A.; and A. Subramanian. 1997. *Water pricing experiences: An international perspective*. World Bank Technical Paper No. 386. Washington, D.C.: The World Bank.

Dinar, Ariel, ed. 2000. *The political economy of water pricing reforms*. Oxford: Oxford University Press and World Bank.

FAO. 1986. *Yield response to water.* Irrigation and Drainage Paper No. 33. Rome.

FAO. 2000. *Crop evapotranspiration: Guidelines for computing crop water requirements.* Irrigation and Drainage Paper No. 56. Rome.

Heath, Ralph C. 1991. *Basic ground-water hydrology*. United States Geological Survey Water-Supply Paper 2220. Denver, Colorado: United States Geological Survey.

Howitt, Richard E. 1995a. Positive mathematical programming. *American Journal of Agricultural Economics* 77:329–342.

Howitt, Richard E. 1995b. A calibration method for agricultural economic production models. *Journal of Agricultural Economics* 46(2): 147–159.

Ismet, M.; A. P. Barkley; and R. V. Llewelyn. 1998. Government intervention and market integration in Indonesian rice markets. *Agricultural Economics* 19:283–295.

JICA (Japan International Cooperation Agency). 1998. *Development of the Brantas river basin: Cooperation of Japan and Indonesia*.

Johansson, R. C. Forthcoming. *Pricing irrigation water: A literature survey*. Washington, D.C.: World Bank.

Keller, A.; R. Sakthivadivel; and D. Seckler. 2000. *Water scarcity and the role of storage in development.* Research Report No. 39. Colombo, Sri Lanka: International Water Management Institute.

Mays, L. W.; and Y. K. Tung. 1992. *Hydrosystems engineering and management*. New York: McGraw-Hill.

McKinney, D. C.; and X. Cai. 1997. *Multiobjective water resources allocation model for the Naryn-Syrdarya cascade*. Technical Report. U.S. Agency for International Development, Environmental Policies and Technology (ETP) Project. Almaty, Kazakstan.

McKinney, D. C.; X. Cai; M. W. Rosegrant; C. Ringler; and C. A. Scott. 1999. *Modeling water resources management at the basin level: Review and future directions*. SWIM Paper 6. Colombo, Sri Lanka: International Water Management Institute.

Optimal Solutions Ltd. 2000. *Development of reservoir operating rules in the Brantas river basin*. Submitted to *Perum Jasa Tirta*. Malang, East Java, Indonesia.

Province of East Java; and Government of East Java, Central Statistics Bureau. 1999. *Jawa Timur Dalam Angka 1998*. (East Java in figures 1998.)

Ramu, Kikkeri. 1999. River basin management corporation: An Indonesian approach. Paper presented at the Third River Basin Management Workshop, World Bank, Washington, D.C., June 24 1999.

Rosegrant, M. W.; C. Ringler; D. C. McKinney; X. Cai; A. Keller; and G. Donoso. 2000. *Integrated economic-hydrologic water modeling at the basin scale: The Maipo river basin*. EPTD Discussion Paper No. 63. Washington, D.C.: International Food Policy Research Institute.

Singh, V. P. 1995. Watershed modeling. Chapter 1 In *Computer models of watershed hydrology*, ed. V. P. Singh. Highland Ranch, Colorado: Water Resources Publications.

Smith, Leslie; and Stephen W. Wheatcraft. 1993. Groundwater flow. Chapter 6 In *Handbook of hydrology*, ed. D. R. Maidment. New York: McGraw-Hill.

Smith, M.; R. G. Allen; J. L. Monteith; A. Perrier; L. Pereira; and A. Segeren. 1992. *Report of the expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirements*. Rome: FAO.

Sunaryo, Trie M. 2000. Case study of Brantas river basin, Indonesia. Paper prepared for the workshop on Integrated Water Resources Management in a River Basin Context: Institutional Strategies for Improving Agricultural Water Management. Malang: Perum Jasa Tirta I.

Suprapto, S.; and B. Hendradjaja. 2000. Soil percolation rates at eight locations within the Brantas basin, wet season. Field report (Duplicated). Malang: Perum Jasa Tirta I.

Tiwari, Dirgha; and Ariel Dinar. 2000. Role and use of economic incentives in irrigated agriculture. Draft paper presented at the World Bank Workshop on Institutional Reform in Irrigation and Drainage, Washington, D.C. 11 December 2000.

Van der Weert. 1994. *Hydrologic conditions in Indonesia*. Jakarta: Delft Hydraulics.

Wopereis, M. C. S.; B. A. M. Bouman; T. P. Tuong; H. F. M. ten Burge; and M. J. Kropff. 1996. *ORYZA-W: Rice growth model for irrigated and rainfed environments*. SARP Research Proceedings. Wageningen, The Netherlands: IRRI/AB-DLO.

Xie, M.; U. Kuffner; and G. Le Moigne. 1993. *Using water efficiently: Technological options*. Washington, D.C.: The World Bank.