RESEARCH
REPORT

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A Diagnostic Model Framework for Water Use in Rice-based Irrigation Systems

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International Water Management Institute

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Contents

List of Abbreviations

ANADER	Agence Nationale d'Appui au Développement Rural
ETC	Evapotranspiration
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FSL	Full supply level
GVC	Groupement à Vocation Coopérative
IWMI	International Water Management Institute
LHS	Left hand side
LP	Linear programming
NET	Net irrigation requirement
P_{eff}	Effective rainfall
PRC	Projet Riz Centre
RHS	Right hand side

Résumé

Dans cette étude, nous présentons un cadre de diagnostic modèle basé sur la programmation linéaire pour l'utilisation de l'eau dans les systèmes irrigués à base-riz. Notre intention est de faciliter la compréhension des conditions et contraintes internes et externes d'un système pour une utilisation productive des ressources disponibles en sol et en eau et l'établissement de référence pour une évaluation de la performance physique, économique et environnementale. L'accent est mis sur l'analyse des contraintes du système particulièrement les facteurs hydrologiques, techniques, économiques et de gestion. Le développement d'une stratégie pour l'amélioration de la performance du système, particulièrement, la productivité de l'eau est prioritaire dans l'utilisation du cadre diagnostic proposé. Dans une étude de cas du système irrigué à base-riz de Sakassou, Côte d'Ivoire, nous avons trouvé qu'un mètre-cube produit 0,48 kg de paddy, ce qui ne constitue qu'environ la moitié de la productivité potentielle de l'eau. L'eau perdue représente environ 50% de l'eau disponible pour le système. Les écoulements non accordés représentent de grandes quantités d'eau. Une stratégie a été suggérée pour exploiter pleinement le potentiel de productivité. Cette stratégie comporte quatre voies: (1) améliorer la qualité des services; (2) augmenter la production par unité d'eau consommée; (3) réduire les déperditions (4) exploiter les écoulements d'eau non accordés. A long terme, on pense qu'il est possible d'avoir une augmentation de la productivité de l'eau de 0,9 kg par m^3 de paddy en adoptant une stratégie graduelle d'interventions à court, moyen et long termes. Les écoulements non accordés à différents niveaux du système peuvent être exploités de manière productive à travers l'harmonisation de la demande et de l'offre de l'eau, l'amélioration des caractéristiques d'écoulement des canaux et le rétablissement du stockage en champ ainsi que la réutilisation de l'eau aux périodes de pic. Une contribution substantielle à l'amélioration de la productivité de l'eau peut s'obtenir avec l'adoption de technologies améliorées et de pratiques culturales avancées comme les nouvelles variétés de riz, la mécanisation agricole, l'utilisation des semis directs à la place du repiquage et une meilleure gestion de la fertilité. Du point de vue économique, il est suggéré de se concentrer sur la première saison culturale qui est plus productive et d'adopter une stratégie de conservation pendant la seconde saison moins productive. Ainsi, on peut affecter un stock d'eau important à la production élevée de la première saison culturale de l'année subséquente.

Summary

In this study, we present a framework for water use in rice-based irrigation systems. This framework intends to facilitate the improved understanding of the system's internal and external conditions for the productive use of the available land and water resources, and thereby create a reference for the system's physical, economic and environmental performance. Detailed attention is given to the analysis of constraints in the system focusing on hydrological, technical, managerial and economic factors. The development of a strategy for improving the system performance, especially its water productivity, is a priority for the use of the proposed framework. In a case study carried out at the Sakssou rice irrigation system, Côte d'Ivoire, it was found that one cubic meter of depleted water produces 0.48 kg of paddy, which is about half of the estimated potential productivity of water. The depleted fraction is about 50 percent of water totally available to the system. Large quantities are utilizable but uncommitted outflow. In order to fully exploit the potential for improved productivity, a strategy, which follows four principal pathways is suggested: (1) improving the quality of services; (2) increasing the production per unit of water consumed; (3) reducing non-beneficial depletion, and (4) tapping uncommitted outflows. In the long term, an increase in water productivity to 0.9 kg of paddy per cubic meter is considered feasible taking a gradual strategy of short- and medium- and long-term interventions. Uncommitted outflows from various system levels could be tapped and used more productively through harmonizing of water supplies and demand, improving canal flow characteristics, and re-establishing field storage and reuse during peak demand periods. A substantial contribution to increased water productivity could be made through the adoption of improved technologies and advanced cultivation practices such as new rice varieties, the use of mechanized farm equipment, a change from transplanting to direct seeding and better fertility management. From an economic perspective, the research suggests that concentrating on the first, more productive cropping season is beneficial and that a water conservation strategy should be adopted during the second, less productive cropping season. Thereby, sufficient storage can be carried over in order to sustain high production during the first cropping season of the following year.

A Diagnostic Model Framework for Water Use in Rice-based Irrigation Systems

Wilfried Hundertmark and Ali Touré Abdourahmane

Introduction

For many Asian and African rice farmers, the availability of sufficient water is a major concern for sustained agricultural production. Half of Asia's total freshwater depletions is used for the production of irrigated rice and there is concern that the per-capita water availability is diminishing (Guerra et al. 1998). Some of the world's most productive systems are found in arid and semi-arid regions where water is becoming increasingly scarce. In the Indus valley of Pakistan and the Nile delta as well as in large parts of India normal water applications range between 10,000 and 35,000 m^3/ha/season. Under the climatic conditions of the Sahel, West Africa, dry-season water applications reach even 50,000 m^3/ha (Jamin, personal communication).

It is not surprising that the water productivity of irrigated systems vary largely from one system to another.[1] In a comparative study, Molden et al. (1998) examined the performance of 18 mainly rice-based irrigation systems around the world and found significant differences in the standardized gross values per unit of water consumed ranging from US$0.1 to 0.9 per cubic meter. It is however difficult to make a judgement regarding the causes and effects of such differences. The availability of water is only one aspect of many that affect system performance. Others include, system diversity and complexity in irrigation infrastructure design, management, service provision, and socioeconomic conditions. In a case study conducted in Niger, Abernethey et al. (2000) concluded that there is a high degree of interactivity among various domains such as water management, agricultural practices, markets and finance, organizational constitution and processes, and management skills. Without proper attention, interventions of an external organization are likely to fail. To fully appreciate the complexity and diversity of rice irrigation systems, Guerra et al. (1998) suggest that a systems approach should be taken for the simulation and quantification of the interaction of physical and socioeconomic processes that control water management on various scales, for high productivity.

Following this suggestion, we propose a framework for water use in rice-based systems. This framework, which is based on linear and non-linear programming techniques and operations research is conceived as a tool for a coherent analysis of the system's internal water and land use conditions. The purpose of the analysis is the development of a strategy for improved and sustained system performance, based on system-specific constraint analysis. In a case study of a rice-based irrigation system in Côte d'Ivoire, the applicability of the framework is demonstrated and its usefulness and generic dimension are discussed and highlighted.

[1]Water productivity gives the production of a crop in kilogram per cubic meter of water used.

Conceptual Framework

Conceptual Model

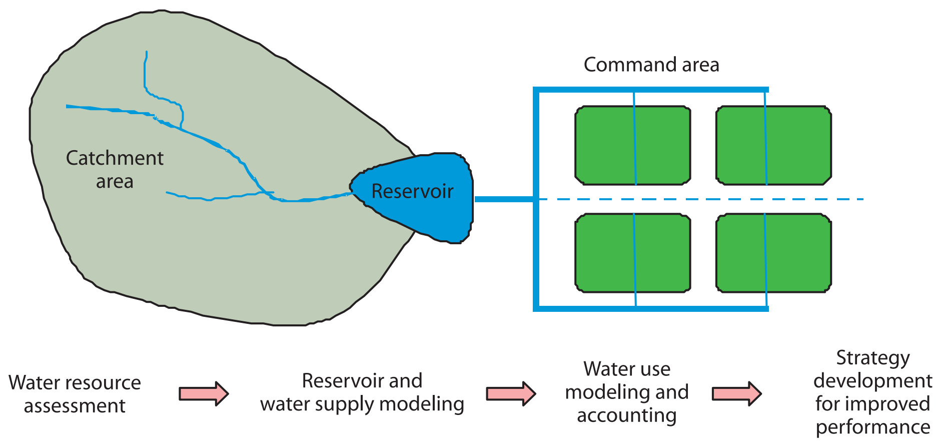
In this conceptual model a reservoir-based rice irrigation system is portrayed from a basin or watershed perspective taking into consideration three main domains: (1) a catchment area from where water is diverted; (2) a reservoir, as the principal storage facility and source for irrigation water supply, and (3) a command area downstream of the reservoir consisting of agricultural land and a network of hydraulic structures including main, secondary and tertiary canals, and a principal drainage exit (figure 1). It is assumed that the command area is sub-divided into a number of block units of variable size. The hydraulic network has an adjustable discharge capacity, and water delivery services are organized in a rotational manner. At the heart of each block a number of farmers collectively produce irrigated rice. At their level, farmers make cropping decisions based on mainly economic grounds, and thereby set the scope for water demand and supply needs of the rice production system. Economic parameters such as the gross margins or net revenues describe the relative importance of each option. In the model, the parameters are taken as drivers for cropping decisions, based on assessed preferences regarding variety, input management, etc.[2] The overall cropping pattern is obtained as a combination of cropping and water use options that maximize the overall net revenue of the system. The objective function is subject to a number of constraints such as land resource needs versus their availability, or water needs versus the availability of water at different levels of the system.

At the basin level, an assessment of the available water resources is made taking into account rainfall patterns and runoff characteristics of the upstream portion of the basin. Monthly discharge rates can be captured and stored. The reservoir is portrayed as the interface between the upstream basin and the downstream command area. Water storage characteristics are integrated into the framework. The actual water storage in the reservoir is calculated as a function of inflow from the upstream catchment, minus losses from the reservoir (evaporation/seepage), minus discharge to the command area, plus/minus storage change. Limited storage is a prime concern for many irrigated systems, and cropping decisions are directly linked to the availability of water.

Field-level irrigation requirements vary between seasons and within the growing season as a function of climate conditions, mode of land preparation, plant establishment, variety, weeding, and field irrigation practices. The overall irrigation needs of the system are evaluated against the availability of water at the reservoir level. At the system level, it is the role of the water delivery system to adequately respond to the field- and farm-level needs with sufficient allocation equity, service quality, reliability and flexibility. Accordingly, the model takes into account the physical and operational characteristics of the hydraulic system at main, secondary and tertiary levels and makes an evaluation against the needs at the field level. Characteristics include discharge capacities, operational and seepage losses as well as operational time aspects.

[2]The use of gross margins of each cropping option implies that a farming system appraisal is being conducted prior to the formulation of the model. Characteristics of the rice-based cropping system provide important input data for the distinction of cropping options.

FIGURE 1.
General outline of model domains and analytical steps.



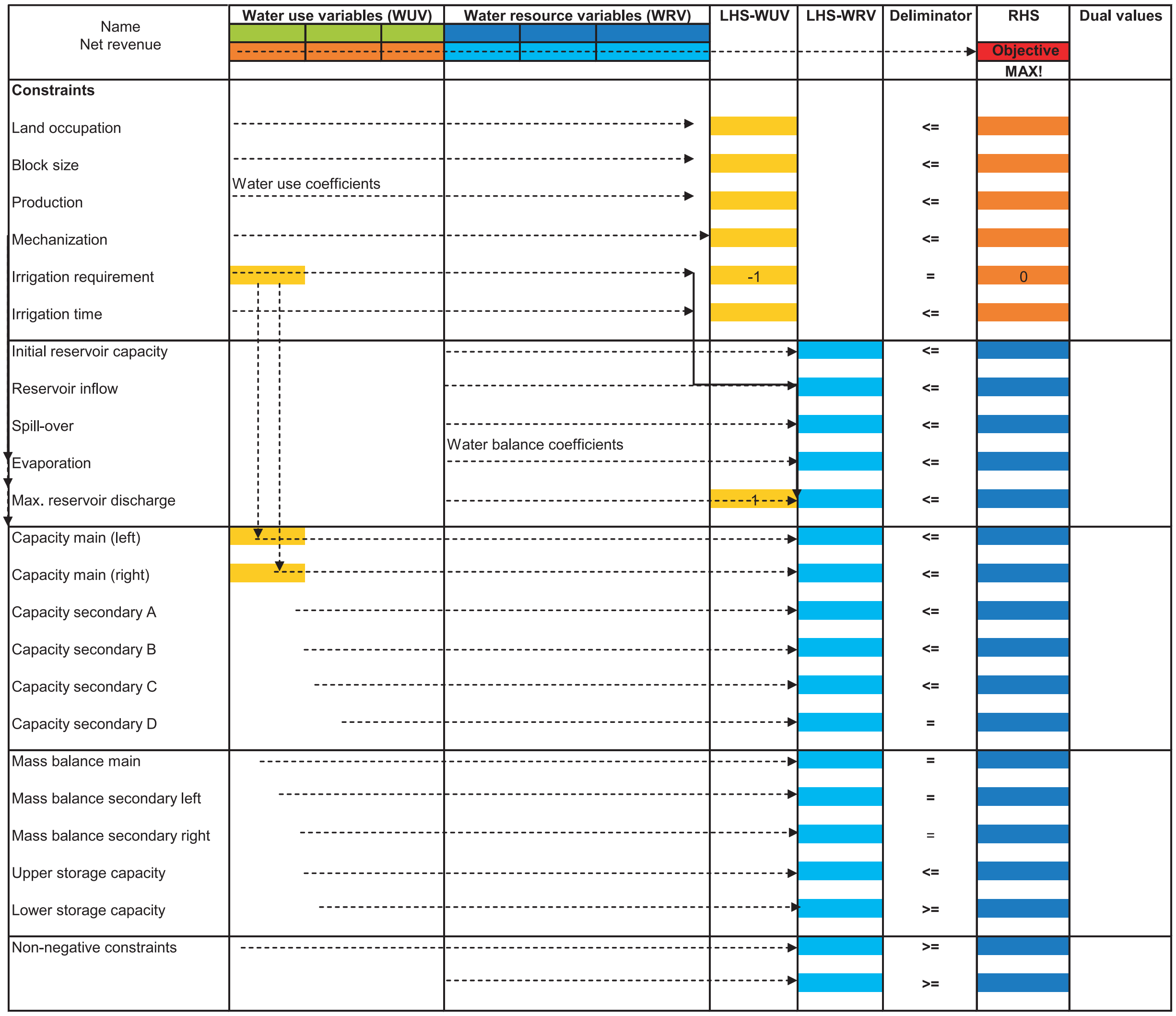
Structured Review of Data Requirements

A spreadsheet-based environment is used for a structured review of data requirements and information for adequate system diagnostics. At the center of the framework is a worksheet containing a matrix, which is based on non-linear programming (figure 2). Cells in the head row contain the acronyms for the cropping options, e.g., "first season rice, cultivated in block X, at medium management input." The row below contains adjustable cells which are to be determined either as an input by the user, or, as an adjustable cell by the optimization algorithm of the software. The proposed solution of this function is assumed to be subject to a number of important constraints, for which the availability of sufficient quality data is seen as an important pre-condition.

Estimates of resource needs are entered on the left hand-side (LHS) of the center worksheet, resource capacities on the right hand side (RHS). The two sides are separated by an operator, defining the direction of the equation. The direction can either be smaller or equal, larger or equal, or equal. Input data sheets containing crop budgets, data on the availability of land and water resources, as well as discharge capacities of the hydraulic system are fully linked to the central worksheet. The output side of this framework comprises a number of sheets that describe the obtained solution and help to enhance its understanding and interpretation. For example, a formal solution report provides details on the found solution. The constraint report summarizes to what extent available resources are utilized, and whether or not a constraint is binding. Water and land resource utilization charts help to identify critical periods of water shortage, and water balance sheets and accounts form the basis for strategic recommendations for improved productivity of water use.

Integrated into the framework is the IWMI water balance framework (Perry1996), which is linked to a set of water accounts that are used as a means to consolidate and interpret model results. At each step of the scenario-based modeling process water accounts are established at the field and system levels (separately for two seasons of rice crops). These accounts contain water-related performance indicators that facilitate the development of a water management strategy and interventions. In addition, agricultural and financial performance

FIGURE 2.
Organization of linear programming (LP) model in matrix format.



Note: LHS = left hand side. RHS = right hand side

indicators such as the total production, average yield levels, water productivity, cropping intensity and net revenues are simultaneously calculated.[3] The proposed approach is largely based on participatory methods, taking advantage of the experiences and expertise of farmers, system managers and extension workers. At various stages of the analysis, both plausibility and accuracy of model results are checked against the perception of the stakeholders. The proposed framework for water use is conceived as a tool that is used interactively in technical group sessions in which structured discussions lead to improved data confidence, and understanding of complex irrigation systems.

[3]The total rice production of the scheme is obtained by taking into account average per hectare yields of each cropping option multiplied by the respective land area.

Sakassou Irrigation System

Background

Location

The Sakassou irrigation system Côte d'Ivoire, is located about 35 km west of Bouaké, the second largest city in the country. About 350 farmers produce rice collectively on 375 ha of land. In 1991, a dam was built at the Loka basin, which is a second-order basin, 740 km^2 in extent, belonging to the Bandama basin, which is by far the largest basin in Côte d'Ivoire. Typically, the landscape of the Loka basin is strongly dissected and undulating. The basin is covered with a dense network of natural drainage streams, of which 75 km are permanent, and about 696 km are classified as temporary. The vegetation consists of typical savanna bushes. The reservoir has a capacity of 8 10^6 m^3. Another reservoir is located about 25 km upstream of Sakassou and is operated by the urban water supply agency, which stores water exclusively for domestic use in the city of Bouaké (figure 3).

Climate

Agro-ecologically, the Loka basin is situated in a transition zone between humid forest and Guinea savanna. Average annual rainfall is about 1,200 mm and annual potential evaporation reaches 1,375 mm. The monthly rainfall distribution within this transition zone follows a typical bimodal pattern, with a first rainfall peak in June and a second peak in September. In the intermediate period, rainfall is significantly reduced (August). As an example, long-term rainfall data from the nearest climate station is presented in table 1.

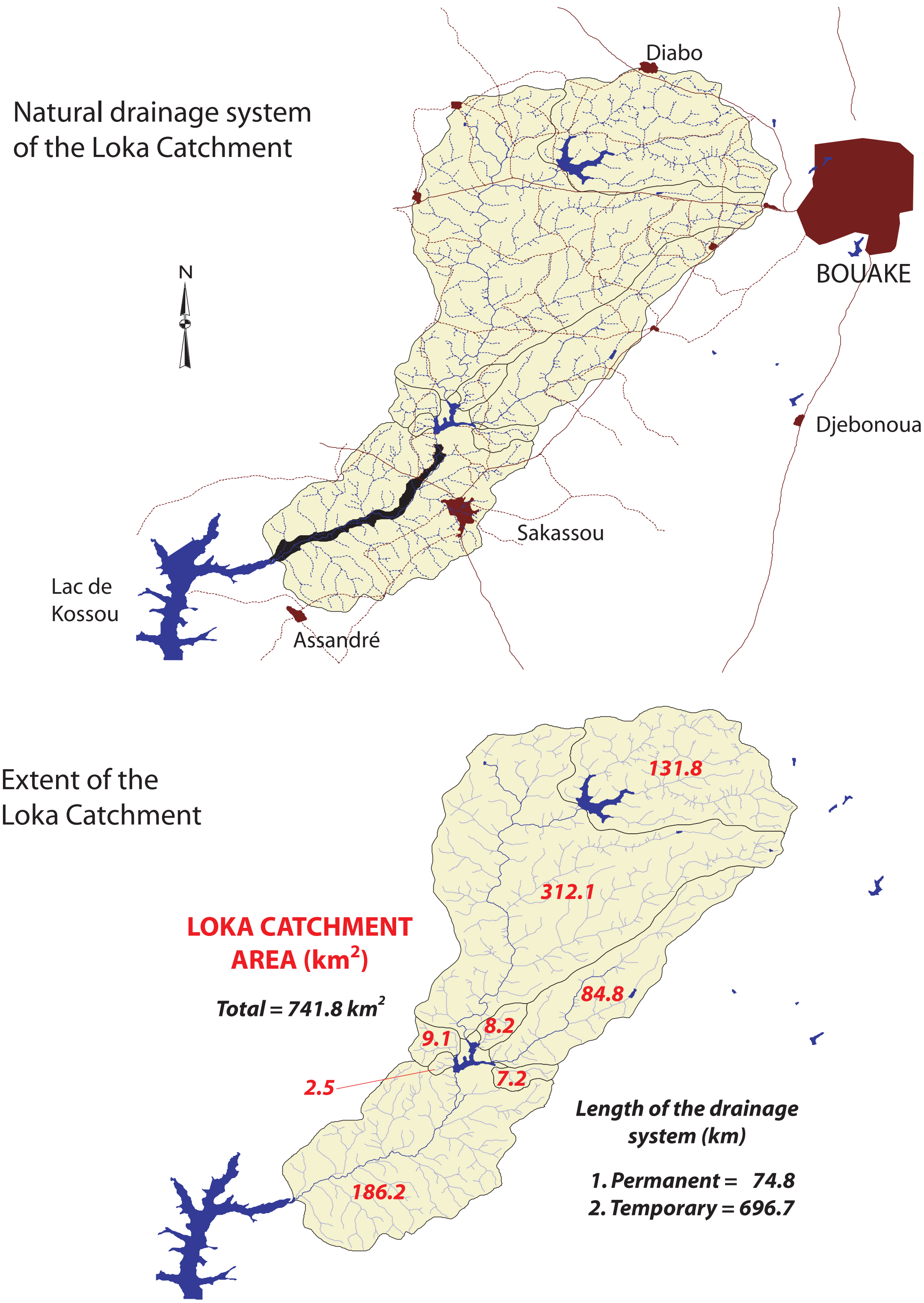
Figures 4a and 4b show monthly rainfall distribution of a series of 73 years, grouped into average, lower and upper quartiles (figure 4a). The general bi-modal distribution is found in all years, from those with less than total rainfall to those with higher than average total rainfall. Standard normal distributions are plotted for the period January to June and July to December (figure 4b).

TABLE 1.
Average precipitation and potential evaporation data for Bouaké.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total for the year
Precipitation (mm)	8	46	86	122	130	145	117	98	176	134	32	15	1,109
Potential ET (mm)	129	138	138	132	120	111	99	93	93	105	108	105	1,371
Balance (mm)	-121	-92	-52	-10	10	34	18	5	83	29	-76	-90	-262

Source: CLIMWAT for CROPWAT—A climatic database for irrigation planning and management 1995.

FIGURE 3.
Loka catchment area, southwest of Bouaké, Côte d'Ivoire.



Production System

The principal irrigated crop is rice, which is grown in two seasons—a first crop season lying within the dry season between the middle of January until the end of June and a second crop season occurring during the wet season between August and December. Average paddy yields reach 3.2 t/ha for the first season and about 2.4 t/ha for the second crop season (Randolph et al. 1998). In addition to activities that farmers at Sakassou carry out on the irrigated system, there are a number of non-irrigated farming activities, to which a large portion of their time is devoted, especially in the second part of the year. Preliminary investigations into the productivity of the scheme suggest that it has reached a level that is above average compared to the overall situation in Côte d'Ivoire (Randolph et al. 1998). According to the farmers' own perception in recent years overall productivity was only about two-thirds of what could have been achieved if water had been managed more effectively.

A look at some historical production data (table 2) shows that since 1995 the average annual marketed production has been 1,323 t, which amounts to 2.3 t/ha. In two out of five years, the annual cropping intensity was only about 100 percent compared with around 190 percent in other years. In 1996, the second season crop was subjected to heavy flooding just prior to harvesting; the perimeter was entirely inundated for more than two weeks, which resulted in complete crop failure.[4] In 1998, no second crop was cultivated because of water scarcity. In some years there is an apparent shortage of water in the reservoir just at the end of the first rice growing season, precluding a second season of irrigated rice. Reduced seasonal rainfall and reduced inflow are given as the causes of this water scarcity.

Institutions

The Sakassou Groupement à Vocation Coopérative (GVC) is a farmer cooperative in charge of the management of the Sakassou irrigated scheme. The GVC assists farmers with the distribution of inputs, particularly fertilizer, herbicides and pesticides and with rice marketing. Inputs are distributed to farmers on

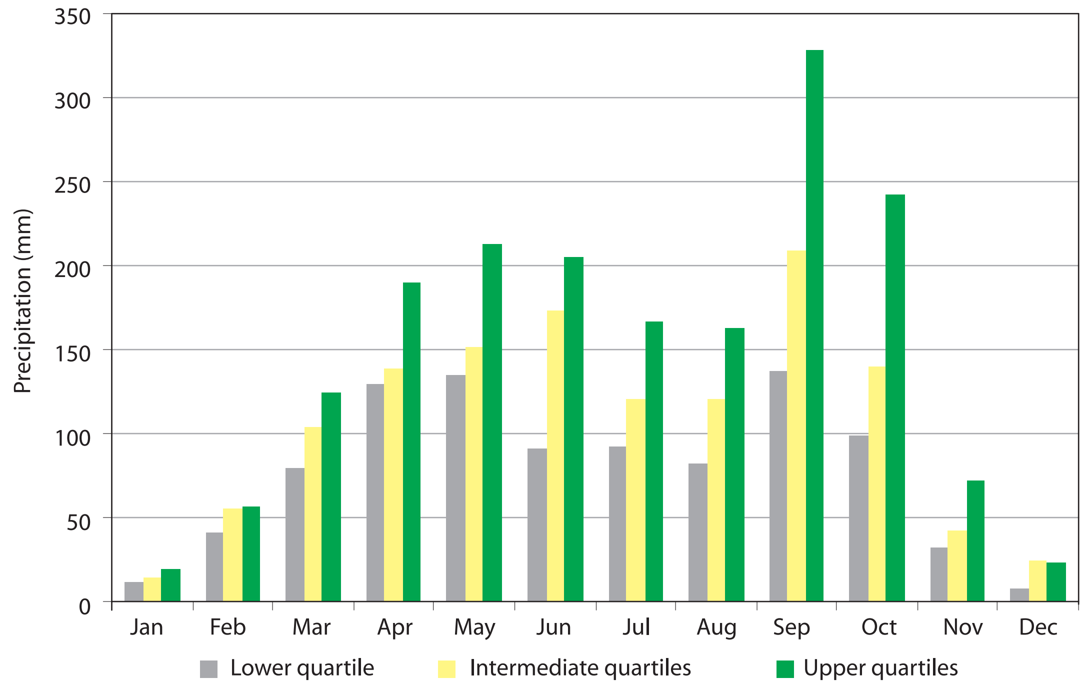
TABLE 2.
Rice production data for the Sakassou irrigation system, 1995-1999.

Year	Cultivated area (ha)	Cropping intensity (%)	Number of farms	Marketed production (tons)	Average yields[1] (tons ha^{-1})
1995	703	187	419	2,133	3.0
1996	375	100	411	547	1.5
1997	701	187	325	1,520	2.2
1998	371	99	339	1,065	2.9
1999	704	188	344	1,351	1.9
Average	571	152	368	1,323	2.3

Notes: 1996, failure of second cycle crop due to flooding; 1998, failure of second cycle crop due to insuffficient storage; calculation of yields based on marketed production.

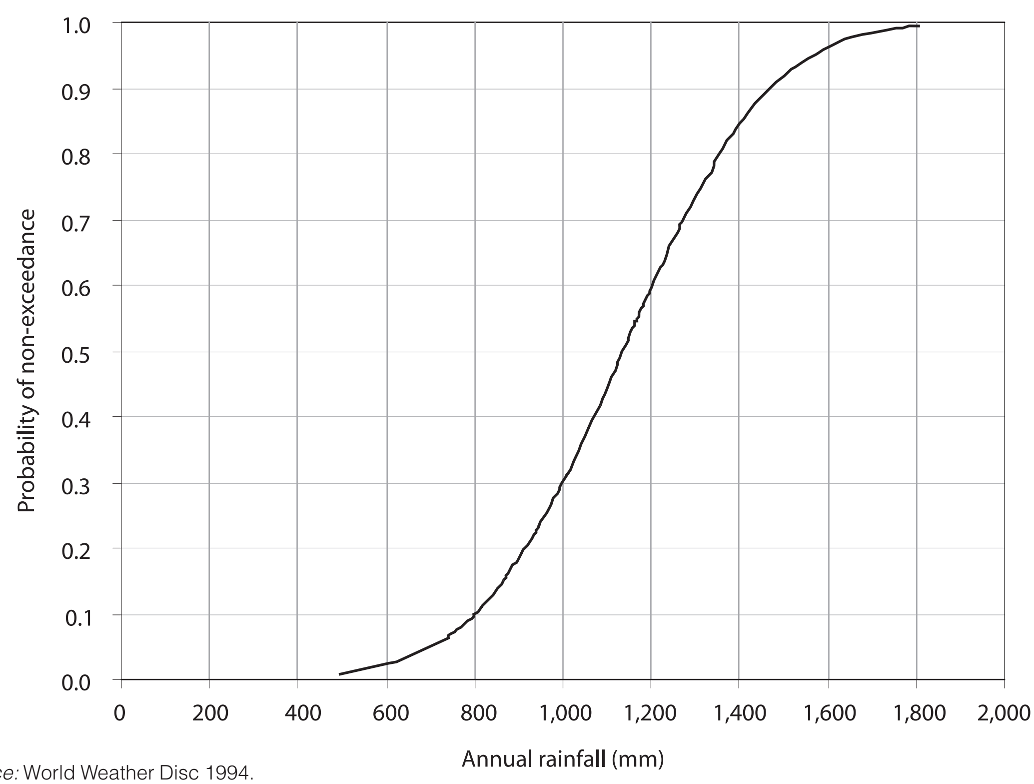
[4]This information was gathered during group discussions with farmers and representatives of the Farmers Cooperative of the Sakassou Irrigation Scheme.

FIGURE 4A.
Long-term (73-year) rainfall distribution at Bouaké, Côte'Ivoire—statistical rainfall analysis.



Source: World Weather Disc 1994.

FIGURE 4B.
Long-term (73-year) rainfall distribution at Bouaké, Côte'Ivoire—normal distribution of annual rainfall.



Source: World Weather Disc 1994.

a loan basis to be reimbursed after each cropping season. A special water management committee is responsible for operation and maintenance of the hydraulic infrastructure, including reservoir, dam, canals and minor structures. Technical assistance to the Sakassou GVC is provided by ANADER (Agence Nationale d'Appui au Développement Rural)—a public agency, providing advice on seasonal planing of irrigation and water needs and irrigation scheduling. The EU-supported "Projet Riz Centre" (PRC, Yamoussoukro) provides agronomic advice, as well as logistical and institutional assistance. Besides this, organizations involved in rice production activities in Sakassou include private rice millers and rice traders. Recently, the farmers' collaborated with COOPEC, which is a micro-credit institution in Côte d'Ivoire.

Model Formulation and Data Input

All formulae of the model are programmed in matrix format as proposed by the *What's Best* software manual (Lindo 1998). A detailed mathematical description of the model code is given in annex 1.

Water Use and Cropping Options (variables)

For each irrigation block we define water use and cropping option variables—one for each season. Rice is the principal cropping option for farmers. Following a preliminary farming system appraisal of the Sakassou Irrigation System, we consider two management input levels: a low-input management and an intermediate- to high-input management level. This gives a total of four variables per block, or a total of 16 variables.

The general reservoir water balance is calculated in monthly terms taking into account inflow from the basin, minus outflow, plus/minus storage change. Evaporation from the reservoir is calculated on the basis of the surface area, which is a function of the actual water level. Both water volume versus level and surface versus level curves are required input data. The relationship between evaporation and the adjustable water resource variable is non-linear, which is why the entire model is non-linear. In order to allow the model to calculate a full cycle of iterations of the reservoir water balance, it is imperative to set an initial storage value for the reservoir.

Characteristic functions of the reservoir are depicted in figure 5, providing information on both storage and surface area as a function of the water level. With regard to the reservoir water storage capacity two important characteristics can be distinguished. First, the upper limit of storage, which in engineering terms, is regarded as full supply level (FSL). Second, the minimum storage capacity, which is the lower capacity limit of the reservoir below which no water can be discharged from the reservoir. The surface area of the reservoir is used for estimating the evaporation from the lake.

Objective Function

The objective of the model is to maximize the sum of net revenues of all water use variables, as a function of cultivated areas multiplied by the estimated per hectare net revenue of each variable. The objective function's right-hand-side (RHS) value is expected to be maximal. Net revenues are retrieved from crop budgets that contain relevant socioeconomic information of a particular cropping. Table 3 provides agro-economic summary data of the cropping options under consideration.

Constraints

The objective function is subject to a number of important constraints, including land resource needs versus land availability, as well as irrigation requirements versus water resource availability. Another important constraint

TABLE 3.
Summary of agro-economic input data.

Agro-economic data	Unit	First season high input	First season low input	Second season high input	Second season low input
Output					
Potential yield	kg ha^{-1}	7,000	5,000	6,000	4,000
Current yield level	kg ha^{-1}	3,916	2,797	3,356	2,237
Price	CFA kg^{-1}	140	140	140	140
Revenue	CFA kg^{-1}	548,172	391,551	469,861	313,241
Costs					
Total fixed cost	CFA kg^{-1}	22,150	22,150	22,150	22,150
Total operating cost	CFA kg^{-1}	240,250	171,125	237,125	168,000
Performance					
Net revenue	CFA kg^{-1}	285,772	198,276	210,586	123,091

considered in the model is the time requirement for irrigation relative to the total time that is available for systems operation. This data is of particular importance for rotational water delivery systems. In addition, delivery capacities at various system levels are included in the constraints.

Land resource needs versus land availability

Prior to the decision over the utilization of available land resources, it is necessary to determine the land resources needs of each variable. Based on field experience the model assumes that it takes 165 days to complete a full rice production cycle. This calculation is based on a staggered system including a two-week period for land leveling and seedbed preparation, and 120 days of vegetation period and harvest. Transplanting activities of the first cropping season are assumed to occur between the middle of February and March. A second season crop can then be cultivated after the first season crop is harvested. In each month, none of the water use variables can occupy a land area larger than the total cultivable area of the command area. The area available for cultivation within each block cannot exceed the block size (table 4).

Irrigation requirement versus water resource availability

The estimated crop water and irrigation requirements are based on FAO standard procedures using the Cropwat Windows model version 4.3 (FAO 1995). Accordingly, the net irrigation requirement is a function of cropping process water needs (ETC), and effective rainfall (P_{eff}). Estimates include water needs for land preparation prior to transplanting of seedlings. The procedure takes account of on-field water management practices, such as submerging and mid-season drainage, which is the removal of the surface water layer about two to four weeks after transplanting in order to weed and to apply fertilizer and maintain a water layer depth of 12 cm on average. We assume that farmers stagger their field operations. Crop water requirements of staggered cropping systems differ from a more rigid system due to longer occupation of land and a reduced cropping intensity at the beginning and at the end of the total growing

TABLE 4.
Summary of command area data.

Land resources	Block A	Block B	Block C	Block D	Total
Command area (ha)	108	95	68	104	375
No. of farms	95	75	65	115	350
Average farm size (ha)	1.1	1.3	1.0	0.9	1.1

FIGURE 5.
Reservoir characteristics—volume stored and surface area relative to the height of the water level.

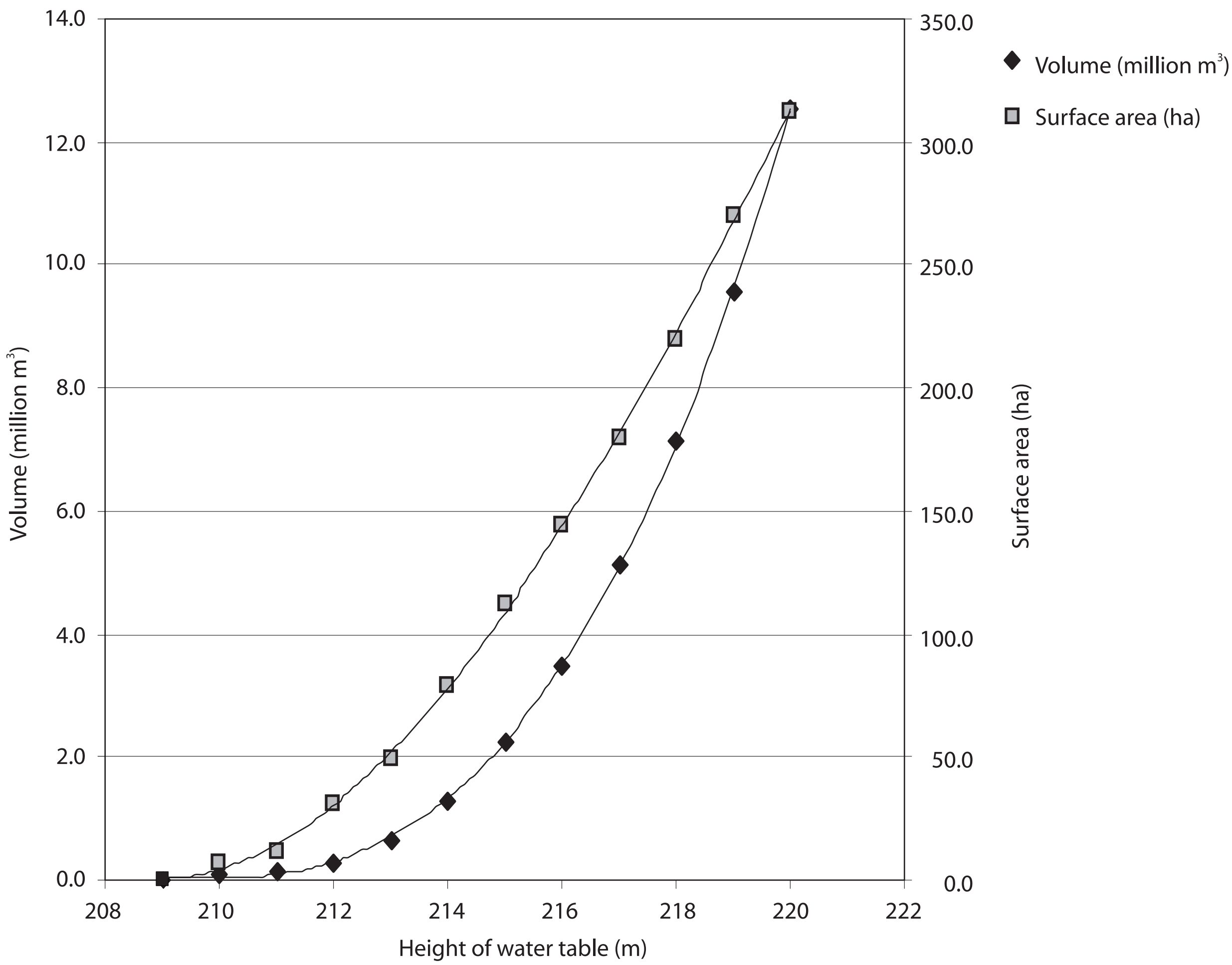


TABLE 5.
Summary of crop and irrigation water requirement input data.

	Unit	First season		Second season	
		ETC	NET	ETC	NET
January	$m^3 ha^{-1}$	500	500	0	0
February	$m^3 ha^{-1}$	1,900	1,560	0	0
March	$m^3 ha^{-1}$	2,000	1,210	0	0
April	$m^3 ha^{-1}$	1,960	940	0	0
May	$m^3 ha^{-1}$	1,480	460	0	0
June	$m^3 ha^{-1}$	380	0	0	0
July	$m^3 ha^{-1}$	0	0	0	80
August	$m^3 ha^{-1}$	0	0	1,440	440
September	$m^3 ha^{-1}$	0	0	1,640	560
October	$m^3 ha^{-1}$	0	0	1,520	570
November	$m^3 ha^{-1}$	0	0	860	350
December	$m^3 ha^{-1}$	0	0	30	0
Total	$m^3 ha^{-1}$	8,220	4,670	5,490	1,920

Note: ETC: Crop water needs including land preparation, submerging, seepage and evapotranspiration.
NET: Net irrigation requirement.

period. To account for seepage from the root zone it is assumed that a constant rate of water is seeping downwards (table 5).[5]

For the estimation of the gross irrigation water requirements, the net irrigation requirement is divided by the inverse of the classical efficiency (1-efficiency). Suggested conveyance (main + watercourse), field application and system efficiencies for two management input levels are given in table 6. Estimates are based on measurements carried out by the national irrigation extension service (ANADER, Bouaké, 1997 personal communication).

The assessment of the available inflow from the Loka basin is based on an empirical study of rainfall-runoff relations established for small basins (up to 500 km^2) in central and northern Côte d'Ivoire (FAO 1996). Accordingly, the depth of runoff from small basins is proportional to a fraction of annual rainfall minus a fixed intercept up to the power 1.28 (for details refer to annex 1).

Runoff is estimated to be 91 mm during average rainfall years. In years with reduced rainfall (one out of four) total yearly runoff reaches only 30 mm. Subsequently, total annual runoff was transformed into monthly runoff on the

TABLE 6.
Estimated irrigation efficiencies.

Irrigation efficiency	Base scenario
Main canal efficiency	80%
Watercourse efficiency	70%
Application efficiency (high input)	60%
Application efficiency (low input)	50%
System efficiency (high input)	34%
System efficiency (low input)	28%

[5]This assumption may result in a slight overestimation of water needs.

FIGURE 6A.
Assumed monthly distribution of runoff in an average rainfall year, Loka basin, Côte d'Ivoire.

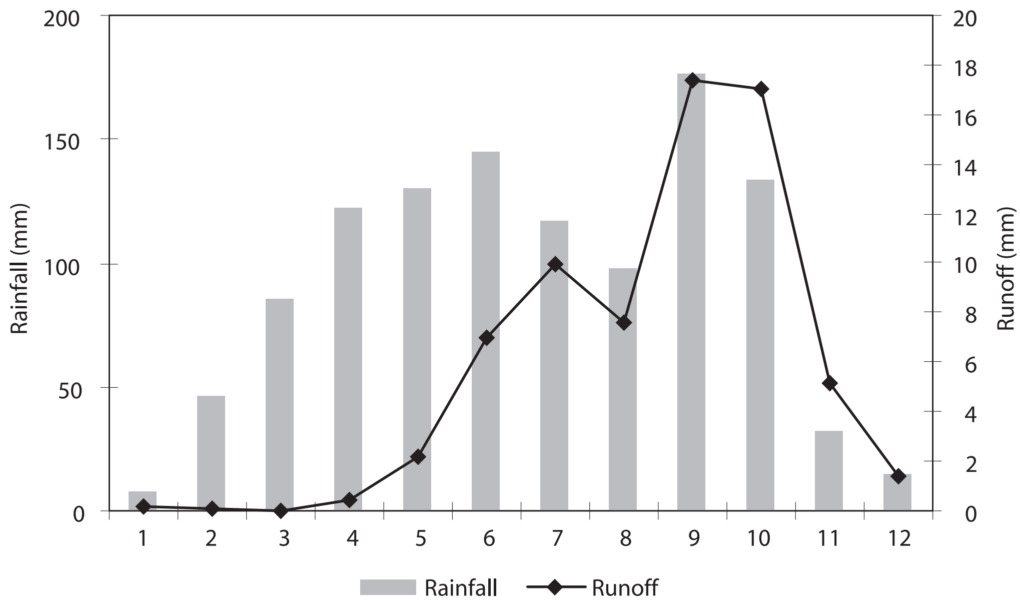
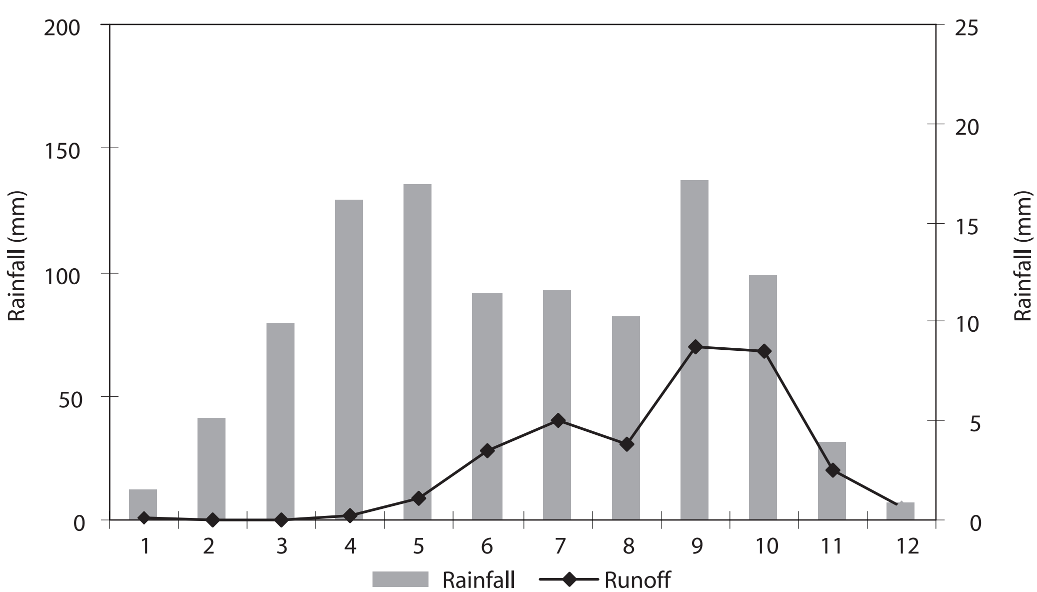


FIGURE 6B.
Assumed monthly distribution of runoff in a "dry" rainfall year, Loka basin, Côte d'Ivoire.



basis of long-term runoff coefficients from the neighboring Kan basin (Girard 1971). Figures 6a and 6b show assumed monthly distribution of runoff of an average rainfall year (figure 6a) and of a dry year (one out of ten years, figure 6b). For the period between January and June no substantial runoff can be expected. Substantial runoff is generated between June and November.

Irrigation system management

Water is delivered through two lined main canals, feeding into a network of 65 secondary earth canals. Each secondary canal has a design delivery capacity of 20 $l\ s^{-1}$, serving a variable number of farmers. No tertiary system of canals exists at Sakassou. The former riverbed functions as the central drain. Water allocation and distribution are organized in a rotational mode. Rotations take between 5 and 10 days. Each day, water is supplied for about 12 to 14 hours. During night time valves at the head of the system are closed. The system is managed in reversed mode: each of the four blocks consists of a number of secondary canals and those located at the downstream side are served first. Once a series of secondary canals has received water for the allocated time, it is the turn of the next group upstream of the former group (table 7).

At the tertiary level, farmers organize the distribution of water freely. This is done in informal groups with no intervention on the part of the system managers. In general, two situations can be distinguished, one for the organization of the water distribution during peak demand and another for the organization of water during the season as a whole. During the season, water is taken out from the secondary canals at relatively low discharge rates just sufficient to maintain a constant water level inside the field. At peak demand, which is the period of land preparation and transplanting, water needs exceed by far the supply capacity of the allocation system. In order to cope with reduced deliveries, farmers take out as much water as possible and store most of it inside a temporary field storage. From there it is distributed on a field-to-field basis. Field-to-field water distribution implies that water is used several times in order to accomplish seedbed preparations. This way farmers gain flexibility compared to the tight time constraints that are inherent to the prevailing rotational management system.

Irrigation system management analysis is the assessment of the system's ability to fulfill water delivery services in accordance with the specific needs of the smallholder farming system. This involves the assessment of both the hydraulic discharge capacity at main, secondary and tertiary levels and adequate timing of service provision.

The peak irrigation requirement is converted into the specific irrigation supply rate, which is 2.3 l/s/ha. The conversion is made based on the assumption of the actual system operation time (12 hours).[6] For each irrigation block, we approximate the capacity of the hydraulic system separately for the main, secondary and tertiary canals. The number of secondary and tertiary canals is multiplied by their average discharge capacity. If only a portion of each canal is operated at the same time—as it is in rotational mode—the actual discharge capacity is less than potential. Consequently, irrigation in rotational mode takes more time compared to demand mode operation. If the rotation system puts a restriction on time, then the desired irrigation service cannot be delivered fully. In order to make an approximation of the time aspects, we elaborate the respective irrigation delay or

[6]The specific irrigation supply rate should not to be confused with the equivalent field discharge rate, which is a minimum field discharge rate depending on soil characteristics and irrigation practices.

rotation factor, which is the number of active canals over the number of canals at this level. The rotation factor is an indicator of the additional time that is required to fulfill a full rotation. For example, where half of the secondary canals is operated at the same time the rotation factor is two. Thus, the time to complete a full cycle is double compared to a situation in which all secondary canals are operated. Taking into account the gross irrigation requirement, the equivalent discharge rate and the rotation factor, we estimate the gross time that is required to irrigate one full irrigation block. This divided by the size of the block gives the equivalent irrigation time in units of hr/ha. This equivalent irrigation time is used in the linear programming matrix as the time coefficient of a cropping option. Any shortage in water supplies—either caused by time or low canal discharge capacity—may impinge on the performance of irrigation at the field level. To portray the effect within the logic of linear programming, we suggest the introduction of a supply deficit parameter, which alters the peak supply irrigation requirement and thus reduces the equivalent time requirement to irrigate 1 ha. Thus, time can become an important constraint without binding the objective function.

TABLE 7.
Summary of irrigation management inputs.

	Unit	First season		Second season	
		high input	low input	high input	low input
Reservoir					
Daily operation time	h	14		12	
Monthly operation time	d	26		26	
Main canal level					
No. of main canals		2		2	
Max. discharge rate	$l\ s^{-1}$	1,325		1,325	
Secondary level					
No. of secondary canals		65		65	
Average discharge rate	$l\ s^{-1}$	20		20	
Tertiary level					
No. tertiary canals		350		350	
Average capacity	$l\ s^{-1}$	15		15	
Farm level					
No. of farms		350		350	
Discharge at farm outlet	$l\ s^{-1}\ ha^{-1}$	14.0		14.0	
Services					
Peak supply level	%	70%		99%	
Rotation factor (R=Rs*Rt*Re)		3.1		3.1	
Monthly supply capacity	m^{-3}	307,944		197,964	

Notes: Rs: Number of secondary canals over number of secondary canals concurrently operated.
Rt: Number of tertiary canals over number of tertiary canals concurrently operated.
Re: Number of farms over number of farms concurrently served.

To summarize, two important parameters are calculated: first, the equivalent time requirement for the irrigation of 1 ha of land and, second, the monthly supply capacity of the main, secondary and tertiary canal network. This is done on the assumption that within a given time window, supply deficits during peak supply may be tolerated (figure 7).

Mechanized production versus access to mechanical traction

Animal traction is not used at Sakassou irrigation perimeter. Instead some farmers use small tractors, so called "*motoculteurs.*" The majority of farmers is heavily reliant on manual work for transplanting, occasional weeding and harvesting. Where a *motoculteur* is used, plowing and leveling of the soil is done in a much more even and homogeneous way compared to manual seedbed preparation. This has a considerable effect on the quantity of water required for transplanting and weed control as well as on the agronomic performance of rice plants. If soils are mechanically ploughed and leveled, it was observed that plants grow more evenly and the transplanting stress is overcome more rapidly. A positive effect of more precise seedbed preparation on the development of young plants is assumed, which normally leads to considerably increased paddy yields. Access to mechanical traction is an important constraint to farmers. At Sakassou the number of *motoculteurs* is 25. Roughly one *motoculteur* can cultivate 1 ha of land per day.

Yield potential

A restriction is introduced into the model to limit potential yields that are obtainable under the prevailing climate and management conditions. This maximum per hectare yield is assumed to be 7 t/ha, an estimate that is based on agro-climatic characterization proposed by Becker et al. (1999).

Base Scenario

Overview

An overview of the main system input characteristics and a result of this base scenario is given in figure 8. The base scenario confirms that available resources and services permit the cultivation of two seasons of rice per year. A first crop season uses 91 percent of the available land resources compared to 100 percent utilization in the second cropping season. The total cropping intensity is therefore 191 percent. A total rice production of 2,273 t can be attained, of which about 1,192 t are produced in the first season and 1,081 t in the second season. On average, 64 percent of the total production is produced at intermediate- to high-input condition. Average per hectare yields are 3.5 t/ha for the first cropping season and nearly 2.9 t/ha for the second season, respectively.[7] In relative terms, the current production at Sakassou irrigation system is at 50 percent of its potential. The estimate is made on the assumption of a per hectare yield potential of 7 t/ha for the first and 5 t/ha for the second crop (Becker et al. 1999).

Financially, the first season crop contributes 57 percent to the theoretical overall gross revenue, whereas the second season crop's financial contribution is only 43 percent. However, in terms of water productivity this order is reversed: the first season crop produces 0.42 kg/m^3 of water compared to 0.55 kg/m^3 of depleted and processed water produced by the second season crop. The latter takes advantage of a higher portion of water deliveries from precipitation.

[7]These figures seem higher compared with the actual yields given in table 2. Yields in table 2 reflect only a portion of the production, which is marketed or sold. Another portion of the actual production must be accounted for as home consumption.

FIGURE 7.
Irrigation management system at the Sakassou irrigation system.

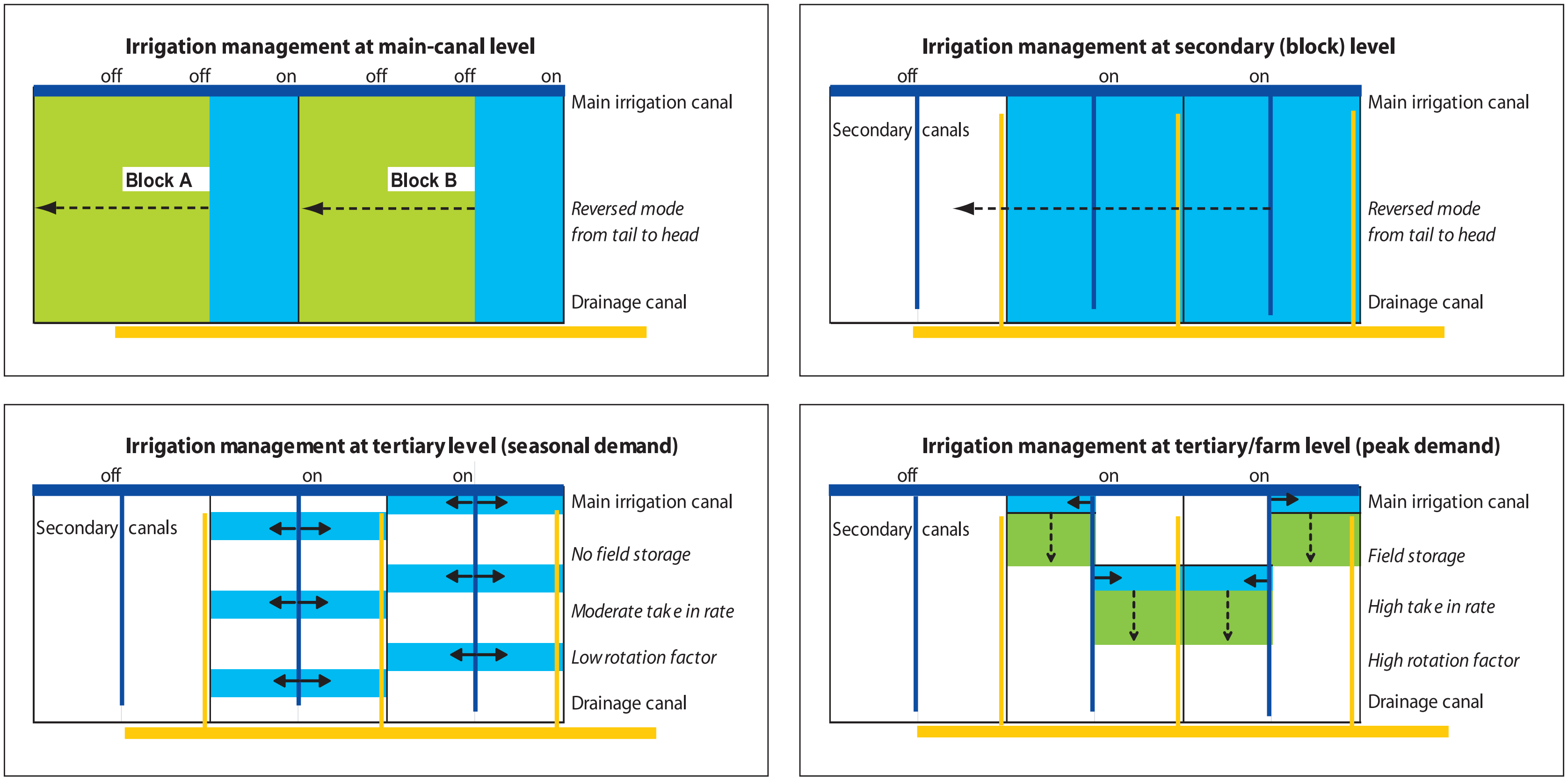
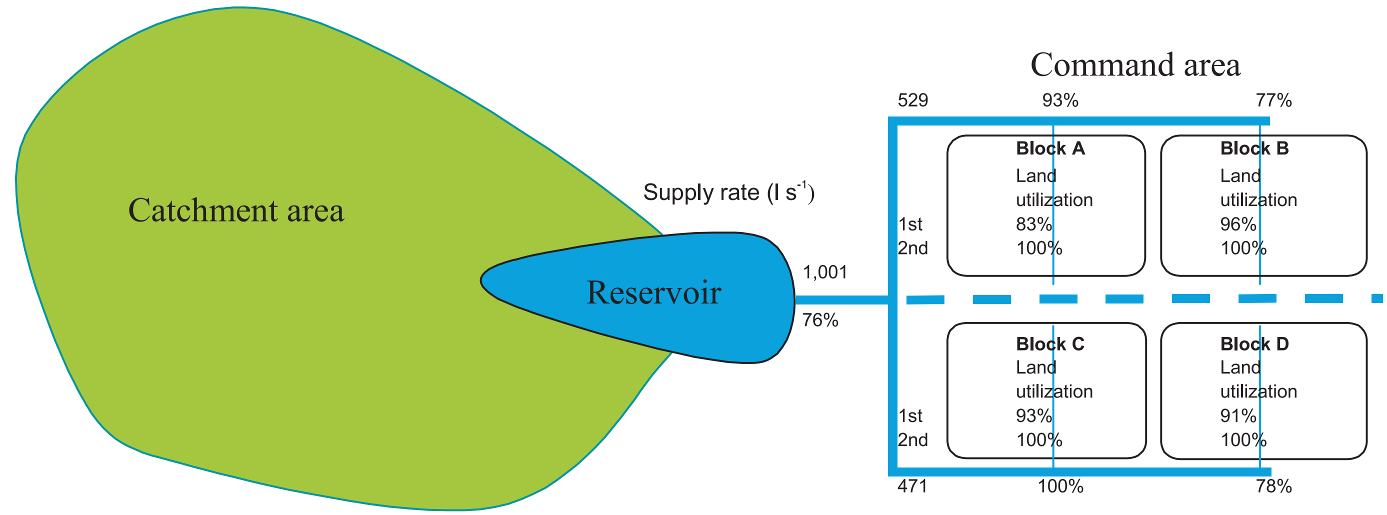


FIGURE 8.
Overview of baseline scenario input and results.



Size	km^2	424
Rain	mm $year^{-1}$	1,109
Discharge	mm year-1	69
Discharge	mill. m^3 $year^{-1}$	29.0

Max. storage	mill. m^3	7.0
Min. storage	mill. m^3	1.0
Initial storage	mill. m^3	6.0
Daily operation	h	14
Monthly operation	h $month^{-1}$	364
Time utilization	%	100%
Peak supply	%	70%
Total supply	%	93%

		First season	**Second season**
Total area cultivated	ha	340	375
Cropping intensity	%	91%	100%
High input fraction	%	64%	58%
Production	tons	1,192	1,081
Productivity	tons ha^{-1}	3,510	2,884
Gross margin	CFA ha^{-1}	254,075	173,620
Financial contribution	%	57%	43%
Water productivity	kg m^{-3}	0.42	0.55

TABLE 8.
Summary of constraint analysis.

	Unit	Left-hand side	Operator	Right-hand side	Utilization	Constraint
Land resources						
Land availability, first season	ha	340	<=	375	91%	FALSE
Land availability, second season	ha	375	<=	375	100%	TRUE
Water resources						
Lower storage capacity	m^3	1,566,612	>=	1,000,000	64%	FALSE
Upper storage capacity	m^3	7,000,000	<=	7,000,000	100%	TRUE
Hydraulic system						
Reservoir discharge rate	$l\ s^{-1}$	1,001	<=	1,325	76%	FALSE
Supply to left main canal	$l\ s^{-1}$	529	<=	750	71%	FALSE
Supply to right main canal	$l\ s^{-1}$	471	<=	575	82%	FALSE
Discharge secondary A	$l\ s^{-1}$	223	<=	240	93%	FALSE
Discharge secondary B	$l\ s^{-1}$	201	<=	260	77%	FALSE
Discharge secondary C	$l\ s^{-1}$	160	<=	160	100%	TRUE
Discharge secondary D	$l\ s^{-1}$	217	<=	280	78%	FALSE
Irrigation management						
System operation time (first season)	h	364	<=	364	100%	TRUE
System operation time (second season)	h	152	<=	312	49%	FALSE
Production technology						
Mechanization	d	650	<=	650	100%	TRUE
Potential annual production	ton	2,273	<=	4,200	54%	FALSE

Notes: TRUE : Constraint is binding.
FALSE : Constraint is not binding.

Constraint Analysis

A summary of the constraint analysis is shown in table 8, containing results with respect to land availability, water resources, water supply and rice production system constraints. The information contained in the “utilization” column is taken from the model’s left-hand side (LHS) and is referred to the model’s right-hand side, indicating whether or not the constraint is binding.

Following is a summary of the constraints associated with this scenario:

1. The availability of irrigated land is a not a constraint in the first season but is a constraint in the second cropping season.

2. The lower storage capacity of the reservoir is not reached in either season. However, the upper storage limit of the reservoir is exceeded at least once.

3. The hydraulic system has sufficient discharge capacity to meet the anticipated supply levels at the main and secondary levels except for block C, where capacity is fully utilized. The supply level is however lower than 100 percent, which is a result of a cut of 30 percent in the peak irrigation supplies during the month of February.

4. The time window for irrigation of 14 hours per day and 26 days per month is insufficient for the fulfillment of irrigation services.

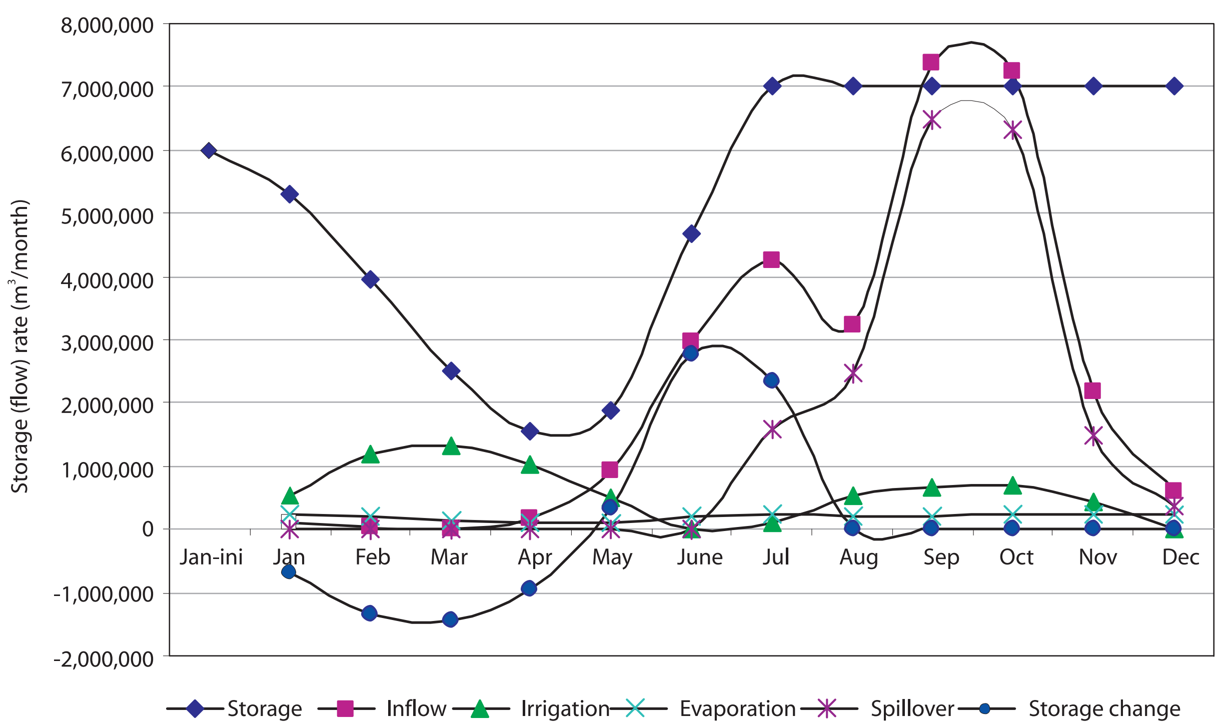
5. Access to mechanized production technology is limiting the achievement of a higher level of productivity.

6. The actual production is at 54 percent of its potential.

Availability of Water

The regime of the water balance components of the reservoir is given in figure 9. The graph contains six lines, one for each water balance component including a total storage line. At the beginning of the year it is assumed that the reservoir is almost entirely filled (initial value, 6 10^6 m^3). During the January to February period farmers start with land preparation activities, which require increased water supplies. Initial storage levels decline rapidly to a minimum of about 2 10^6 m^3 in May. Evaporation from the reservoir is potentially very high during this period. From May onwards the change of storage is positive. The storage line increases gradually until the maximum of 7 10^6 m^3 is reached in June. Beyond maximum storage level, additional inflow from the basin cannot be captured and stored. The surplus of water is discharged via the dam's spillway into the central drain from

FIGURE 9.
Reservoir water regime giving actual storage, inflow, storage, irrigation supplies, evaporation from the reservoir, spill-over and storage change.



were it is carried away into Lake Koussou. This portion of spillover must be regarded as non-utilizable outflow which leaves our domain. Figure 9 shows that a full storage of 7 10^6 m^3 is carried over to the next year. Discharge from the Loka basin is far greater than the holding capacity of the reservoir, which has some important implications for the cultivation of the second season crop. If masses of water are spilling into the command area, rice crops may be at risk of being inundated, or even, damaged.

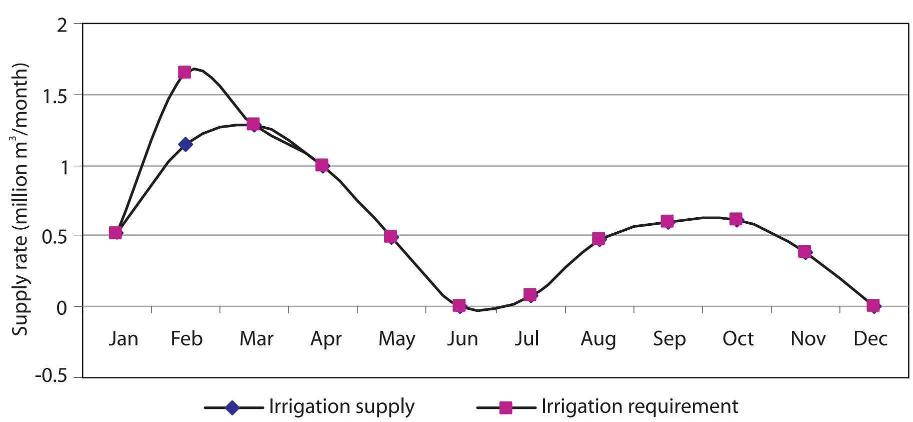
With an overall rotation factor of 5 and 14 hours of systems operation per day, time is the most critical constraint for meeting irrigation requirements. The peak supplies in February and March do not meet the assumed irrigation requirements. Under such pre-set management conditions, peak irrigation supplies are in fact heavily reduced. Imposed peak supply reductions put pressure on the farmers, which is why farmers tend to take out water from canals at times when that is not permitted.

The scheme management was questioned as to why water levels within the main canals are kept fairly high whereas supplies to the blocks are restricted through strict time constraints. We discovered that the system design was inadequate at one of the irrigation blocks located downstream. Land levels are slightly above the normal operating water levels in the main canal. It was therefore necessary to maintain relatively high water levels in the main canal to irrigate the block (figure 10).

Water Balance of the Command Area

On an annual basis about 10.6 10^6 m^3 of water enter the command area as inflow, of which 7.1 10^6 m^3 is supplied by the reservoir and 3.5 10^6 m^3 by rainfall (figure 11). The bulk of the total inflow used by the cropping process is accounted for as evapotranspiration including land preparation and weed control (4.8 10^6 m^3). Another large part of the annual inflow leaves the domain via surface drain (2.4 10^6 m^3) or is deep seepage to groundwater (2.6 10^6 m^3). The residual 0.9 10^6 m^3 is assumed to be non-beneficial evapotranspiration from irrigated and non-irrigated land. In this balance, storage change is not considered.

FIGURE 10.
Total monthly irrigation requirement and supplies.



Note: Actual supplies for the month of June are zero.

Water Accounting

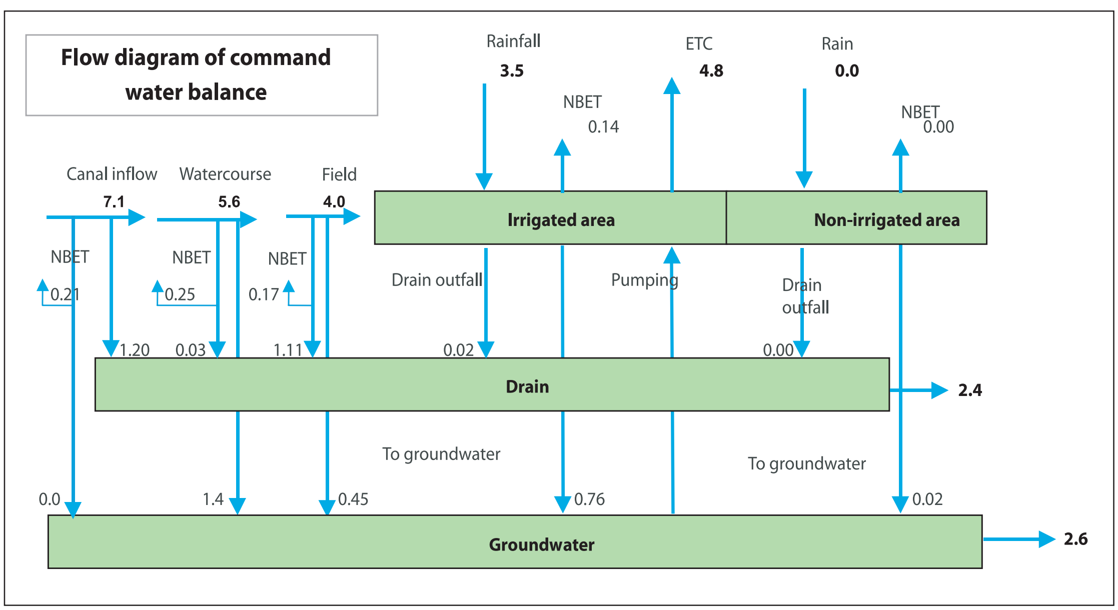
Water accounts include performance indicators for both field and system levels. An average per-hectare yield of about 3.51 t is obtained for the first season crop and an average of 2.8 t/ha is calculated for the second season crop (table 9). No distinction is made between low-input and intermediate- to high-input crop production. Water productivity is reported relative to inflow, total depletion and process depletion. Inflow includes rainfall and irrigation, and total depletion includes non-beneficial evaporation.

On average, annually, one cubic meter of depleted water is processed into 0.47 kg of paddy rice. Water productivity of the first and second season is 0.42 kg/m^3 and 0.55 kg/m^3, respectively. In relative terms, the water productivity of the second crop is 31 percent higher than that of the first rice crop. This is a net result of the relationship between reduced total production and reduced water consumption (table 9).

Water productivity results need to be interpreted cautiously as farmers are forced to a tight operation regime, which generates a water supply-demand gaps at farm level of about 30 percent during peak demand periods. Farmers overcome this periodic water supply gaps through the adoption of more productive on-field irrigation practices including on-field night storage, and also unauthorized water abstraction from canals.

At the system level, 48 percent of the totally available water is depleted, of which 94 percent is utilized for the processing of rice. Annually, 753 of 3,002 mm of available water is accounted for as uncommitted outflow, i.e., not utilized within the domain. The rest is accounted for as non-beneficial depletion (table 10).

FIGURE 11.
Estimated water balance of the command area (in 10^6 m^3) using the IWMI water balance framework (Perry 1996).



Note: NBET : Non-beneficial evaporation.
ETC : Evapotranspiration.

TABLE 9.
Field-level water account.

	First season		Second season		Annually	
	$m^3 ha^{-1}$	mm	$m^3 ha^{-1}$	mm	$m^3 ha^{-1}$	mm
Inflow						
Irrigation	7,670	767	3,597	360	11,267	1,127
Precipitation	5,320	532	4,550	455	9,870	987
Subsurface						
Lateral seepage flows						
Gross inflow	12,990	1,299	8,147	815	21,137	2,114
Storage change	-57	-6	37	4	-20	-2
Net inflow	12,933	1,293	8,183	818	21,117	2,112
Depletive use						
Crop/process (land preparation+transpiration)	8,434	843	5,216	522	13,651	1,365
Evaporation (non-beneficial)	613	61	277	28	890	89
Total depletion	9,048	905	5,493	549	14,541	1,454
Outflow						
Surface drainage	1,500	150	1,500	150	3,000	300
Sub-surface drainage	92	9	22	2	114	11
Deep percolation	2,407	241	1,095	110	3,502	350
Total outflow	3,999	400	2,617	262	6,616	662
Performance						
Depleted fraction (gross)	0.70		0.67		0.69	
Process fraction (depleted)	0.93		0.95		0.94	
Production (kg ha^{-1})	3,510		2,884		6,394	
Production per unit of inflow (kg m^{-3})	0.27		0.35		0.30	
Production per unit total depletion (kg m^{-3})	0.39		0.52		0.44	
Production per unit process depletion (kg m^{-3})	0.42		0.55		0.47	

TABLE 10.
System-level water account.

	First season		Second season		Annually	
	m³	mm	m³	mm	m³	mm
Inflow						
Goss inflow	6,457,325	1,902	4,126,885	1,101	10,584,210	3,002
Canal Inflow	4,650,829	1,370	2,420,635	646	7,071,464	2,015
Precipitation	1,806,496	532	1,706,250	455	3,512,746	987
Groundwater						
Storage change						
Surface						
Subsurface						
Net inflow	6,457,325	1,902	4,126,885	1,101	10,584,210	3,002
Depletive use						
Process depletion (ET)	2,864,034	843	1,956,068	522	4,820,103	1,365
Non-process depletion						
Flows to sinks						
Other evaporation	208,319	61	103,848	28	312,166	89
TOTAL DEPLETION	3,072,353	905	2,059,916	549	5,132,269	1,454
Outflow						
Total utilizable outflow	1,739,410	512	902,848	241	2,642,259	753
Surface outflow	812,965	239	423,069	113	1,236,034	352
Subsurface outflow	926,445	273	479,780	128	1,406,225	401
Committed water						
Domestic use						
Industrial use						
Environment						
Downstream users						
Uncommitted	1,739,410	512	902,848	241	2,642,259	753
Available water	6,457,325	1,902	4,126,885	1,101	10,584,210	3,002
Indicators						
Depleted fraction (available)	0.48		0.50		0.48	
Process fraction (depleted)	0.93		0.95		0.94	
Process fraction (available)	0.44		0.47		0.45	

Sensitivity Analysis

A sensitivity analysis was carried out taking into account variations of two input parameters: first, variations of rainfall and runoff, and second, variation of the initial storage of the reservoir. Rainfall was reduced in two scenarios starting with average rainfall ($P_{0.5}$) with an estimated runoff of 29 10^6 m^3, to a one-in-four-year rainfall ($P_{0.25}$) with an estimated runoff of 14.5 10^6 m^3, and subsequently to a one-in-ten-year rainfall ($P_{0.1}$) with and estimated 5.9 10^6 m^3 runoff.

Modeling results of the reduced rainfall scenarios suggest no change of the overall optimum cropping intensity. However, in the $P_{0.1}$ case (figure 12) the storage level at the end of the year is significantly reduced to 3.5 10^6 m^3—about half of the full capacity of the reservoir. Assuming this reduced storage is carried over to the next year, it is likely that this will not be sufficient to support the cultivation of all available land. A 50 percent reduction in the initial stored water resource would be sufficient to irrigate only 257 ha of rice in the first season. The overall cropping intensity is expected to drop from 192 to 169 percent.

Altogether, the findings of the base scenario suggest that the Sakassou irrigation system is operating relatively well. However, time constraints imposed on farmers are extremely tight. It is assumed that the current performance and productivity levels cannot be sustained under such unfavorable conditions.

Future Scenarios

Approach and Process

Our proposed modeling approach is broken down into three scenarios: short-, medium- and long-term. This is based on a proposal put forward by members of the water management committee of the Sakassou GVC, who suggested that a process-based approach should be taken. At each stage of this process, group discussions were held with committee members and technical staff of ANADER. Supported by the model

FIGURE 12.
Reservoir water balance dynamics taking into account a one-in-ten-year rainfall and runoff distribution ($P_{0.1}$).

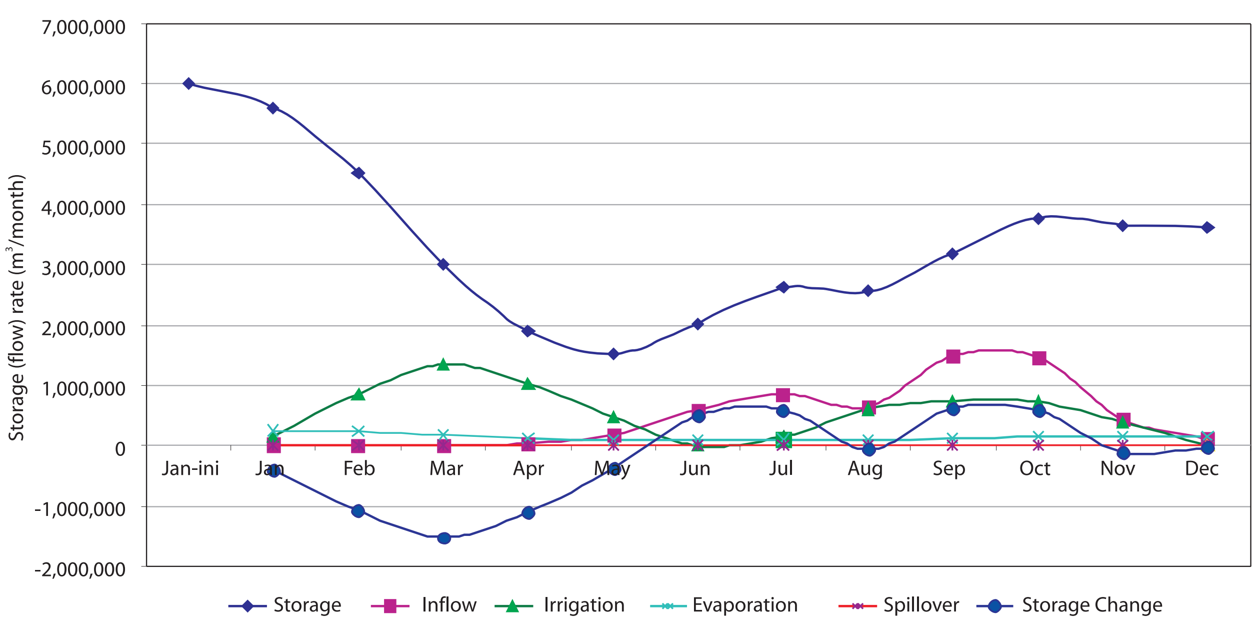
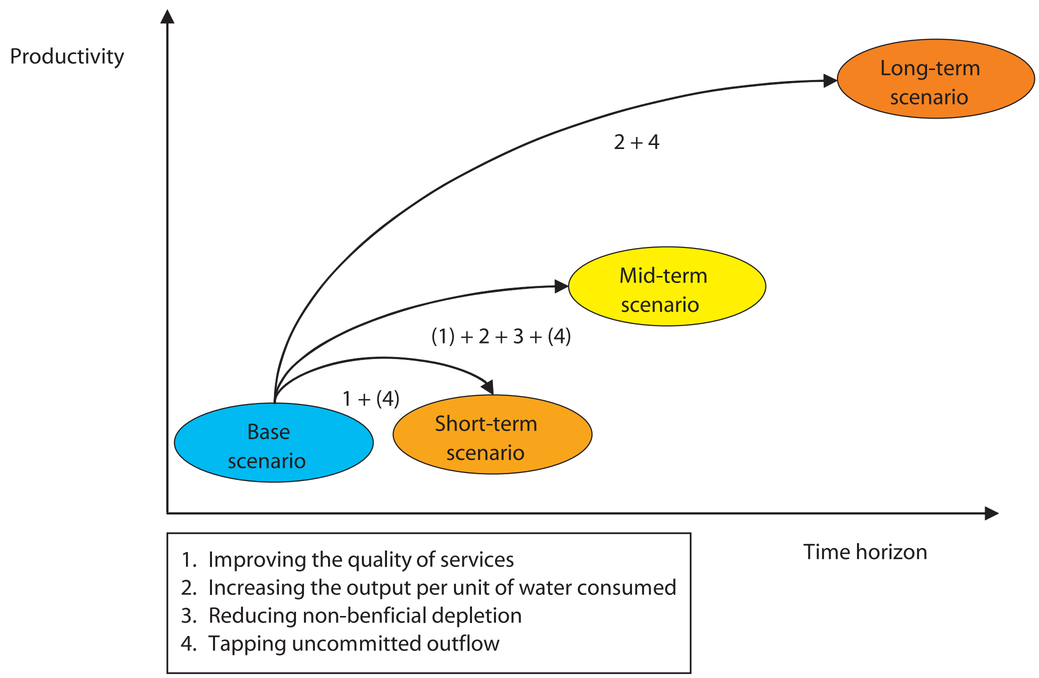


FIGURE 13.
Principal pathways for improving water productivity of rice irrigation systems.



output, possible interventions at various levels of the irrigation system were discussed and technical and managerial implications assessed. In this context, the model was used as an interactive analytical tool, providing a reference for participatory planning and decision-taking.

Four principal strategic pathways for improving the productivity of the rice-based system are proposed, all of which include relaxing of constraints (see figure 13 and table 11).

1. Improved service management. This category contains interventions for improving the quality of services through design change and operational adjustments in the delivery system. Proposed interventions include the extension of the daily reservoir operation time, relaxing peak supply restrictions, a change of rotation at secondary and tertiary levels and increasing the number of secondary canals. The proposed interventions were assumed to have a short-term effect on system performance, except for those which required a design change or physical works like adding secondary canals. Such interventions would require more time and resources.

2. Increasing the output per unit of water consumed. The proposed interventions focus on both increased agricultural output (numerator) and reducing the water input (denominator). Typical field-level interventions include an increase of the application efficiency through improvement of land leveling and the adoption of plot-to-plot irrigation. Also, better access to improved varieties and cultural practices is proposed. The latter implies a change of crop establishment from transplanting to direct seeding or the adoption of more effective weeding. System-level interventions focus on increasing the cropping intensity, that is increasing the area irrigated or cultivated

TABLE 11.
Strategies and interventions to improve the productivity of water use.

Strategic Intervention	Level of intervention			Period of intervention		
	Reservoir	System	Field	Short-term	Medium-term	Long-term
I. Improving the quality of services (service management)						
1. Changing system operations						
(a) Extending the daily system operation time	X	X		X		
(b) Relaxing peak supply restrictions		X		X		
(c) Changing rotation system		X		X		
2. Design change of the delivery system						
(a) Increasing the number of secondary canals		X				X
(b) Increasing discharge capacity through lining		X			X	
II. Increasing the output per unit of water consumed						
1. Increasing field application efficiency						
(a) Improving field levelling			X		X	
(b) Facilitating plot to plot irrigation			X		X	
2. Improving cultural practises						
(a) Change from transplanting to direct seeding			X			X
(b) Increasing effectiveness of weeding			X		X	
(c) Improved soil fertility management			X			X
3. Increasing management level of production						
(a) Facilitating access to mechanised production technology			X			X
(b) Facilitating the adoption of improved varieties			X		X	
(c) Increasing cropping intensity		X	X			
III. Reducing non-beneficial depletion						
1. Reducing non-beneficial evapotranspiration						
(a) Canal maintenance (weeding) to reduce non-beficial evaporation		X			X	
(b) Improved drainage to avoid evaporation from residual field ponds			X		X	
IV. Tapping uncommitted outflow						
1. Increasing the availability of water						
(a) Adding storage capacity	X					X
(b) Desiltation of reservoir	X				X	
2. Reducing outflow from main canal						
(a) Improving canal maintenance		X			X	
(b) Lining of earth canals		X			X	
3. Reducing outflow from the watercourse						
(a) Improving flow characteristics through improved maintenance		X			X	
(b) Reducing deep percolation through canal compaction		X			X	
4. Reducing outflow from fields						
(a) Improving control of water layer			X		X	
(b) Add field storage to facilitate reuse of water			X		X	

over the managed command area. Most interventions to increase the output per unit of water require a medium- to long-term time horizon in order to be effective.

3. Reducing non-beneficial depletion. Included in this category of interventions are the lining of secondary canals to reduce seepage from canals and improved leveling in order to reduce non-beneficial evaporation from small residual water ponds on fields. Such interventions would be effective in the medium to long term.

4. Tapping of uncommitted outflow. This category of interventions is to increase the availability of water and thereby reduce outflow from the various system levels. Reservoir interventions involve the creation of additional storage capacity by adding another layer to the dam or the desiltation of the reservoir.

The next step involved an assessment of possible effects that proposed interventions would have on the parameters considered in the model. For example, if land leveling is improved we assume that the application efficiency would increase. Therefore, this parameter is assumed to increase from 60 to 65 percent in the medium term and from 65 to 70 percent in the long term (table 12). Overall, the system irrigation efficiency is assumed to increase in two steps: first from 28 to 41 percent in the medium term and second from 41 to 43 percent in the long term.

Overview

An overview of the obtained scenario results is given in table 13 showing effects of the proposed interventions on system performance. For each scenario—base-, short-, medium- and long-term—land and water use and irrigation supply performance indicators are given. Land use indicators include the cultivated area, cropping intensity, total annual production, the portion that is contributed by medium- and high-input management, the production level relative to its potential as well as average yields. The irrigation supply/demand ratio is used to describe the overall irrigation supply level relative to the irrigation demand. Water use performance indicators comprise of both system- and field-level indicators. In general, considerable effects of the assumed interventions can be expected only in the medium to long term. In the short term, the proposed improvement of the supply/demand ratio is indicative of improved water service provision. Details are discussed in the following sections.

TABLE 12.
Proposed irrigation efficiency change.

Irrigation efficiency	Base scenario	Short-term	Medium-term	Long-term
Main canal efficiency	80%	80%	85%	90%
Watercourse efficiency	70%	70%	80%	80%
Application efficiency (high input)	60%	60%	65%	70%
Application efficiency (low input)	50%	50%	55%	60%
System efficiency (high input)	34%	34%	48%	50%
System efficiency (low input)	28%	28%	41%	43%

TABLE 13.
Land- and water-use performance indicators of scenarios.

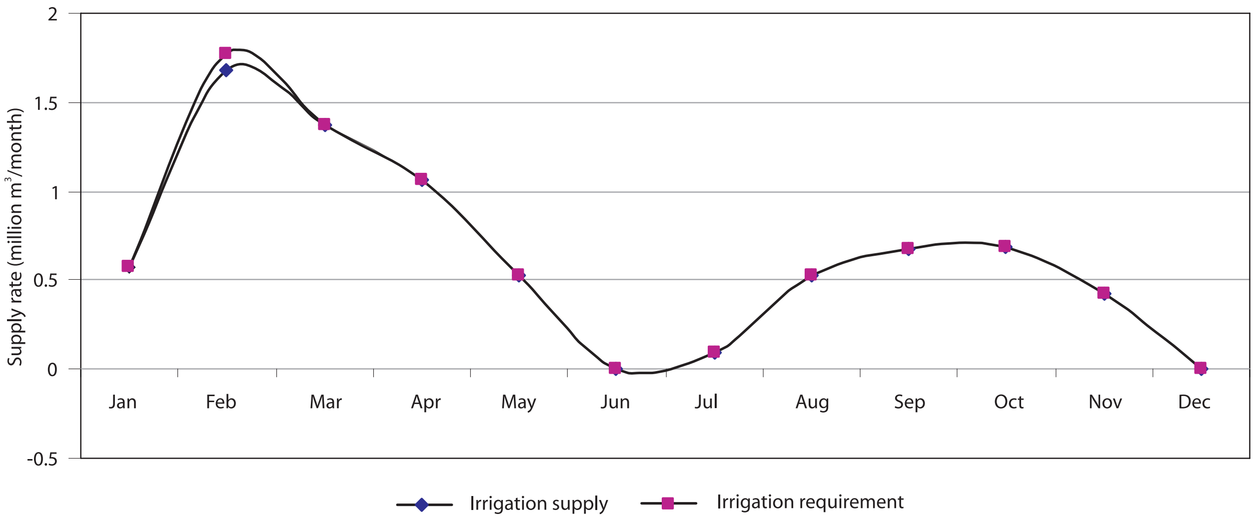
	Unit	Base	Short-term	Medium-term	Long-term
Land use					
Cultivated area	ha	715	729	750	750
Cropping intensity		191%	195%	200%	200%
High input level area	ha	433	433	520	703
		61%	59%	69%	94%
Total annual production (paddy)	ton	2,273	2,455	3,054	4,781
Production relative to potential		47%	50%	63%	98%
Productivity (average)	ton ha^{-1}	3.4	3.5	4.1	6.4
Irrigation supply					
Irrigation supply/demand ratio[1)]		93%	99%	99%	100%
Water use					
System level					
Depleted fraction (available)		0.48	0.48	0.56	0.64
Process fraction (depleted)		0.94	0.94	0.94	0.94
Process fraction (available)		0.45	0.45	0.52	0.60
Field level					
Depleted fraction (gross inflow)		0.69	0.69	0.72	0.77
Process fraction (depleted)		0.94	0.94	0.94	0.94
Production per unit of inflow	kg m^{-3}	0.30	0.31	0.39	0.65
Production per unit total depletion	kg m^{-3}	0.44	0.45	0.54	0.85
Production per unit process depletion	kg m^{-3}	0.47	0.48	0.58	0.91

Note: [1)]Irrigation supply/demand ratio = system input divided by gross irrigation requirement.

Short-term Scenario

The most important management intervention considered in the short-term scenario is a change in system operation time during the first cropping season from 14 to 20 hours per day. With this change of operation, time would no longer be a constraint although farmers are expected to irrigate at night. A second intervention is a change of the organization of the irrigation rotation (tour d'eau). Accordingly, all secondary canals are assumed to be operated at the same time. This is, however, with a reduced number of farmers taking water at the same time. This intervention would transfer the rotation from the secondary to the tertiary/farm level and thereby keep the overall rotation factor unchanged. The expected advantage would be that farmers from the upstream blocks, who were served last under the current arrangements, could start their field activities much earlier and thus perform their field operations in a more flexible manner. Another beneficial effect associated with this intervention is that all farmers could take advantage of high early-season prices for paddy rice.

FIGURE 14.
Monthly water supply and demand after system operations change.



With the considered short-term interventions, peak supply restrictions will no longer be valid. A considerable change can be noted on the supply side. The irrigation-supply level has increased from 93 to 99 percent relative to the total irrigation requirement. Peak supplies are now moved forward to February (figure 14) compared to the base scenario where supplies peaked in March (figure 10). During the first season the overall field-level irrigation inflow is 840 mm compared to 767 mm in the base scenario (table 9). Land use performance indicators are slightly increased. The cultivated area has gone up by 14 ha from 715 to 729 ha, which is also shown in the increased cropping intensity of 195 percent. The incremental productivity of this short-term interventions is 0.1 t/ha. With an annual production of 2,455 t only 50 percent of the theoretical potential is reached.

Water use performance indicators remain constant or slightly increased compared to the base scenario. At the system level only 48 percent of the available water is depleted, of which 94 percent is accounted for as processed. The difference is accounted for as non-beneficial depletion. At the field level, the depleted fraction of the gross inflow is 69 percent, of which 94 percent is processed. The difference is either outflow as drainage or deep percolation to groundwater. The production per unit of process depletion is found to be 0.49 kg of rice per cubic meter.

As a consequence of the proposed short-term interventions, the storage level in the reservoir would reach its lower limit of 1.0 10^6 m^3 in the month of May. The availability of water resources could become a constraint for future land preparations of a second crop if the expected rainfall in September is delayed. Bearing this in mind, the water management committee agreed to implement a slightly modified irrigation schedule based on 18 hours of daily operation.

Medium-term Scenario

In the second scenario, substantial improvements on the assumed irrigation efficiencies are proposed (see table 11). The most significant interventions considered in the medium-term scenario would be an increase in the conveyance efficiency of the main canal from 0.8 to 0.85 and an increase at watercourse level from 0.7 to 0.75. Field application efficiencies would increase from 60 to 65 percent in the case of high medium to high management and from 50 to 55 percent for low input management. The increase could be achieved through improved land preparations and the promotion of plot-to plot irrigation.

It is further assumed that through the adoption of improved rice varieties the general yield level could be increased by 15 percent. Improved varieties are readily available, which out-perform those which had gone through a decline in potential yields through improper seed production and a loss of resistance against both biotic and abiotic stresses.

Another intervention is the facilitation of investment into mechanization. Accordingly, the number of *motoculteurs* could be doubled from 25 to 50 within a period of one to two years. The mechanization intervention is considered catalytic for a shift from low-input to intermediate-level input production. If land preparation can be done more precisely, farmers can more easily choose a change of crop establishment from transplanting to direct seeding. This would have a considerable effect on both productivity (avoiding stress during transplanting) and reduced water needs for land preparation.

Proper cleaning and maintenance of canals at main and watercourse levels would be an important intervention especially where the flow velocities have declined or where water seepage occurs. This would have an effect on reducing non-beneficial evaporation along canals. Similarly, evaporation from small field depressions where water ponds reside could be reduced by better field leveling and drainage. Finally, it is suggested that the control of a water layer for weed control could be improved through effective drainage and better plot leveling and thereby uncommitted outflow from the field can be tapped.

Altogether, interventions considered in this medium-term scenario show a significant effect on the performance of the system (table 13). Average yields would increase from 3.5 to 4.1 t/ha. The depleted fraction of the available water would be at a level of 0.56 compared to 0.48 in the base scenario. Accordingly, relatively more water is used for the process of rice production. The productivity of water per unit processed was found to be at 0.58 kg/m^3 compared to 0.47 kg/m^3 in the base scenario.

Long-term Scenario

Long-term interventions would include a continued adoption of improved varieties, provision of access to mechanized farming technology, encouraging direct seeding as opposed to transplanting as well as the adoption of improved fertility management practices. In the long-term scenario we assume that the production potential could be nearly fully utilized. A high potential of the irrigated system implies a high degree of homogeneity in terms of on-field water management, variety choice, cultural practices and in level of mechanization. In addition, uncommitted outflows from various system levels could further be tapped and used more productively through improving canal flow characteristics, re-establishing field storage and reuse during peak demand periods.

In the long-term, it is suggested that a high production level with average yields of 6.4 t/ha and two harvests a year could be achieved. This would push the level of production per unit process depletion to 0.91 kg/m^3, which is nearly double that attained in the base scenario. However, given the high variability of rainfall, it would be important that the availability of water in the reservoir be monitored carefully.

Conclusions

The productive use of water in rice irrigation systems is subject to considerable variation as a result of system complexity, different settings and variable framework conditions. Operations research tools, such as linear and non-linear programming, offer an opportunity for a more in-depth systems analysis of the performance of a rice-based irrigation system relative to processes and their constraints. The non-linear optimization model presented in this paper is part of an integrated systems analytical framework, which compares water resource availability at watershed, reservoir and system levels versus water needs of the rice-based production system. The model maximizes net returns of the assumed production system variables taking into account restricted resource availability and system capacity. At each stage of the analysis both plausibility and accuracy of model results are checked against the perception of the stakeholders. Hence, it is not just a modeling exercise of a decision support system. The model is conceived as a reference tool for structured input data analysis and as a guide for interactive group discussions on future management options for improved system performance.

In the case of the Sakassou irrigation system, proper reservoir management was found to be crucial for improved year-round water availability at the system level. A change of operation hours from 14 to 20 hours per day improved the supply situation and reduced time constraints on the part of farmers. Following model-supported group discussions, this proposed intervention into the system's management was found agreeable to the water management committee members and technical staff of the supporting agency. The committee took a decision to change the system operational mode accordingly, which was encouraging. However, a change in the water management regime should ensure that water supplies are carefully fitted to water needs during each stage of the production cycle. Otherwise, outflow from the system could rapidly increase and storage could be easily exhausted before the end of the first cropping season. In years with reduced rainfall a low level of storage at the end of the second season could pose a serious constraint on sustainable production levels in the following year.

There is an apparent contradicting interest between maximizing the production's water productivity and its financial revenues. A higher productivity per unit of water is attained by the second season crop compared to the first season crop. This is a net result of reduced yields and much reduced water use during this period. However, financially, the first crop's net returns are superior to those of the second crop. Assuming cropping decisions are based on financial viability rather than on productivity, the first crop is more attractive to farmers. It is therefore suggested that efforts be concentrated on the first season crop and that cropping and water allocation decisions are made during the second cropping season according to the availability of water. In particular, under water-scarce conditions, we suggest the adoption of a strict water conservation regime during the second, less productive cropping season in order to carry over the conserved storage to the next season to ensure full resource availability during this more productive cropping season.

In the long term, the productivity of water could be nearly doubled if the proposed interventions are implemented. In addition to interventions to improve the productivity per unit of water consumed, major contributions to higher water productivity could be attained through full utilization of the internal productive potential. Access to mechanization is identified as a key internal constraint. In the model it is assumed that 25 small tractors are insufficient to allow farmers to move from labor-intensive, low-input to an intermediate- to high-input production system. Other factors that could be added include access to credit, a standard constraint to most irrigated systems in the region, as well as access to improved varieties. In group discussions with farmers from Sakassou, a mechanization strategy was strongly confirmed as critical to improved land preparation including leveling, on-field water management and cultural practices.

There are a number of important issues associated with the system performance analysis that are not captured within this model analysis, including institutional arrangements or the quality of support service provisions. Discussions with scheme collaborators made the study team conclude that institutional issues were part of an internal discussion process which should be kept separate. We believe that this framework has its merits for institutional discussions as well. It is conceived as an action research tool feeding results from scenarios into discussions among researchers and systems managers and key farmers. Institutional discussion on the implications of the proposed interventions are a logical consequence and will be more readily adapted once the technical effectiveness and advantages of the proposed interventions are fully appreciated by all parties involved.

Annex 1—Mathematical Description

Introduction

The non-linear programming technique is used for the formulation of the water use model. All formulae are programmed in matrix format as proposed by the *What's Best* software manual (Lindo 1998). The formulae used in this study are explained below.

Variables

Two types of variables are distinguished: water use/cropping options and water balance components.

Water use/cropping options: A water use or cropping option designates a unit area of land within an irrigation block that is utilized by a certain crop at a certain input management level, e.g., rice at medium input management level.

$X_{i,j,k}$: Land area X of crop i, situated within block j at input management level k;
for crop i = 1...n;
block j = 1…m;
input management level k = 1…p;

Water resource variables: These variables refer to the water balance of the reservoir, calculated in the following form:

$$S_t = S_{t-1} + I_t - E_t - SP_t - TIS_t \quad (1)$$

$$E_t = f\ (Eto\ (A_t)); \quad (2)$$

where:

A_t	=	Open reservoir surface area during time t (m^2)
E_t	=	Evaporation from reservoir during time t (m^3 $month^{-1}$)
Eto	=	Reference evapotranspiration during time t (m^3 $month^{-1}$)
I_t	=	Recharge from watershed during time t (m^3 $month^{-1}$)
SP_t	=	Spill-over from reservoir during time t (m^3 $month^{-1}$)
S_t	=	Storage of actual period during time t (m^3 $month^{-1}$)
S_{t-1}	=	Storage of previous time period (m^3 $month^{-1}$)
TIS	=	Total irrigation supply (m^3 $month^{-1}$)
t	=	1…z (month)
f	=	fraction

The general reservoir water balance is calculated at monthly time increments taking into account inflow from the basin minus outflow, plus/minus storage change. The actual evaporation from the reservoir is calculated as a fraction of the potential evapo-transpiration, which is a function of the surface area. Water volume versus level and surface versus level curves are required input data. The relationship between evaporation and the adjustable water resource variables is non-linear. In order to allow the model to calculate a full cycle of iterations of the reservoir water balance, it is imperative to set an initial storage value for the reservoir.

Objective Function

The objective of the model is to maximize the total net revenues of all water use variables as a function of cultivated areas multiplied by the estimated per-hectare-net-revenue of each variable. Hence, the objective function's right-hand-side (RHS) value is expected to be maximal.

$\Sigma\ (NR_{i,j,k} * X_{i,j,k})$ = MAX! (3)
for
crop i = 1...n;
block j = 1…m;
input management level k = 1…p;
where:
NR: net revenue (monetary unit * ha^{-1}).

Constraints

Land resource needs (occupation) versus land availability

In no case can water use variables (cropping options) occupy more commanded land area than is totally available for irrigation.

$\Sigma\ (lr_{1,1,1,1} * X_{1,1,1}) <= TAL_{1,1}$ (4)
$\Sigma\ (lr_{i,j,k,t} * X_{i,j,k}) <= TAL_{j,t}$
$\Sigma\ (lr_{n,m,p,z} * X_{n,m,p}) <= TAL_{m,p}$
for
crop i = 1...n;
block j = 1…m;
input management level k = 1…p;
period t = 1…z (monthly)
where:
lr: land resource needs {0,1}
TAL: totally available land resources (ha)

Irrigation requirement and supply versus water resource availability

In each period, the product of gross irrigation requirement (ir) of each cropping option and the respective land area occupied is equal to the total irrigation requirement of this period. IR is a function of crop water needs (evapotranspiration ET_c), minus effective rainfall (P_{eff}), multiplied by the inverse conventional irrigation efficiency (1-ie).

$$\Sigma\ (ir_{1,1,1,1} * X_{1,1,1}) = TIR_1 \quad (5)$$
$$\Sigma\ (ir_{i,j,k,t} * X_{i,j,k}) = TIR_t$$
$$\Sigma\ (ir_{n,m,p,z} * X_{n,m,p}) = TIR_z$$

where:

ir: irrigation requirement (m^3 * $month^{-1}$)

TIR: total irrigation requirement (m^3 * $month^{-1}$)

The adjusted irrigation requirement (ir*) of each cropping option¾taking into account possible peak supply reduction[8]—multiplied by the land area occupied cannot exceed the total water supply, which cannot exceed the totally available storage in each period.

$$\Sigma\ (ir^*_{1,1,1,1} * X_{1,1,1}) <= TWS_1 \quad (6)$$
$$\Sigma\ (ir^*_{i,j,k,t} * X_{i,j,k}) <= TWS_t$$
$$\Sigma\ (ir^*_{n,m,p,z} * X_{n,m,p}) <= TWS_z$$

and

$$TWS_1 <= S_1 \quad (7)$$
$$TWS_t <= S_t$$
$$TWS_z <= S_z$$

where

ir*: adjusted irrigation requirement (m^3 * $month^{-1}$)

TWS: total water supply (m^3 * $month^{-1}$)

S_t : storage of actual period (m^3 *$month^{-1}$)

Initial storage value

An initial value (S_{INI}) is required for the calculation of the water balance of the reservoir.

$$S_0 = S_{INI} \quad (8)$$

where

S_{INI}: initial storage value (m^3)

[8]Optionally the management of the system can impose a general peak water supply cut in order to overcome capacity bottlenecks of the hydraulic network.

Reservoir recharge from watershed

Monthly run-off from the watershed is an important input data. If available, estimates can be based on empirical data and runoff coefficients, or otherwise on hydrological modeling. In this case an empirical formula was suggested.

$$I_1 = RO_1 \qquad (9)$$
$$I_t = RO_t$$
$$I_z = RO_z$$

and

$$RO_t = S \times DR_t; \qquad (10)$$

with

$$DR_t = A^{x} (P_t - B)^{1.28} \qquad (11)$$

where

DR: depth of runoff (mm)
RO: runoff (m^3)
P: precipitation (mm)
S: surface area (km^2)
B: empirical intercept (mm)
A: empirical factor (-)

Evaporation from the reservoir

Evaporation from the open reservoir is taken as a fraction of the potential evapotranspiration (Eto) as a function of the actual surface area.

$$E_1 = f(A_1)^* \beta \qquad (12)$$
$$E_t = f(A_t)^* \beta$$
$$E_z = f(A_z)^* \beta$$

and

$$A_1 = f(H_1) \qquad (13)$$
$$A_t = f(H_t)$$
$$A_z = f(H_z)$$

where:

E_t: potential evaporation from reservoir (m^3 $month^{-1}$)
H: height of water level in the reservoir (m)
β: estimated fraction of actual evapotranspiration (0.8 to 0.9)

System management

Many rice-based irrigation systems are managed in a rotational manner. In this mode a part of the system is serviced while another part is turned off from water supplies. The interval at which one rotation cycle is completed varies from several days up to weeks. The completion of a full rotation depends on the specific irrigation requirement, the available time for irrigating a unit area, and the hydraulic discharge capacity¾the rate the canal network is able to deliver the required service to the field. The following diagnostic steps were taken to assess the irrigation management system.

1. Determine the peak net irrigation requirement for each cropping option:

   $ir_{net\ max}$ = MAX (ir_1, ir_2, ir_z)

   where

   $ir_{net\ max}$: maximal net irrigation requirement ($m^3\ ha^{-1}$)

2. Estimate gross irrigation requirement considering irrigation efficiency and peak supply conditions.

   Irp_{gross} = ir_{max} * (1-ie_s) * ps

   ie_s = ie_c * ie_w * ie_a

   where

   irp_{gross}: gross adjusted irrigation requirement ($m^3\ ha^{-1}$)

   ie_s : system efficiency

   ie_c : conveyance efficiency at main canal level

   ie_w : conveyance efficiency at watercourse level)

   ie_a : field application efficiency

   ps : relative peak supply

3. By dividing the gross irrigation requirement per hectare by the total system operation time, and by subsequent conversion into liters per second, we obtain the specific irrigation requirement.

   Irp_{spec} = irp_{gross} * TOT^{-1} * 3.6^{-1}

   where

   TOT : total system operating time per months (h)

   Irp_{spec} : specific irrigation requirement ($l\ s^{-1}\ ha^{-1}$)

4. The supply capacity of the secondary system level is estimated as average canal discharge rate multiplied by the number of canals operated simultaneously.

   Q_{sec} = q_{sec} * N_{sec}

   where

   Q_{sec} : discharge capacity of the secondary system ($m^3\ month^{-1}$)

   q_{sec} : average discharge rate of secondary canals ($l\ s^{-1}$)

   N_{sec} : number of secondary canals

5. The supply capacity of the tertiary system level is estimated as average canal discharge rate multiplied by the number canals operated simultaneously.

Q_{ter} = q_{ter} * no_{ter}

where

Q_{ter} : discharge capacity of the tertiary system ($l\ s^{-1}$)

q_{ter} : discharge rate of tertiary canals ($l\ s^{-1}$)

no_{ter} : number of tertiary canals

6. System rotation factor. The rotation factor is a parameter for the completion of a full irrigation cycle.

The rotation factor of a certain system level is the number of canals belonging to the same level of a given block over the number of canals operated at the same time. For example, if half of the secondary canals are operated at the same time, the rotation factor is two. Thus, the time to complete a full cycle is double compared to a situation in which all secondary canals are operated concurrently.

r_{sys} = r_{sec} * r_{ter} * r_{farm}

with

r_{sec} : no_{sec} * no_{sec-on}

r_{ter} : no_{ter} * no_{ter-on}

r_{farm} : no_{farm} * $no_{farm-on}$

where

r_{sec} : rotation factor at secondary system level

r_{ter} : rotation factor at tertiary system level

r_{farm} : rotation factor at farm level

no_{sec} : number of secondary canals

no_{sec-on} : number of secondary canals turned on

no_{sec} : number of tertiary canals per secondary

no_{sec-on} : number of tertiary canals turned on

no_{farm} : number of farms per tertiary

$no_{farm-on}$: number of secondary canals turned on

7. Equivalent discharge rate. The discharge rate of the secondary and tertiary system levels are referred to the equivalent command area.

eq_{sec} = Q_{sec-on} * C_{sec}^{-1}

and

eq_{ter} = Q_{ter-on} * C_{ter}^{-1}

with

C_{sec} : command area actually commanded at the secondary system level (ha)

C_{ter} : command area actually commanded at the tertiary system level (ha)

8. Farm discharge rate. The minimum equivalent discharge rate of the secondary and tertiary system level is referred to an average farm size.

q_{farm} : MIN (q_{sec}, q_{ter}) * A_{farm}

where

q_{farm} : farm discharge rate (l s^{-1})

A_{farm} : average farm size (ha)

9. Equivalent farm discharge rate.

eq_{farm} = r_{sys} * ir_{spec} * a_{farm}

where

a_{farm} : average farm size

eq_{farm} : equivalent farm discharge (l s^{-1} ha^{-1})

10. Equivalent farm irrigation time.

et_{farm} = irp_{gross} * q_{farm}^{-1} * a_{farm} * 3.6

where

et_{farm} : time to irrigate a farm (h)

11. Block irrigation time.

t_{block} = t_{farm} * R_{sys}

and

et_{block} = t_{block} * a_{block}^{-1}

where

t_{block} : time to complete a block irrigation cycle (h)

a_{block} : block size (ha)

et_{block} : equivalent irrigation time (h ha^{-1})

12. Monthly block discharge capacity.

Q_{block} = MIN (q_{sec}, q_{ter}) * t_{op} * 3.6

where

Q_{bloc} : monthly block discharge capacity (m^3 $month^{-1}$)

t_{op} : monthly system operation time (h)

System supply capacity

Following the above calculation, the equivalent time required to irrigate one ha with the respective block is evaluated against the totally available operation time (TOT).

$\Sigma\ (eqt_{1,1,1,1} * X_{1,1,1}) <= TOT_{1,1}$ (14)

$\Sigma\ (ept_{i,j,k,t} * X_{i,j,k}) <= TOT_{j,t}$

$\Sigma\ (eqt_{n,m,p,z} * X_{n,m,p}) <= TOT_{m,p}$

where

eqt: equivalent operation time (h ha^{-1})

TOT : totally available management time (h)

Maximum discharge from reservoir

$\Sigma\ (ir_{1,1,1,1} * X_{1,1,1}) <= Q_r\ max_1$ (15)

$\Sigma\ (ir_{i,j,k,t} * X_{i,j,k}) <= Q_r\ max_t$

$\Sigma\ (ir_{n,m,p,z} * X_{n,m,p}) <= Q_r\ max_t$

where

ir : irrigation requirement (m^3 $month^{-1}$)

Q_r max : maximum discharge from reservoir (m^3 $month^{-1}$)

Maximum discharge rate of main canal

$\Sigma\ (ir_{1,1,1,1} * X_{1,1,1}) * (1-ie_c) <= Q_{main}\ max_1$ (16)

$\Sigma\ (ir_{i,j,k,t} * X_{i,j,k}) * (1-ie_c) <= Q_{main}\ max_t$

$\Sigma\ (ir_{n,m,p,z} * X_{n,m,p}) * (1-ie_c) <= Q_{main}\ max_z$

where:

$Q_m$max : maximum supply rate main canal (m^3 $month^{-1}$)

ie_c : conveyance efficiency at main canal level

Maximum discharge rate of secondary canals

$\Sigma\ (ir_{1,1,1,1} * X_{1,1,1}) * (1-ie_c) * (1-ie_w) <= Q_{sec}\ max_1$ (17)

$\Sigma\ (ir_{i,j,k,t} * X_{i,j,k}) * (1-ie_c) * (1-ie_w) <= Q_{sec}\ max_t$

$\Sigma\ (ir_{n,m,p,z} * X_{n,m,p}) * (1-ie_c) * (1-ie_w) <= Q_{sec}\ max_z$

where

Q_{sec} max : maximum supply rate secondary canal (m^3 $month^{-1}$)

ie_s : conveyance efficiency of secondary canals

Storage boundaries

The storage capacity of the reservoir is determined by two boundaries, namely the upper storage limit, which is regarded as full supply level (FSL), and the lower supply level (LSL), which is the lower boundary from below which no water can be discharged. The surface area of the reservoir is used for estimating the evaporation from the reservoir.

$S_1 >= LSL$ (18)

$S_t >= LSL$

$S_{,z} >= LSL$

and

$S_1 <= FSL$ (19)

$S_t <= FSL$

$S_{,z} <= FSL$

where:

FSL : full supply level (m^3)

LSL : low supply level (m^3)

All water that is in excess of the storage capacity of the reservoir is regarded as spillover or uncommitted outflow.

$S_t - S_{t-1} - I_t + E_t + SP_t + TIS_t >= 0$ (20)

Access and availability of mechanized production technology

$\Sigma (tmc_{1,1,1,} {}_* X_{1,1,1}) <= TMC_{1,1}$ (21)

$\Sigma (tmc_{i,j,k,} {}_* X_{i,j,k}) <= TMC_{j,t}$

$\Sigma (tmc_{n,m,p} {}_* X_{n,m,p}) <= TMC_{m,p}$

for: crop i = 1...n;

block j = 1…m;

input management level k = 1…p;

period t = 1…z (months)

where

tmc : equivalent time requirement of mechanized activities (1 d^{-1} ha^{-1})

TMC : totally available mechanization capacity (h)

Actual versus potential production

The upper limit of production is introduced in the form of potential yields that are obtainable under the prevailing climate and management conditions.

$\Sigma\ (ay_{1,1,1\ *}X_{1,1,1})\ \ <=\ \ TPP_{1,1}$ (22)
$\Sigma\ (ay_{i,j,k*}X_{i,j,k})\ \ <=\ TPP_{j,t}$
$\Sigma\ ay_{n,m,p\ *}X_{n,m,p})\ \ <=\ TPP_{m,p}$
for
crop i = 1...n;
block j = 1…m;
input management level k = 1…p;
where
ay : actual crop yield (t ha^{-1})
TPP : total potential production (t)

Yield response to irrigation supply deficit

In order to estimate the effect of reduced irrigation supplies on yield levels we assume that the relative yield response is proportional to the relative water supply. The relative supply is the fraction of the overall restricted supplies relative to the overall irrigation requirement.

$\Sigma\ (irp_{i,j,k,t\ *}X_{i,j,k})\ /\ S\ (ir_{i,j,k,t\ *}X_{i,j,k}) = RIS$ (23)
and
$Y_{act}\ =\ Y_{apt}\ *\ RIS$ (24)
and
$Y_{act}\ =\ Y_{pot}\ *\ RYP$ (25)
where:
RIS : relative irrigation supply (%)
RYP : relative yield potential (%)
Y_{act} : actual yield (t ha^{-1})
Y_{apt} : anticipated yield (t ha^{-1})
Y_{pot} : potential yield (t ha^{-1})

Non-negative conditions

All water use variables must be greater or equal than zero.
$X_{i,j,k};\ S_t;\ I_{t;}\ E_{t;}\ SP_{t;}\ TIR_t\ \ >\ \ = 0$ (26)

Annex II: Glossary

A—Terms used in water accounting (Molden 1997)
Available water: The amount of water available to a service or use, which is equal to the inflow less the committed water.

Basin or sub-basin accounting: The macro scale of water accounting for all or part of water basins, including several uses of water.

Closed basin: A basin where utilizable outflows are fully committed.

Committed water: The part of outflow that is reserved for other uses.

Depleted fraction: The fraction of inflow or available water that is depleted by process and non-process uses. Depleted fraction can be related to gross inflow (Depleted Fraction of Gross Inflow), net inflow (Depleted Fraction of Net Inflow), or available water (Depleted Fraction of Available Water).

Domain: The area of interest where accounting is to be done, bounded in time and space.

Gross inflow: The total amount of inflow crossing the boundaries of the domain.

Net inflow: The gross inflow less the change in storage over the time period of interest within the domain. Net inflow is larger than gross inflow when water is removed from storage.

Non-depletive uses of water: Uses where benefits are derived from an intended use of water without depleting water.

Non-process depletion: Depletion of water by uses other than the process that the diversion was intended for.

Process depletion: That amount of water diverted and depleted to produce an intended good.

Process fraction: The ratio of process depletion total to depletion (Process Fraction of Depleted Water) or available water (Process Fraction of Available Water).

Productivity of water: The physical mass of production or the economic value of production measured against gross inflow, net inflow, depleted water, process depleted water, or available water.

Uncommitted outflow: Outflow from the domain that is in excess of requirements for downstream uses.
Use level accounting: The micro scale of water accounting such as an irrigated field, a household, or a specific industrial process.

Utilizable water: Outflow from a domain that could be used downstream.

Water depletion: A use or removal of water from a water basin that renders it unavailable for further use.

Water services level accounting: The mezzo scale of water accounting for water services such as irrigation services or municipal services.

B: Terms used in the IWMI Water Balance Framework (Perry 1996)

Command area: The physical command area of the project (or subproject)—the maximum area that could be irrigated in a season in the absence of constraints on water or other inputs.

Irrigation intensity: The proportion of the area that is irrigated from surface water or groundwater, or both, in the period under analysis. The irrigated area is equal to the area multiplied by irrigation intensity.

Canal inflow: Surface water delivery at the canal head for the period of analysis (season, year, etc.) in cubic meters.

Operational losses: The proportion of canal inflow that is released through escapes, and hence to drains, expressed as a percentage of canal inflow.

Canal seepage: The proportion of canal inflow that goes to seepage. Such losses may be recovered through pumping from groundwater.

Watercourse seepage: The proportion of watercourse inflow that is lost to seepage.

Field efficiency (surface): The proportion of water arriving at the field from canals that is used in evapotranspiration in the course of the growth of the crop. Conventionally, this value includes evaporation of moisture from the wetted field surface.

Drain seepage: The proportion of flows in drains lost to seepage. This value may be different from the value used for canal or watercourse seepage. Drains are usually low-lying and often in areas with a relatively high water table, tend to reduce seepage.

Non-beneficial evapotranspiration (NBET): The proportion of seepage and field losses that is evaporated by weeds or trees or directly from the surface, excluding those evaporation losses that are conventionally accounted for as a part of crop demand. Residual losses go to groundwater.

Rainfall: Total depth of rain during the analysis period.

Effective rain (irrigated): The percent-age of rain falling on irrigated land that is used for crop transpiration. That portion of the rainfall that is not used by the crop goes to runoff, NBET (from weeds, trees along canals, or evaporation directly from the surface), or groundwater in accordance with specified ratios.

Effective rain (unirrigated): The proportion of rain falling on unirrigated land that is lost through evapotranspi-ration.

Rain to runoff: The proportion of rainfall that is not used by the irrigated crop and goes to surface drainage as runoff.

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