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Producing More Rice with Less Water from Irrigated Systems

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Producing more rice with less water from irrigated systems

L.C. Guerra, S.I. Bhuiyan, T.P. Tuong, and R. Barker

Over the past decade, we have witnessed a growing scarcity of and competition for water around the world. As the demand for water for domestic, municipal, industrial, and environmental purposes rises in the future, less water will be available for agriculture. But the potentials for new water resource development projects and expanding irrigated area are limited. We must therefore find ways to increase the productivity of water used for irrigation. This paper reviews the literature on irrigation efficiency and on the potential for increasing the productivity of water in rice-based systems. It identifies the reasons for the wide gap between water requirement and actual water input in irrigated rice production systems and discusses opportunities for bridging the gap both on-farm and at the system level. The potentials for water savings in rice production appear to be very large. But we do not know the degree to which various farm and system interventions will lead to sustainable water savings in the water basin until we can quantify the downstream impact of the interventions. Studies on the economic benefits and costs of alternative interventions are also lacking. Without this additional information, it will be difficult to identify the potential benefits and the most appropriate strategies for increasing irrigation water productivity in rice-based systems. This paper emphasizes the need for integrating various water-saving measures into practical models and for conducting holistic assessments of their impact within and outside irrigation systems in the water basin.

1. INTRODUCTION

Rice is the staple food for nearly half of the world's population, most of whom live in developing countries. The crop occupies one-third of the world's total area planted to cereals and provides 35–60% of the calories consumed by 2.7 billion people. More than 90% of the world's rice is produced and consumed in Asia (Barker and Herdt 1985, IRRI 1989). Rice is the most widely grown of all crops under irrigation. More than 80% of the developed freshwater resources in Asia are used for irrigation purposes and more than 90% of the total irrigation water is used for rice production (Bhuiyan 1992).

The abundant water environment in which rice grows best differentiates it from all other important crops. But water is becoming increasingly scarce. Per capita availability of water resources declined by 40–60% in many Asian countries between 1955 and 1990 (Gleick 1993). In 2025, per capita available water resources in these countries are expected to decline by 15–54% compared with 1990. For most of contemporary history, the world's irrigated area has grown faster than the population. Since 1980, irrigated area per person has declined and per capita cereal grain production has stagnated (Fig. 1). Agriculture's share of water will decline at an even faster rate because of increasing competition for available water from urban and industrial sectors (Tuong and Bhuiyan 1994).

The likely outcome of the unprecedented industrial and urban growth in the past decade experienced by many Asian countries is increased diversion of water from irrigation projects, especially those that are near growth centers, for nonagricultural purposes, overexploitation of groundwater, and disposal of untreated or undertreated industrial and domestic waste into freshwater bodies. Thus, agriculture's share of water will diminish in both quantity and quality. Because urban and industrial demands are likely to receive priority over irrigation, agricultural production may be reduced in irrigation systems, especially in years with a low water supply at the source. *The future of rice production will therefore depend heavily on developing and adopting strategies and practices that will use water efficiently in irrigation schemes.* Such strategies and practices are also important for other parts of the world, particularly in parts of Africa where demand for rice is high and water is less abundant than in Asia.

This paper deals with issues of improving the efficiency and productivity of water for rice production on-farm and in

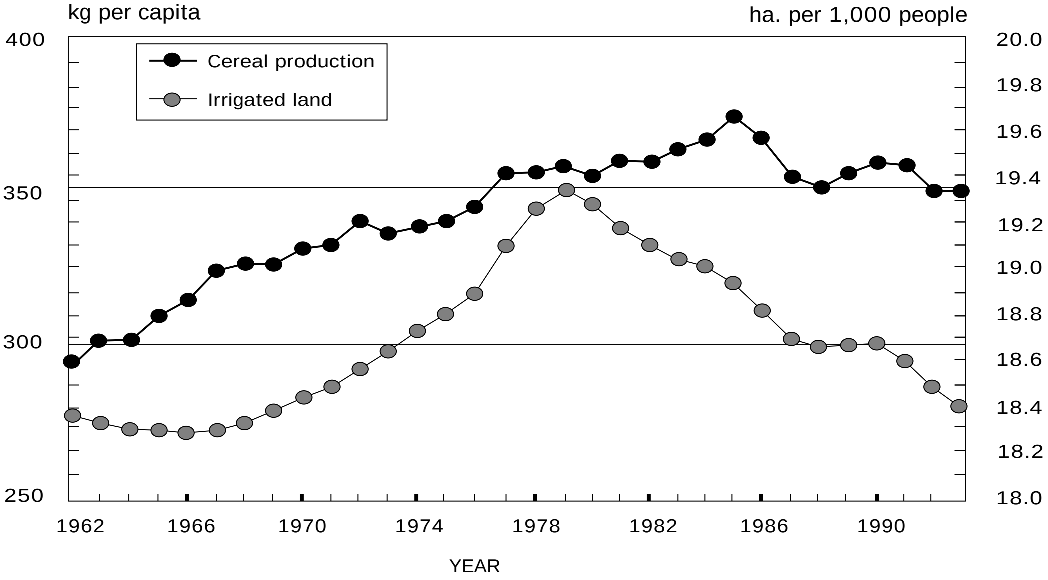

Fig. 1. World cereal production per capita and irrigated land per 1,000 people.

the irrigation system. In the next section, we discuss the concepts of efficiency and productivity for the use of irrigation water. We then analyze the gaps, and their causes, between water requirement (evapotranspiration demand of the rice crop) and water use on-farm and in the irrigation system. Options to reduce or control losses and to increase on-farm water productivity are discussed in part 4, and those at the system level in part 5. While using the basin context in the analyses, the paper will not discuss in detail water efficiency and productivity in the basin because of the lack of data at the basin level. We lack sufficient data to quantify the interactions among different scales; these interactions determine the main "research needs" (part 6) for improving the efficiency and productivity of water in irrigated rice-based systems.

2. WATER EFFICIENCY AND PRODUCTIVITY: FUNDAMENTAL BUT LESS WELL UNDERSTOOD CONCEPTS

One of the most extensively used terms to evaluate the performance of an irrigation system is "water efficiency." In general terms, water efficiency is defined as the ratio between the amount of water that is used for an intended purpose and the total amount of water input within a spatial domain of interest. In this context, the amount of water supplied to a domain of interest but not used for the intended purpose is a "loss" from that domain. Clearly, to increase the efficiency of a domain of interest, it is important to identify losses and minimize them. Depending on the intended purpose and the domain of interest, many "efficiency" concepts are involved, such as crop water-use efficiency, water-application efficiency, and others (Israelsen 1950, Jensen 1980). Although these terms appear to be simple, failure to describe clearly the intended purpose of the water supply and the boundaries of the domain of interest can lead to misuses and a misunderstanding of the term "efficiency."

For food production, the ultimate purpose of supplying water is to satisfy crop evapotranspiration demand. On-farm water components such as seepage and percolation (S&P) are losses, because they flow out of the farm without being consumed by the intended crop. Reducing the amount of S&P would lead to an improvement in water efficiency on-farm. But if this water can be recovered for crop consumption at some point downstream, these are not losses of the irrigation system. By the same token, losses of an irrigation system may not contribute to losses in the water basin. Based on these premises, and from a basin perspective, a number of recent reports argued that improvements in local efficiency, where lost water is recovered downstream, result only in "paper" or "dry" water savings (Seckler 1996, Keller et al 1996). According to these reports, it is only useful to save water ("real" water savings) that would otherwise be lost to a sink (a saline water body) or the atmosphere.

Globally, water cannot be created or destroyed, so there is no such thing as true water loss. Though we may not lose water itself, we can lose control over it for a particular purpose. The concept of "wet" and "dry" water savings may be valid when it costs nothing to gain control, to supply water, or to recycle water. In reality, developing irrigation facilities always entails labor, capital, or energy costs. Losses are undesirable to those who have to bear these costs. Water recovery also involves an additional development cost, particularly if pumping is involved. Furthermore, it is not always possible to recover water and put it to use when it is needed. The "wet" and "dry" water savings argument thus ignores several important factors, especially the cost of water development, which usually determines the water management options selected by farmers, irrigation system managers, or regional policymakers. It is, however, a useful reminder of the complication of changing the scales of analysis between farms, irrigation systems, and water basins. It can also be used to assess possible off-site impacts on the surroundings of increased water-use efficiency in a particular domain.

The efficiency concept provides little information on the amount of food that can be produced with an amount of available water. In this respect, water productivity, defined as the amount of food produced per unit volume of water used (Viets 1962, Tabbal et al 1992, Tuong et al 1998, Molden 1997), is more useful. Because the water used may have various components (evaporation, transpiration, gross inflow, net inflow, etc.), it is important to specify which components are included when calculating water productivity (Tuong and Bhuiyan 1997, Molden 1997). Similar to efficiency, for practical purposes the concept of water productivity needs a clear specification of the boundaries of the domain of interest.

Water productivity can be increased by increasing yield per unit land area, for example, by using better varieties or agronomic practices, or by growing the crop during the most suitable period. Water productivity is also determined by factors other than water management. To use this concept for the purpose of improving water management, the contributions of other factors that contribute to crop yield have to be taken into account. Higher productivity does not necessarily mean that the crop effectively uses a higher proportion of the water input. For this reason, water productivity alone would not be particularly useful in identifying water savings opportunities of the system under consideration.

In summary, water efficiency and productivity terms should be used complementarily to assess water management strategies and practices to produce more rice with less water. Both terms are scale-sensitive; therefore, failure to clearly define the boundaries of the spatial domain of interest can lead to erroneous conclusions. It is also important to specify the water-use components that are taken into account when deriving water efficiency and productivity.

3. THE GAP BETWEEN WATER REQUIREMENT AND USE IN RICE CULTURE

This section explains some measurements of the amount of water required by the plant and of water "loss" in the fields and from canals of the irrigation system. It should be emphasized that measurements of efficiency or loss are site-specific not only because of variation in physical environment but also because of variation in physical infrastructure and management capacity reflected at each location. For example, East Asian systems (including those in China) have a much higher degree of management and control than those in South and Southeast Asia, and rice cultivation practices are markedly different even within the same region. This is reflected not only in the level of efficiency or productivity found at different sites, but must also be taken into account in the choice of interventions designed to save water.

3.1 The gap at the farm level

Rice grown under traditional practices in medium- to heavy-textured soils in the Asian tropics and subtropics requires between 700 and 1,500 mm of water (Bhuiyan 1992). This consists of: (1) the land preparation requirement of 150–250 mm, (2) the water requirement of about 50 mm for growing rice seedlings in the nursery or seedbed before transplanting (Yoshida 1981), and (3) a water need of between 500 and 1,200 mm (5–12 mm d^{-1} for 100 d) to meet the evapotranspiration (ET) demand and unavoidable seepage and percolation in maintaining a saturated root zone during the crop growth period.

Table 1 shows that rice yield per unit ET can be as high as 1.6 kg m^{-3}, which is comparable to that of other cereal crops. But when other water-use components are taken into account, the field-level water productivity of rice is reduced markedly.

The actual amount of water used by farmers for land preparation is often several times higher than the typical requirement of 150–250 mm. Ghani et al (1989) reported water use for land preparation as high as 1,500 mm in the Ganges-Kobadak irrigation project in Bangladesh. Several factors cause this high water use. Typical wetland preparation for rice culture involves supplying adequate amounts of water to saturate the soil (land soaking) and to maintain a wet soil condition that facilitates plowing, harrowing, puddling, and land leveling so that rice seedlings can be easily transplanted. During the first (wet) season, land soaking often involves applying water on cracked soils that resulted from soil drying during the fallow period after the harvest of the previous crop.

Table 1. On-farm water productivity of rice (*WP*, in kg of grain yield m^{-3} of water used) when different components of water inputs are taken into account.

Water productivity with respect to:			Source of data used in calculating *WP*	Location
ET[a]	ET + S&P	ET + S&P + LpR		
1.61	0.68 (0.42)[b]	0.39 (0.24)	Bhuiyan et al (1995), wet-seeded rice	Philipinnes
1.39	0.48 (0.35)	0.29 (0.22)	Bhuiyan et al (1995), transplanted rice	Philipinnes
1.10	0.45 (0.41)		Sandhu et al (1980)	India
0.95	0.66 (0.69)	0.58 (0.61)	Kitamura (1990), dry season	Malaysia
0.95	0.48 (0.50)	0.33 (0.35)	Kitamura (1990), wet season	Malaysia
0.88	0.34 (0.36)		Mishra et al (1990), continuous flooding	India
0.89	0.37 (0.42)		Mishra et al (1990), alternate wet and dry	India

[a] ET = evapotranspiration, S&P = seepage and percolation, LpR = land preparation requirement.

[b] Numbers in parentheses are water-use efficiency (ratio of ET to water input).

Tuong et al (1996) reported that in fields with relatively permeable subsoils, 45% of the water applied for land soaking moved through the cracks, bypassing the topsoil matrix, and flowed to the surroundings through lateral drainage. The amount of water that flows out of the field may become very high when farmers take a long time to complete land preparation. Long land preparation can be caused by inadequate canal discharge, and by the farmers' practice of soaking the field while they prepare the seedbed where seeds are germinated and nurtured for about 1 mo until transplanting. It can also be caused by socioeconomic problems such as nonavailability of labor and use of animals for draft power. Valera (1977) reported that in Central Luzon, Philippines, with 650 mm of irrigation water inflow to a 145-ha block of rice fields in 48 d, land preparation was completed for only half of the area.

During the crop growth period, the amount of water usually applied to the field is much more than the actual field requirement. This leads to a high amount of surface runoff, and seepage and percolation. S&P accounts for about 50–80% of the total water input to the field (Sharma 1989). In large irrigated areas, seepage occurs only in peripheries, but percolation occurs over the whole area. S&P rates vary widely depending on soil texture and other factors but usually increase as soil texture becomes lighter. Although values of 1–5 mm d^{-1} are often reported for puddled clay soils, percolation rates can be as high as 24–29 mm d^{-1} in sandy loam or loamy sand soils (Khan LR 1992, Gunawardena 1992).

Percolation rate increases as the depth of water standing in the field increases. In traditional transplanted rice, farmers prefer to maintain a relatively high depth of water in order to control weeds and reduce the frequency of irrigation (and hence labor cost). *When water supply within the irrigation system is unreliable, farmers try to store much more water in the field than needed* as insurance against a possible shortage in the future. In rice irrigation systems where the plot-to-plot method of water distribution predominates, farmers have to build up the water head at the upper end of the farm to ensure the flow of water, which is often accompanied by excessive percolation.

Underbund percolation could cause a further 2-5-fold increase in percolation rate, depending on the size of the field. Underbund percolation results from lateral movement of ponded water into the bunds and then (because of the absence of a semi-impermeable layer under the bunds) vertically down to the water table (Tuong et al 1994).

3.2 The gap in the irrigation system

Overall irrigation efficiency (E_p) of an irrigation system can be defined as the ratio of water used by the crop to water released at the headworks. It can be subdivided into three components: conveyance efficiency (E_c), field channel efficiency (E_b), and field application efficiency (E_a). E_c is the ratio of water received at the inlet to a block of fields to water released at the headworks. E_b is the ratio of water received at the field inlet to water received at the inlet of the block of fields, and E_a is the ratio of water used by the crop to water received at the field inlet (Doorenbos and Pruitt 1992). Conveyance and field channel efficiencies are sometimes combined as distribution efficiency (E_d), where $E_d = E_c \times E_b$.

Factors affecting conveyance efficiency are wetted area in the canal network, size of the rotational unit, canal lining, and managerial skills for water control. Lee Seung Chan (1992) reported that in many irrigation systems in Korea, less than 50% of the irrigation water reaches the command area. Percolation in earth canals accounts for about 35% in

Table 2. Conveyance (E_c), field channel (E_b), and distribution ($E_d = E_c \times E_b$) efficiencies of the irrigation system.

Efficiency	%
Conveyance efficiency	
• Continuous supply with no substantial change in flow	90
• Rotational supply in projects of 3,000–7,000 ha and rotation areas of 70–300 ha, with effective management	80
• Rotational supply in large schemes (>10,000 ha) and small schemes (<1,000 ha) with problematic communication and less effective management:	
based on predetermined schedule	70
based on advance request	65
Field channel efficiency	
• Blocks larger than 20 ha: unlined	80
lined	90
• Blocks up to 20 ha: unlined	70
lined	80
Distribution efficiency	
Average for rotational supply with management and communication:	
adequate	65
poor	30

Sources: Bos and Nugteren (1974) and Doorenbos and Pruitt (1992).

Table 3. Overall irrigation efficiency of some irrigation systems.

Country/irrigation system	Overall irrigation efficiency (%)	Remarks	Reference
Indonesia	40–65		Hutasoit (1991)
Malaysia/Kerian irrigation scheme	35–45	Command area = 23,560 ha	Keat (1996)
Thailand/northern, Mae Klong, Chao Phraya >12,800 ha		Irrigable area	
	37–46	Wet season	Khao-Uppatum (1992)
	40–62	Dry season	Khao-Uppatum (1992)
India			
Canal systems, northern India	38		Ali (1983)
Tungabhadra irrigation scheme, Karnataka State	30		Bos and Wolters (1991)

Korea (Lee Seung Chan 1994) and Iran (Nickrawan and Nozari 1992), and about 25% in Bangladesh (Khan TA 1992) and the Indus basin system in Pakistan (Ahmad 1994).

Field channel efficiency is affected primarily by the method and control of operation, soil type in relation to canal losses, length of field channels, and size of the irrigation blocks and fields. Table 2 shows the effects of the various factors on conveyance, field channel, and distribution efficiencies and indicates that only 30–65% of the water released at the headworks reaches the intended field inlets.

Conveyance, field channel, and field application efficiencies are normally evaluated separately within an irrigation system. The proportion of the seepage and percolation from the water distribution system that is recycled within the whole irrigation system or basin is not often quantified. Studies to evaluate overall irrigation efficiency and productivity of irrigation systems using a system-level water balance accounting approach are lacking. Data on overall irrigation efficiency are scarce and, when available, the method of derivation is often not described. Nevertheless, available data indicate that overall efficiency is low in rice-based irrigation systems in Asia (Table 3).

4. BRIDGING THE GAP: STRATEGIES AND PRACTICES ON-FARM

Based on our discussions in the previous section, on-farm productivity of irrigation water can be increased by doing one of the following: (1) increasing yield per unit evapotranspiration during crop growth; (2) reducing evaporation, especially during land preparation; (3) reducing S&P during the land preparation and crop growth periods; and (4) reducing surface runoff. Introducing management practices and infrastructure improvements that result in either of the first two will increase the efficiency of the system and basin. The impact of the last two on system and basin productivity depends on opportunities for and costs of recycling at downstream locations.

4.1 Increasing production per unit evapotranspiration: capitalizing on new varieties and improved agronomic management

The Green Revolution ushered in a period of rapid growth in both land and water productivity through the development of improved crop varieties. The adoption of improved, early maturing, high-yielding varieties of rice during the past 25 years has increased the average yield of irrigated rice from 2–3 t ha^{-1} to 5–6 t ha^{-1} and reduced crop duration from about 140 d to about 110 d. This has contributed to a 2.5-3.5-fold increase in water productivity with respect to evapotranspiration. The availability of hybrid varieties, which have 15–20% higher yield potentials than inbred high-yielding rice of comparable maturity periods, offers another opportunity for increasing water productivity in rice culture. Returns to investment in research on rice varietal improvement have always been high. Advances in biotechnology should facilitate further improvement in varieties with tolerance for drought and salinity, and hence higher water productivity.

Better soil nutrient management results in higher yield although the amount of water consumed by rice remains almost unchanged. Each kilogram of nitrogen fertilizer applied to the field may produce 10–15 kg more rice (Peng 1997, personal communication). With on-farm water productivity of rice at 0.5 kg m^{-3} (Table 1), were it not for fertilizer, farmers would have to apply 20–30 m^3 of water to another field to produce the same amount of rice.

Proper weed management also helps increase water productivity. Tuong et al (1998) showed that water productivity, under experimental conditions at the IRRI farm, could be increased from 0.24 kg m^{-3} in unweeded plots to 0.7–0.8 kg m^{-3} in plots where weeds were controlled by herbicide or by early flooding after seeding. Low water productivity in unweeded plots accrued from very low yield as a result of severe weed infestation.

Another way to increase economic productivity per unit of water for transpiration is to shift to higher-valued crops. In the face of declining returns for rice, diversification to higher-valued crops has been encouraged in many countries, but often without an assured water supply and support for research, extension, and marketing services that are needed for success.

4.2 Reducing water use in land preparation

In Part 3, we noted the excessive amount of water often used in land preparation. *Reducing the period of land preparation would lead to a substantial savings in water, including water lost because of evaporation, seepage and percolation, and surface runoff. The time needed for distributing water in the field can be shortened significantly by using more field channels instead of the plot-to-plot method. Some crop establishment methods also encourage reduced periods of land preparation.* These will be discussed later.

The amount of bypass flow can be reduced by measures that restrict the formation of soil cracks or impede the flow of water through the cracks. *Shallow, dry tillage soon after harvesting the previous rice crop is an effective strategy for minimizing the formation of soil cracks and occurrence of bypass flow.* The tilled layer acts as mulch and therefore reduces soil drying and consequent cracking. In soils that already have cracks, dry tillage produces small soil aggregates that block the cracks, thereby reducing bypass flow. Cabangon and Tuong (1998) found that in farmers' fields in Bulacan and Nueva Ecija, Philippines, shallow tillage reduced the total water input for land preparation by 31–34%, which corresponds to 108–117 mm of water. Dry tillage is now widely practiced in the Muda irrigation scheme in Malaysia and is responsible for reduced water released from the reservoir and timely crop establishment in the area (Ho Nai Kin et al 1993). The increasing access to high-powered tractors makes dry tillage possible in many irrigated rice systems in Asia.

4.3 Adopting a water-efficient method of rice establishment

In recent years, there has been a shift from transplanted rice to the direct-seeded (i.e., sowing seeds directly on rice fields) method of crop establishment in several countries in Southeast Asia (Erguiza et al 1990, Khan et al 1992, Sattar and Bhuiyan 1993, Khoo 1994). This change was brought about largely by increased wages that had to be paid for the transplanting operation because of the acute farm labor

Table 4. Water use, time taken for land preparation, and water depth maintained in the field for wet-seeded rice (WSR) and transplanted rice (TPR) in the Upper Pampanga River integrated irrigation system, Philippines, 1990-91 dry season.

Parameters	WSR	TPR
Water use (mm)		
Land preparation	740	895
Crop irrigation	1,007	1,300
Total	1,747	2,195
Time taken to complete land preparation (d)	6	24
Water depth (cm) at:		
crop establishment	1.0	3.0
crop growth	6.0	6.5
Yield (t ha^{-1})	6.9	6.3
Water productivity (kg rice m^{-3} water)	0.4	0.3

Source: Bhuiyan et al (1995).

shortage (De Datta 1986, Chan and Nor 1993). This shift from transplanting to direct seeding, however, offers opportunities to improve water-use efficiency in rice culture by reducing the irrigation inflow requirement during land preparation.

There are two forms of direct-seeded rice: wet seeding and dry seeding. In wet-seeded rice (WSR), pregerminated seeds are broadcast on saturated and usually puddled soil. In contrast, dry-seeded rice (DSR) is grown by sowing ungerminated seeds on dry or moist but unpuddled soil.

In research conducted in Central Luzon, Philippines, WSR systems used less water than transplanted rice for both land preparation and crop irrigation and the total water use dropped from 2,195 to 1,700 mm (Table 4). The Muda irrigation scheme reported a reduction in irrigation duration from 140 to 105 d and water use from 1,836 to 1,333 mm with the shift from transplanted rice to WSR (Fujii and Cho 1996).

In the case of the Philippines (Table 4), less water used during land preparation is attributed mainly to the shorter time over which WSR farmers complete land preparation activities compared with transplanted-rice farmers (Bhuiyan et al 1995). In WSR, seeds require only 24–36 h of soaking and incubation to be ready for sowing in the field. In contrast, in the transplanted-rice system, seedlings are usually nurtured in the seedbed for about 1 mo and therefore farmers have no reason to complete land soaking, plowing, and harrowing activities until the seedlings are ready. There are, of course, transplanted-rice systems in countries such as China, where land preparation time is already very short.

Because there is a high risk of lodging with WSR, farmers maintain a shallower water depth in their fields than for transplanted rice and this results in less percolation. It should be noted, however, that maintaining a shallow water depth is not unique for WSR. These same water-saving practices have been followed with transplanted rice in China (SWIM Mission Report 1997).

In summary, although the shift to WSR may lead to water savings in some countries, where water-saving practices are already in place with transplanted rice there may be no benefit. Lee Seung Chan (1992) reports that under Korean conditions WSR requires a more stringent water level control and an increase in irrigation water supply. This is because wet seeding exposes seedlings in the field to cold temperature, which prolongs crop growth.

Dry-seeded rice technology offers a significant opportunity for conserving irrigation water by using rainfall more effectively. In transplanted and wet-seeded rice systems, farmers normally wait for delivery of canal water before they start soaking land for plowing. Early in the first season, the reservoir often has insufficient water to be released for land preparation and crop establishment. In DSR, early premonsoon rainfall is used effectively for crop establishment and during the early stage of crop growth. Later in the season, when the reservoir has been filled and irrigation has begun, the crop can be irrigated as needed. Early crop establishment results in early harvest of the first crop. This permits a reduction in irrigation inflow requirements from reservoirs in the wet season, leading to an increase in the availability of water in the dry season.

Studies conducted by the Muda Agricultural Development Authority (MADA) in the Muda irrigation scheme, Malaysia, showed that DSR required less water for land soaking than WSR, and WSR required less than transplanted rice (Table 5).

Ho Nai Kin et al (1993) reported that in the Muda irrigation scheme dry seeding in the first season could save up to 500 mm of irrigation water compared with traditional transplanted rice. In 1991, when no water was released to the canal system because of very low storage in the reservoir, farmers were still able to grow dry-seeded rice. In a similar situation in 1978, however, the cropping season had to be canceled because of insufficient water for transplanted rice.

In the United States, dry-seeded rice is referred to as nonflooded rice. In trials in Texas, experiments were carried

Table 5. Water consumption for land soaking under three methods of crop establishment in the Muda irrigation scheme, 1987 off-season[a].

	Transplanted rice with field water management by:		Wet-seeded rice	Dry-seeded rice
	Farmers on their own	MADA supervised		
Water consumption (mm)	383	297	242	160
Excess in consumption over dry-seeded rice (%)	140	86	52	–

[a] The off-season is the first season, which usually begins in February/March and ends in July/August; the main season is the second season, which begins in August/September and ends in January/February in the following year.

out to compare rice yields under flooded and nonflooded conditions using sprinkler irrigation. The average yield of sprinkler-irrigated rice was 20% less than the yield of flooded rice on similar soils (McCauley 1990).

Several interrelated problems constrain the successful adoption of direct seeding. Good drainage is a prerequisite. Drainage control has to be such that on-farm excess water can be easily drained out during crop establishment and early growth. This is the reason for less area under WSR in the wet season. Poor germination and profuse weed growth resulted from direct seeding on unleveled land (Upasena 1978).

Weed competition is greater in direct-seeded rice (Moody 1993). Poor germination and profuse weed growth result from direct seeding on unleveled land (Upasena 1978). The reduction in rice yield because of weeds is more severe in direct-seeded than transplanted rice because soil conditions during crop establishment and early growth are more favorable in direct-seeded rice for the germination and growth of grassy weeds. The widespread adoption of direct seeding in the Muda area, Malaysia, has caused a drastic change in the weed flora and population from less competitive broadleaf weeds and sedges to more competitive grassy weeds (Itoh et al 1996).

4.4 Reducing seepage and percolation during the crop growth period

Puddling the soil during land preparation is an effective way to reduce percolation during crop growth. Puddling causes the formation of a semi-impermeable layer with a very low hydraulic conductivity beneath the puddled topsoil (Sanchez 1973, De Datta and Kerim 1974, Tuong et al 1994). Dayanand and Singh (1980) reported that puddling can reduce input water by 40–60% during crop growth because of the reduced percolation rate. In permeable subsoil conditions, even a small area of unpuddled soil (on the order of 1% of the area of puddled soil) could increase the percolation rate in the field by a factor of five (Tuong et al 1994). In most cases, however, a semipermeable soil layer or hard pan develops through years of puddling the soil, which substantially reduces percolation loss (De Datta 1981). Hence, in soils with a developed hard pan, puddling is not needed every year to reduce percolation.

Underbund percolation can be minimized by reducing lateral infiltration into the bunds (Tuong et al 1994). During land preparation, farmers seal bund walls with clay taken from the plow layer. In Japan, farmers line field bunds with plastic sheets. These measures, although practiced by some farmers, are not yet well documented.

Numerous studies conducted on the manipulation of depth and interval of irrigation to save on water use without any yield loss have demonstrated that continuous submergence is not essential for obtaining high rice yields. Hatta (1967), Tabbal et al (1992), and Singh et al (1996) reported that maintaining a very thin water layer, saturated soil condition, or alternate wetting and drying could reduce water applied to the field by about 40–70% compared with the traditional practice of continuous shallow submergence, without a significant yield loss. In general, the lighter the soil, the greater the reduction in water needed for the rice field when these water-saving irrigation (WSI) techniques are used. The dry period after the disappearance of ponded water depends on the depth of the groundwater table. The shallower the groundwater table, the longer the interval between irrigations (Mishra et al 1990, 1997).

Farmers often practice continuous submergence of rice fields to reduce weed problems. Tabbal et al (1992) found in Central Luzon, Philippines, that in situations where weed pressure was high, continuous submergence up to the panicle initiation stage followed by continuous saturation required 35% less water input than continuous flooding, without any yield reduction or increase in weed infestation. Soil nitrate and ammonium concentrations were similar in continuously shallow-flooded and saturated soil water regimes, implying that plant N availability was not adversely affected when a saturated soil regime was maintained.

Since the 1990s, WSI techniques have spread to about one million hectares in the Guangxi Autonomous Region and Hunan Province in southern China (Guangxi Water and Power Department 1996). One of the WSI techniques practiced in southern China also involves maintaining a very thin water layer in the field, saturated soil condition, and alternate wetting and drying. In another practice, soil water is maintained at 60–100% of the soil saturation value throughout the period following the start of the booting stage (SWIM Mission Report 1997).

The WSI techniques such as those applied in China, however, require a high degree of management control and infrastructure at both the farm and system levels. For much of developing Asia, management capacity to implement such a strategy does not yet exist. Because of smaller quantities of irrigation water and more frequent applications, more supervision and labor are required than in the traditional shallow-flooding system. Adoption may also be hampered by farmers' concern about not having access to water when they need it because of the lack of reliability in the system's water supply performance. The lack of field channels, which are necessary for effective water distribution, is another constraint to the adoption of WSI regimes. In the case of China, we need to understand more about the costs and benefits of WSI techniques, including the requirement for other inputs such as labor and fertilizer, and their effect on crop protection.

All methods for reducing water use in the crop growth period aimed at minimizing seepage and percolation. This is important for farmers when water applied to the field is costly. Although minimizing S&P increases on-farm water efficiency and productivity (with respect to the total water input), their effects on overall system water efficiency and productivity are much less understood and defined. The effects would depend heavily on the consequences of runoff and S&P after they leave the farm. Some authors, such as Keller et al (1996), argued that reducing S&P of upstream farms may not improve overall efficiency if S&P water is reused downstream. But systematic analyses of scale effects in moving the analysis from the farm to the irrigation system to the river basin are lacking. The effect of a large-scale application of WSI in China on system and basin water productivity needs to be quantified.

5. BRIDGING THE GAP: STRATEGIES AND OPTIONS IN THE IRRIGATION SYSTEM

The irrigation system is the conduit for delivering water to the farm to meet local water needs for crop production. In canal-based rice irrigation systems, ultimate water efficiency depends on the control, reduction, and management of runoff and seepage and percolation in both the water delivery system and on-farm independently and interactively. System water losses (the amount of water that leaves the system without contributing to rice production) caused by interacting problems may be quite serious in certain situations. For example, nonsynchrony between water demand on-farm and water delivery schedules in canals can lead to major water losses and the basic cause of the loss may not always be clearly understood without proper investigation.

Five major strategies or options for increasing the effective use of irrigation water in rice irrigation systems follow.

5.1 Changing the crop and irrigation schedule to use rainfall more effectively

There is normally no water or only a small amount of water available for release from the reservoir at the beginning of the rainy season. Farmers do not often start their rainy season crop until irrigation water is released from the canal, that is, when enough water is collected in the reservoir. Complete dependence on the irrigation water supply at that time leads to a delayed start of the rice crop, which cannot make use of early rainfall. *Developing and adopting new irrigation schedules for preparing land using early season rainfall could enable farmers to conserve water in the reservoir, allowing more opportunity for increasing irrigated area in the dry season.* This can be facilitated by adopting the dry-seeded rice system, as discussed earlier. But considerable coordination is needed between farmers who must adjust their planting schedules and irrigation administrators who must provide the timely release of water for farmers' adoption of this system.

In Sri Lanka, success in adjusting the irrigation schedule has been mixed. Projects such as the Kadulla irrigation scheme (Bird et al 1991) and the Walagambahuwa minor-tank settlement scheme (Upasena et al 1980) reported initial success. But as one colleague studying the latter project stated, "when we withdrew, they withdrew" (Nimal Ranaweera, Dept. of Agriculture, personal communication). Management and control requirements to successfully implement this procedure would appear to be fairly modest. The failure on the part of farmers may be related to their own economic situation (e.g., lack of money to finance inputs for early planting) and/or risk-averting decision-making, whereas the failure on the part of irrigation administrators may reflect a lack of motivation and incentives.

5.2 Water distribution strategies

Irrigation managers need to implement an orderly system of water allocation and distribution that promotes not only an adequate, equitable, and reliable supply to intended beneficiaries but also efficient water use. Large irrigation systems in the humid tropics are mostly designed and operated for a continuous flow of canal water. Water is supplied at the same time to all canals, laterals, and farm ditches. The supply is distributed within the system proportionally to the area served and is adjusted according to changing irrigation requirements over the season. In the dry season, however, the continuous water supply mode often cannot meet the demand of the entire irrigation system. The result is often an inequitable water distribution—the tail-end areas receive insufficient water and produce lower yields, while overirrigation of head-end areas results in excessive surface and subsurface runoff, not all of which is easily recoverable.

With the rotational water distribution system, a more reasonable regulation and even distribution of water over the upper, middle, and lower reaches of the canal system can be achieved. In rotational water distribution, the water supply is provided in turns to the different sections of main or lateral canals, or to the different farm ditches. Water efficiency and productivity are enhanced because of reduced runoff from the head-end areas and increased yields of tail-end farms.

Several forms of water rotation implemented in each of the four districts of the Upper Pampanga River integrated irrigation system during the 1983 and 1984 drought seasons produced mixed results. One form worked well in one district but not in another. De la Viña et al (1986) concluded that the method that will best suit a given service area depends on the degree of water control available, the physical nature of the service area, and the amount of farmer cooperation. The authors emphasized that effective communication between the system managers and the farmers, and among farmers, must be maintained to achieve farmer cooperation in implementing efficient water allocation and distribution methods.

The implementation of rotational water distribution in the Gal Oya left bank in Sri Lanka, the lower Gugera branch in Pakistan, and the Tungabhadra pilot irrigation project in India was not successful. Murray-Rust and Snellen (1993) attributed the failure to the lack of communication and cooperation between the irrigation agency and farmers. In addition, the rotational schedule did not fit in with the normal working conditions of the irrigation agency in Gal Oya.

The same authors cited one example of effective communication and cooperation between the agency and farmers in rotational water distribution that led to improved system performance. Prior to the research program conducted jointly by IRRI and the National Irrigation Administration (NIA), inequity was very high and water efficiency low in the Lower Talavera River irrigation system in Central Luzon, Philippines. The agency and the farmers throughout the system worked together to solve this problem and developed and implemented a rotational water supply schedule that produced dramatic results. It improved water-use efficiency and increased yields throughout the system.

As in the case of all interventions that began and were funded through special projects and external agencies, the question is always whether the introduced practices will continue once the pilot projects end. Both irrigation administrators and local politicians have much to say about the distribution of water. A project to redistribute water in a major lateral of the Peneranda irrigation system was successfully implemented by NIA in cooperation with IRRI for two years in the 1970s. The project substantially increased production in the lower half of the system without reducing yields in the upper half. At the end of the project, the water distribution strategy was discontinued because of the political power exercised by landowners at the head of the system. This, unfortunately, is an all too common occurrence.

5.3 Water recycling and conjunctive use of groundwater

Surface and subsurface (e.g., seepage and percolation) runoff from the field and from the conveyance network may eventually find its way into drainage systems. Reuse (recycling) of this water offers an effective way to increase the water efficiency and productivity of an irrigation system. In the river basin, recycling of water occurs for both agricultural and nonagricultural uses and its importance is often ignored in studies on water scarcity (Seckler et al 1998).

Recycling is being practiced in the rice irrigation systems of many countries. Seang (1986) reported that the Muda irrigation project of Malaysia undertook a major scheme of recycling the irrigation outflow within the project by installing six pumping stations, each with multiple submersible pumps. As of 1991, about 12,000 ha under the Muda II area were supported by 123 million m^3 of recycled drainage water per year, which supplemented the 740 million m^3 of water supplied from the project reservoirs (Khoo 1994). In a rice irrigation system in Niigata Prefecture, Japan, average drainage water reuse was about 14–15% of the original irrigation water inflow (Zulu et al 1996).

The conjunctive use of groundwater (with surface water) constitutes an irrigation reuse system of a special kind (Bhuiyan 1989). In rice irrigation systems, seepage and percolation from the water conveyance network and irrigated fields may become a recharge to shallow unconfined aquifers. The water stored in the aquifer can be pumped up and used to supplement irrigation supplies from the canal to the rice crop (Wardana et al 1990, Malik and Strosser 1993).

The possibility of recycling does not negate the need to conserve water on-farm. Water recycling and the conjunctive use of groundwater are rarely considered in the original design and implementation of rice irrigation schemes. They mostly happen as a desperate response from farmers who are unable to obtain their share of irrigation water from the canal or from system managers as a way to "rectify" problems of management capacity and shortcomings of the original design.

The recycling of surface or groundwater illustrates the strong interactions among different components and scales of an irrigation system—a "loss" from one component is not necessarily a loss to the system. Farm- and system-level options for increasing water-use efficiency and productivity have to be analyzed interactively. One important factor is the cost-effectiveness of water recycling and the conjunctive use of groundwater compared with that of other water-conserving strategies such as canal lining to reduce seepage and percolation from canal networks.

5.4 Rehabilitation and modernization

During the 1980s, following the completion of many major irrigation schemes, growing concern arose about the rapid deterioration of many systems. The focus shifted from new construction to rehabilitation. In its strict interpretation, *rehabilitation* is defined as investment to restore infrastructure to its original form. When improvements were considered, the initial emphasis was on physical infrastructure such as regulators and canal lining. But rehabilitation investments now typically take on a much broader agenda and involve institutional, organizational, and technical changes. This clearly signifies a move to a higher level of management and control. *Modernization* involves all of the above elements. But there is currently no commonly agreed upon definition of modernization.

Relatively few studies have measured the impact of rehabilitation on water productivity. Among these, the Gal Oya left bank rehabilitation project is almost unique in that it has been possible to analyze data over a period of 23 years, from 1969 to 1992, before, during, and after the rehabilitation (Amarasinghe et al 1998). Rehabilitation was undertaken in 1982 and 1983. Table 6 compares the period before and after rehabilitation. The authors attributed this success to the simultaneous implementation of physical and institutional improvements.

Table 6. Actual changes in mean levels of irrigated area and land and water productivity from the preintervention period (1969–1982) to the postintervention period (1983–1992) of the Gal Oya left bank rehabilitation project.

Period	Irrigated area[a] (000 ha)		Land productivity[b] (t ha^{-1})		Water productivity[b] (kg m^{-3})	
	Yala	Maha	Yala	Maha	Yala	Maha
1969–1982	10.2	13.7	2.6	2.7	0.10	0.29
1983–1992	14.0	16.3	3.9	4.0	0.21	0.56
Change (%)	37	19	51	48	108	95

[a]Yala = dry season, Maha = wet season. [b]Husked rice yield.
Source: Amarasinghe et al (1998).

Taylor (1980) examined studies involving an economic evaluation of rehabilitating and modernizing five communal irrigation systems in the Philippines and Indonesia. Although benefits accrued from these improvements varied greatly from one project to another, they were high for all projects. The Tertiary Improvement Program of the Jatiluhur irrigation system, Indonesia, produced similar successes (Purba 1981). But the findings reflected the period immediately after rehabilitation, when the study was conducted, and therefore could not be extrapolated for later times.

Results were not so encouraging with the Government of India's Command Area Development (CAD) program in the early 1970s, which aimed to improve use of the unrealized potential of existing major and medium irrigation schemes[1]. According to Singh (1983), the CAD experience proved that on-farm development alone could not overcome the deficiencies of the main canal system. The Camiling River irrigation system (IRRI 1983) and Sta. Cruz River irrigation system, Philippines (Kikuchi 1996), are examples in which most of the upgraded facilities did not meet farmers' irrigation needs, remained unused, and deteriorated quickly within less than 10 years after the completion of major rehabilitation programs.

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[1] The classification of irrigation schemes in India is based on the extent (size) of the cultivable command area (CCA) serviced by an irrigation work. A scheme with a CCA of more than 10,000 ha is called major irrigation and a scheme with a CCA of more than 2,000 ha but less than 10,000 ha is called medium irrigation.

The above examples indicate inconclusive results with regard to the strategic advantage of system rehabilitation and modernization. *To sustain their functionality, it is essential that irrigation infrastructure be properly maintained regardless of whether it may be rehabilitated at some time in the future.* Irrigation agencies often cite lack of funds for operation and maintenance (O&M) as the reason for failure to perform regular and adequate maintenance activities. Although it is true that revenue generation is often inadequate in most irrigation systems, the absence of incentives to improve their revenue is often a chronic problem. A review of 208 World Bank-funded irrigation projects revealed that the revenue from irrigation water charges usually goes to the central treasury and is not earmarked for O&M (World Bank 1994). In the Philippines, irrigation systems “have been trapped by a vicious cycle of downward spiral: low quality of O&M → low system performance → low fee payment → low quality of O&M” (Kikuchi 1996). We believe that sustainable improvements in O&M cannot be achieved without the support and participation of water users.

5.5 Strengthening managerial capacity and farmer cooperation

Most quantitative evaluations of the performance of rice irrigation systems in Asia indicate a rather disappointing situation. A study of 15 irrigation systems in South and Southeast Asia indicated that little systematic measurement of performance is done by system managers. Wide gaps existed between operational targets and actual achievements and there was little feedback from the field and little capacity to respond to information when it was available. The study concluded that without addressing managerial capacity, it is highly unlikely that increasing the control potential of an irrigation system will lead to improved performance (Murray-Rust and Snellen 1993).

Management functions are often inadequately defined for system managers. The essential functions for which the management team should acquire adequate capacity to successfully operate and maintain irrigation systems include water allocation-distribution, feedback and response, communication, organization, maintenance, productivity protection, and cost recovery (Bhuiyan 1985). The required capacities for successful system operation and maintenance are usually all in short supply. The most compelling reasons for these deficiencies are lack of accountability and incentives, and inadequate farmer participation.

The agency that builds and operates the irrigation system is often not directly responsible for water use on-farm. It is often difficult to coordinate the activities of different agencies and there is an inherent problem of institutionalizing accountability for irrigation system performance. Within irrigation agencies, there is a marked lack of enforced accountability with respect to the O&M functions of the various groups of staff. Supervision of the work of various field staff by supervising officers is often seriously lacking because they have to spend too much time on routine administrative duties that are imposed on them. Incentives for staff to perform well are often inadequate and promotions are based more on length of service than on performance in assigned roles.

Recently, there has been a global recognition of the value of consulting and involving water users in various water management plans and activities of the irrigation system. For the past two decades, more and more countries around the world have been turning over management authority for irrigation systems to farmer groups or local entities, in a process commonly referred to as irrigation management transfer (IMT). There have been a number of studies on this process and the literature shows a mixture of positive and negative results (Vermillion 1997). Though most of the studies are deficient in assessing the real cost of farmers’ participation, government expenditures for irrigation tend to decline and costs to farmers often rise. Little evidence suggests that yields, water productivity, and farm income have increased. Rice (1997) showed that poor operation and management have a negligible impact on the irrigated crop. Studies that make it possible to separate the impact of IMT from other factors such as weather are lacking. In many instances, the responsibility for rehabilitation in the IMT agreement between the government and local entities is not clearly spelled out.

The key to sustained success of farmers’ participation is the incentive structure and quality of leadership, which can vary widely from place to place and from time to time. There is no available model to follow for molding the farmer-agency relationship that will work in all societies for all situations. Many innovations may be needed for developing the right model for a given set of conditions. We could hope that as the real value of water is better internalized by all users and more realistic water pricing becomes feasible, workable models of sharing responsibility in managing irrigation water between agencies and users will emerge.

6. RESEARCH NEEDS FOR IMPROVING EFFICIENCY IN RICE IRRIGATION SYSTEMS

We have described a number of interventions with the potential for raising the productivity of irrigation water. The potential for cost-effective gains in water productivity will vary over time and space. Research is needed to identify the most appropriate strategies.

6.1 Method of accounting for water use and productivity

Data on the efficiency and productivity of water over irrigation systems are scarce. When data are available, the method of derivation is often not described. Components of water-use and water-saving techniques are often described and measured for plots but not for the system. The inadequacy of data makes it difficult to assess opportunities for increasing water productivity over the system and basin. For example, flow measurements have focused on the headgate, but data on drainage outflow are almost completely missing. Without proper water-balance measurements, the consequences of water “losses” caused by seepage and percolation cannot be assessed.

We need a common water-accounting procedure for analyzing the use, depletion, and productivity of water at the farm, system, and basin levels. This procedure is necessary to assess the impact of alternative interventions on water productivity on different scales. We also need a better understanding of the relationship between productivity changes at different levels. This is especially important as we enter a period of growing competition for water between the agricultural and nonagricultural sectors.

Molden (1997) has developed procedures to identify the status of water resource uses that require water balances on different scales. These procedures are being tested in watersheds in Sri Lanka and India by scientists from the International Irrigation Management Institute (IIMI) in collaboration with national organizations. Procedures include the use of remote sensing, which now makes it possible to measure basin evapotranspiration and estimate crop yields. Apart from technical issues, the cost of data collection must be carefully evaluated.

6.2 Off-site impact assessment of increasing water productivity

Too few studies (such as the Gal Oya left bank, Table 6) have assessed the impact of intervention on irrigated area, water and land productivity, and related factors. Such studies require careful monitoring over time to capture before and after effects and separate out changes caused by intervention from other factors such as weather.

Little quantitative evidence establishes the degree to which the large-scale adoption of water-saving irrigation practices such as those being pursued in China leads to water savings and higher productivity over the entire irrigation system or water basin. Improvements in on-farm efficiency may not necessarily lead to increasing efficiency and productivity in the system. For example, when the downstream flow from an irrigation system is the source of water for other purposes, increased water efficiency upstream may adversely affect downstream enterprises. A similar effect may take place where the recharge of groundwater aquifers, which supply water for domestic or other uses, depends on seepage and percolation losses in irrigation canals and cropped areas. By the same token, increasing the water-use efficiency of an irrigation system may affect people downstream from the system who have been relying on its outflow. We therefore need to develop a new methodology to account for such interdependent systems within a water basin.

6.3 The economics of water productivity

Interventions that lead to higher water productivity almost always require more input of other resources such as management, labor, and capital. Economic analyses of alternative techniques for raising water productivity are scarce mainly because of the lack of adequate data describing physical relationships. Such analyses will be in greater demand as we attempt to establish irrigation systems with greater financial autonomy and less reliance on government subsidies, and to increase irrigation charges.

6.4 Improved irrigation management

Management is often seen as the bottleneck to improved performance of irrigation. Major changes are needed in the way water rights are exercised and excessive water application is practiced in rice fields before any action to reduce the water supply to farms is accepted by water users, especially those at the head-end of supply canals. *Appropriate institutions for sustainable improvement are mostly lacking. It may take many years before both agencies and users in the rice irrigation sector treat water as a true economic good. Privatization of irrigation systems may be considered by some to hold the key to future improvement.* Although privatization of groundwater-based systems, which are very small in size relative to canal-based surface water systems, has proven to be effective and sustainable in many countries, *applying the privatization concept to large rice irrigation systems remains speculative.*

6.5 On-farm impact of water-saving irrigation practices

The effects of WSI practices on rice performance need in-depth investigation and understanding from an integrated agronomic perspective. For example, the possible effects on nitrogen uptake efficiency, the environment, and weed population dynamics stemming from the alternate wetting and drying of WSI practices should be determined. The possible trade-off between water-use efficiency and nutrient-use efficiency has to be evaluated to identify the optimum combination of water and agronomic management.

WSI techniques require more control over the amount and timing of water application than traditional practices. We need further research to determine how to implement effective soil saturation or very thin standing water in irrigation systems where the plot-to-plot method of water distribution is dominant and whether the sustainable adoption of WSI regimes would require a greater density of field irrigation channels. Additional infrastructure in the irrigation system (such as control structures) may also be needed for WSI implementation. We need information on all input requirements and outputs to be able to compare the overall profitability and impact of the traditional versus the new system of water management. This will also have to be analyzed in the context of a future scenario of increasing labor cost.

6.6 Water management for direct-seeded rice systems

The impact of direct seeding on water-use efficiency, when practiced over the entire irrigation system, has yet to be determined. More studies should be conducted of the type reported by IRRI (Table 4) and the Muda Agricultural Development Authority (Table 5) that compare water requirements and productivity for direct-seeded and transplanted rice under different physical and socioeconomic conditions. We need to better understand where and how direct-seeded rice systems can be established widely and sustained within major rice irrigation schemes.

Water management for direct seeding is different from transplanting, particularly in the crop establishment and early growth periods. We therefore need to fully assess the required changes in managing irrigation water, from the source to the farm ditch, as a result of the shift from transplanting to direct seeding. Because the drainage requirement is also more stringent with direct-seeded rice, a change in the water management program may be necessary. We also need to develop an effective and affordable method of land leveling, which is crucial for good crop establishment of direct-seeded rice. Further research is needed on weed dynamics and alternative environmentally friendly weed management strategies for direct-seeded rice systems.

6.7 The systems approach and basin study

Few past studies used a systems approach for analyzing or improving the performance of irrigated systems. Data are almost always collected and analyzed by different members of a study team and reported in separate chapters or reports. Although in the end the findings of different disciplines and scales are often brought together in a qualitative manner, they are not specific enough to assist in decision making. We need a more quantitative systems approach to simulate the interaction of physical and socioeconomic processes that control water management on various scales for high productivity.

One example of the need for a systems approach is to assess when and where it is more worthwhile to focus on the reuse of drainage water rather than on improving management of the water delivery and application systems. We need a systems approach to quantify all of these research issues. As competition for water among sectors and users grows, the requirements for irrigation water must be considered in conjunction with demands for other uses. We need to adopt a systems approach for research and development for the farm, the irrigation system, and the water basin that will help practitioners, planners, and policymakers to more effectively allocate the increasingly scarce supply of water among competing uses.

7. CONCLUSIONS

Issues related to water availability and distribution will be increasingly important globally in the coming years. The impact of greater water scarcity on agriculture will be manifested prominently in the rice production sector. It is therefore important to determine how to grow more rice with less water.

A future scenario for irrigated rice production systems would have the following components:

- a dwindling supply of water per unit of rice area,
- increased contamination of water resources by agrochemicals,
- less farmer income from rice production,
- escalating labor costs (although this may be tempered in some areas of Asia in the short run by the changing economic climate, and
- an increased use of herbicides for weed control.

Because of the wide range of options for increasing the productivity of irrigation water in rice-based systems, the most appropriate strategy to adopt will vary over time and space. We therefore need information to guide us in choosing interventions. But pitifully few data are available on the productivity of irrigation water and on the cost of various options for increasing productivity. Implementing these options may be constrained by the continuing lack of incentives for irrigation systems managers to improve performance or devolve responsibility for operation to nongovernment entities and by poorly defined land and water rights and inadequate support systems that discourage farmer participation in management.

Therefore, the challenge to improve water management and control on-farm and in the irrigation system and to grow more rice with less water is formidable. The Systemwide Initiative on Water Management (SWIM) Project provides a unique opportunity for synthesizing the results of research conducted on improving water productivity by the Consultative Group on International Agricultural Research centers and national agricultural research systems since the late 1970s. It is now time to tailor and integrate the prospective elements into widely usable models, and implement and evaluate these models in selected public-sector rice irrigation schemes. *In doing so, we must consider the irrigated rice production system as a whole and address its issues holistically, with full attention to interactions among them, rather than separately at the farm level or at the irrigation system level*. Bold, but scientifically sound and systematic, actions are needed now because the cost of not acting may be too high to bear.

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