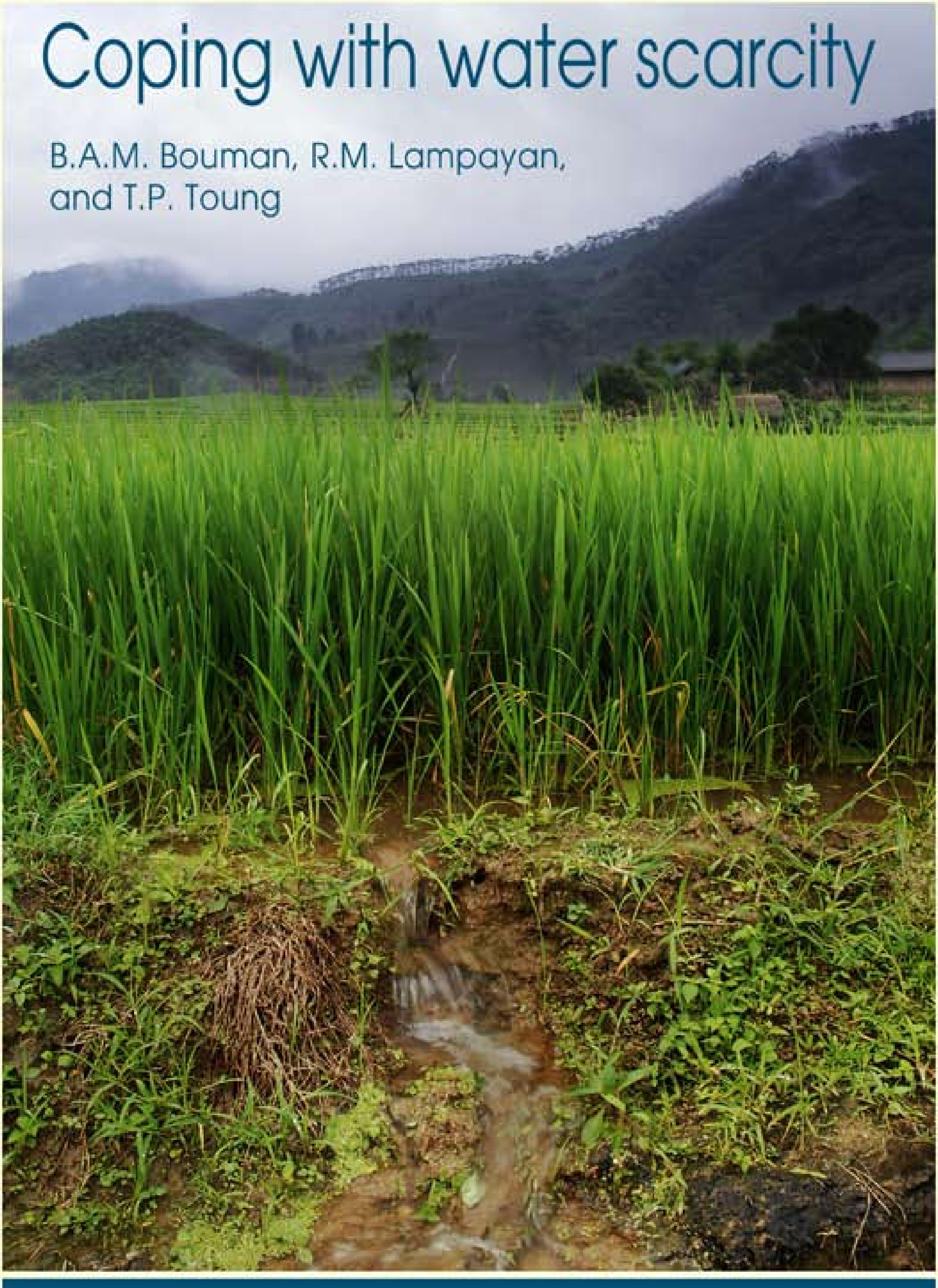
Water management in irrigated rice

Coping with water scarcity

B.A.M. Bouman, R.M. Lampayan, and T.P. Toung



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Preface

Worldwide, about 79 million ha of irrigated lowlands provide 75% of the total rice production. Lowland rice is traditionally grown in bunded fields that are continuously flooded from crop establishment to close to harvest. It is estimated that irrigated lowland rice receives some 34–43% of the total world's irrigation water, or 24–30% of the total world's freshwater withdrawals. With increasing water scarcity, the sustainability, food production, and ecosystem services of rice fields are threatened. Therefore, there is a need to develop and disseminate water management practices that can help farmers to cope with water scarcity in irrigated environments.

This manual provides an overview of technical response options to water scarcity. It focuses on what individual farmers can do at the field level, with a brief discussion on response options at the irrigation system level. The manual is meant as a support document for training on water management in rice production. It combines scientific background information (with many literature references for further reading) with practical suggestions for implementation. The target audience is people involved in agricultural extension or training with an advanced education in agriculture or water management, who wish to introduce sound water management practices to rice farmers (such as staff of agricultural colleges and universities, scientists, irrigation operators, and extension officers).

Introductory chapters analyze the water use and water balance of rice fields, and water movement in the plant-soil system, and discuss the concepts of water scarcity and water savings. Consequences of water scarcity for sustainability, environmental impacts, and ecosystem services of irrigated rice fields are discussed at the end. An appendix introduces two simple instruments to characterize the water status of rice fields that can help farmers in applying water-saving technologies.

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The authors
Los Baños, 2007

Rice and water

1

1.1 Rice environments

Worldwide, there are about 150 million hectares of rice land, which provide around 550–600 million tons of rough rice annually (Maclean et al 2002). Rice is unique among the major food crops in its ability to grow in a wide range of hydrological situations, soil types, and climates. Rice is the only cereal that can grow in wetland conditions.

Depending on the hydrology of where rice is grown, the rice environment can be classified into irrigated lowland rice (79 million ha), rainfed lowland rice (54 million ha), flood-prone rice (11 million ha), and upland rice (14 million ha). Lowland rice is also called "paddy rice." Lowland rice fields have saturated (anaerobic) soil conditions with ponded water for at least 20% of the crop's duration. In irrigated lowlands, the availability of irrigation assures that ponded water is maintained for at least 80% of the crop's duration. In rainfed lowlands, rainfall is the only source of water to the field and no certain duration of ponded water can be assured (depending on vagaries of rainfall). In flood-prone environments, the fields suffer periodically from excess water and uncontrolled, deep flooding (more than 25 cm for 10 days or more). Deepwater rice and floating rice are found in these environments. Upland rice fields have well-drained, nonsaturated (aerobic) soil conditions without ponded water for more than 80% of the crop's duration.

1.2 Irrigated lowlands

The 79 million ha of irrigated lowlands provide 75% of the world's rice production (Maclean et al 2002; Fig. 1.1). At the turn of the Millennium, country-average irrigated rice yields in Asia ranged from 3 to 9 t ha^{-1}, with an overall average of about 5 t ha^{-1} (Maclean et al 2002). Irrigated rice is mostly grown with supplementary irrigation in the wet season, and is entirely reliant on irrigation in the dry season. Significant areas of rice are grown in rotation with a range of other crops, such as the 15–20 million ha of rice-wheat systems (Timsina and Connor 2001, Dawe et al 2004). Irrigation systems vary widely, and include

- Individual pump irrigation from shallow tubewells (down to about 15-m depth).
- Small- to medium-scale community-based pump irrigation from deep wells (down to 200–300-m depth).
- Small- to medium-scale community-based surface irrigation where water is diverted from ponds or reservoirs (for example, the tank system in southern India and Sri Lanka).
- Small- to medium-scale community-based surface irrigation where water is directly diverted from a river (run-off-the-river irrigation).
- Large-scale surface irrigation where water is diverted from reservoirs or lakes.
- Conjunctive groundwater-surface-water irrigation schemes (can be small to large scale).

In each type of system, the ownership and control of water may vary widely.

1.3 The rice field and its water balance

Irrigated lowland rice is grown under flooded conditions. Mostly, rice is first raised in a separate seedbed and subsequently transplanted into the rice field when the seedlings are 2–3 weeks old.

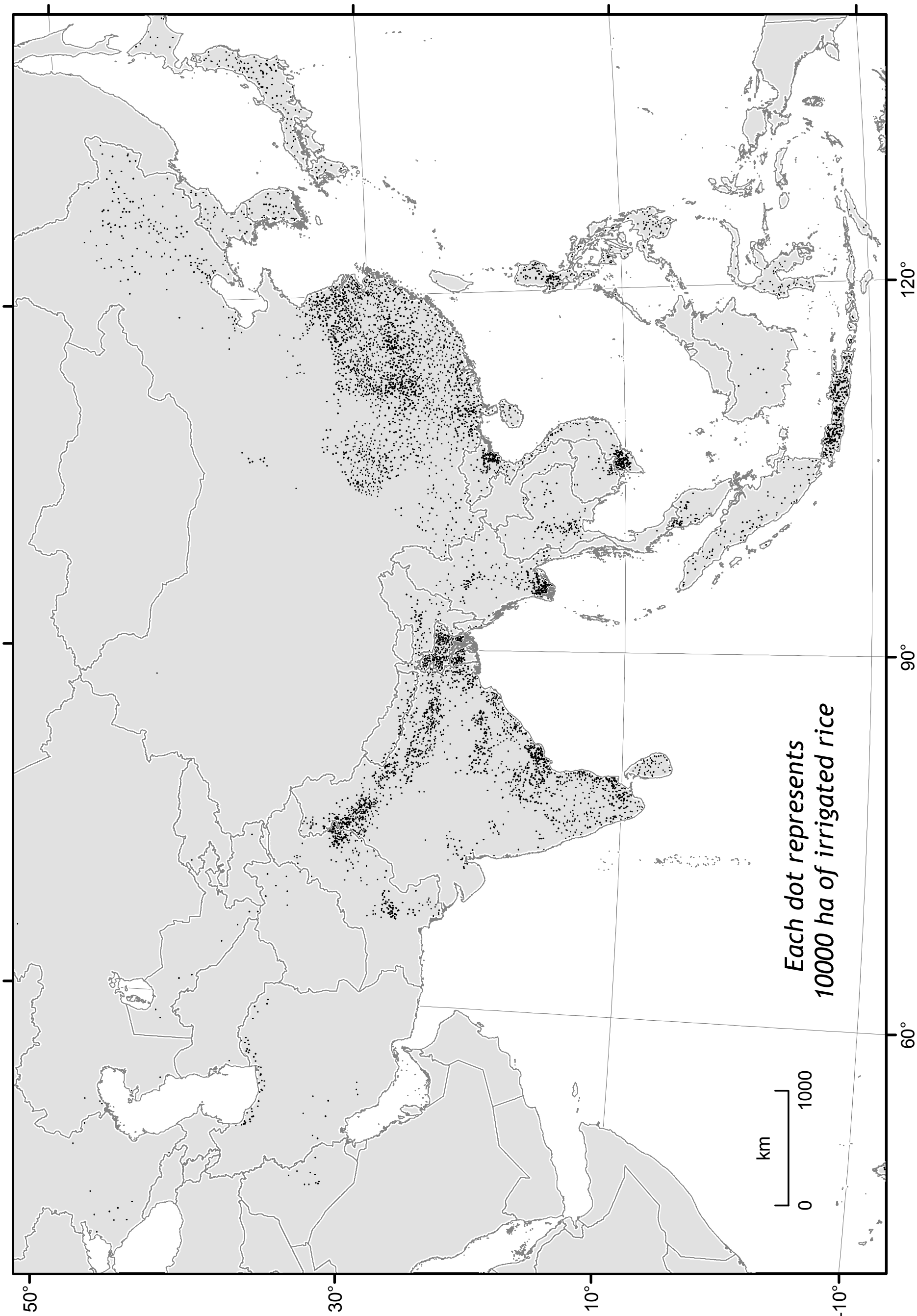


Fig. 1.1. Distribution of irrigated lowland rice in Asia. Source: IRRI GIS unit, 2006.

Rice can also be established by direct wet seeding (broadcasting pregerminated seeds onto wet soil) or direct dry seeding (broadcasting dry seeds onto dry or moist soil) in the main field. As of the late 1990s, it was estimated that one-fifth of the area in Asia was direct seeded (Pandey and Velasco 2002). After crop establishment, the main field is usually kept continuously flooded as this helps control weeds and pests. Before crop establishment, the main field is prepared under wet conditions. This wet land preparation consists of soaking, plowing, and puddling (i.e., harrowing or rotavating under shallow submerged conditions). Puddling is done to control weeds, to reduce soil permeability, and to ease transplanting. Puddling leads to a complete or partial destruction of soil aggregates and macro-

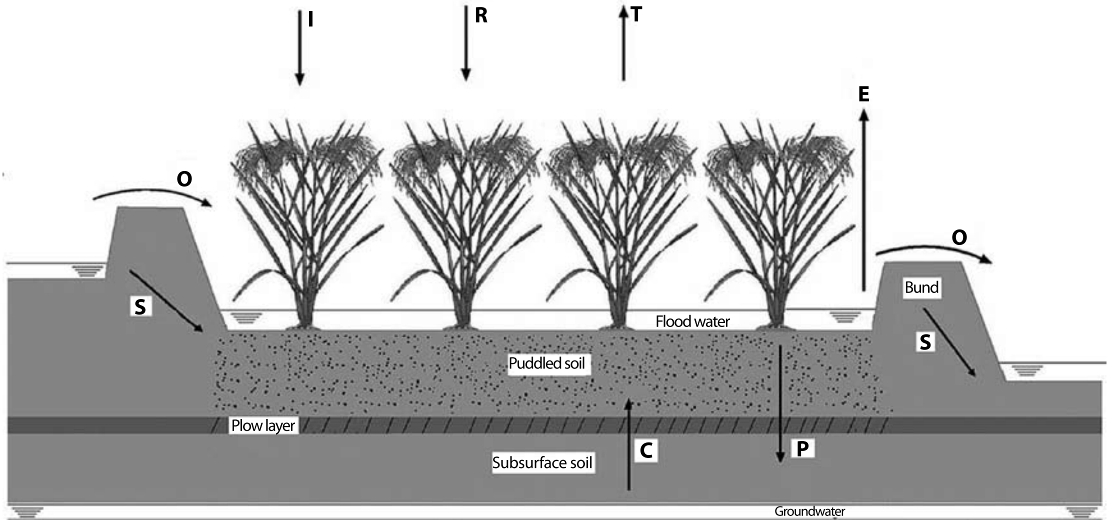


Fig. 1.2. Water balance of a lowland rice field. C = capillary rise, E = evaporation, I = irrigation, O = overbund flow, P = percolation, R = rainfall, S = seepage, T = transpiration.

pore volume, and to a large increase in micropores (Moorman and van Breemen 1978). A typical vertical cross-section through a puddled rice field shows a layer of 0–10 cm of ponded water, a puddled, muddy topsoil of 10–20 cm, a plow pan that is formed by decades or centuries of puddling, and an undisturbed subsoil (Fig. 1.2). Rice roots are usually contained within the puddled layer and are therefore quite shallow. The plow pan reduces the hydraulic conductivity and percolation rate of rice fields dramatically.

Because of its flooded nature, the rice field has a water balance that is different from that of dryland crops such as wheat or maize. The water balance of a rice field consists of the inflows by irrigation, rainfall, and capillary rise, and the outflows by transpiration, evaporation, overbund flow, seepage, and percolation (Fig. 1.2). Capillary rise is the upward movement of water from the groundwater table. In nonflooded (aerobic) soil, this capillary rise may move into the root zone and provide a crop with extra water. However, in flooded rice fields, there is a continuous downward flow of water from the puddled layer to below the plow pan (called "percolation"; see below) that basically prevents capillary rise into the root zone. Therefore, capillary rise is usually neglected in the water balance of rice fields.

Before the crop actually starts growing, water input is already needed for wet land preparation. After puddling, the field is usually left fallow and flooded for a few days (or 1 to 4 weeks) before the seedlings are transplanted. The amount of water used for wet land preparation can be as low as 100–150 mm when the turnaround time between soaking and transplanting is a few days only or when the crop is direct wet seeded. However, in large-scale irrigation systems that have poor water control, the turnaround time between soaking and transplanting can go up to 2 months and water inputs during this period can reach 940 mm (Tabbal et al 2002). After crop establishment, the soil is usually kept ponded with a 5–10-cm layer of water until 1–2 weeks before harvest. During both the turnaround time and the crop growth period, water outflows are by overbund runoff, evaporation, seepage, and percolation. During crop growth, water also leaves the rice field by transpiration. Of all water outflows, runoff, evaporation, seepage, and percolation are nonproductive water flows and are considered losses from the field. Only transpiration is a productive water flow as it contributes to crop growth and development.

When rainfall raises the level of ponded water above the height of bunds, excess rain leaves the rice field as surface runoff or *overbund flow*. This surface runoff can flow into a neighboring field, but, in a sequence of fields, neighboring fields will pass on the runoff until it is lost in a drain, creek, or ditch.

Evaporation leaves the rice field directly from the ponded water layer. *Transpiration* by rice plants

Table 1.1. Total seasonal water input and daily seepage and percolation rates from lowland rice fields with continuously ponded water conditions. Data collected from field experiments and from farmers' fields in China and the Philippines.

Site	Total seasonal water input by rain plus irrigation (mm)	Seepage and percolation rate (mm d^{-1})	References
Zanghe Irrigation System, Hubei, China			
• Field experiment	750 to 1,110	4.0 to 6.0	Cabangon et al (2001, 2004)
• Farmers' fields	650 to 940	1.6 to 2.8	Dong et al (2004), Loeve et al (2004a,b)
• Irrigation system level	750 to 1,525	4.0 to 8.0	Dong et al (2004), Loeve et al (2004a,b)
Shimen, Zhejiang, China			Cabangon et al (2001, 2004)
• Early rice	850 to 950	1.0 to 6.0	
• Late rice	575 to 700	1.0 to 6.0	
Guimba, Philippines			Tabbal et al (2002)
• Experiment 1988	2,197	18.3	
• Experiment 1989	1,679	12.5	
• Experiment 1990	2,028	16.4	
• Experiment 1991	3,504	32.8	
Muñoz, Philippines, 1991	1,019 to 1,238	5.2 to 7.0	Tabbal et al (2002)
Muñoz, Philippines, 2001	600	1.1 to 4.4	Belder et al (2004)
Talavera, Philippines	577 to 728	0.3 to 2.0	Tabbal et al (2002)
San Jose, Philippines			Tabbal et al (2002)
• Experiment 1996	1,417	9.6	
• Experiment 1 1997	1,920	15.2	
• Experiment 2 1997	2,874	25.8	

withdraws water from the puddled layer. Since the roots of rice plants generally don't penetrate the compacted layer, the contribution to transpiration from the subsoil is mostly absent. Since evaporation and transpiration are difficult to measure separately in the field, they are usually taken together as "evapotranspiration." Typical evapotranspiration rates of rice fields are 4–5 mm d^{-1} in the wet season and 6–7 mm d^{-1} in the dry season, but can be as high as 10–11 mm d^{-1} in subtropical regions (Tabbal et al 2002). During the crop growth period, about 30–40% of evapotranspiration is evaporation (Bouman et al 2005, Simpson et al 1992).

Seepage is the subsurface flow of water underneath the bunds of a rice field. With well-maintained bunds, seepage is generally small. In a toposequence of rice fields, seepage loss from one field may be offset by incoming seepage from another field located higher up. Considerable seepage can occur from top-end fields and from bottom-end fields that border drains, ditches, or creeks. Seepage rates are affected by the soil physical characteristics of the field and bunds, by the state of maintenance and length of the bunds, and by the depth of the water table in the field and in the surrounding drains, ditches, or creeks (Wickham and Singh 1978). *Percolation* is the vertical flow of water to below the root zone. The percolation rate of rice fields is affected by a variety of soil factors (Wickham and Singh 1978): structure, texture, bulk density, mineralogy, organic matter content, and salt type and concentration. Soil structure is changed by the physical action of puddling. In a heavy-textured, montmorillonitic clay, sodium cations and a high bulk density are favorable for effective puddling to reduce percolation rates. The percolation rate is further influenced by the water regime in and around the field. Large depths of ponded water favor high percolation rates (Sanchez 1973, Wickham and Singh 1978). In a field survey in the Philippines, Kampen (1970) found that percolation rates were higher for fields with deep groundwater tables (> 2 m depth) than for fields with shallow groundwater tables (0.5–2 m depth). In practice, seepage and percolation flows are not easily separated because of transition flows that cannot be classified as either percolation or seepage (Wickham and Singh 1978). Typical combined values for seepage and percolation vary from 1–5 mm d^{-1} in heavy clay soils to 25–30 mm d^{-1} in sandy and sandy loam soils (Bouman and Tuong 2001). Some examples of seepage and percolation rates measured at different sites are given in Table 1.1. Water losses by seepage and percolation account for about 25–50% of all water inputs in heavy soils with shallow groundwater tables of 20–50-cm depth (Cabangon et al 2004, Dong et al 2004), and 50–85% in coarse-textured soils with deep groundwater tables of 1.5-m depth or more (Sharma et al 2002, Singh et al 2002). Though seepage and percolation are losses at the field level, they are often captured and reused downstream (just like overbund flow; Chapter 5.1). The actual amount of water reuse in rice-based irrigation systems is not known and is expected to vary widely among irrigation systems.

Daily seepage and percolation losses from the ponded water do not occur in dryland crops such as wheat and maize. Percolation of water below the root zone can also occur in dryland crops when the amount of water infiltrating into the soil (either after heavy rainfall or after irrigation) is larger than the storage capacity of the root zone, but this is not a daily water flow as in lowland rice. Also, evaporation from ponded water surfaces is higher than from soil surfaces (as in dryland crops). Therefore, it is the relatively large water flows by seepage, percolation, and evaporation that make lowland rice fields heavy "water users." Total seasonal water input to rice fields (rainfall plus irrigation) can be up to 2–3 times more than for other cereals such as wheat or maize (Tuong et al 2005). It varies from as little as 400 mm in heavy clay soils with shallow groundwater tables (that directly supply water for crop transpiration) to more than 2,000 mm in coarse-textured (sandy or loamy) soils with deep groundwater tables (Bouman and Tuong 2001, Cabangon et al 2004). Around 1,300–1,500 mm is a typical value for irrigated rice in Asia. Table 1.1 lists some values for water inputs and daily seepage and percolation rates for lowland rice fields in China and the Philippines.

It is useful to distinguish between the water outflows from rice fields that can, in principle, be reused and those that cannot be reused. Nonreusable outflows are called "depleted water" (Molden 1997) and are evaporation and transpiration. Overbund flow, seepage, and percolation are generally reusable flows. Only when these flows enter very deep or saline groundwater (or saline surface water) from where they cannot be recovered are they not reusable any more and they become depletion flows as well.

1.4 Groundwater under rice fields

The role of groundwater in providing water to rice plants may be large, but it has been neglected in most studies of the rice water balance. Recent data collection suggests that through the (decade- to age-old) practice of continuous flooding, the large amounts of percolating water have raised groundwater tables to very close to the surface. This is especially true in soils with a heavy texture that are poorly drained in the subsoil, as is the case in many traditional irrigated rice environments.

Figure 1.3 gives the groundwater table measured under flooded rice fields at some sites in China and the Philippines. When the groundwater is less than 20 cm deep, it provides a "hidden" source of water to the rice crop as the roots of the plants can directly take up water from the groundwater. When for some reason fields are not flooded (Chapter 3), capillary rise may reach into the root zone and again provide extra water to the crop. In most water balance studies, the effect of groundwater on water supply is not taken into account, and the beneficial effect of water-saving technologies can be overestimated. With shallow groundwater, crop growth with a small irrigation water supply can still be good because of the "hidden" water supply of groundwater.

1.5 Rice water productivity

Water productivity (WP) is a concept of *partial productivity* and denotes the amount or value of product (in our case, rice grains) over volume or value of water used. Discrepancies are large in reported values of WP of rice (Tuong 1999). These are partially caused by large variations in rice yields, with commonly reported values ranging from 3 to 8 tons per hectare. But the discrepancies are also caused by different understandings of the denominator (water used) in the computation of WP. To avoid confusion created by different interpretations and computations of WP, it is important to clearly specify what kind of WP we are referring to and how it is derived. Common definitions of WP are

- WP_T : weight of grains over cumulative weight of water transpired.
- WP_{ET}: weight of grains over cumulative weight of water evapotranspired.
- WP_I : weight of grains over cumulative weight of water inputs by irrigation.

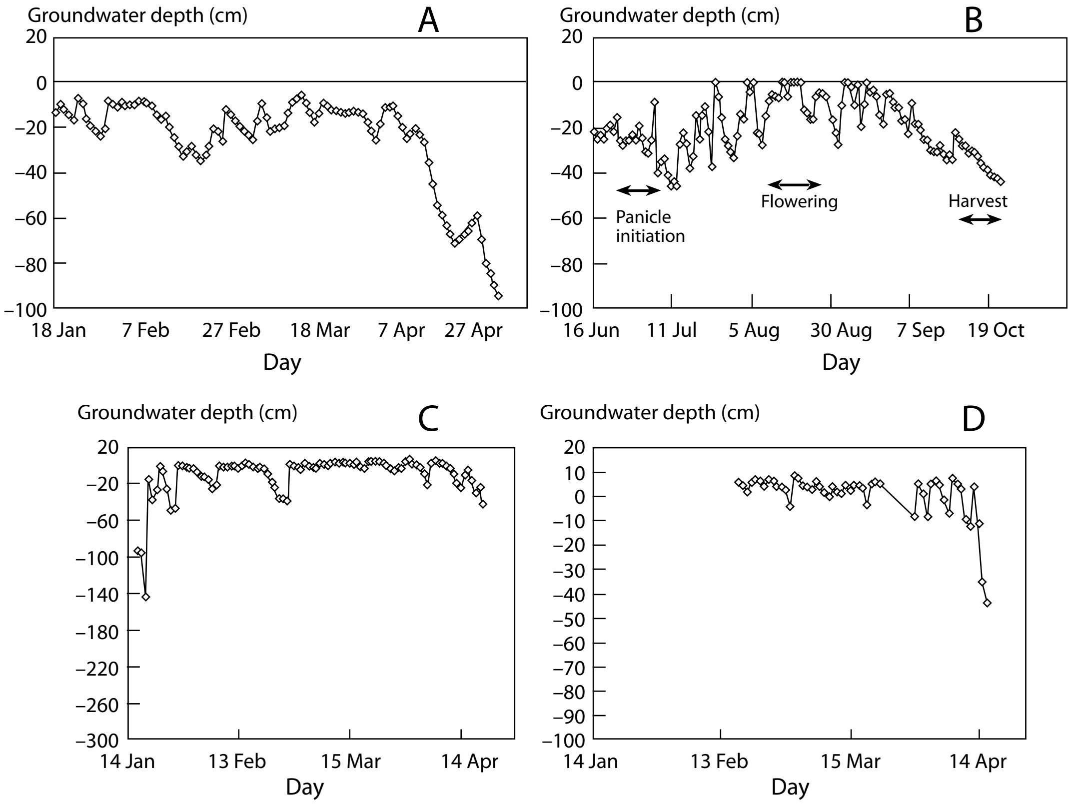


Fig. 1.3. Groundwater depth under flooded rice at Tuanlin, Hubei Province (A), and Changle (B), Beijing, China, in 2002. Adapted from Belder et al (2004) and unpublished data from China Agricultural University/IRRI. Groundwater depth under flooded rice in Dolores (C) and Gabaldon (D) in 2002, Central Luzon, Philippines. Adapted from Lampayan et al (2005).

WP_{IR} : weight of grains over cumulative weight of water inputs by irrigation and rain.

WP_{TOT}: weight of grains over cumulative weight of all water inputs by irrigation, rain, and capillary rise.

Breeders are interested in the productivity of the amount of transpired water (WP_T), whereas farmers and irrigation engineers/managers are interested in optimizing the productivity of irrigation water (WP_I). To regional water resource planners, who are interested in the amount of food that can be produced by total water resources (rainfall and irrigation water) in the region, water productivity with respect to the total water input by irrigation and rainfall (WP_{IR}) or to the total amount of water that can no longer be reused (WP_{ET}) may be more relevant.

Modern rice varieties, when grown under flooded conditions, have similar water productivity with respect to transpiration (WP_T) as other C_3 cereals such as wheat, at about 2 g grain kg^{-1} water transpired (Bouman and Tuong 2001, Tuong et al 2005). The few available data indicate that water productivity with respect to evapotranspiration is also similar to that of wheat, ranging from 0.6 to 1.6 g grain kg^{-1} of evapotranspired water, with a mean of 1.1 g grain kg^{-1} (Tuong et al 2005, Zwart and Bastiaanssen 2004, Fig. 1.4A). Compared with wheat, the higher evaporation rates from the water layer in rice than from the underlying soil in wheat are apparently compensated for by the higher yields of rice. For maize, being a C_4 crop, the water productivity with respect to evapotranspiration is higher, ranging from 1.1 to 2.7 g grain kg^{-1} water, with a mean of 1.8 g grain kg^{-1}. Water productivity of rice with respect to total water input (irrigation plus rainfall) ranges from 0.2 to 1.2 g grain kg^{-1} water, with 0.4 as the average value, which is about half that of wheat (Tuong et al 2005, Fig. 1.4B).

Comparing WP among seasons and locations can be misleading because of differences in climatic yield potential, evaporative demands from

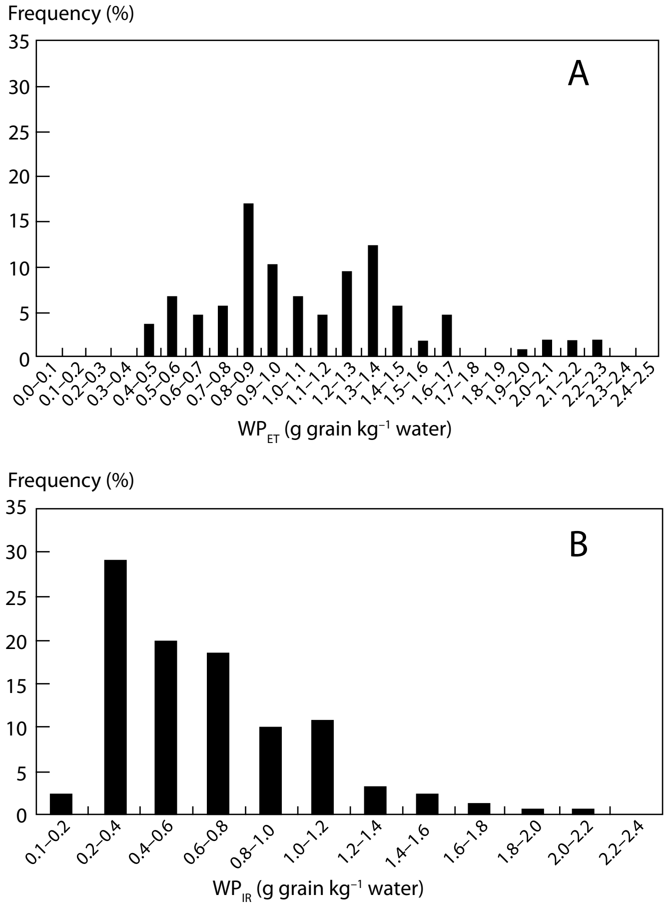


Fig. 1.4 (A) Frequency distribution of water productivity of rice with respect to evapotranspiration (WP_{ET}). Data from Zwart and Bastiaanssen (2004). (B) Frequency distribution of water productivity of rice with respect to water inputs by irrigation and rainfall (WP_{IR}). Data from Tuong et al (2005).

the atmosphere, or crop management practices such as fertilizer application. It is more relevant to study what the potential and actual WP values are in a particular environment, and to identify measures to close the gaps between them, rather than to compare WP values across environments (and sometimes years). For example, in rainy seasons, a small amount of supplementary irrigation can lead to very high WP_I levels (e.g., > 10 g grain kg^{-1} irrigation water in Tuan Lin, China, Cabangon et al [2003]) because rainfall supplies most of the water needed for crop growth. This does not mean that irrigation water is better used in the rainy season than in the dry season. The impact of the supplementary irrigation can be better assessed by the "incremental irrigation water productivity," defined as the increase in the amount or value of the product (compared with no irrigation) over the volume of supplementary irrigation water. Unfortunately, data on this kind of water productivity are scarce.

The concept of water productivity becomes important when water is scarce. Examples of the use of water productivity in the design or management of irrigation systems are given in Chapter 5.4 and 5.5.

1.6 Global rice water use

There are no data available on the amount of irrigation water used by all the rice fields in the world. However, estimates can be made based on total worldwide water withdrawals for irrigation, the relative area of irrigated rice land (compared with other crops), and the relative water use of rice fields. Total worldwide withdrawals of fresh water are estimated at 3,600 km^3 annually, of which

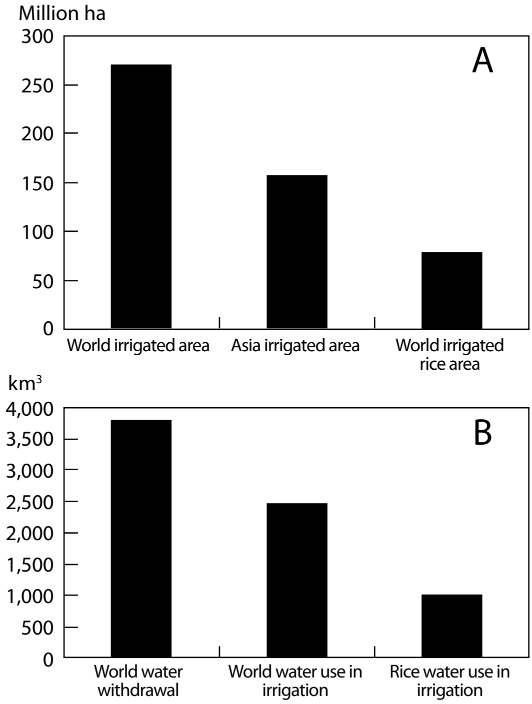


Fig. 1.5. Irrigated areas (A) and volumes of irrigation water used (B) in the world, in Asia, and in rice production.

2,500 km^3 is used to irrigate crops (Falkenmark and Rockström 2004). The rest is used in industry and for domestic purposes. Approximately 56% of the world's 271 million ha of irrigated area of all crops is in Asia, where rice accounts for 40–46% of the net irrigated area of all crops (Dawe 2005). At the field level, rice receives up to 2–3 times more water than other irrigated crops (Chapter 1.3), but an unknown proportion of the water losses from individual fields is reused by other fields downstream (Chapter 5.1). Assuming a reuse fraction of 25%, it can be estimated that irrigated rice receives some 34–43% of the total world's irrigation water, or 24–30% of the total world's freshwater withdrawals. Figure 1.5 gives irrigated areas and volumes of irrigation water used in agriculture and in rice.

1.7 Water scarcity in rice-growing areas

Worldwide, water for agriculture is becoming increasingly scarce (Rijsberman 2006). The causes are diverse and location-specific, but include decreasing resources (e.g., falling groundwater tables, silting of reservoirs), decreasing quality (e.g., chemical pollution, salinization), malfunctioning of irrigation systems, and increased competition from other sectors such as urban and industrial users. There is no systematic inventory, definition, or quantification of water scarcity in rice-growing areas. Tuong and Bouman (2003) estimated that, by 2025, 15–20 million ha of irrigated rice will suffer from some degree of water scarcity. There are no indications yet of water scarcity in some of Asia's largest irrigated rice ecosystems in the river deltas of the Yangtze, the Mekong, or the Irrawady. However, in South Asia, the Ganges and Indus rivers have little outflow to the sea in the dry season, thus affecting downstream rice-growing areas (Postel 1997). Overexploitation of groundwater during recent decades has caused serious problems in northern China and South Asia (Postel 1997, Shu Geng et al 2001, Singh 2000), affecting rice-wheat-growing areas. Groundwater tables have dropped on average by 1–3 m y^{-1} in the North China Plain; by 0.5–0.7 m y^{-1} in the Indian states of Punjab, Haryana, Rajasthan, Maharashtra, Karnataka, and northern Gujarat; and by about 1 m y^{-1} in Tamil Nadu and southern India, where flooded rice is the dominant cropping system. In Bangladesh, the heavy use of groundwater has led to shallow wells falling dry by the end of the dry season and to severe problems of arsenic pollution in rice-growing areas (Ahmed et al 2004). Heavy competition for river water between states and different sectors (city, industry) is causing water scarcity in southern India's Cauvery delta and in Thailand's Chao Phraya delta (Postel 1997), which are major regional rice bowls. Several case studies suggest local hot-spots of water scarcity because of increased competition between different users of water, even in areas generally not considered water scarce, for example, the Zanghe Irrigation System in the middle reaches of the Yangtze (Dong et al 2004) and Angat reservoir near Manila, Philippines (Bhuiyan and Tabbal, as referenced in Pingali et al 1997). In principle, water is always scarce in the dry season when the lack of rainfall makes cropping impossible without irrigation.

Usually, interventions to respond to water scarcity are called "water savings" and imply a reduced use of water. For many of us, the term "water savings" suggests an active action or decision to save water. This suggests that water is available, but farmers may opt not to use it for irrigation but to save it for a later time or for a different purpose, or

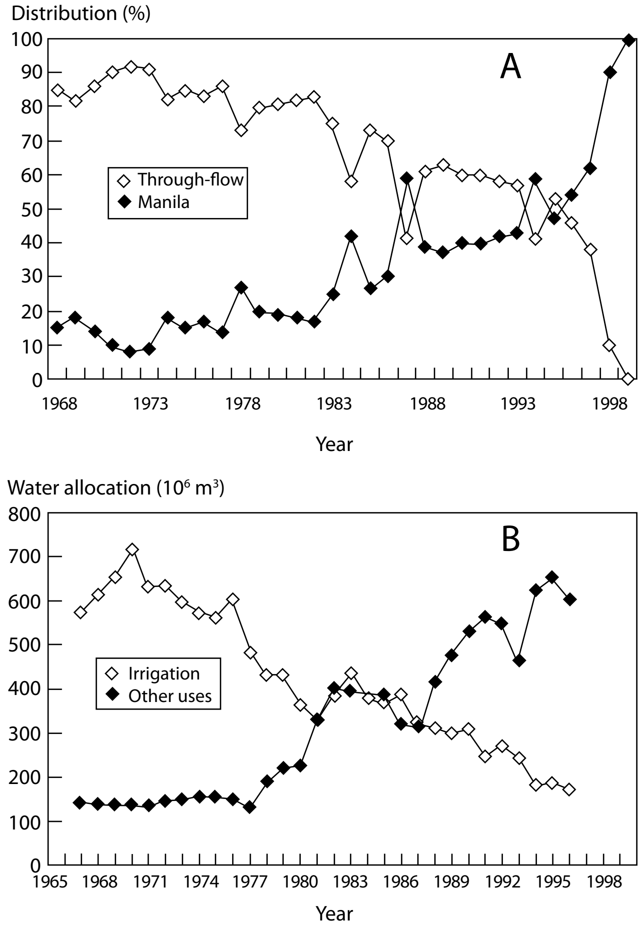


Fig. 1.6. (A) "Imposed water scarcity": change in percentage water allocation from Angat reservoir, Philippines, to through-flow in the river for potential agricultural use downstream and to the city of Manila. Data from Pingali et al (1997) and unpublished data from the National Irrigation Administration, Philippines. (B) "Imposed water scarcity": change in water allocation to agricultural and nonagricultural use in Zanghe Irrigation System, Hubei, China, between 1965 and 2002. Data points are 5-year moving averages. Data from Hong et al (2001) and unpublished data.

to cut down on costs if irrigation water is expensive. However, for most rice farmers, there is no deliberate choice to save water as they are just confronted by a lack of water. Under such conditions, saving water simply means coping with scarcity. Thus, the objectives of saving water depend on the nature of the water scarcity and the control farmers have over the water. Drawing parallels with general definitions of "savings," we discuss three reasons for saving water:

Definition 1: to reduce current expenditures on one commodity to allow for redirected expenditures on other commodities. In water terms, this translates into "reducing water used for irrigation so that it can be used for another purpose." In agriculture, the motivation for this type of water savings is usually not an absolute shortage of water but a desire to use the available water not for irrigation but for other purposes such as domestic or industrial. Increasing competition for water between sectors of society is the driving force behind such savings in agricultural water use. The examples of what is happening in the Zanghe Irrigation System in China and at the Angat reservoir in the Philippines are a case in point: the managers of these reservoirs are reducing the amount of water released for agriculture and redirecting this water to cities (Manila, in the case of Angat) and to industry and hydropower (in the case of Zanghe) (Loeve et al 2004a,b; Fig. 1.6). These water savings in agriculture are not an active and deliberate choice by farmers. The choice to withdraw water from agriculture is made at a higher level: the irrigation system, provincial, or national level. Farmers must face the consequences of these decisions: they receive less water and have to cope with "imposed water scarcity." The notion that we should ask farmers to actively save water so it can be used elsewhere, such as by industry and cities, is a fallacy. Farmers can be encouraged to voluntarily reduce water use, for example, by introducing volumetric water pricing, but this is the exception rather than the rule and "enforced water scarcity" is prevalent. Voluntary water savings by farmers for redirected use work well only with properly functioning water markets. For example, in Australia, rice farmers in irrigation schemes in the Murray basin can sell their water rights in a water market to other users, such as other farmers who grow high-value crops such as fruits (Thompson 2002).

Definition 2: to reduce expenditures because of reduced income. In water terms, this translates into "reducing the use of irrigation water because there is less of it." This type of water savings in agriculture is induced by actual and physical water scarcity. An example of this situation for farmers is the "enforced water shortage" discussed above. However, an absolute water shortage can also be induced by natural causes. For example, when seasonal rains have failed to fill up reservoirs or ponds, the amount of water may not be sufficient to keep all rice fields flooded throughout the year. When the reservoir forms part of a large-scale irrigation system, reservoir managers usually respond by reducing the "program area" for irrigation: fewer farmers will receive irrigation water. However, with smaller reservoirs such as individual ponds, farmers themselves can decide how to cope with the water scarcity. They may decide to reduce their land under irrigation or they could decide to "reduce current expenditures to allow for future expenditures": to deliberately save water early in the season to have it available later in the season. Farmers can save water by reducing the amount of irrigation applied to their fields early in the season. The best way to do this is by reducing the nonproductive outflows seepage, percolation, and evaporation (Chapter 3).

Definition 3: to reduce costs to increase profit. In water terms, this translates into "reducing the use of irrigation water to lower the costs." This scenario is applicable when farmers pay a high cost for water and have the means to reduce their water use to increase their profits. There may be plenty of water, but it is relatively expensive ("economic water scarcity"). In most surface irrigation systems in Asia, farmers either pay no cost for their water or pay a flat rate (a fixed sum per unit land area), and water costs cannot be reduced by reducing water use. When farmers pump their own water, either individually or collectively, they pay a relatively high price for their water when pumping is from deep aquifers and/or when the price for electricity or fuel is high. In this case, water savings by farmers are a voluntary and deliberate choice of their own. The means to save water are the same as in the scenario above: to reduce irrigation water to their fields.

These examples illustrate that water scarcity is usually imposed upon farmers (either by nature or by decision makers at higher levels) and that saving water is hardly a voluntary choice (except in definition 3). Farmers just have to cope with physical water scarcity, and the term "water-scarcity coping technology" may be more appropriate than the term "water-saving technology."

The plant-soil-water system

2

2.1 Water movement in the soil-plant-atmosphere continuum

Rice plants take up water from the soil and transport it upward through the roots and stems and release it through the leaves and stems as vapor in the atmosphere (called transpiration). The movement of water through the plant is driven by differences in water potential: water flows from a high potential to a low potential (imagine free water flow over a sloping surface: water flows from the top, with a high potential, to the bottom, with a low potential). Different units express water potential (Table 2.1) and, unfortunately, different authors report different units. In this report, we usually use the term Pascal (P).

In the soil-plant-atmosphere continuum, the water flows from the soil, with a relatively high potential, through the plant to the atmosphere just outside the leaves, which has a relatively low potential. Potentials in the soil-plant-atmosphere are usually negative and we also use the term "tension," which has the opposite value. For example, a tension of +10 kPa is the equivalent of a potential of –10 kPa. The term tension is intuitively easier to understand: a high tension suggests a high "pulling force." Thus, water flows from a low tension in the soil (low pulling force) to a high tension in the atmosphere (high pulling force). The water tension in the atmosphere outside the leaves is determined by climatic factors: relative humidity, wind speed, temperature, and solar radiation. This atmospheric tension translates into the "evaporative demand" of the atmosphere, which determines potential transpiration rates. The water tension in the soil is determined by the amount of water in the soil and by soil physical properties such as texture and bulk density. The speed with which water moves through the plant is determined by the difference in water tension between the soil and the atmosphere (the higher the differences, the faster the water will flow) and by the resistance to water flow in the plant (Ehlers and Goss 2003). First, soil water needs to overcome a physical resistance (the epidermis) to enter the roots. Then it flows through cells or through spaces between cells into so-called xylem or vascular bundles that will transport it upward. The water flows easier and faster in wide bundles

Table 2.1. Units to express water potential and some corresponding values. pF is calculated as $^{10}\log(-H)$, where H is water height in cm.

Unit name	Corresponding value				
Water height (cm)	0	−10	−100	−1,000	−15,850
pF (–)	−∞	1	2	3	4.2
Bar (bar)	0	0.01	0.1	1	15.85
Pascal (Pa)	0	1,000	10,000	100,000	1,585,000
Kilo Pascal (kPa)	0	1	10	100	1,585
Mega Pascal (MPa)	0	0.001	0.01	0.1	1.585

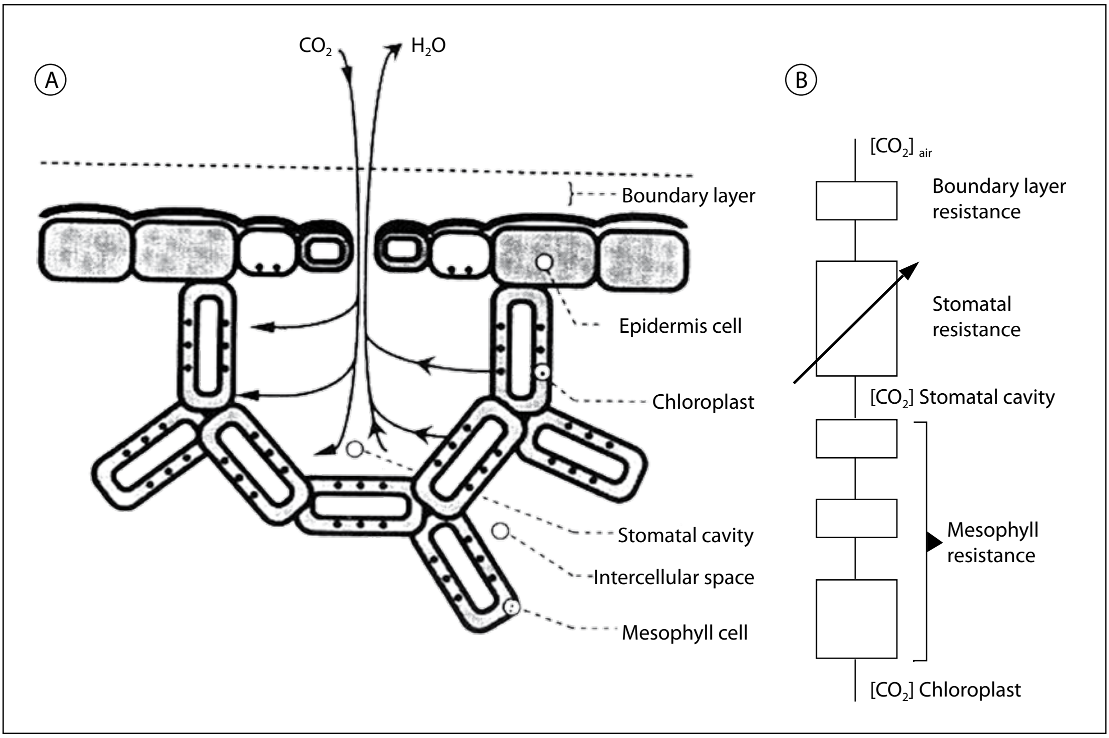


Fig. 2.1. Schematic cross section of a leaf stomata (A) indicating components of resistance (B). Source: Lövenstein et al (1992).

(with less resistance) than in narrow bundles (with large resistance). From the bundles, the water flows through the cells or spaces between the cells of the leaves to the "stomata": small cavities in the leaves that connect to the outside world (Fig. 2.1). The stomata are the last barrier (resistance) to water flowing out of the plant. The process of water release through the stomata is called (stomatal) transpiration (there is also a cuticular transpiration directly through cells of the leaves, but this is much lower than stomatal transpiration). Figure 2.2 gives an example of water potentials in the soil-plant-atmosphere system as water moves gradually from the soil through the plant into the atmosphere.

The flow of water through the plant serves several purposes: it transports nutrients (in its stream) from the soil to the plant organs where they are needed, it provides the plant with water in its cells so it will stay erect (this is called "turgor"), and transpiration cools the plant so it doesn't get overheated. Plants can actively regulate the rate of water flow (transpiration) by regulating the size of the opening of the stomata. If there is not enough water in the soil to satisfy the demand from the atmosphere (that is, to give in to the pulling force of the atmosphere), the plant can close its stomata and reduce or even completely stop transpiration. Besides the reduction in transpiration, several growth processes of the plant become affected when there is not enough water. We usually call these "drought effects," and they are summarized in Chapter 2.2. Some typical tension levels of soil water that are important for upland crops are given in Table 2.2.

Nonrice soils usually have a mixture of water, air, and solid soil particles, and the water potential is negative (positive tension). However, under flooded conditions, as in the muddy layer above the plow pan of rice fields, the soil is saturated with water and the potential is positive. Negative potentials (positive tensions) occur in this layer only when it dries out. Generally, rice plants experience the shift from flooded conditions (negative tensions) to nonflooded conditions (positive tensions) as "drought stress." A flooded soil that is saturated with water is also called an "anaerobic soil," whereas a soil that is not saturated but has a mixture of air and water in the pores is called an "aerobic soil." The water status of a soil has major implications for water supply to the crop and for pH (acidity), nutrient

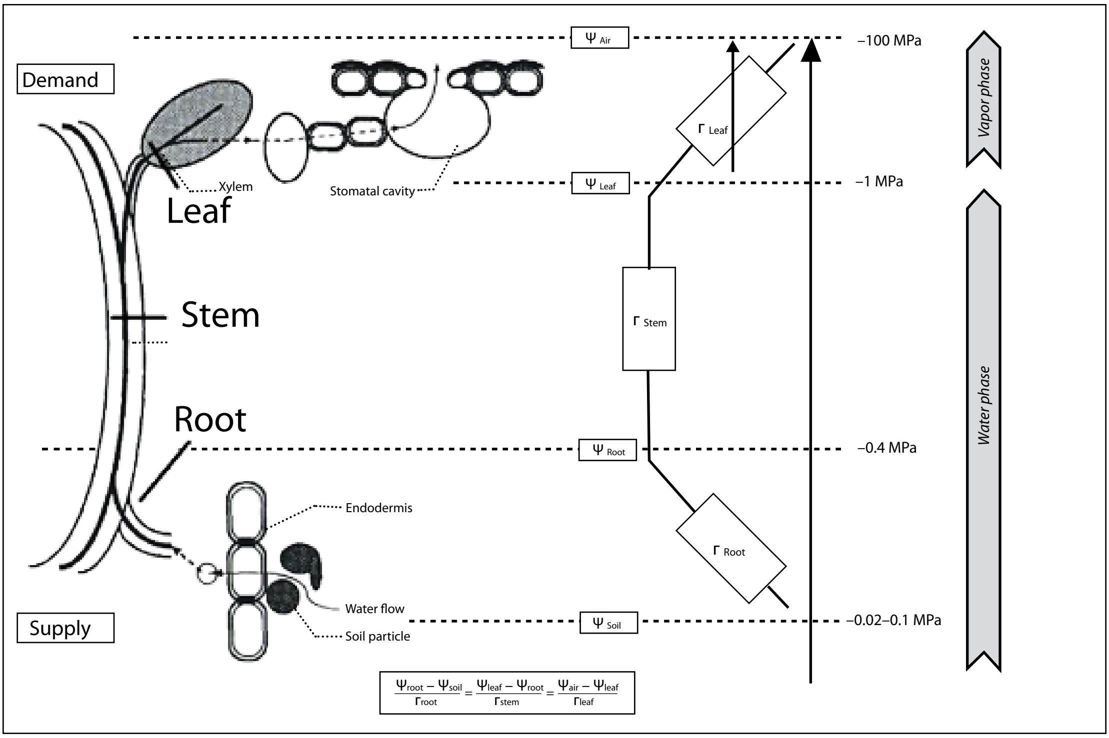


Fig. 2.2 Schematic overview of water flow and water potentials in the soil-plant-atmosphere continuum. Adapted from Lövenstein et al (1992).

Table 2.2. Some typical soil water tension levels in relation to the growth of upland crops (e.g., wheat, maize, cotton).

Name	pF value	Explanation
Saturation	–∞	All soil pores are filled with water
Field capacity	2	Soil water content that is considered optimum for upland crops
Permanent wilting point	4.2	Soil water content at which most upland crops cannot extract water from the soil any more and show permanent wilting
Air dryness	7	No free water in soil pores any more

availability, soil microbial population, soil organic matter buildup/decomposition, and occurrence of soil pests and diseases (Chapter 3.6). Figure 2.3 illustrates soil water tensions measured in an aerobic soil where rice was grown under nonflooded conditions like an upland crop.

Each soil has a specific relationship between the tension of the water and the amount of water: the lower the amount, the higher the tension. Thus, a small amount of water in the soil and a high tension both reflect a condition of relative "water scarcity" and drought. The relationship between soil water tension and soil water content is called the "soil water retention curve" or the "pF curve." The shape of the pF curve depends on soil type, especially on its texture (mixture of clay, silt, and sand particles), bulk density (the weight of a soil over its volume), mineralogy, and organic matter content. Examples are given in Figure 2.4 for a typical clay soil and a typical sand soil. There are four important points on the pF curve for upland crops: saturation = pF –∞ (H = 0 cm), field capacity = pF 2, permanent wilting point = pF 4.2, and air dryness = pF 7 (see Table 2.2). The amount of water at each of these four tensions is different for each soil type. When rice fields are flooded, the pF curve is not needed as soil water contents are always at saturation. However, when a rice soil

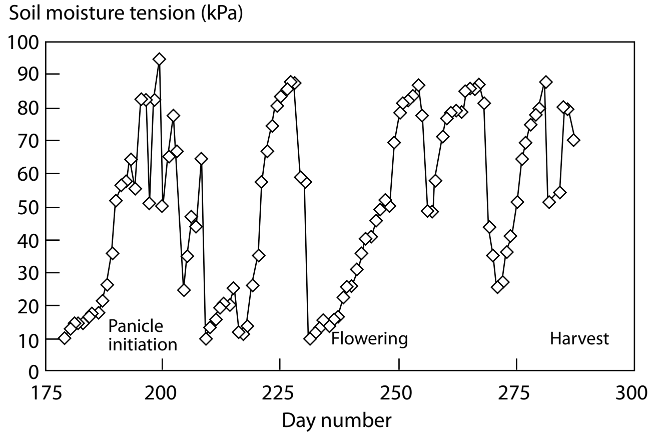


Fig. 2.3. Time course of soil water tension in the root zone of rice grown in a nonpuddled, nonflooded soil (this system is called "aerobic rice," Chapter 3.4). The dips in tension are associated with rainfall or an irrigation event. Adapted from Yang Xiaoguang et al (2005).

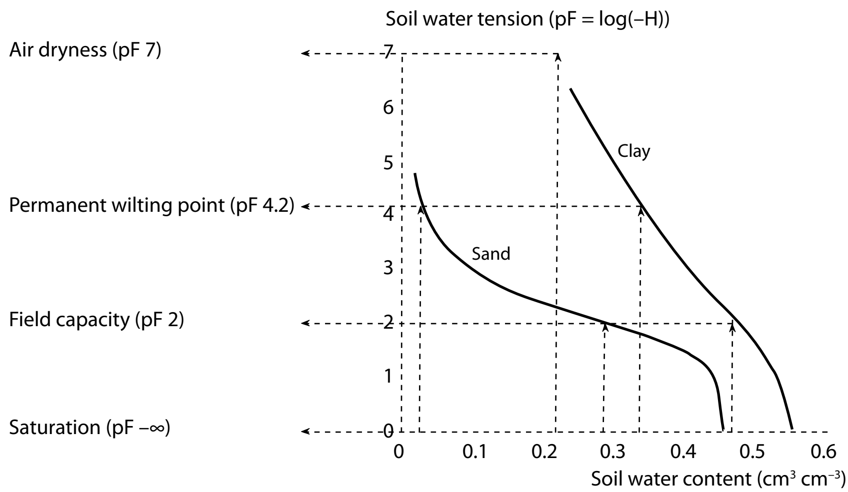


Fig. 2.4. Typical soil water retention curve (or pF curve) for a clay soil and a sand soil. Notice the differences in water content at the four critical tension levels (Table 2.2) for the two soil types. Adapted from Lövenstein et al (1992).

becomes dry, the pF curve becomes meaningful as it indicates the amount of water available for plant uptake at different tensions.

2.2 The rice plant and drought

Cultivated rice evolved from a semiaquatic perennial ancestor (Lafitte and Bennett 2002). The wetland ancestry of rice is reflected in a number of morphological and physiological characteristics that are unique among crop species. Lowland rice is extremely sensitive to water shortage and drought effects occur when soil water contents drop below saturation. Rice has a variety of mechanisms by which it reacts to such conditions. The following is a list compiled by Bouman and Tuong (2001):

1. Inhibition of leaf production and decline in leaf area, leading to retarded leaf growth and light interception, and hence to reduced canopy photosynthesis. Drought stress affects both cell division and enlargement, though cell division appears to be less sensi-

tive to water deficit than cell enlargement. Leaf area expansion is reduced as soon as the soil dries below saturation (tensions higher than 1 kPa) in most cultivars, and when only about 30% of the available soil water has been extracted in cultivars with aerobic adaptation (Lilley and Fukai 1994, Wopereis et al 1996).

2. Closure of stomata, leading to reduced transpiration rate and reduced photosynthesis. Leaf stomata do not close immediately with drought stress, however, and the crop keeps on photosynthesizing for a certain period before stomata close. The assimilates are not used for leaf growth or expansion (see point 1), but are stored in the existing leaves, stems, and roots. When drought stress is relieved, these assimilates may become available and lead to a flush in leaf growth. In the modern high-yielding variety IR72, stomatal closure starts at soil water tensions of 75 kPa (Wopereis et al 1996).
3. Leaf rolling, leading to a reduction in effective leaf area for light interception. Leaf rolling in IR72 starts at soil water tensions of 75 kPa (Wopereis et al 1996). Leaves unroll again when drought stress is relieved.
4. Enhanced leaf senescence, leading to reduced canopy photosynthesis. Enhanced senescence in IR72 starts at soil water tensions of 630 kPa (Wopereis et al 1996).
5. Changes in assimilate partitioning. Roots grow more, at the expense of the shoot, during vegetative development, whereas partitioning of assimilates among various shoot components is not affected. Deeper roots are effective for exploring water stored in deeper soil layers.
6. Reduced plant height (though it is not likely that reduced plant height in itself will result in yield reduction).
7. Delayed flowering. Drought in the vegetative development stage can delay flowering up to 3 to 4 weeks in photoperiod-insensitive varieties. The delay in flowering is largest with drought early in the vegetative stage and is smaller when drought occurs later.
8. Reduced tillering and tiller death. Drought before or during tillering reduces the number of tillers and panicles per hill. If the drought is relieved on time, and the source size (i.e., photosynthesizing leaves and stems) is sufficiently large, the reduced number of tillers/panicles may be compensated for by an increased number of grains per panicle and/or by an increased grain weight.
9. Reduced number of spikelets with drought between panicle initiation and flowering, resulting in decreased number of grains per panicle.
10. Rice is very sensitive to reduced water availability in the period around flowering as this greatly affects spikelet sterility (Cruz and O'Toole 1984, Ekanayake et al 1989). Increased spikelet sterility with drought at flowering results in decreased percentage of filled spikelets and, therefore, decreased number of grains per panicle. Especially at anthesis, there is a short time span when spikelet fertility is especially sensitive to drought.
11. Decreased grain weight with drought after flowering.

The above processes appear roughly in order of crop development and/or severity of drought, though numbers 2–4 also occur in the reproductive stage. Some effects lead to irreversible processes of yield reduction, such as numbers 4, 9, 10, and 11, whereas others may be restored when drought is relieved, such as numbers 2 and 3, and others may be compensated for by other effects later in the growing season, such as numbers 1, 2, and 8. Drought may also affect nutrient-use efficiency by the crop since water flow is the essential means of nutrient transport. How yield is finally affected by drought depends on its timing, severity, duration, and frequency of occurrence. The most sensitive stage of rice to drought is around flowering.

Coping with water scarcity

3

In this chapter, we present technology options to help farmers to cope with water scarcity at the field level. The way to deal with reduced (irrigation or rain) water inflows to rice fields is to reduce the nonproductive outflows by seepage, percolation, or evaporation, while maintaining transpiration flows (as these contribute to crop growth). This can be done at land preparation, at crop establishment, and during the actual crop growth period.

3.1 Land preparation

Land preparation lays the foundation for the whole cropping season and it is important in any situation to "get the basics right." Especially important for good water management are field channels, land leveling, and tillage operations (puddling, and bund preparation and maintenance).

3.1.1 Field channels

Many irrigation systems in Asia have no field channels (or "tertiary" irrigation or drainage channels) and water flows from one field into the other through breaches in the bunds. This is called "plot-to-plot" irrigation. The amount of water flowing in and out of a rice field cannot be controlled and field-specific water management is not possible. This means that farmers may not be able to drain their fields before harvest because water keeps flowing in from other fields. Also, they may not be able to have water flowing in if upstream farmers retain water in their fields or let their fields dry out to prepare for harvest. Moreover, a number of technologies to cope with water scarcity require good water control for individual fields (Chapter 3.5). Finally, the water that continuously flows through rice fields may remove valuable (fertilizer) nutrients. Constructing separate channels to convey water to and from each field (or to a small group of fields) greatly improves the individual control of water and is the recommended practice in any type of irrigation system.

3.1.2 Land leveling

A well-leveled field is a prerequisite for good crop husbandry. When fields are not level, water may stagnate in depressions, whereas higher parts may become dry. This results in uneven crop emergence and uneven early growth, uneven fertilizer distribution, and maybe extra weed problems. Information on technologies for land leveling can be found at www.knowledgebank.irri.org.

3.1.3 Tillage: reducing soil permeability

Seepage and percolation flows from rice fields are governed by the permeability (hydraulic conductivity) of their soils: their capacity to conduct water downward and sideward (Chapter 1.3). A rice field can be compared to a bathtub: the material of a bathtub is impregnable and it holds water well—however, if you have only one hole (by removing the plug), the water runs out immediately. Rice fields just need a few rat holes or leaky spots and they will rapidly lose water by seepage and percolation.

Large amounts of water can be lost during soaking prior to puddling when large and deep cracks are present that favor rapid "by-pass flow" to below the root zone. Cabangon and Tuong (2000) showed the beneficial effects of additional shallow soil tillage before land soaking to close the cracks: the amount of water used in wet land preparation was reduced from about 350 mm to about 250 mm (Fig. 3.1).

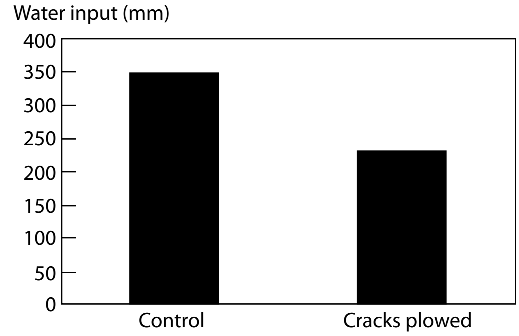


Fig. 3.1. Effect of shallow tillage to fill cracks before soaking on water input during land preparation, Bulacan, Philippines. Data from Cabangon and Tuong (2000).

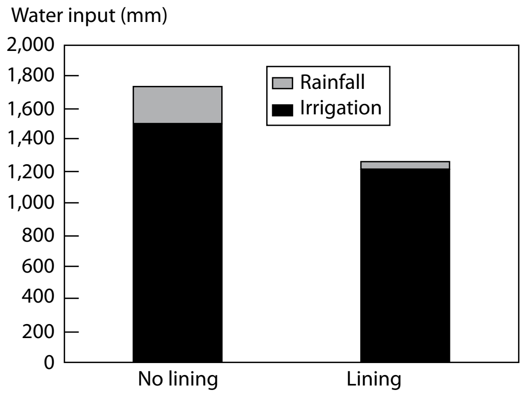


Fig. 3.2. Effect on total water input of lining bunds with plastic in a field experiment at IRRI, Los Baños, Philippines. Data from Bouman et al (2005).

Thorough puddling results in a good compacted plow sole that reduces permeability and percolation rates throughout the crop growing period (Chapter 1.3; De Datta 1981, Tuong et al 1994). The efficacy of puddling in reducing percolation depends greatly on soil properties. Puddling may not be effective in coarse soils, which do not have enough fine clay particles to migrate downward and fill up the cracks and pores in the plow sole. On the other hand, puddling is very efficient in clay soils that form cracks during the fallow period that penetrate the plow pan (Tuong et al 1994). Although puddling reduces percolation rates of the soil, the action of puddling itself consumes water, and there is a trade-off between the amount of water used for puddling and the amount of water "saved" during the crop growth period by reduced percolation rates. Puddling may not be necessary in heavy clay soils with low vertical permeability or limited internal drainage. In such soils, direct dry seeding on land that is not puddled but tilled in a dry state is very well possible with minimal percolation losses (Tabbal et al 2002; Chapter 3.2).

Soil compaction using heavy machinery has been shown to decrease soil permeability in sandy soil with loamy subsoils with at least 5% clay (Harnpichitvitaya et al 2000). Although most farmers cannot afford to compact their soils, this technology may be feasible on a large scale with government support.

3.1.4 Bund preparation and maintenance

Good bunds are a prerequisite to limit seepage and underbund flows (Tuong et al 1994). To limit seepage losses, bunds should be well compacted and any cracks or rat holes should be plastered with mud at the beginning of the crop season. Make bunds high enough (at least 20 cm) to avoid overbund flow during heavy rainfall. Small levees of 5–10-cm height in the bunds can be used to keep ponded water depth at that height. If more water needs to be stored, it is relatively simple to close these levees. Researchers have used plastic sheets in bunds in field experiments to reduce seepage losses. For example, Bouman et al (2005) demonstrated a reduction of 450 mm in total water use in a rice field by lining the bunds with plastic (Fig. 3.2). Although such measures are probably financially not attractive to farmers, the author came upon a farmer in the Mekong Delta in Vietnam who used old plastic sheets to block seepage through very leaky parts of his bunds.

3.2 Crop establishment

Minimizing the turnaround time between land soaking for wet land preparation and transplanting reduces the period when no crop is present and when outflows of water from the field do not contribute to production. Especially in large-scale irrigation systems with plot-to-plot irrigation, water losses during the turnaround time can be very high. For instance, in the largest surface irrigation scheme in Central Luzon, called UPRIIS (Upper Pampanga River Integrated Irrigation System), it took up to 63 days in a contiguous 145-ha block from the first day of water delivery for land preparation until the whole area was completely transplanted (Tabbal et al 2002). The total amount of water input during that time was some 940 mm, of which 110 mm was used for soaking, 225 mm disappeared as surface runoff, 445 mm was lost by seepage and percolation, and 160 mm was lost by evaporation. In UPRIIS, farmers raise seedlings in part of their main field. Because of a lack of tertiary field channels, the whole main field is soaked when the seedbed is prepared and remains flooded during the entire duration of the seedbed. In systems such as UPRIIS, the turnaround time can be minimized by the installation of field channels, the adoption of common seedbeds, or the adoption of direct wet or dry seeding. With field channels, water can be delivered to the individual seedbeds separately and the main field does not need to be flooded. Common seedbeds, either communal or privately managed, can be located strategically close to irrigation canals and be irrigated as one block.

With direct seeding, the crop starts growing and using water from the moment of establishment onward. Direct dry seeding can also increase the effective use of rainfall and reduce irrigation needs as shown for the MUDA irrigation scheme in Malaysia (Cabangon et al 2002). However, dry seeding with subsequent flooding is possible only in heavy (clayey) soils with low permeability and poor internal drainage. A major driving force for the adoption of direct seeding in Asia is scarcity of labor since direct seeding does not use labor for transplanting and can be a mechanized operation.

3.3 Crop growth period

3.3.1 Saturated soil culture

In saturated soil culture (SSC), the soil is kept as close to saturation as possible, thereby reducing the hydraulic head of the ponded water, which decreases the seepage and percolation flows. SSC in practice means that a shallow irrigation is given to obtain about 1 cm of ponded water depth a day or so after the disappearance of ponded water. Tabbal et al (2002) reported water savings under SSC in transplanted and direct wet-seeded rice in puddled soil, and in direct dry-seeded rice in nonpuddled soil (Table 3.1). Analyzing a data set of 31 published field experiments with an SSC treatment, Bouman and Tuong (2001) found that water input decreased on average by 23% (range: 5% to 50%) from the continuously flooded check, with a nonsignificant yield reduction of 6% on average. Thompson (1999) found that SSC in southern New South Wales, Australia, reduced both irrigation water input and yield by a bit more than 10%.

Raised beds can be an effective way to keep the soil around saturation. Rice plants are grown on beds and the water in the furrows is kept close to the surface of the beds. In Australia, Borell et al (1997) experimented with raised beds that were 120 cm wide and separated by furrows of 30-cm width and 15-cm depth to facilitate SSC practices. Compared to flooded rice, water savings were 34% and yield losses 16–34%. More information on raised beds is found in Chapter 3.4.1.

Practical implementation
Although conceptually sound, SSC will be difficult to implement practically since it requires frequent (daily or once every two days) applications of small amounts of irrigation water to just keep a standing water depth of 1 cm on flat land, or to keep furrows filled just to the top in raised beds.

3.3.2 Alternate wetting and drying

In alternate wetting and drying (AWD), irrigation water is applied to obtain flooded conditions after a certain number of days have passed after the disappearance of ponded water. The number of days of nonflooded soil in AWD before irrigation is applied can vary from 1 day to more than 10 days. Though

Table 3.1a. Yield, water input, and water productivity with respect to total water input (WP_{IR}) in transplanted and wet-seeded rice under continuous flooding and SSC, Muñoz, 1991 dry season. Data from Tabbal et al (2002).

Treatment	Transplanted			Wet-seeded		
	Yield (t ha^{-1})	Water input (mm)	WP_{IR} (g grain kg^{-1} water)	Yield (t ha^{-1})	Water input (mm)	WP_{IR} (g grain kg^{-1} water)
Flooded	7.4	694	1.06	7.6	631	1.20
SSC	6.7	373	1.81	7.3	324	2.27

Table 3.1b. Yield, water input, and water productivity with respect to total water input (WP_{IR}) and irrigation (WP_I) in dry-seeded rice under continuous flooding and SSC, San Jose City, Philippines, 1996-97. Data from Tabbal et al (2002).

Treatment		Water input (mm)		Water productivity (g grain kg^{-1} water)	
	Yield (t ha^{-1})	Irrigation + rainfall	Irrigation	WP_{IR}	WP_I
1996					
Flooded	4.3	1,417	531	0.31	8.16
SSC	4.2	1,330	432	0.32	9.65
1997					
Flooded	4.7	1,920	941	0.25	4.99
SSC	4.5	1,269	355	0.36	12.81

Table 3.2. Yield, water use, and water productivity with respect to irrigation and rainfall of rice under alternate wetting and drying (AWD) and continuously flooded conditions. Data from Bouman et al (2006a).

Location	Year	Treatment	Yield (t ha^{-1})	Total water input (mm)	Water productivity (g grain kg^{-1} water)
Guimba, Philippines	1988	Flooded	5.0	2,197	0.23
(Tabbal et al 2002)		AWD	4.0	880	0.46
	1989	Flooded	5.8	1,679	0.35
		AWD	4.3	700	0.61
	1990	Flooded	5.3	2,028	0.26
		AWD	4.2	912	0.46
	1991	Flooded	4.9	3,504	0.14
		AWD	3.3	1,126	0.29
Tuanlin, Huibei, China	1999	Flooded	8.4	965	0.90
(Belder et al 2004)		AWD	8.0	878	0.95
	2000	Flooded	8.1	878	0.92
		AWD	8.4	802	1.07
Muñoz, Philippines,	2001	Flooded	7.2	602	1.20
(Belder et al 2004)		AWD	7.7	518	1.34

some researchers have reported a yield increase using AWD (Wei Zhang and Song 1989, Stoop et al 2002), recent work indicates that this is the exception rather than the rule (Belder et al 2004, Cabangon et al 2004, Tabbal et al 2002; Table 3.2). In 31 field experiments analyzed by Bouman and Tuong (2001), 92% of the AWD treatments resulted in yield reductions varying from just more than 0% to 70% compared with those of the flooded checks. In all these cases, however, AWD increased water productivity (WP_{IR}) with respect to total water input because the reductions in water inputs were larger than the reductions in yield. The large variability in results of AWD in the analyzed data set was caused by differences in the number of days between irrigations and in soil and hydrological conditions.

Experimenting with AWD in lowland rice areas with *heavy soils and shallow groundwater* tables in China and the Philippines, Cabangon et al (2004), Belder et al (2004), Lampayan et al (2005), and Tabbal et al (2002) reported that total (irrigation and rainfall) water inputs decreased by around 15–30% without a significant impact on yield. In all these cases, groundwater depths were very shallow (between 10 and 40 cm), and ponded water depths almost never dropped below the root zone during the drying periods (Fig. 3.3), thus turning AWD effectively into a kind of near-saturated soil culture. Even without ponded water, plant roots still had access to “hidden” water in the root zone (Chapter 1.4). More water can be saved and water productivity further increased by prolonging the

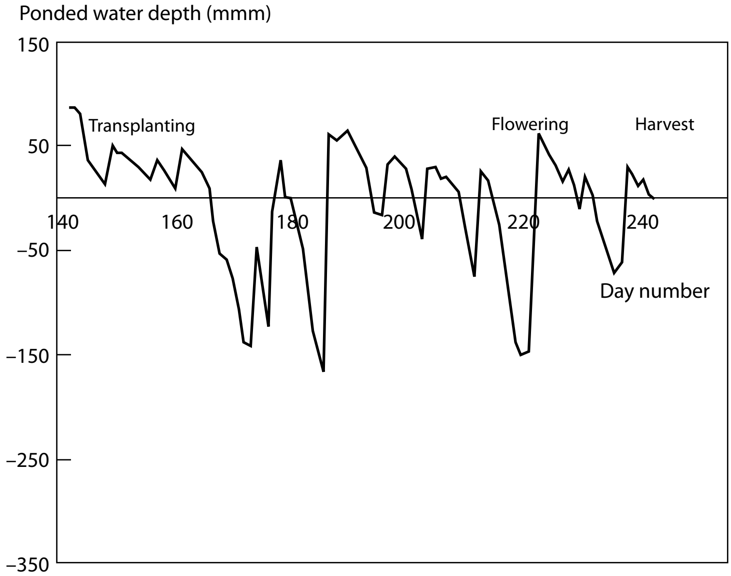


Fig. 3.3. Depth of ponded water on the soil surface (above the horizontal line) and below the soil surface (below the horizontal line) in an AWD experiment, Tuanlin, Hubei, China. Adapted from Belder et al (2004).

periods of dry soil and imposing a slight drought stress on the plants, but this usually comes at the expense of yield loss (Bouman and Tuong 2001). Research in more *loamy and sandy soils with deeper groundwater* tables in India and the Philippines showed reductions in water inputs of more than 50% coupled with yield loss of more than 20% compared with the flooded check (Sharma et al 2002, Singh et al 2002, Tabbal et al 2002).

AWD is a mature technology that has been widely adopted in China (Li and Barker 2004). It is also a recommended practice in northwest India, and is being tested by farmers in the Philippines. Figures 3.4 and 3.5 give an example of yields and water inputs obtained by farmers in Central Luzon, Philippines, who practiced AWD irrigation (Lampayan et al 2005). The farmers used communal deep-well pumps or their own shallow tubewell pumps to irrigate their fields. They divided their fields into two, one with AWD management and the other with continuous flooding. Table 3.3 gives an economic comparison among AWD and continuously flooded fields. The AWD fields had the same yield as continuous flooding, but saved 16–24% in water costs and 20–25% in production costs.

Very little research has been done to quantify the impact of AWD on the different water outflows of rice fields: evaporation, seepage, and percolation. The little work done so far suggests that AWD

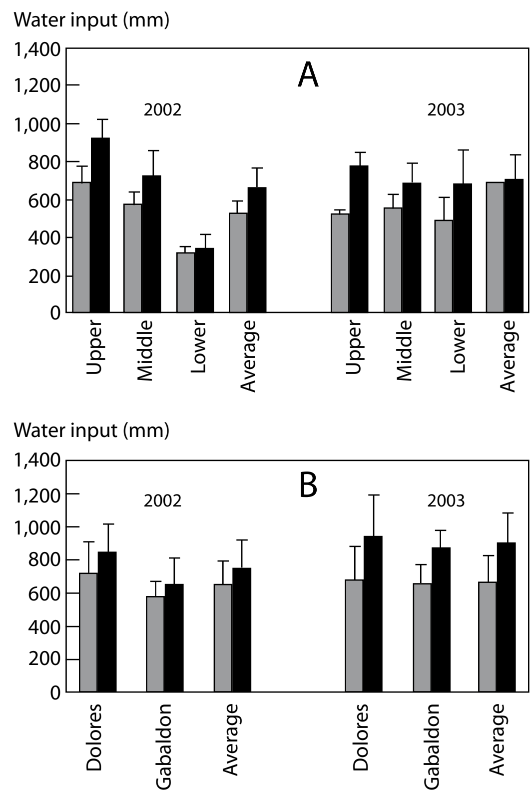
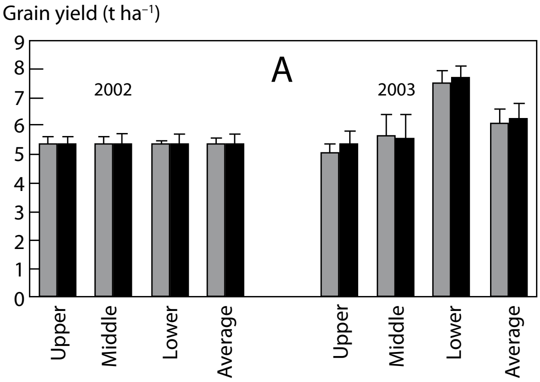


Fig. 3.4. Total water input (mm) under AWD (shaded columns) and continuous flooding (black columns) in farmers' fields in Tarlac (A) and Nueva Ecija (B), Philippines, 2002 and 2003 dry seasons. Data from Lampayan et al (2005).



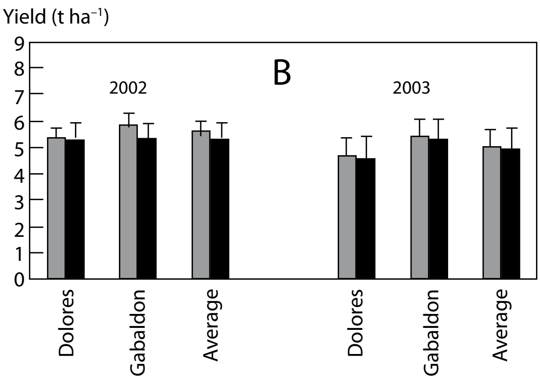


Fig. 3.5 Average yield under AWD (shaded columns) and continuous flooding (black columns) in farmers' fields in Tarlac (A) and Nueva Ecija (B), Philippines, 2002 and 2003 dry seasons. Data from Lampayan et al (2005).

mostly reduces seepage and percolation flows and has only a small effect on evaporation flows. Belder et al (2007) and Cabangon et al (2004) calculated that evaporation losses decreased by 2–33% compared with fully flooded conditions.

The following potential benefits of AWD have been suggested: improved rooting system, reduced lodging (because of a better root system), periodic soil aeration, and better control of some diseases such as golden snail. On the other hand, rats find it easier to attack the crop during dry soil periods.

3.3.3 The System of Rice Intensification

AWD is the water management practice of the System of Rice Intensification (SRI), an integrated crop management technology developed by the Jesuit priest Father Henri de Laulanie in Madagascar (Stoop et al 2002). SRI is characterized by the following practices (Uphoff 2007):

- Transplanting 8- to 12-day-old seedlings very carefully (root tip down)
- Transplanting single seedlings
- Spacing the plants widely apart in a square pattern (25 × 25 cm or wider)
- Controlling weeds by weeding with a rotating hoe, which aerates the soil
- Applying compost to increase the soil's organic matter content (optional)

Table 3.3. Average cost and returns of rice grown under AWD and FP (farmers' practice = continuously flooded) in farmers' fields at three sites in Central Luzon, Philippines, in 2002 and 2003 dry seasons. Data from Lampayan et al (2005).

Item	Tarlac		Nueva Ecija (Gab)		Nueva Ecija (Dol)	
	FP	AWD	FP	AWD	FP	AWD
2002						
Gross returns ($ ha⁻¹)	933	933	1,183	1,292	1,073	1,043
Production cost ($ ha⁻¹)	441	397	1,030	870	597	574
Net profit ($ ha⁻¹)	491	535	152	422	477	469
Net profit-cost ratio	1.1	1.3	0.1	0.5	0.8	0.8
2003						
Gross returns ($ ha⁻¹)	1,134	1,105				
Production cost ($ ha⁻¹)	519	491				
Net profit ($ ha⁻¹)	615	614				
Net profit-cost ratio	1.2	1.2				

Practical implementation of AWD

A practical way to implement AWD is to monitor the water depth in the field using the "field water tube" described in the Appendix (A.1). After an irrigation application, the field water depth will gradually decrease over time. When the water level (as measured in the tube) is 15 cm below the surface of the soil, it is time to irrigate and flood the soil with a depth of around 5 cm. Around flowering, from 1 week before to 1 week after the peak of flowering, ponded water should be kept at 5-cm depth to avoid any water stress that would result in potentially severe yield loss (Chapter 2.2). The threshold of 15 cm is called "Safe AWD" as this will not cause any yield decline since the roots of the rice plants will still be able to take up water from the saturated soil and the perched water in the root zone. The field water tube helps farmers see this "hidden" source of water. In Safe AWD, water savings may be relatively small, on the order of 15%, but there is no yield penalty. After creating confidence that Safe AWD does not reduce yield, farmers may experiment by lowering the threshold level for irrigation to 20 cm, 25 cm, 30 cm, or even deeper. Some yield penalty may be acceptable when the price of water is high or when water is very scarce (Chapters 1.7 and 3.5). Remember that, in many irrigated areas, the groundwater is very shallow and may reach into the field water tube!

In Safe AWD, the following rules should be observed. AWD irrigation can be used from a few days after transplanting (or a 10-cm-tall crop after direct seeding) till first heading. In the period of first heading to 1 week after flowering, keep the field flooded with 5-cm depth. After that, during grain filling and ripening, apply AWD again. When many weeds are present in the early stages of crop growth, the implementation of AWD can be postponed for 2–3 weeks until weeds have been suppressed by the ponded water. Under Safe AWD, no special N management regime is needed and local recommendations as for flooded rice can be used (Belder et al 2004). Apply fertilizer N preferably on the dry soil just before irrigation is applied.

- No continuous flooding during the crop growth period, applying small amounts of water regularly or alternating wet and dry (AWD) field conditions to maintain a mix of aerobic and anaerobic soil conditions. After flowering, a thin layer of water should be kept on the field, although some farmers find alternate wetting and drying of fields throughout the crop cycle to be feasible and even beneficial.

The benefits of SRI are the topic of scientific debate and controversy (Sinclair and Cassman 2004, Surridge 2004). Proponents of SRI claim that SRI farmers are usually able to attain yields of 7–8 t ha^{-1}, while, with proper and sustained use of the SRI method, yields can go beyond 15 t ha^{-1} (Uphoff 2007). A large number of success stories and "testimonies" are reported on the SRI Web site (http://ciifad.cornell.edu/sri/). Independent researchers, however, have not been able to confirm these high yields and success stories (Dobermann 2003, Sheehy et al 2004). When compared with local best-management practices, SRI usually gives similar or even lower yields. In Bangladesh, in an on-station comparison, rice yield with management practices recommended by the Bangladesh Rice Research Institute (BRRI) was significantly higher than under SRI management (Latif et al 2005). In on-farm trials, the BRRI-recommended management performed significantly better than SRI and resulted in higher yield, lower cost, and higher profit. SRI is especially labor-intensive. On average, SRI required 13% more labor than the BRRI practice and 19% more than the farmers' practice. McDonald et al (2006) analyzed 40 site-years of SRI versus local best-management practices (BMP) that included data from Madagascar, Nepal, China, Thailand, Laos, India, Sri Lanka, Indonesia, Bangladesh, and the Philippines. Aside from one set of experiments in Madagascar, they found no evidence of a systematic yield advantage of SRI. None of the 35 experimental records besides the Madagascar cases demonstrated yield increases that exceeded BMP by more than 22%. Excluding the Madagascar cases, the typical SRI outcome was even negative, with 24 of 35 site-years having on average 11% lower yields than BMP. McDonald et al (2006) found no evidence that SRI fundamentally changes the physiological yield potential of rice, and advocated caution in extending SRI beyond its origin of development. Investigating the use of SRI in the original country of development, Madagascar, Moser and Barett (2003) reported a disadoption of the system, partly because of its relatively high labor requirements and the high needs for extension support.

For the purpose of water savings, we recommend the combination of AWD with well-researched and site-specific best management practices (integrated crop management).

3.4 Aerobic rice

A fundamentally different approach to reduce water outflows from rice fields is to grow the crop like an

Table 3.4. Water input (I = irrigation R = rainfall) and yield of two aerobic rice varieties (HD502, HD297) under flooded and aerobic conditions in 2001 and 2002, Beijing, China. Data from Yang Xiaoguang et al (2005).

Year	Water management	Water input (mm)		Yield (t ha^{-1})	
		I	I + R	HD502	HD297
2001	Flooded	1,057	1,351	6.8	5.4
	aerobic	350	644	5.3	4.7
		283	577	4.6	4.3
		292	586	4.3	4.2
		225	519	3.5	3.4
		175	469	3.0	2.5
2002	Flooded	900	1,255	4.6	5.3
	aerobic	522	917	5.7	5.3
		374	769	4.8	4.7
		225	620	4.0	3.9
		300	695	4.3	4.6
		152	547	3.6	2.9

upland crop, such as wheat or maize. Unlike lowland rice, upland crops are grown in nonpuddled, nonsaturated (i.e., “aerobic”) soil without ponded water. When rainfall is insufficient, irrigation is applied to bring the soil water content in the root zone up to field capacity after it has reached a certain lower threshold level, such as halfway between field capacity and wilting point (Doorenbos and Pruit 1984). The amount of irrigation water should match evaporation from the soil and transpiration by the crop (plus any application inefficiency losses). The potential water reductions at the field level when rice can be grown as an upland crop are large, especially on soils with high seepage and percolation rates (Bouman 2001; Chapter 3.5). Besides seepage and percolation losses declining, evaporation decreases since there is no ponded water layer, and the large amount of water used for wet land preparation is eliminated altogether (Chapter 3.1.3).

In Asia, “upland rice” is already grown aerobically with minimal inputs in the upland environment, but mostly as a low-yielding subsistence crop to give stable yields under the adverse environmental conditions of the uplands (Lafitte et al 2002). Upland rice varieties are drought tolerant, but have a low yield potential and tend to lodge under high levels of external inputs such as fertilizer and supplemental irrigation. Alternatively, high-yielding lowland rice varieties grown under aerobic soil conditions, but with supplemental irrigation, have been shown to save water, but at a severe yield penalty (Blackwell et al 1985, Westcott and Vines 1986, McCauley 1990). Achieving high yields under irrigated but aerobic soil conditions requires new varieties of “aerobic rice” that combine the drought-tolerant characteristics of upland varieties with the high-yielding characteristics of lowland varieties (Lafitte et al 2002, Atlin et al 2006).

The development of *temperate* aerobic rice started in the mid-eighties in northern China and Brazil. In China, breeders have produced aerobic rice varieties with an estimated yield potential of 6-7 t ha^{-1} (Wang Huaqi et al 2002). In experiments with Chinese aerobic rice varieties close to Beijing in 2001 and 2002, Yang Xiaoguang et al (2005) and Bouman et al (2006b) obtained aerobic rice yields of 2.5–5.7 t ha^{-1} with only 500–900 mm of total (irrigation plus rainfall) water input (Table 3.4). For comparison, the aerobic varieties yielded 5.4–6.8 t ha^{-1} under flooded lowland conditions, receiving about 1,300 mm of total water input. At the same site, Xue et al (2007) reported yield maxima of 3.6–4.5 t ha^{-1} with 688 mm of total water input in 2003, and 6.0 t ha^{-1} with 705 mm of water input in 2004 (Table 3.5). The relatively high yields of aerobic rice at Beijing were obtained under “harsh” conditions for growing rice. The soil contained more than 80% sand, was permeable, and held water above field capacity for a few hours after irrigation only. The groundwater table was deeper than 20 m, the soil moisture content in the root zone was mostly between 50% and 80% of saturation, and soil moisture tensions went up to 90 kPa (see Fig. 2.3 in Chapter 2.1). In field experiments near

Table 3.5. Water input (I = irrigation, R = rainfall) and yield of aerobic rice variety HD297 under aerobic conditions in 2003 and 2004, Beijing, China. Data from Xue Changying et al (2007).

2003				2004		
Water input (mm)		Yield (t ha^{-1})		Water input (mm)		Yield (t ha^{-1})
I	I + R	Exp 1	Exp 2	I	I + R	
408	688	4.25	3.11	535	705	5.58
408	618	3.70	2.54	535	675	5.35
408	648	2.11	1.26	535	645	5.35
408	578	–	0.46	535	605	4.99

Table 3.6. Performance of aerobic rice grown by farmers around Kaifeng, northern China, in terms of yield and water use, 2002-03. Data from Bouman et al (2007).

Farmer (code letter)	A	B	C	D	E	F	G
Yield (t ha^{-1})	3.8	4.4	3.8	5.1	5.5	4.7	3.4
Irrigation (mm)	225	225	80	231	230	300	225
Rainfall (mm)	337	337	337	337	337	337	337
Total water input (mm)	562	562	417	568	567	637	562
Farmer (code letter)	U	V	W	X	Y	Z	
Yield (t ha^{-1})	1.2	3.8	2.4	3.8	3.6	3.0	
Irrigation (mm)	156	159	145	169	146	162	
Rainfall (mm)	674	674	674	674	674	674	
Total water input (mm)	830	833	819	843	820	836	

Kaifeng in the North China Plain, Feng Liping et al (2007) obtained relatively low yields of 2.4–3.6 t ha^{-1} with 750–1,000 mm of total water input. It is estimated that aerobic rice systems are currently being pioneered by farmers on some 80,000 ha in northern China using supplementary irrigation (Wang Huaqi et al 2002). Bouman et al (2007) reported yields of aerobic rice obtained by farmers around Kaifeng of up to 5.5 t ha^{-1} with sometimes as little as 566 mm of total water input, with only one or two supplementary irrigation applications (Table 3.6). Table 3.7 compares the performance indicators of aerobic rice, lowland rice, and maize obtained by farmers in the same area. Simulation model predictions even suggested that no irrigation would be needed for high yields with some 400–600 mm of rainfall and groundwater tables of 2 m deep and less. In Brazil, a breeding program to improve upland rice has resulted in aerobic varieties with a yield potential of up to 6 t ha^{-1} (Piñheiro et al 2006). Farmers grow these varieties in rotation with crops such as soybean and fodder on large commercial farms with supplemental sprinkler irrigation on an estimated 250,000 ha of flat lands in the Cerrado region, realizing yields of 3–4 t ha^{-1}.

The development of *tropical aerobic rice* is of relatively recent origin. De Datta et al (1973) grew lowland variety IR20 in aerobic soil under furrow irrigation at IRRI in the Philippines. Water savings were 55% compared with flooded conditions, but yield fell from about 8 t ha^{-1} under flooded conditions to 3.4 t ha^{-1} under aerobic conditions. Using improved upland rice varieties, George et al (2002) reported aerobic rice yields of 1.5–7.4 t ha^{-1} in uplands with 2,500 to 4,500 mm of annual rainfall in the Philippines. Yields of 6 t ha^{-1} and more, however, were realized only incidentally in the first years of cultivation, and most yields were in the 2–3 t ha^{-1} range. Atlin et al (2006) reported aerobic rice yields of 3–4 t ha^{-1} using recently developed aerobic

Table 3.7. Average performance of aerobic rice, lowland rice, and maize near Kaifeng, northern China, 2002-03. Unpublished data from China Agricultural University and IRRI.

Item	Lowland rice	Aerobic rice	Maize
Number of farmers, 2002	5	7	3
Field size (ha)	0.12	0.12	0.15
Yield (t ha^{-1})	7.3	4.4	7.5
Irrigation (mm)	1,407	217	77
Rainfall (mm)	337	337	337
Total water (mm)	1,744	553	414
WP_{IR} (g grain kg^{-1} total water)	0.42	0.79	1.81
Input costs ($ ha^{-1})	379	230	140
Production value ($ ha^{-1})	1,097	706	1,071
Net income ($ ha^{-1})	718	487	906
Own labor (d ha^{-1})	116	93	109
Net income (including labor) ($ ha^{-1})	500	312	703
Number of farmers, 2003	2	6	3
Field size (ha)	0.11	0.11	0.56
Yield (t ha^{-1})	3,7	3.0	5.7
Irrigation (mm)	476	156	0
Rainfall (mm)	674	674	674
Total water (mm)	1,149	830	674
WP_{IR} (g grain kg^{-1} total water)	0.32	0.36	0.85
Input costs ($ ha^{-1})	378	261	129
Production value ($ ha^{-1})	643	520	856
Net income ($ ha^{-1})	265	259	727
Own labor (d ha^{-1})	162	75	41
Net income (including labor) ($ ha^{-1})	−34	120	651

rice varieties in farmers' fields in rainfed uplands in the Philippines. Though the amount of rainfall was not reported, the conditions of the trials were described as "well watered." Bouman et al (2005) and Peng et al (2006) quantified yield and water use of the recently released tropical aerobic rice variety Apo under irrigated aerobic and flooded conditions. In the dry season, yields under aerobic conditions were 4–5.7 t ha^{-1} and in the wet season they were 3.5–4.2 t ha^{-1}. These yields were obtained in relatively wet soil with seasonal-average soil moisture tensions in the root zone of 10–12 kPa and with maximum values of around 40 kPa. On average, the mean yield of all varieties was 32% lower under aerobic conditions than under flooded conditions in the dry season and 22% lower in the wet season. Total water input was 1,240–1,880 mm in flooded fields and 790–1,430 mm in aerobic fields. On average, aerobic fields used 190 mm less water in land preparation and had 250–300 mm less seepage and percolation, 80 mm less evaporation, and 25 mm less transpiration than flooded fields. Successful examples of the adoption of aerobic rice by farmers in the tropics are in some rainfed uplands in Batangas Province, Philippines (Atlin et al 2006). In the hilly regions of Yunnan Province, southern China, farmers grow rainfed aerobic rice under intensified management, realizing yields of 3–4 t ha^{-1} (Atlin et al 2006).

Practical implementation

Temperate environment/China. Promising aerobic rice varieties in northern China are HD277, HD297, and HD502. Before sowing, the land should be dry prepared by plowing and harrowing to obtain a smooth seedbed. Seeds should be dry seeded at 1–2-cm depth in heavy (clayey) soils and at 2–3-cm depth in light-textured (loamy) soils. Optimum seeding rates still need to be established but are probably in the 60–80 kg ha^{-1} range. In experiments so far, row spacings between 25 and 35 cm gave similar yields. Sowing of the seeds can be done manually (e.g., dibbling the seeds in slits opened by a stick or a tooth harrow) or using direct-seeding machinery. The total amount of fertilizer N application could probably follow local recommendations for lowland rice aiming at a 4–6 t ha^{-1} yield level. The total amount of N to be applied depends on indigenous soil N supply and other sources of N (such as atmospheric deposition). If no knowledge on local recommendations is available, an amount of 90 kg N ha^{-1} could be a useful starting point (to be subsequently optimized). Instead of basal application of the first N split, the first application can best be applied 10–12 days after emergence to minimize N losses by leaching (the emerging seedlings can't take up N fast, so it will easily leach out). Second and third split applications can be given around maximum tillering and panicle initiation, respectively. With future research, principles of site-specific nutrient management (SSNM) for aerobic rice should be developed. If the crop is grown in a dry season, a light irrigation application (say 30 mm) should be given after sowing to promote emergence. Subsequent irrigation applications should aim to frequently restore the soil water content to field capacity, and depend on the rainfall pattern, the depth of groundwater, and on availability and/or cost of irrigation water. Irrigation can be applied by the same means as used for upland crops: flash flood, furrow, or sprinkler.

Tropical aerobic rice systems for water-short irrigated environments are still in the research and development phase. More research is especially needed to develop high-yielding aerobic rice varieties and sustainable management systems. In the tropical Philippines, the most promising variety so far is Apo, but the breeding of improved varieties is in full swing. In general, the same management practices as for northern China can be followed. However, sustainability seems so far more of a problem in tropical areas than in temperate areas such as northern China. Aerobic rice should not be grown consecutively on the same piece of land, and—depending on the cropping history and soil type—even complete yield failures can occur on fields cropped to aerobic rice the very first time in their history! The main problems to overcome in the development of tropical aerobic rice are listed in Chapter 3.6.

3.4.1 Raised beds

One of the recently proposed innovations to deal with water scarcity in the rice-wheat system in the Indo-Gangetic Plain is the use of raised beds, inspired by the success of the system in high-yielding, irrigated wheat-maize areas in Mexico (Sayre and Hobbs 2004). In the system of raised beds, rice is grown on beds that are separated by furrows through which irrigation water is coursed. In irrigation engineering terms, the system of raised beds is comparable with "furrow irrigation." Irrigation is intermittent and the soil of the beds is dominantly in aerobic conditions; hence, the system can be considered an aerobic rice system (this is different from the use of beds in heavy soils to maintain saturated soil conditions, Chapter 3.3.1). In general, furrow irrigation is more water efficient than flash-flooding (depending on soil type, field dimensions, and slope of the land), and furrow irrigation should hold promise for aerobic rice. Though dimensions may vary, beds are usually around 35 cm wide, separated by furrows that are 30 cm wide and 25 cm deep. Rice can be transplanted or direct-seeded on the beds. So far, the raised-bed system has mostly been tested with current lowland rice varieties, and yield gains can be expected when suitable aerobic varieties are developed/used. Tractor-pulled equipment has been developed that shapes the beds and drills seed (sometimes together with fertilizers) in one operation.

Among the suggested benefits of raised beds are improved water-use and nutrient-use efficiency, improved water management, higher yields, and—when the operations are mechanized—reduced labor requirements and improved seeding and weeding practices (Connor et al 2003, Hobbs and Gupta 2003). Balasubramanian et al (2003) and Hobbs and Gupta (2003) reported initial results of on-station trials and farmer participatory evaluation of rice on beds in the rice-wheat belt in India. Yield of rice transplanted or direct-seeded on beds was plus/minus 5–6% of that of puddled transplanted rice, while irrigation water savings averaged about 37–40%. In a recent review, however, Kukal et al

(2006) reported that "*the performance of rice on beds in NW India has been variable, but generally disappointing to date. Even with similar irrigation scheduling, yields on permanent beds are generally 20–40% lower than puddled transplanted rice, with serious problems of iron deficiency, weeds, accurate sowing depth, and sometimes nematodes. Strategies for overcoming these problems are urgently needed, including breeding and selection for rice grown in aerobic soil and for the wide row spacing between adjacent beds. There are many reports of substantial irrigation water savings with rice on beds compared with continuously flooded puddled transplanted rice. However, some studies suggest that where similar irrigation scheduling is used, irrigation water use of transplanted rice on beds and puddled flats is similar, or even higher on the beds due to higher percolation rates in the nonpuddled furrows and longer duration of direct-seeded rice.*"

Choudhury et al (2007) compared the yield, water input (rainfall, irrigation), and water productivity of dry-seeded rice on raised beds and flat land with that of flooded transplanted and wet-seeded rice, and analyzed the effects of beds on the subsequent wheat crop. Their experiments were conducted in 2001-03 at New Delhi, India. The yields varied from 3.2 t ha^{-1} (flat land and raised beds) to 5.5 t ha^{-1} (flooded transplanted). Yields on raised beds that were kept around field capacity were 32–42% lower than under flooded transplanted conditions, and 21% lower than under flooded wet-seeded conditions. Total water input varied from 930 mm on raised beds to 1,600 mm in the flooded transplanted fields. Total water input in rice on raised beds was 38–42% lower than in flooded transplanted rice, and 32–37% lower than in flooded wet-seeded rice. However, the reduced water inputs in raised beds were also realized with dry seeding on flat land with the same water management. Reduced water inputs and yield reductions balanced each other so that water productivity was comparable among most treatments. It should be noted that this study was done in small plots (compared with farmers' fields), where edge effects (seepage losses under and adjacent to the bunds) can dominate the water balance.

A distinction needs to be made between "permanent beds" and "fresh beds." Permanent beds are constructed once and reshaped only afterward with subsequent cropping. They are used in crop rotations (rice-nonrice crops) and have advantages in terms of cost savings, timeliness of planting, and opportunities for rapid crop diversification in response to market options. The raised beds can especially benefit the nonrice crop in heavy waterlogged soils because of improved drainage (removal of water through the furrows; beds remain relatively dry). However, just like with aerobic rice on flat land (Chapter 3.6), yield of both transplanted and direct-seeded rice has been noted to decline under continuous cropping on permanent raised beds (E. Humphreys, personal communication).

Practical implementation

Growing rice on raised beds shows promise but is still in its infancy of development (Humphreys et al 2005, Kukal et al 2006). In the Indo-Gangetic Plain, farmers are experimenting with raised beds for rice and other crops with different degrees of success. More information on raised beds can be obtained from the Rice-Wheat Consortium (www.rwc.cgiar.org/index.asp). Problems to overcome are listed in Chapter 3.6.

3.4.2 Conservation agriculture

With aerobic rice, technologies of conservation agriculture, such as mulching and zero- or minimum tillage as practiced in upland crops, become available to rice farmers as well (Hobbs and Gupta 2003). Various methods of mulching (e.g., using dry soil, straw, and plastic sheets) are being experimented with in nonflooded rice systems in China and have been shown to reduce evaporation as well as percolation losses while maintaining high yields (Dittert et al 2002). In hilly areas in Shiyan, Hubei Province, in China, farmers are adopting the use of plastic sheets to cover rice fields in which the soil is kept just below saturation. The local government subsidizes and actively promotes this use of plastic sheets, and, in 2006, there were an estimated 6,000 ha of farmer adopters. The proclaimed advantages are earlier crop establishment by 3 weeks (rice is established in early spring when temperatures are still low, and the plastic sheets increase the soil temperature), higher yields, less weed growth, and less water use (important during dry spells). However, little research has been done to verify these benefits. The leftover plastic after harvest may cause environmental degradation if not properly taken care of.

Practical implementation
Specific information on minimum tillage and conservation agriculture technologies for rice can be obtained from the Rice-Wheat Consortium (www.rwc.cgiar.org/index.asp).

3.5 What option where?

The relative "attractiveness" of the above technologies for farmers to respond to water scarcity depends on the type and level of water scarcity (Chapter 1.7), on the irrigation infrastructure (or the level of control that a farmer has over the irrigation water), and on the socioeconomics of their production environment.

With absolute, or physical, water scarcity, farmers have little choice but to adapt to receiving less water than they would need to keep their fields continuously flooded. Figure 3.6 presents a gradient in relative water availability and some appropriate response options. On the far right-hand side of the (horizontal) water axis, water is amply available and farmers can practice continuous flooding of lowland rice and obtain the highest yields. On the far left-hand side, water is extremely short, such as in rainfed uplands, and yields are very low. Going from right to left along the water-availability axis, water gets increasingly scarce and yields will decline.

Even with sufficient water available, good land leveling, bund maintenance, construction of field channels, and thorough puddling (in the case of puddled systems) will contribute to good crop growth and high yields. "Getting the basics right" is something that all farmers can do, no matter whether they operate in large- or small-scale irrigation systems or whether they use their own sources of irrigation (such as tubewells) or shared sources. After crop establishment, continuous ponding of water generally provides the best growth environment for rice and will result in the highest yields. After transplanting, water levels should be around 3 cm initially, and gradually increase to 5–10 cm with increasing plant height. With direct wet seeding, the soil should be kept just at saturation from sowing to some 10 days after emergence, and then the depth of ponded water should gradually increase with increasing plant height. With direct dry seeding, the soil should be moist but not saturated from sowing till emergence, or else the seeds may rot in the soil. After sowing, apply a flush irrigation if there is no rainfall to wet the soil. Saturate the soil when plants have developed three leaves, and gradually increase the depth of ponded water with increasing plant height. In special problem soils, introducing some form of alternate wetting and drying (AWD)

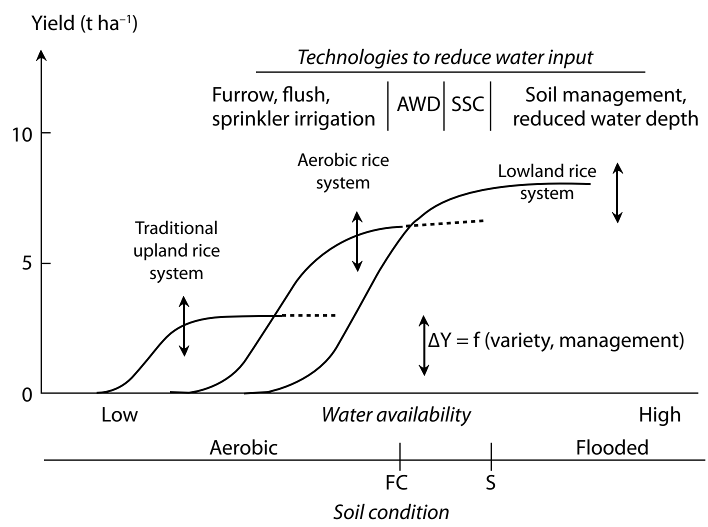


Fig. 3.6. Schematic presentation of yield responses to water availability and soil condition in different rice production systems and their respective technologies to reduce water inputs. AWD = alternate wetting and drying, SSC = saturated soil culture, FC = field capacity, S = saturation point, ΔY = change in yield. Adapted from Tuong et al (2005).

or increasing the internal drainage rate may improve crop growth and yield (Ramasamy et al 1997). The underlying reason may be improved soil aeration or the removal of toxic substances.

The first response option to decreasing water availability would be to check "the basics." The amount of water loss that can be reduced depends on the initial condition of the rice field; if the basics are right from the start, there is not much that can be done any more. With progressing water scarcity, establishment options alternative to transplanting can be considered if the turnaround time between soaking and transplanting is relatively large, such as in some large-scale irrigation systems. If community seedbeds or a commercial provider of seedlings could be organized, this would be the least water-consuming method of getting a crop established. Seedlings could get transplanted a few days after land soaking and puddling only, while the large-scale raising of seedlings would ensure an efficient use of water during that period (main fields do not yet have to be soaked). Both direct wet and direct dry seeding are alternative options. Dry seeding will be effective only in relatively clayey and impermeable soils that don't need puddling to reduce the permeability any more.

With further increasing water scarcity, water management practices during the whole growing season need to be considered. Instead of keeping a 5–10-cm depth of ponded water during the growing season, the depth can be reduced to around 3 cm. This will reduce the hydrostatic pressure and minimize seepage and percolation losses. In saturated soil culture (SSC), the depth of ponded water is reduced to 0–1 cm. Around flowering, from 1 week before to 1 week after the peak of flowering, ponded water should best be kept at 5-cm depth to avoid any possible water stress that could result in severe yield loss. The practice of SSC would require frequent (once in 2 days) applications of small amounts of irrigation water, and hence require a high level of control over irrigation water. The practice of safe AWD can reduce water losses by a small to considerable amount without a yield penalty. To what extent water losses can be reduced under SSC or AWD depends mainly on soil type and depth of the groundwater table: with a heavy clay soil and shallow groundwater (10–40 cm deep), water losses are small to start with and reductions in water losses are equally small. With more loamy or sandy soils and/or deeper groundwater tables, reductions in water losses can be higher, but the risk of a reduction in yield also becomes higher. If water is getting so scarce that "safe AWD" is no longer possible, the periods between irrigation will have to become longer (letting the water in the field water tubes go deeper than 15 cm) and yield loss becomes inevitable. All forms of AWD require water control by the farmer. With own water sources, such as tubewells, this is not a problem. In community-based or large-scale irrigation systems, a communal approach to AWD is required in which delivery of water to groups of farmers is scheduled to realize a certain pattern of AWD. Irrigation system upgrading or modernization may be required to do this, or small storage facilities (such as on-farm reservoirs) may provide the required water control (Chapter 5).

With still further increasing water scarcity, yield of lowland rice under AWD will continue to go down. At a certain point, aerobic rice systems become a viable alternative. How much less water is used under aerobic conditions than under flooded conditions depends mostly on the seepage and percolation (SP) losses under flooded conditions and on the deep percolation losses of irrigation water under aerobic conditions. Typical SP rates of flooded rice fields are given in Table 1.1 in Chapter 1.3. Under aerobic conditions, the amount of deep percolation depends on the combination of soil water-holding capacity and method of irrigation, and is reflected in the irrigation application efficiency (EA). With a precise dosage and timing of irrigation in relation to crop transpiration and soil water-holding capacity, the EA in flash-flood irrigation can be up to 60% (Doorenbos and Pruit 1984). If furrow irrigation (or raised beds) is used, the EA can go up to 70%, and with sprinkler irrigation up to 80% or more. Assuming an average growth duration of 100 days, and mean ET values for rice, we can roughly calculate the "break-even" point for SP rates in flooded fields that would result in similar water requirements in aerobic fields with different irrigation methods (Table 3.8). When the SP rate in flooded rice is 3.5 mm d^{-1} or higher, aerobic systems with flash-flood irrigation will require less water, and, if the SP rate is 0.5 mm d^{-1} or lower, only aerobic systems with sprinkler irrigation require less water. When aerobic rice systems are direct (dry) seeded, as is the typical target technology, an additional amount of water input can be saved by forgoing the wet land preparation. An example of the cross-over point in terms of water availability where aerobic rice gives

Table 3.8. Comparison of water use in a hypothetical aerobic rice crop with that of lowland rice on different soil types characterized by their seepage (S) and percolation (P) rates.

Water flow process	Aerobic rice (mm)		Lowland rice (mm)		
Lowland soil SP rate	–	–	1 mm d^{-1}	5 mm d^{-1}	15 mm d^{-1}
Irrigation efficiency	85%	60%	–	–	–
Evaporation	100	100	200	200	200
Transpiration	400	400	400	400	400
Seepage and percolation	–	–	100	500	1,500
Irrigation inefficiency loss	90	335	–	–	–
Total	590	835	700	1,100	2,100

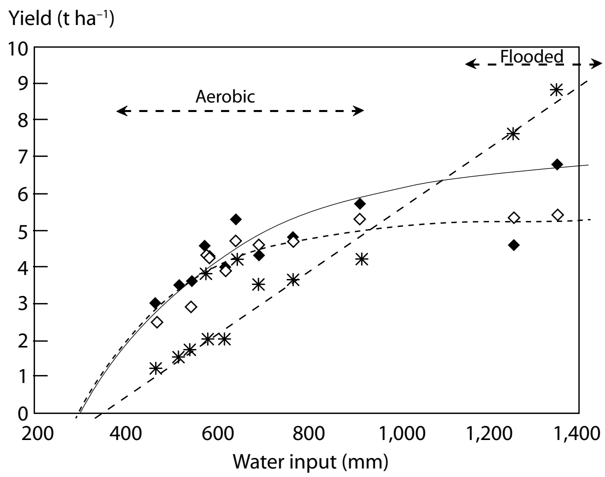


Fig. 3.7. Yield of aerobic rice varieties HD297 (◇) and HD502 (◆) and lowland rice variety JD305 (✳) at different levels of water input. Data from Yang Xiaoguang et al (2005).

higher yields than flooded lowland rice is given in Figure 3.7 for field experiments at Beijing in China (Yang Xiaoguang et al 2005). Two aerobic rice varieties (HD297 and HD502) and one lowland rice variety (JD305) were grown under flooded conditions and under aerobic soil conditions with different amounts of total water input. Under flooded conditions with 1,300–1,400 mm of water input to the right-hand side of the horizontal (water) axis, lowland variety JD305 gave the highest yields of 8–9 t ha^{-1}. The yield of JD305, however, quickly declined with increasing water shortage and aerobic soil conditions. With less than 1,100 mm of water input, and under aerobic soil conditions, aerobic rice varieties HD297 and HD502 outperformed the lowland variety.

When water is physically available, but has a high cost, the choice of adopting any of the water-saving technologies becomes more of an economic issue. Adopting certain water-saving technologies may reduce water but at the expense of yield loss. If the financial savings incurred by using less irrigation water under a certain technology outweigh the financial loss of reduced yield, then the adoption of that technology becomes attractive. Figure 3.8 gives so-called “water-response curves” obtained from two different field experiments in India where different forms of AWD were implemented (different intervals between irrigations). The experiment of the lower curve was done in Cuttack, Orissa (Jha et al 1981). The climatic yield potential was relatively low since the experiment was performed

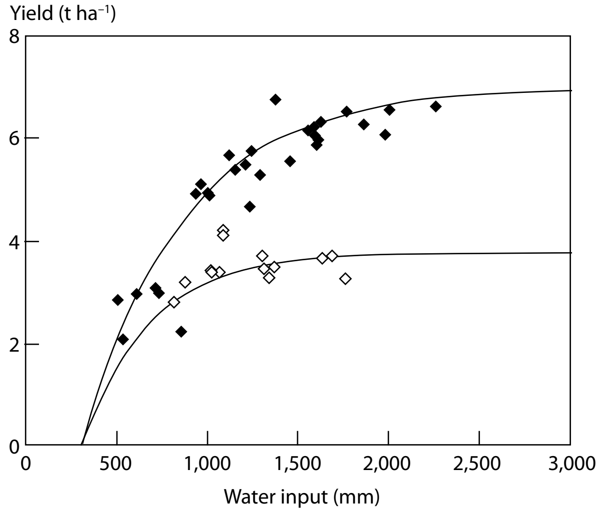


Fig. 3.8. Yield versus water input in two experiments in India. Top curve data (◆) are from Pantnagar, Uttar Pradesh (Tripathi et al 1986), and bottom curve data (◇) are from Cuttack, Orissa (Jha et al 1981). The curved lines are fitted production functions of the shape [yield = a*(1 – $e^{(b*(\text{water input} - c))}$)]. Adapted from Bouman and Tuong (2001).

in the winter season (low radiation levels). Fertilizer application was only 80 kg N ha^{-1} and zero P and K. The soil SP rate was about 21 mm d^{-1}. The experiment of the top curve was done in Pantnagar, Uttar Pradesh (Tripathi et al 1986). The climatic yield potential was higher because the experiment was done in the summer (high radiation levels). To realize the higher yield potential, fertilizer applications were also higher: 120 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 40 kg K_2O ha^{-1}. The soil SP rate was 9–14 mm d^{-1}. Going from right to left on the horizontal axis, water use decreased with adopting increasing intervals between irrigations in AWD. Yields were initially not affected, but, after a certain point, yields declined with less water use. This happened somewhere below 1,750 mm for the top curve and somewhere below 1,000 mm for the bottom curve. This example illustrates the site-specificity of results of AWD. Farmers will decide on the type/severity of AWD to adopt based on the site-specific financial trade-off between yield decline and water savings.

3.6 Sustainability

While relatively much work has been done on the development of technologies to maintain crop productivity under water scarcity, little research has been done on their long-term sustainability and environmental impacts. Given assured water supply, lowland rice fields are extremely sustainable and able to produce continuously high yields, even under continuous double or triple cropping each year (Dawe et al 2000). Flooding of rice fields has beneficial effects on soil acidity (pH); soil organic matter buildup; phosphorus, iron, and zinc availability; and biological N fixation that supplies the crop with additional N (Kirk 2004). When fields cannot be continuously flooded any more because of water scarcity, these beneficial effects gradually disappear. A change to more aerobic soil conditions (such as in AWD and aerobic rice) will negatively affect the soil pH in some situations and decrease the availability of phosphorus, iron, and zinc. Under the "safe AWD" practice (Chapter 3.3.2), these problems do not occur, but, when more severe forms of AWD are implemented, they may start to occur. Under fully aerobic conditions, whether on flat land or on raised beds, problems with micronutrient deficiencies have been reported by Choudhury et al (2007), Sharma et al (2002), Singh et al (2002), and Tao Hongbin et al. (2006). The introduction of aerobic phases in rice fields may also decrease the soil organic carbon content. In a long-term experiment at IRRI, where a continuous rice system is compared with a maize-rice system, 12 years of maize-rice cropping caused a 15% decline in soil organic C and indigenous N supply relative to

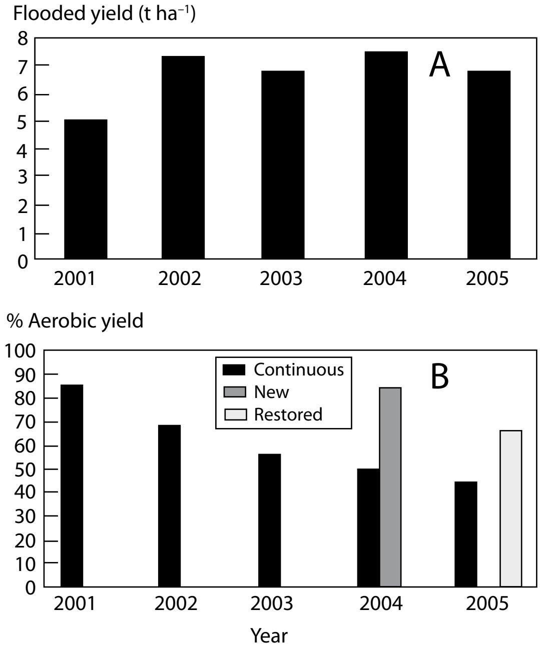


Fig. 3.9. Yield of aerobic rice variety Apo under flooded conditions (A) and relative yield of Apo under aerobic conditions (as % of the Apo yield under flooded conditions) (B). In B, the black columns indicate continuous aerobic conditions, the darkly shaded column indicates yield under new aerobic conditions after conversion of flooded fields, and the lightly shaded column indicates yield under restored aerobic conditions after 1 year of fallow or flooded conditions (average is given). Data from Bouman et al (2006a).

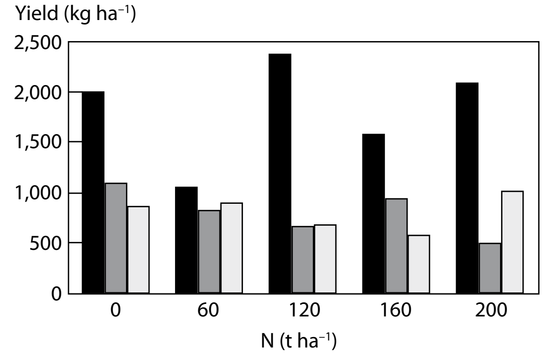


Fig. 3.10. Yield of aerobic rice variety Apo under aerobic soil conditions at IRRI in 2004, at four levels of fertilizer N supply, and under three levels of water input (black column = 1,147 mm, darkly shaded column = 772 mm, and lightly shaded column = 632 mm). Unpublished data, IRRI.

flooded rice-rice cropping (Roland Buresh, personal communication).

There are indications that soil-borne pests and diseases such as nematodes, root aphids, and fungi occur more in nonflooded rice systems than in flooded rice systems (Sharma et al 2002, Singh et al 2002, Ventura and Watanabe 1978, Ventura et al 1981). Current experience is that under fully aerobic soil conditions, rice cannot be grown continuously on the same piece of land each year (as can be successfully done with flooded rice) without a yield decline (George et al 2002). Figure 3.9 presents recent data from a continuous aerobic rice cropping experiment at IRRI (Bouman et al 2005, Peng et al 2006). Since 2001, aerobic rice variety Apo has been continuously grown under flooded and aerobic conditions in the same field. Flooded yields in the dry season are usually 6.5–7 t ha^{-1}, except in 2001, when diseases depressed yields. In 2001, yield under aerobic conditions was 86% of that under flooded conditions, but this gradually declined until it was only 45% in 2005. In 2003, half of the flooded fields were converted to aerobic conditions, and aerobic yields returned to 85% of the flooded yields, as in the first year, 2001. In 2004, half of the continuous aerobic fields were left fallow or were flooded for the whole year, and returned to aerobic conditions in 2005. This "restoration" attempt brought aerobic yields back to 65% of flooded yields, and was only partially successful. The mechanisms behind the gradual yield decline and the restoration effect are not yet understood, although high levels of the nematode *Melodoigyne graminicola* are found in the aerobic rice fields (up to 3,000 counts g^{-1} fresh root) compared with the flooded fields (6–400 counts g^{-1} fresh root; unpublished data).

In some field experiments and farmers' fields, nearly complete yield failure has been observed in fields where aerobic rice was established the very first year (Fig. 3.10). Usually, such fields had a light soil texture and a history of being partially cropped to upland crops or to rice under nonflooded conditions before aerobic rice got established. Always, nematodes were found when yield failures were observed, sometimes aggravated by the presence of root aphids, fungi, and/or nutrient disorders. Crop rotation is necessary under such conditions, and breeders are trying to develop aerobic rice varieties with tolerance of these soil sicknesses.

4

Ecosystem services and the environment

4.1 Ecosystem services

Although the main function of rice fields is to produce rice, they also provide a range of other "ecosystem services" (also referred to as "multi-functionality") (Bouman et al 2006a). Ecosystem services can be grouped into the following categories (Millennium Ecosystem Assessment 2005):

- Provisioning (e.g., fresh water and commodities such as food, wood, timber, and fuel)
- Regulating (e.g., water purification, and climate and flood regulating)
- Supporting (e.g., nutrient cycling, soil formation, primary production)
- Cultural (e.g., aesthetic, spiritual, educational, recreational)

The most important *provisioning function* of rice environments is, of course, the production of rice. Examples of other provisioning services are the raising of fish and ducks in rice fields, ponds, or canals. Frogs and snails are collected for consumption in some countries.

As part of *regulating services*, bunded rice fields may increase the water storage capacity of catchments and river basins, lower the peak flow of rivers, and increase groundwater flow. For example, in 1999 and 2000, 20% of the floodwater in the lower Mekong River Basin was estimated to be temporarily stored in upstream rice fields (Masumoto 2004). Other possible regulatory services of bunded rice fields and terraces include the prevention or mitigation of land subsidence, soil erosion, and landslides (PAWEES 2005). Percolating water from rice fields, canals, and storage reservoirs recharges groundwater systems (Mitsuno 1982). The moderation of air temperature by rice fields has been recognized as an important function in peri-urban areas where rice fields and urban land are intermingled (Oue 1994). This function is attributed to relatively high evapotranspiration rates resulting in reduced ambient temperature of the surrounding area in summer, and in lateral heat emission from the water body in winter. Rice can be used as a desalinization crop because the continuously percolating water (Chapter 1.3) leaches salts from the topsoil (Bhumbla and Abrol 1978). The leachate should be removed by a good drainage system, or else there is risk for increased salinization of the groundwater. Rice soils that are flooded for long periods of the year contribute to the mitigation of the greenhouse effect by taking CO_2 from the atmosphere and sequestering the carbon (C) (Bronson 1997a, Dobermann 2003).

As a *supporting service*, flooded rice fields and irrigation channels form a comprehensive water network, which, together with the contiguous dry land, provides a complex mosaic of landscapes. Irrigated rice land has been classified as human-made wetlands by the Ramsar Convention on Wetlands (Ramsar 2004). Surveys show that such landscapes sustain a rich biodiversity, including unique as well as threatened species, and also enhance biodiversity in urban and peri-urban areas (Fernando et al 2005).

The *cultural services* of rice fields are especially valued in Asian countries where, for centuries, rice has been the main staple food and the single most important source of employment and income for rural people. Many old kingdoms as well as small communities have been founded on the construction of irrigation facilities to stabilize rice production. Rice affects daily life in many ways and the social concept of *rice culture* gives meaning to rice beyond its role as an item of production and consumption (Hamilton 2003). Many traditional festivals and religious practices are associated with rice cultivation and rice fields are valued for their scenic beauty.

4.2 Environmental impacts

The production of lowland rice affects the environment in negative ways, such as the emission of greenhouse gases and water pollution. In this section, environmental impacts that have a relationship with water and the hydrology of rice fields are summarized.

4.2.1 Ammonia volatilization

Ammonia (NH_3) volatilization from urea fertilizer is the major pathway of N loss in tropical flooded rice fields, often causing losses of 50% or more of the applied urea-N (Buresh and De Datta 1990). Ammonia-N emissions from lowland rice fields are estimated to be roughly 3.6 Tg per year (compared with a total of 9 Tg y^{-1} emitted from all agricultural fields), which is some 5–8% of the estimated 45–75 Tg of globally emitted ammonia-N per year (Kirk 2004). The magnitude of ammonia volatilization largely depends on climatic conditions, field water status, and the method of N fertilizer application. Volatilized ammonium can be deposited on the earth by rain, which can lead to soil acidification (Kirk 2004) and unintended N inputs into natural ecosystems.

4.2.2 Greenhouse gases

Irrigated rice systems are a significant sink for atmospheric CO_2 (Chapter 4.1), a significant source of methane (CH_4), and a small source of nitrous oxide (N_2O). In the early 1980s, it was estimated that lowland rice fields emitted some 50–100 Tg of methane per year, or about 10–20% of the then estimated global methane emissions (Kirk 2004). Recent measurements, however, show that many rice fields emit substantially less than those investigated in the early 1980s, especially in northern India and China. Also, methane emissions have actually decreased since the early 1980s because of changes in crop management such as a decreased use of organic inputs (Van der Gon et al 2000). Current estimates of annual methane emissions from rice fields are in the range of 20 to 60 Tg, being 5–10% of total global emissions of about 600 Tg (Kirk 2004). The magnitude of methane emissions from rice fields is mainly determined by water regime and organic inputs, and to a lesser extent by soil type, weather, tillage, residue management, fertilizer use, and rice cultivar (Bronson et al 1997a,b, Wassmann et al 2000). Flooding of the soil is a prerequisite for sustained emissions of methane. Mid-season drainage, a common irrigation practice adopted in major rice-growing regions in China and Japan, greatly reduces methane emissions. Similarly, rice environments with an uneven supply of water (for example, those suffering from water scarcity, Chapter 1.7) have a lower emission potential than fully irrigated rice.

Few accurate assessments have been made of emissions of nitrous oxide from rice fields (Abao et al 2000, Bronson et al 1997a,b, Dittert et al 2002), and the contribution to global emissions has not yet been assessed. In irrigated rice systems with good water control, nitrous oxide emissions are quite small except when excessively high fertilizer-N rates are applied. In irrigated rice fields, nitrous oxide emissions mainly occur during fallow periods and immediately after flooding of the soil at the end of the fallow period.

4.2.3 Water pollution

Changes in water quality associated with rice production may be positive or negative, depending mainly on management practices such as fertilization and biocide (all chemicals used for crop protection, such as herbicides, pesticides, fungicides, etc.) use. The quality of the water leaving rice fields may be improved as a result of the capacity of the rice fields to remove nitrogen and phosphorus (Feng et al 2004, Ikeda and Watanabe 2002). On the other hand, nitrogen transfer from flooded rice fields by direct flow of dissolved nitrogen through runoff warrants more attention. High nitrogen pollution of surface fresh waters can be found in rice-growing regions where fertilizer rates are excessively high, such as in Jiangsu Province in China (Cui et al 2000).

Contamination of groundwater may arise from the leaching of nitrate or biocides and their residues (Bouman et al 2002). Nitrate leaching from flooded rice fields is quite negligible because of rapid denitrification under anaerobic conditions (Buresh and De Datta 1990). For example, in the Philippines, nitrate pollution of groundwater under rice-based cropping systems surpassed the 10 mg L^{-1} limit for safe drinking water only when highly fertilized vegetables were included in the cropping system (Bouman et al 2002). In traditional rice systems, relatively few herbicides are used as puddling, transplanting, and the ponding of water are effective weed control measures. Mean biocide use in irrigated rice varies from some 0.4 kg active ingredients (a.i.) ha^{-1} in Tamil Nadu, India, to 3.8 kg a.i. ha^{-1} in Zhejiang Province, China (Bouman at al 2002). In the warm and humid conditions of the tropics, volatilization is a major process of biocide loss, especially when biocides are applied on the surface of water or on wet soil (Sethunathan and Siddaramappa 1978). The relatively high temperatures further favor rapid transformation of the remaining biocides by (photo)chemical and microbial degradation, but little is known about the toxicity of the residues. In case studies in the Philippines, mean biocide concentrations in groundwater underneath irrigated rice-based cropping systems were one to two orders of magnitude below the single (0.1 μg L^{-1}) and multiple (0.5 μg L^{-1}) biocide limits for safe drinking water, although temporary peak concentrations of 1.14–4.17 μg L^{-1} were measured (Bouman et al 2002). As for nitrogen, however, biocides and their residues may be directly transferred to open water bodies through drainage water flowing overland out of rice fields. The potential for water pollution by biocides is greatly affected by field water management. Different water regimes result in different pest and weed populations and densities, which farmers may combat with different amounts and types of biocides. Residual biocides interact differently with soil under different water regimes (Sethunathan and Siddaramappa 1978).

4.3 Effects of water scarcity

Water scarcity affects not only the ability of rice fields to produce food but also the environment and the other ecosystem services of rice fields. Increasing water scarcity is expected to shift rice production to more water-abundant delta areas, and to lead to less flooded conditions in rice fields and to the introduction of upland crops that do not require flooding. These changes will have environmental consequences and will affect the traditional ecosystem services of the rice landscape.

Rice that is not permanently flooded tends to have more weed growth and a broader weed spectrum than rice that is permanently flooded (Mortimer and Hill 1999). It is expected that water shortages will lead to more frequent use of herbicides, which may increase the environmental load of herbicide residues. With less water, the numbers and types of pests and predators (e.g., spiders) may change as well as predator-pest relationships. The possible shift in the use of pesticides by farmers in response to these changes, and what this means for the environment, is as yet unknown. More leaching of nitrate is expected with increased soil aeration (either with growing rice under nonflooded conditions, or with the shift to upland crops) than under flooded conditions. Less methane emissions are expected under aerobic conditions than under flooded conditions, but higher nitrous oxide emissions are expected (Bronson et al 1997a,b). However, the relative emissions of these greenhouse gases vary with environment and management practices (Dittert et al 2002). Flooded rice is effective in leaching accumulated salts from the soil profile, and the change to more aerobic conditions may result in increased salinization.

There is little information on how water scarcity will affect the ecosystem services of rice lands listed in Chapter 4.1. There is a growing recognition throughout the rice-growing world that a better understanding of the ecosystem services of the rice environment is needed. Although some methodologies exist to measure and estimate different services of agricultural systems, quantifying and valuing the positive and negative externalities still presents a major challenge. In many countries, relevant data at the appropriate geographic level are not available.

Irrigation systems

5

5.1 Water flows in irrigation systems

Irrigated rice fields are characterized by large volumes of outflows by surface drainage, seepage, and percolation (Chapter 1.3). Although these outflows are losses from an individual field, there is great scope for reuse of these flows within a landscape that consists of many interconnected fields (Fig. 5.1). Surface drainage and seepage water usually flow into downstream fields and the loss of one field is the gain of another. At the bottom of a toposequence, these flows enter drains or ditches. However, farmers can use small pumps to lift water from drains to irrigate fields that are inadequately, or not, serviced by irrigation canals. In many irrigation systems in low-lying deltas or flood plains with impeded drainage, the continuous percolation of water (from fields, but also from canals) has created shallow groundwater tables close to the surface that may directly provide the rice crop with water (Chapter 1.4). Again, farmers can either directly pump water up from the shallow groundwater or pump groundwater when it becomes surface water as it flows into creeks or drains.

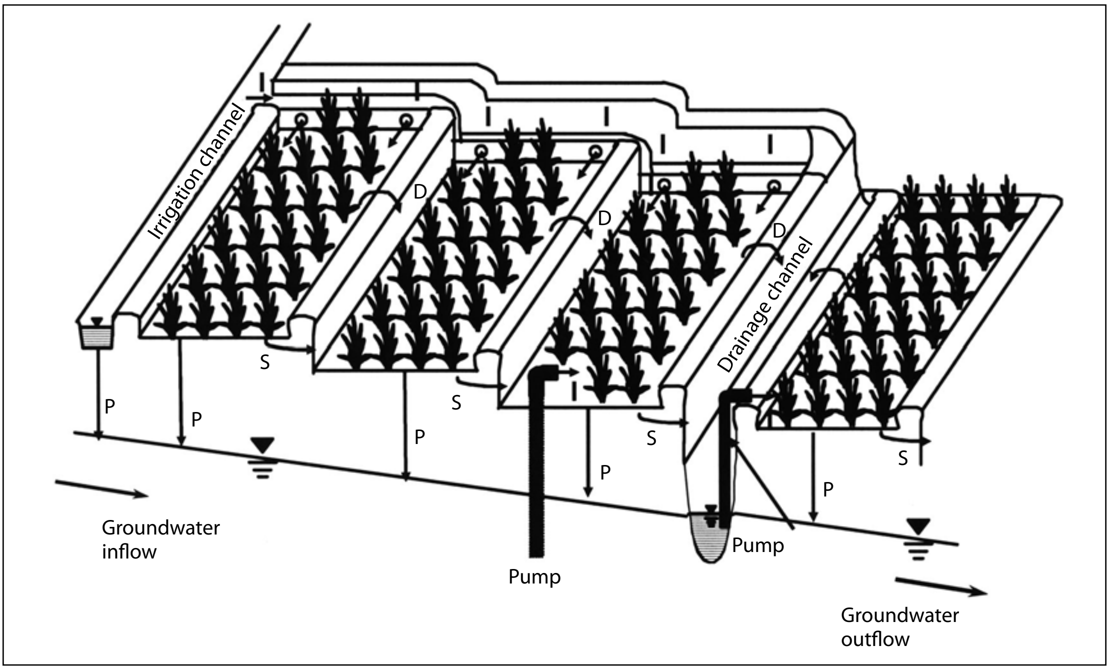


Fig. 5.1. Surface and subsurface water flows across a toposequence of rice fields. D = drainage (overbund flow), I = irrigation, P = percolation, S = seepage.

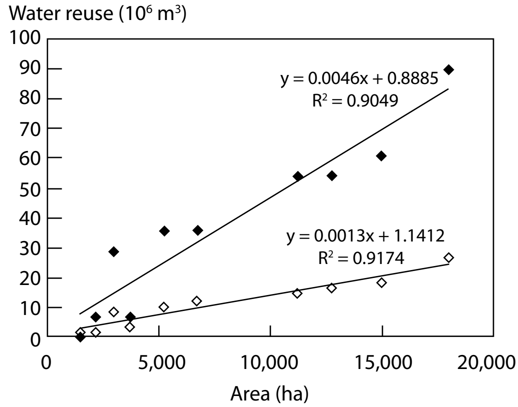


Fig. 5.2. Volume of reuse of surface water by check dams (◆) and by groundwater pumping (◇) versus spatial scale in District I of UPRIIS. The lines are linear regressions. Data from Hafeez (2003).

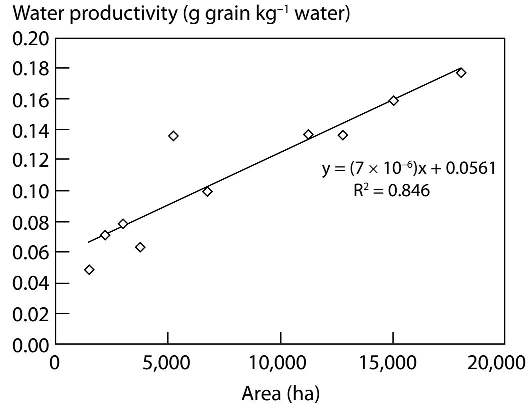


Fig. 5.3. Water productivity (WP_{IR}; g rice grains kg^{-1} water supplied (irrigation plus rainfall)) versus spatial scale in District I of UPRIIS. The line is a linear regression. The absolute values of WP_{IR} are low (compare with values in Chapter 1.5) because a lot of water still flows out of the area (drainage water) but is reused by downstream irrigators. Data from Hafeez (2003).

Recent studies of rice-based irrigation systems in China and the Philippines indicate that many water performance indicators (such as water productivity, fraction of applied water used by the crop) improve with increasing spatial scale because of the reuse of water (Hafeez 2003, Loeve et al 2004a,b). Much of this reuse is done informally by farmers who take their own initiative to pump water, block drainage waterways, or construct small on-farm reservoirs for secondary storage. Most of these farmers are found in tail-end portions of irrigation systems where water does not reach because too much water is lost upstream (e.g., by upstream farmers taking too much water, by canal seepage losses, and by operational losses). Hafeez et al (2007) reported quantitative data on water reuse on 18,000 ha of District I of the rice-based Upper Pampanga River Integrated Irrigation System (UPRIIS) in Central Luzon, Philippines. A total of 16 check dams were found for reuse of surface drainage water, and 12% of all farmers owned a pump for groundwater extraction. In the whole study area, 57% of all available surface water was reused by the check dams and 17% through pumping. The amount of water pumped from the groundwater was about 30% of the groundwater recharge by percolation from rice fields. Figure 5.2 shows that the amount of water reused by the check dams and by pumping increased with spatial scale (because, with increasing scale, the options for reuse increase). Because of this increase in water reuse with increasing scale, the water productivity increased with spatial scale as well (Fig. 5.3).

Although water can be efficiently reused this way, it does, however, come at a cost, especially to downstream farmers. The current debate on the improvement of irrigation systems focuses on the relative benefits and costs of system modernization vis-à-vis those of internal and (mostly informal) reuse of water. System modernization aims to improve the irrigation system delivery infrastructure and operation scheme to supply each farmer with the right amount of water at the right time. Gains in water productivity are possible by providing more reliable irrigation supplies, for example, through precision technology and the introduction of on-demand delivery of irrigation supplies (e.g., Gleick 2000, Rosegrant 1997). The argument is that when farmers have control over timing and amount of water supplies to their farm, they need not take their turn in a fixed rotational schedule of deliveries if the soil is still wet from rainfall. Matching system delivery and field-level demand needs further research, as optimal scheduling of irrigations is difficult when a large part of the crop water requirement is met from rainfall. This is especially true in large irrigation systems with a considerable time lag between diversion of water at the source (river or reservoir) and its arrival at the farmer's gate. In some parts of China, although the main system is supply-driven, farmers have control over the timing and amount of water at the farm gate because water is stored in small farm ponds, which can also provide water for other uses (Mushtaq et al 2006).

5.2 Field versus irrigation system level

The relationships between water use at the field and at the irrigation system level are complex and involve hydrological, infrastructural, and economic aspects. At the field level, farmers can reduce water losses by adopting water-saving technologies (Chapter 3). If they pay for the cost of the water they use, they can thereby increase the profitability of rice farming. At the irrigation system level, the adoption of field-level water-saving technologies will reduce the total amount of water lost as evaporation, but by relatively small amounts only. Most of the water saved at the field level is by reduced seepage, percolation, and drainage flows. On the one hand, this results in more water retained at the surface (in the irrigation canals), which is available for downstream farmers. On the other hand, it reduces the amount of water re-entering the hydrological cycle and thus reduces the options for informal reuse downstream. Reducing percolation from rice fields can lower groundwater tables. This can adversely affect yields since rice plants may be less able to extract water directly from the groundwater (Chapter 1.4; Belder et al 2004). Deeper groundwater tables will also increase the cost of pumping for reuse downstream. Any adoption of water-saving technologies requires considerable water control by the farmers. This is not much of a problem for farmers using their own pump, but it is so for farmers in large-scale surface irrigation systems that lack flexibility in, and reliability of, water delivery. It is also a problem for farmers using electricity to pump groundwater where supplies are unreliable, as in northwest India. To allow farmers to profit from water-saving technologies, such irrigation systems need to be modernized, which comes at an economic cost.

The "beneficiaries" of water savings at the field and irrigation system level are different in most cases. At the irrigation system level, the irrigation system management can save water in agriculture and use this water for other purposes such as hydropower generation or industry. Farmers will be interested in saving water only if they can derive benefits such as reduced irrigation costs. A detailed discussion of motives to save water is presented in Chapter 1.7.

5.3 Integrated approaches

Approaches that integrate agronomic measures, improved policies, institutional reforms, and infrastructural upgradings may have the best chance of successfully responding to water scarcity. A recent success story is the Zanghe Irrigation System (ZIS) in the middle reaches of the Yangtze Basin in China (Loeve et al 2004a,b). ZIS has a command area of about 160,000 ha and services mainly rice in the summer season. Since the early 1970s, the amount of water released to agriculture has been steadily reduced in favor of increased releases to cities, industry, and hydropower (Fig. 5.4). Since the mid-1990s, the amount of water received by agriculture has been less than 30% of the amount received in the early 1970s. In the same period, however, total rice production has increased, with a production peak of around 650,000 tons in the late eighties that was nearly twice the amount produced in the late sixties. Although rice production has leveled off to a stable 500,000 tons in the last decade, more rice has been produced with less water over the past 30 years. This feat has been accomplished by a variety of integrated measures (Dong et al 2004, Hong et al 2001, Loeve et al 2001, 2004a,b, Mushtaq et al 2006, Moya et al 2004):

- Double rice cropping has been replaced by more water-efficient single rice cropping. This was possible because of the availability of modern short-duration high-yielding varieties.
- The alternate wetting-drying water-saving technology has been promoted and widely adopted.
- Policies, such as volumetric water pricing, and institutional reforms, such as water-user associations, have been introduced that drive and promote efficient use of water by farmers.
- The irrigation system has been upgraded (e.g., canal lining).
- Secondary storage has been developed through the creation of thousands of small- to large-size ponds and reservoirs.

The ZIS case study suggests that win-win situations can exist where rice production can be

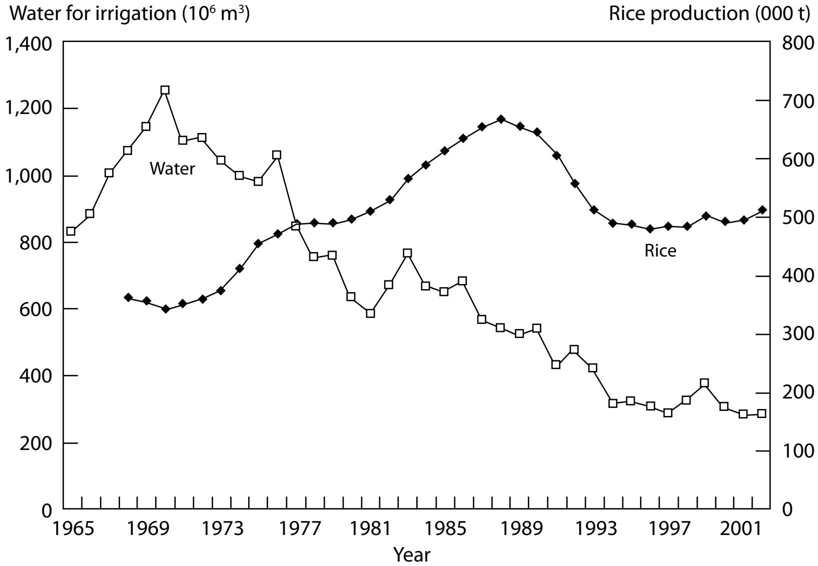


Fig. 5.4. Total rice production and irrigation water supply in Zanghe Irrigation System, Hubei, China, between 1965 and 2002. Data points are 5-year moving averages. See also Fig. 1.6B from Hong et al (2001).

maintained, or even increased, while freeing up water for other purposes.

5.4 Irrigation system management

When water is scarcer than land, it may be beneficial to maximize water productivity rather than land productivity (which is yield; kg ha^{-1}) in irrigation system management. Take, for example, a typical rice-based irrigation system that faces water shortage in the main reservoir. A usual response option of the irrigation system manager is to program less area for irrigation than the designed command area. In practice, this means that upstream farmers would get sufficient water for flooded rice production, and downstream farmers would not get any water at all and their land would be left fallow. However, to maximize total production from the irrigation system, and to improve equity among farmers, it would be more beneficial to spread out the available amount of water over the complete command area and "impose" some water scarcity on all farmers. Instead of upstream farmers practicing continuously flooded irrigation, and downstream farmers having no water at all, there could be a mix of farmers growing flooded rice and adopting a water-saving technology such as AWD. Table 5.1 quantifies the water use and total rice production of a hypothetical irrigation system in two contrasting scenarios of water distribution. The productivity and water-use parameters of flooded rice and AWD rice used in our example are taken from Table 3.2 (Guimba, 1989 data), and are repeated in Table 5.2. To simplify the calculations, we assume there is no rainfall and that all water is supplied by irrigation. The system is 10,000 ha, with a storage capacity of the reservoir of 168 10^6 m^3. With a full reservoir, this amount of water is sufficient to have 10,000 ha of flooded rice, producing a total of 58 10^3 tons of rice. Suppose there is a water scarcity and that the reservoir is filled only to 80%, storing 134 10^6 m^3 of water. In scenario I, only 80% of the command area receives water, allowing these farmers to grow flooded rice, whereas the remaining 20% is left fallow. In scenario II, 65% of the command area receives the "full" amount of water, allowing these farmers to grow flooded rice, and the remaining 35% receives a reduced amount that is sufficient to grow rice under AWD. In scenario I, the total rice production in the irrigation system is 46 10^3 tons, and, in scenario II, it is 53 10^3 tons. Moreover, there is more equity among the farmers in scenario II than in scenario I.

The above example is quite simple (and ignores the complexities of diversified cropping and of systems operation to allow farmers to practice AWD)

Table 5.1. Area, water use, and total production of flooded rice and of rice grown under AWD, in a hypothetical irrigation scheme of 10,000 ha with 134 10^6 m^3 of water available.

Land use	Area (ha)	Water use (10^6 m^3)	Production (tons)
Scenario I (80% farmers, flooded rice; 20% farmers, no crop)			
Flooded	8,000	134	46,400
AWD	0	0	0
Fallow	2,000	0	0
Sum	10,000	134	46,400
Scenario II (65% of farmers, flooded rice; 35% farmers, AWD)			
Flooded	6,560	110	38,048
AWD	3,440	24	14,852
Fallow	0	0	0
Sum	10,000	134	52,900

Table 5.2. Yield, water productivity with respect to total water input (WP_{IR}), and water input of flooded rice and rice grown under AWD (from Table 3.2, Guimba 1989).

	Yield (t ha^{-1})	WP_{IR} (kg m^{-3})	Water use (m^3 ha^{-1})
Flooded	5.8	0.345	1,679
AWD	4.3	0.614	700

Table 5.3. Area under rice production, and total water use, rice production, and number of farmers, with flooded rice and with AWD as design criteria.

Design criterion	Rice area (ha)	Water use (10^6 m^3)	Production (tons)	Farmers (number)
Flooded	10,000	168	58,000	10,000
AWD	23,986	168	103,000	23,986

but illustrates the effect of including the concept of water productivity (besides yield) in irrigation system management.

5.5 Irrigation system design

AWD irrigation can be taken as a starting point in the design of a new irrigation system. Suppose that a hypothetical reservoir can be constructed with a capacity of 168 10^6 m^3, and that a command area will be designed for rice farmers getting 1 ha each. If AWD irrigation is the design criterion rather than flooded rice, the irrigated rice area and total rice production are larger, and more farmers will benefit from irrigation development (Table 5.3). If reuse of percolation and drainage water is taken into consideration in the design, the rice area under irrigation can increase further in both scenarios. With 100% reuse of water, the irrigated rice areas would be similar in both scenarios since AWD mostly saves water by reducing percolation flows (that can be reused) and only a little by reducing evaporation (which cannot be reduced). However, 100% water reuse is in practice not attainable and the implementation of AWD would lead to the largest area under irrigation.

This example demonstrates the impact that water-saving technologies can have on irrigation system design. Rather than taking continuous flooding of fields as a design criterion, a rotation of water delivery can be used that is designed to let the fields dry out for a few days during each rotation cycle.

Field water requirements during the flooded days should be based on evapotranspiration, seepage, and percolation, whereas, during the nonflooded days, they can be based on evapotranspiration alone.

A system can also be designed to maximize the reuse of seepage and percolation water as much as possible through check dams and pumping. If there is a salinization hazard, care should be taken to avoid using water that has become too saline by reuse through judicious mixing of drainage and fresh water.

Construction of field channels (irrigation, drainage) and land leveling should be considered to facilitate good water management. Farmers in a new irrigation system should be trained in sound water management practices such as those detailed in this manual (bund maintenance, crack plowing, etc.).

Appendix: Instrumentation

Detailed descriptions and user guides of equipment to measure water flows and soil physical and hydrological properties of rice soils are given by IRRI (1987) and Wopereis et al (1994). Calculation and measurement procedures for evapotranspiration are given by FAO (1998). Here, we introduce two simple tools that are practical in characterizing the water status (hydrological conditions) of rice fields and can help guide the implementation of water-saving technologies.

A.1 Field water tube

The field water tube is used to measure the depth of standing water on the field, be it on top of the surface or just below the surface (Fig. A.1). Perforate

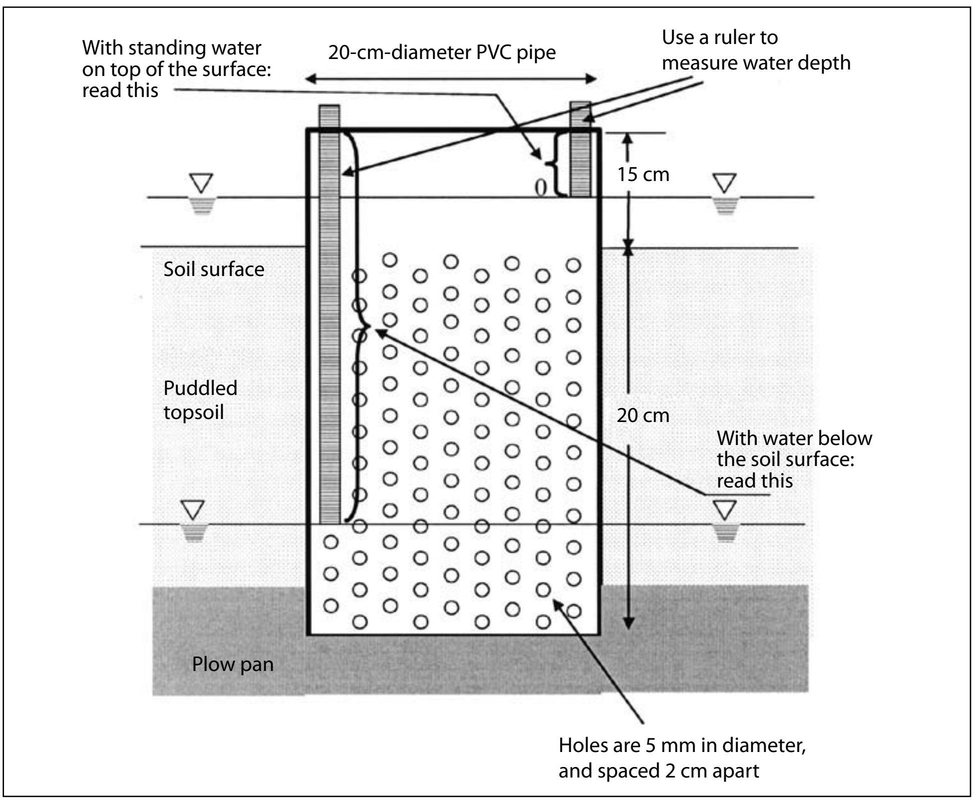
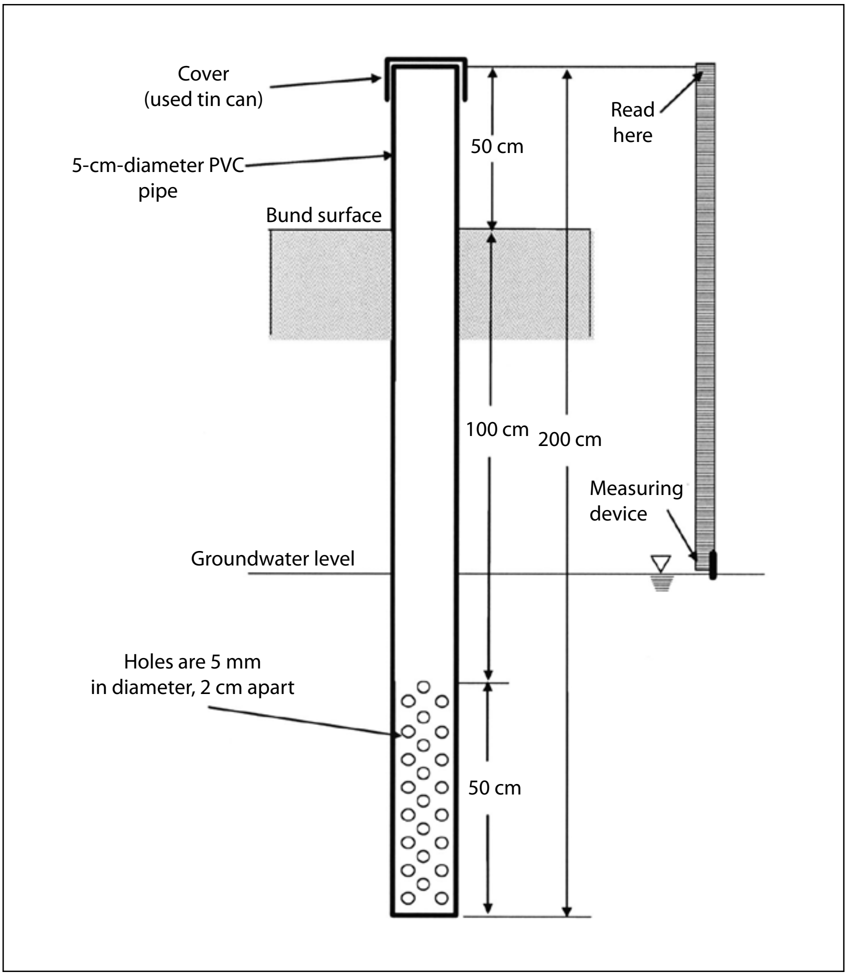


Fig. A.1. Field water tube for monitoring the depth of standing water on a rice field.

Fig. A.2. Groundwater tube for monitoring groundwater depth below rice fields.



a hollow and bottomless PVC-tube of about 20 cm in diameter and 35 cm long with small holes using a drill. The holes should be about 0.5 cm in diameter and spaced 2 cm apart. Install this tube in the field so that the bottom of the tube is buried in the plow sole (about 20 cm deep) and that some 15 cm of the tube protrudes above the soil surface. Remove the soil from inside the tube down to the bottom of the tube. Water will flow through the holes into the tube, so that the water level inside the tube is the same as outside. After irrigation, the level of the water in the tube can be seen going down every day. The tube can be placed at the side of the field close to the bund (but at least 1 m away from the bund), so it is easy to record the water depth (no need to walk very deep into the field). Make sure that the spot chosen to install the tube is representative for the whole field (don't place it in a depression or in an elevated patch).

The water depth is measured from the top of the tube to the level of the water in the field using a simple ruler. Subtract 15 cm from the reading to obtain the depth of ponded water. A negative value means that the water is standing on the field; a positive value means that the water level is below the surface. To make the measurement more accurate, the height of the tube protruding above the surface can be measured a few times during the season to check whether it is 15 cm.

A.2 Groundwater tube

The groundwater tube is used to measure the depth of the groundwater below the rice fields (Fig. A.2). Cut a length of 175 to 250 cm of hollow and bottomless PVC-tube of about 5 cm in diameter. Use a drill to make holes along a section of 50-cm length at one end of the tube. The holes should be about

0.5 cm in diameter and spaced 2 cm apart. Wrap the perforated part of the tube in rough cloth such as an old jute sack to prevent the holes from getting clogged. Install this tube in a good and solid bund between the rice fields so that the tube protrudes about 50 cm above the soil surface. An auger drill can be used to drill the hole to place the tube in. Once the tube is installed, any groundwater will flow through the holes into the tube, so that the water level inside the tube indicates the depth of the groundwater. Place a cap (can be made of an old tin) on top of the tube to prevent anything from falling in and blocking the tube.

The water depth is measured from the top of the tube to the level of the water in the field using a long stick or a piece of bamboo. Subtract 50 cm from the reading to obtain the depth of the groundwater (if the height of the tube above the bund is different from 50 cm, subtract the real height instead of 50 cm). A negative value means that the groundwater has risen above the bund and that the area is flooded. To make the measurement more accurate, the height of the tube protruding above the bund can be measured a few times during the season to check whether it is 50 cm. To relate the measured groundwater depth to the soil surface of the fields, subtract the height of the bunds from the measurements. For example, with a bund height of 20 cm, a groundwater depth of 100 cm below the bund equals a groundwater depth of 80 cm below the rice field.

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