

Water management in irrigated rice - Coping with water scarcity

DRAFT FEBRUARY 2007

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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 (paddies) 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.

This manual provides an overview of technical response options to water scarcity. It focuses at what individual farmers can do at the field level, with a brief discussion on response options at irrigation system level. Introductory chapters analyze the water use and water balance of rice fields, discuss the concepts of water scarcity and water saving, and touch upon environmental impacts and ecosystem services of irrigated rice fields. Consequences of water scarcity for sustainability, environmental impacts, and ecosystem services of irrigated rice fields are discussed at the end. The concluding chapter introduces two simple instruments to characterize the water status of rice fields and that can help farmers in applying water-saving technologies. The manual is meant as a support document for trainings 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 audiences are irrigation managers and agricultural extension agents who wish to introduce sound water management principles to rice farmers.

This manual was developed through the Water Workgroup of the Irrigated Rice Research Consortium (which is co-funded by the Swiss Agency for Development and Cooperation) and the Comprehensive Assessment of Water Management in Agriculture (supported by a grant from the Dutch Government of the Comprehensive Assessment of Water Management in Agriculture). The contributions on aerobic rice are also part of the CGIAR Challenge Program on Water and Food through the project "Developing a System of Temperate and Tropical Aerobic Rice in Asia (STAR)". Many partners from National Agricultural Research and Extension Services in Asia have contributed to the work described in this manual.

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Los Baños, 2007

1. The rice environments

Worldwide, there are about 150 million hectare of rice land which provide around 550-600 million tones 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 (Figure 1.1). 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”. Irrigated lowland rice is grown in banded fields with assured irrigation for one or more crops per year. Rainfed lowland rice is grown in banded fields that are flooded with rainwater for at least part of the cropping season to water depths that exceed 100 cm for no more than 10 days. In flood-prone environments, the fields suffer periodically from excess water and uncontrolled, deep flooding. Deepwater rice and floating rice are found in these environments. Upland rice is grown under dryland conditions without irrigation, usually in nonbanded fields.

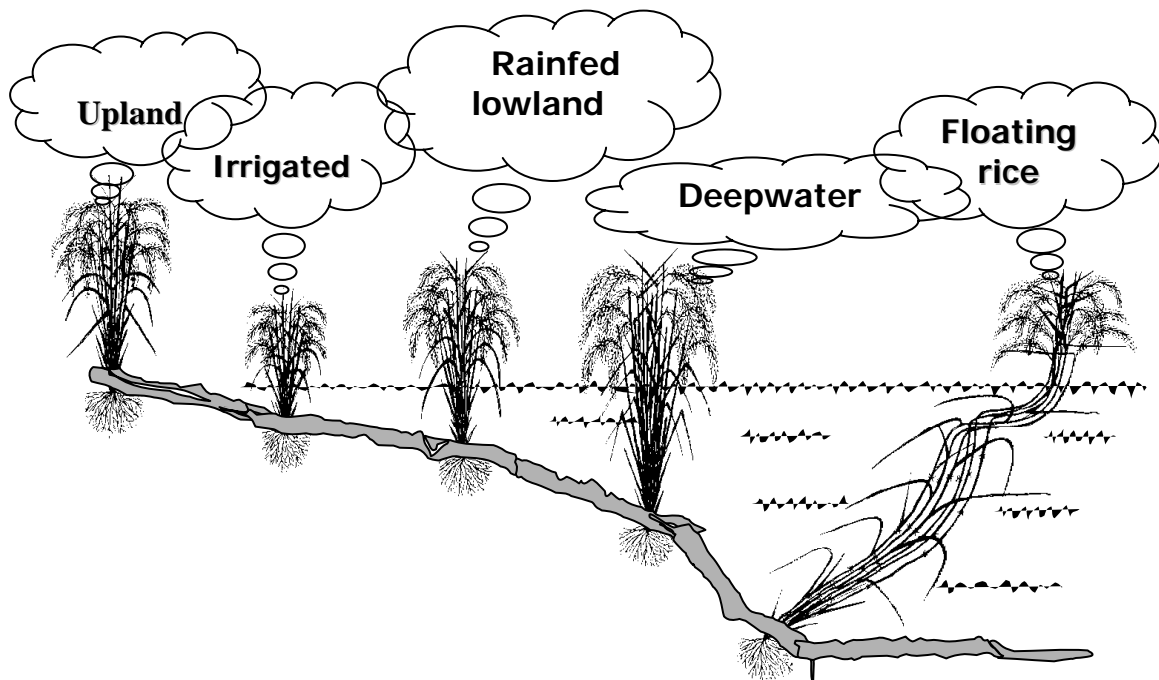


Figure 1.1 The rice environments.

1.1 Irrigated lowlands

The 79 million ha of irrigated lowlands provide 75% of the world's rice production (Maclean *et al.*, 2002; Figure 1.2). 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 South India and Sri Lanka)
- Small to medium scale community-based surface irrigation where water is directly diverted from a river (run-of-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.

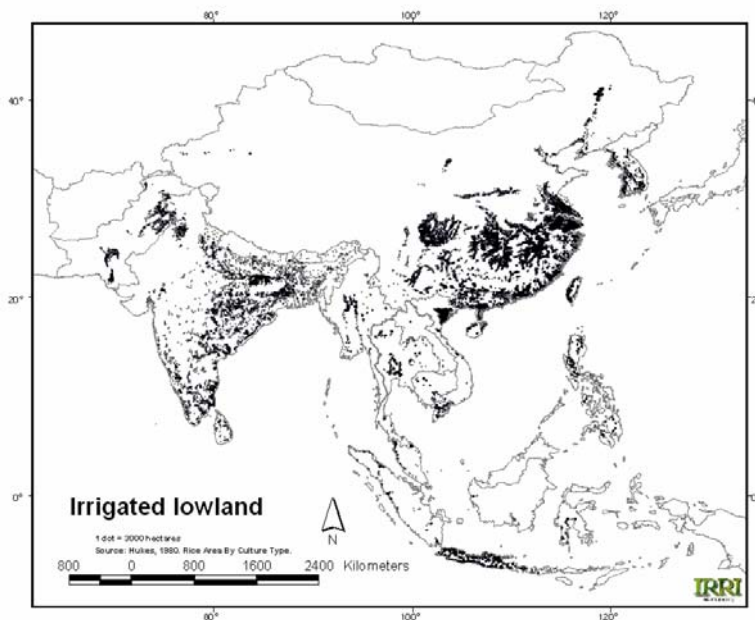


Figure 1.2. Distribution of irrigated lowland rice in Asia. Source: IIRI GIS unit, 2006.

1.2 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 ‘multifunctionality’) (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, flood, and disease 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 paddy fields (Masumoto *et al.*, 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 *et al.*, 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 *et al.*, 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 2.1) leaches salts from the topsoil (Bhumbla and Abrol, 1978). Rice soils that are flooded for long periods of the year contribute to the mitigation of the greenhouse effect by taking CO₂ from the atmosphere and sequestering the carbon (C) (Bronson *et al.*, 1997a; Dobermann *et al.*, 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.

1.3 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 are summarized which have a relationship with water and the hydrology of rice fields.

1.3.1 Ammonia volatilization

Ammonia (NH₃) 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 yr⁻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.

1.3.2 Greenhouse gases

Irrigated rice systems are a significant sink for atmospheric CO₂ (Chapter 1.2), a significant source of methane (CH₄), and a small source of nitrous oxide (N₂O). 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 4) 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.

1.3.3 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 was 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 *et 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).

2. Rice and water

2.1 The paddy field and its water balance

Irrigated lowland rice is grown under flooded conditions in so-called paddy fields. Mostly, rice is first raised in a separate seedbed and subsequently transplanted into the paddy field when the seedlings are 2-3 weeks old. Rice can also be established by direct wet seeding (broadcasting pre-germinated seeds on to wet soil) or direct dry seeding (broadcasting dry seeds on to dry or moist soil) directly in the main field. As of the late 1990s it is estimated that one-fifth of the area in Asia is 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 macropore volume, and to a large increase in micropores (Moorman and van Breemen, 1978). Consequently, the hydraulic conductivity and percolation rate are reduced dramatically. A typical vertical cross-section through a puddled rice field shows a layer of 0-10 cm 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 (Figure 2.1).

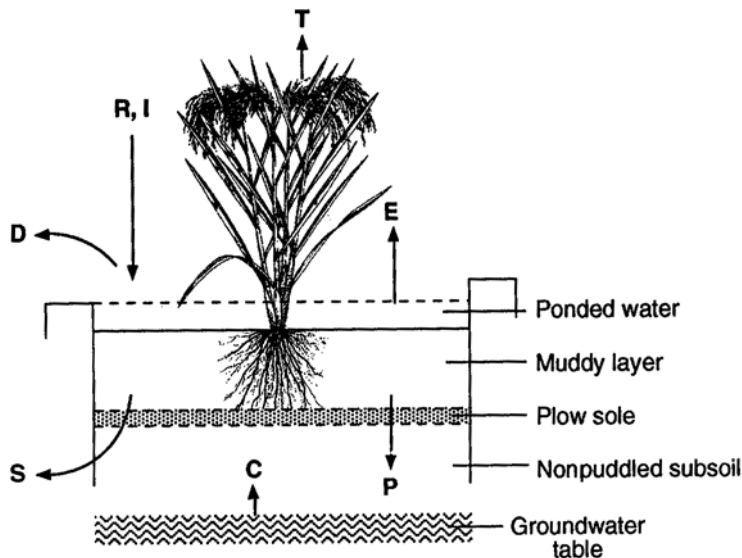


Figure 2.1. Schematic illustration of a paddy soil with water flows. C = capillary rise; E = Evaporation; I = irrigation, D = over-bund drainage; P = percolation; R = rainfall, S = seepage; T = transpiration. Source: Bouman et al. (2001).

Because of its flooded nature, the water balance of a paddy field is different from that of dryland crops such as wheat or maize. The water balance of a paddy consists of the inflows by irrigation, rainfall, and capillary rise, and the outflows by evaporation, transpiration, seepage, and percolation (Figure 2.2). Capillary rise is the upward movement of water from the groundwater table. In nonflooded (aerobic) soil, this capillary rise may move into the rootzone 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 rootzone. Therefore, capillary rise is usually neglected in the water balance of paddies.

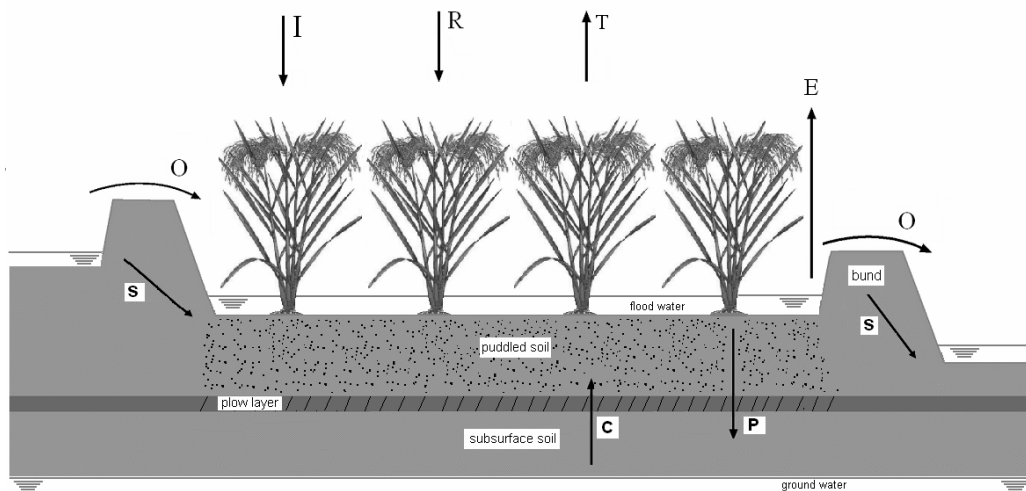


Figure 2.2. Water balance of a lowland (paddy) rice field. C = capillary rise; E = Evaporation; I = irrigation, O = over-bund flow; P = percolation; R = rainfall, S = seepage; T = transpiration.

Before the crop actually starts growing, water input is already needed for wetland preparation. After puddling, the field is usually left fallow and flooded for a few days (to 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 turn-around 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 turn-around time between soaking and transplanting can go up to two months and water inputs during this period can go up to 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. Both during the turn-around time and the crop growth period, water outflows are by overbund runoff, evaporation, seepage, and percolation. During crop growth, water also leaves the paddy 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 the ponded water above the height of the bunds, the excess rain leaves the paddy 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 paddy directly from the ponded water layer or the soil. Transpiration by the rice plants withdraws water from the puddled layer. Since the roots of rice plants generally don't penetrate the compacted layer, 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 sub-tropical regions (Tabbal *et al.*, 2002). 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 drain, ditch or creek (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, and salt type and concentration. Soil structure is changed by the physical action of puddling. In a heavy texture, 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 low ground water tables (> 2m depth) than for fields with shallow ground water tables (0.5-2 m). In practice, seepage and percolation flows are not easily separated because of transition flows that can neither 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 2.1. Water losses by seepage and percolation account for about 25-50% of all water inputs in heavy soils with shallow water tables of 20-50 cm depth (Cabangon *et al.*, 2004; Dong *et al.*, 2004), and 50-85% in coarse textured soils with deep water 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 and do not necessarily lead to true water depletion at the irrigation area or basin scales (just like overbund flow; Chapter 7.1).

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 rootzone 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 rootzone, but this is not a daily water flow as in lowland rice. Also, evaporation from ponded water surfaces is larger 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 a heavy “water user”. 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 2000 mm in coarse textured (sandy or loamy) soils with deep groundwater tables (Bouman and Tuong, 2001; Cabangon *et al.*, 2004). Around 1300-1500 mm is a typical value for irrigated rice in Asia. Table 2.1 lists some values for water inputs and daily seepage and percolation rates for lowland rice fields in China and the Philippines.

Table 2.1. 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)	Reference
Zanghe Irrigation System, Hubei, China			
• Field experiment	750-1110	4.0-6.0	Cabangon et al., 2001; 2004
• Farmer fields	650-940	1.6-2.8	Dong et al., 2004; Loeve et al., 2004ab
• Irrigation system level	750-1525	4.0-8.0	Dong et al., 2004; Loeve et al., 2004ab
Shimen, Zhejiang, China			Cabangon et al., 2001; 2004
• Early rice	850-950	1.0-6.0	
• Late rice	575-700	1.0-6.0	
Guimba, Philippines			Tabbal et al., 2002
• Experiment 1988	2197	18.3	
• Experiment 1989	1679	12.5	
• Experiment 1990	2028	16.4	
• Experiment 1991	3504	32.8	
Munoz 1991, Philippines	1019-1238	5.2-7.0	Tabbal et al., 2002
Munoz 2001, Philippines	600	1.1-4.4	Belder et al., 2004
Talavera, Philippines	577-728	0.3-2.0	Tabbal et al., 2002
San Jose, Philippines			Tabbal et al., 2002
• Experiment 1996	1417	9.6	
• Experiment 1 1997	1920	15.2	
• Experiment 2 1997	2874	25.8	

2.2 Groundwater under rice fields

Groundwater may play a hitherto underestimated role in the irrigated rice environment. 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.

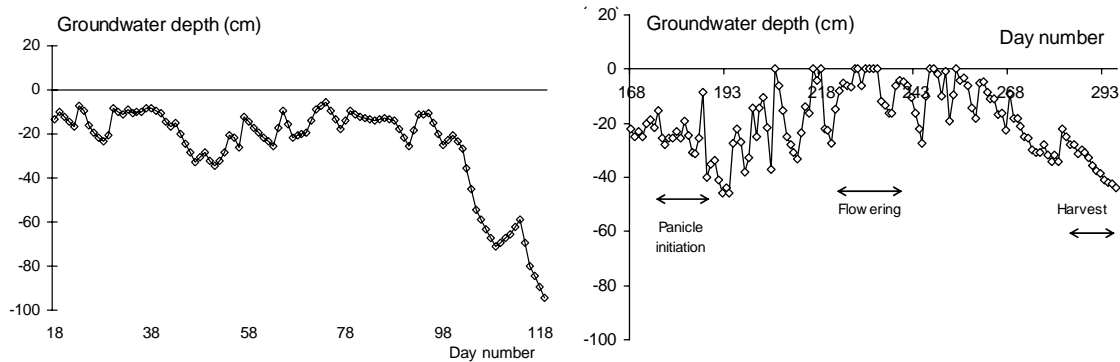


Figure 2.3a. Groundwater depth under flooded rice at Tuanlin, Hubei Province (left panel) and Changle, Beijing, China, in 2002. Adapted from: [Belder et al. \(2004\)](#), and unpublished data China Agricultural University/IRRI.

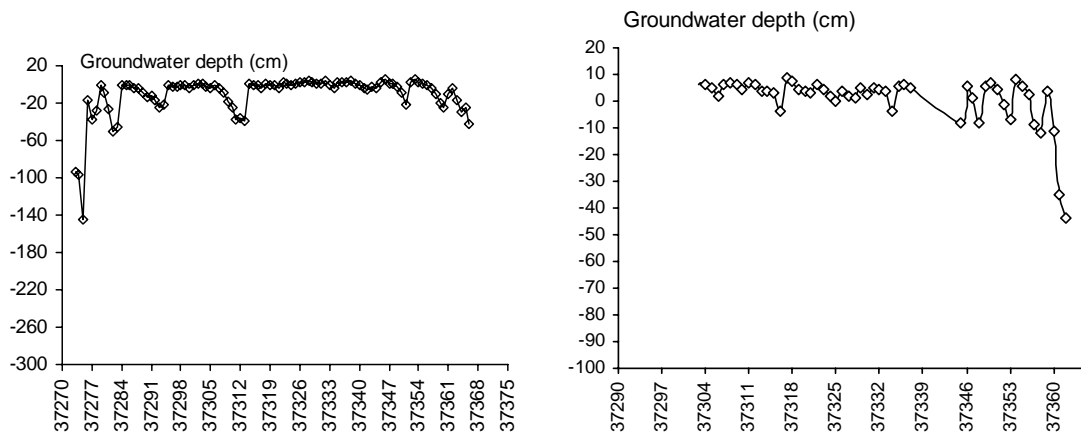


Figure 2.3b. Groundwater depth under flooded rice in Dolores (left panel) and Gabaldon (right panel) in 2002, central Luzon, Philippines. Adapted from: [Lampayan et al. \(2005\)](#).

Figure 2.3 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 5), capillary rise may reach into the rootzone 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 little irrigation water supply can still be good because of the "hidden" water supply of groundwater.

2.3 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 due to 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 (all in kg grain kg⁻¹ water):

WP_T: weight of grains over cumulative weight of water transpired
(also known as transpiration efficiency)

WP_{ET}: weight of grains over cumulative weight of water evapotranspired.

WP_I: weight of grains over cumulative weight of water inputs by irrigation.

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

While breeders are interested in the productivity of the amount of transpired water (WP_T), farmers and irrigation engineers/managers are interested in optimizing the productivity of irrigation water (WP_I). To regional water resources 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.

The modern rice varieties, when grown under flooded conditions, have similar water productivity with respect to transpiration (WP_T) as other C₃ cereals such as wheat, at about 2 kg grain m⁻³ 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 kg grain m⁻³ of evapotranspired water, with a mean of 1.1 kg grain m⁻³ (Tuong *et al.*, 2005; Zwart and Bastiaanssen, 2004; Figure 2.4a). 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 C₄ crop, the water productivity with respect to evapotranspiration is higher, ranging from 1.1 to 2.7 kg grain m⁻³ water, with a mean of 1.8 kg grain m⁻³. Water productivity of rice with respect to total water input (irrigation plus rainfall) ranges from 0.2 to 1.2 kg grain m⁻³ water, with 0.4 as average value, which is about two times smaller than that of wheat (Tuong *et al.*, 2005; Figure 2.4b).

Comparing WP among seasons and locations can be misleading because of differences in climatic yield potential, evaporative demands from 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., $> 10 \text{ kg rice m}^{-3}$ 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 7.4](#).

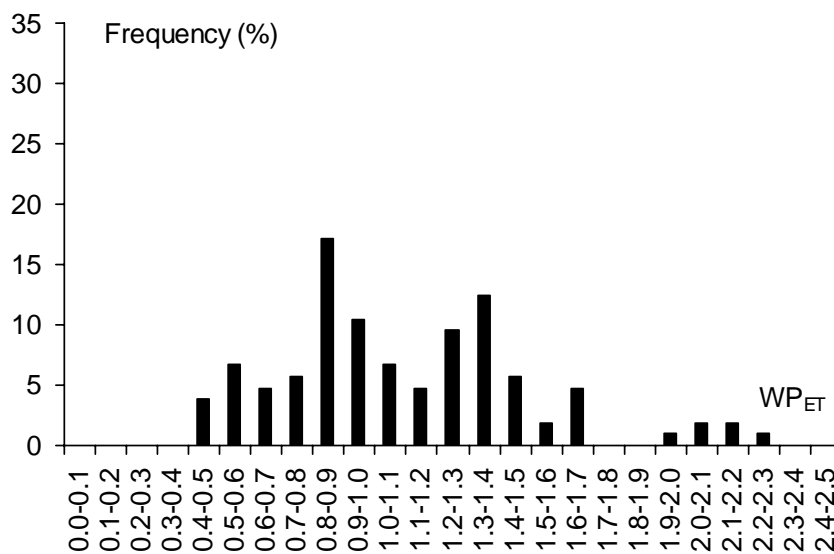


Figure 2.4a. Frequency distribution of crop water productivity of rice with respect to evapotranspiration (WP_{ET}). Data from: [Zwart and Bastiaanssen \(2004\)](#).

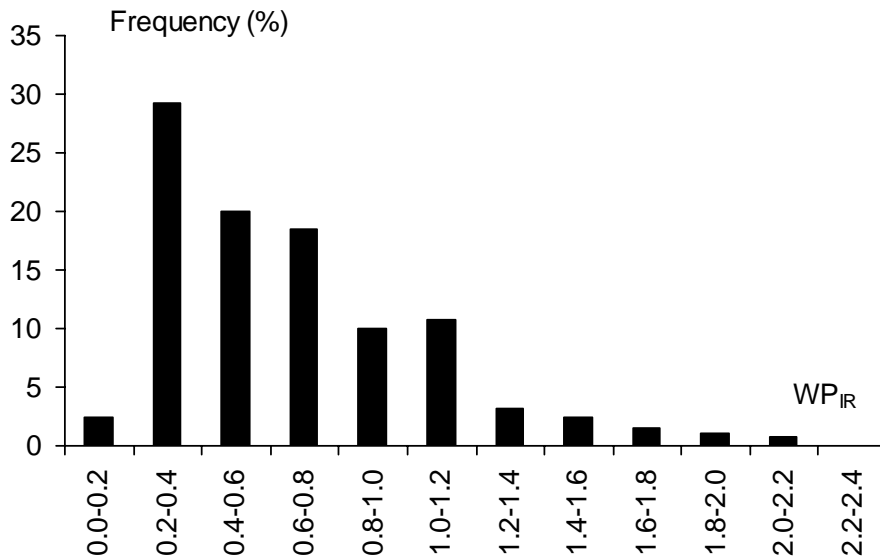


Figure 2.4b. Frequency distribution of water productivity of rice with respect to total water inputs (WP_{ET}) from field experiments in India, the Philippines, China, and Malaysia. Most of the data on the left of the x-axis are from India, with local varieties on light soils and deep groundwater table, while those on the right are from China, with hybrid rice, clay soil, and shallow groundwater table. Data from: [Tuong et al. \(2005\)](#).

2.4 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 3600 km^3 annually, of which 2500 km^3 is used to irrigate crops ([Falkenmark and Rockstrom, 2004](#)). The rest is used in industry and for domestic purposes. Approximately 56% of the world's 271 million ha 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 2.1](#)), but an unknown proportion of the water losses from individual fields is reused by other fields downstream ([Chapter 7.1](#)). 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 2.5](#) gives irrigated areas and volumes of irrigation water used in agriculture and in rice.

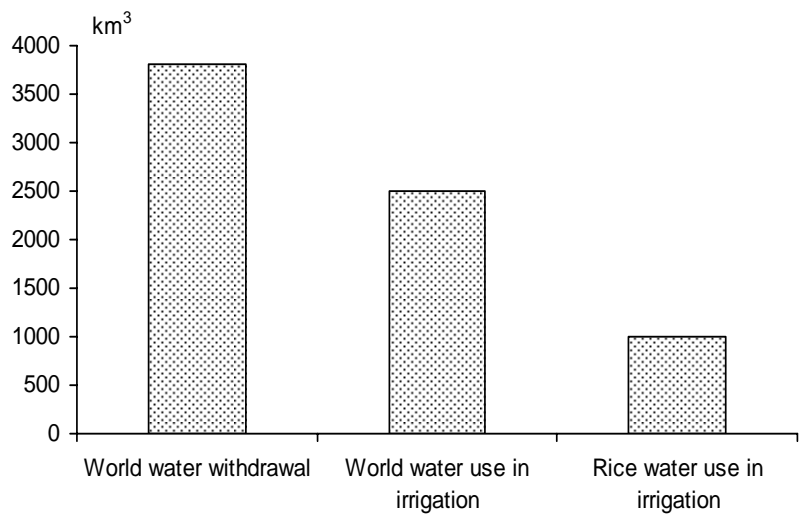
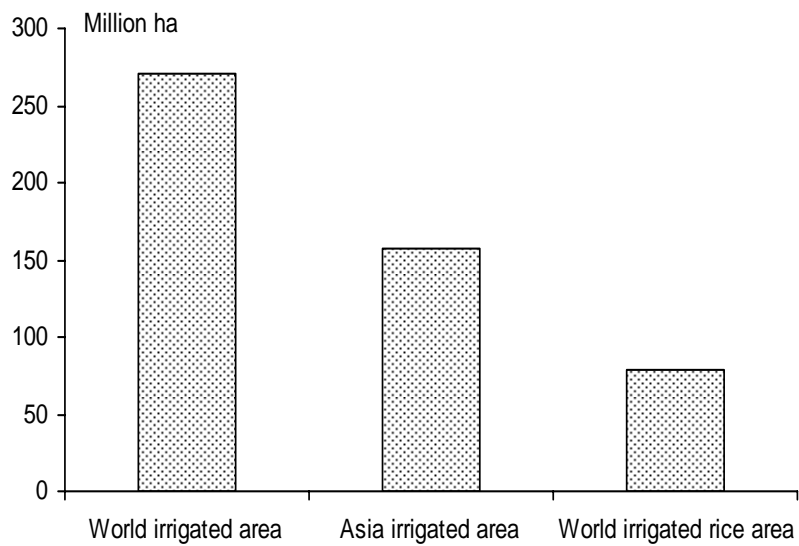


Figure 2.5. Irrigated areas (top panel) and volumes of water used (bottom panel) in the world, in Asia, and in rice production.

3. The plant-soil-water system

3.1 Water movement in the soil-plant-atmosphere continuum

Rice plants take up liquid 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). There are different units to express soil water potential (Table 3.1), and, unfortunately, different units are reported by different authors. In this report, we usually use the term Pascal (P).

Table 3.1. Units to express soil water potential and some corresponding values. pF is calculated as $10\log(\text{cm water})$.

Unit name	Corresponding value				
Water height (cm)	1	10	100	1000	15850
pF (-)	0	1	2	3	4.2
Bar (bar)	0.001	0.01	0.1	1	15.85
Pascal (Pa)	100	1000	10000	10000	1585000
Kilo Pascal (kPa)	0.1	1	10	100	1585
Mega Pascal (MPa)	0.0001	0.001	0.01	0.1	1.585

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 (with smaller 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 (**Figure 3.1**). 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 smaller than stomatal transpiration). **Figure 3.2** gives an example of water tensions 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 the transpiration cools the plant down 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), it can close its stomata and reduce or even completely stop transpiration. Besides the reduction in transpiration, a number of growth processes of the plant get affected when there is not enough water. We usually call these ‘drought effects’, and they are summarized in the **Chapter 3.2**.

In nonrice soils, there usually is a mixture of water, air, and solid soil particles in the soil, and the water potential is negative (positive tension). However, under flooded conditions, as in rice paddies, the soil is saturated with water and the potential is positive. **Figure 3.3** gives an example of soil water potential in a typical paddy soil. By definition, where liquid water touches the atmosphere, such as at the surface of ponded water in rice fields, the potential is zero. Within the layer of ponded water, the potential increases from top to bottom because of its own weight pressing down. In the puddled topsoil, there is a water-saturated muddy suspension that behaves the same as a layer of water, and the potential still increases with increasing depth. Beneath the plow plan, however, the soil is usually not saturated with water anymore and there is a mixture of air and water in the soil pores so that the potential decreases quickly to negative values. Deeper in the soil profile, the potential increases again until it is back to zero at the top of the groundwater (liquid water touches the air in the soil). These dynamics of the soil water potential are quite complex and beyond this manual to explain in detail (see [Ehlers and Goss \(2003\)](#) for more details). The most important observation is that, in flooded rice soils, the soil water potential in the root zone is positive, whereas in nonflooded soils, it is negative. Negative potentials (positive tensions) occur in rice fields when they fall dry and start to dry 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’. **Figure 3.4** gives an illustration of soil water tensions measured in an aerobic soil where rice was grown under nonflooded conditions like an upland crop.

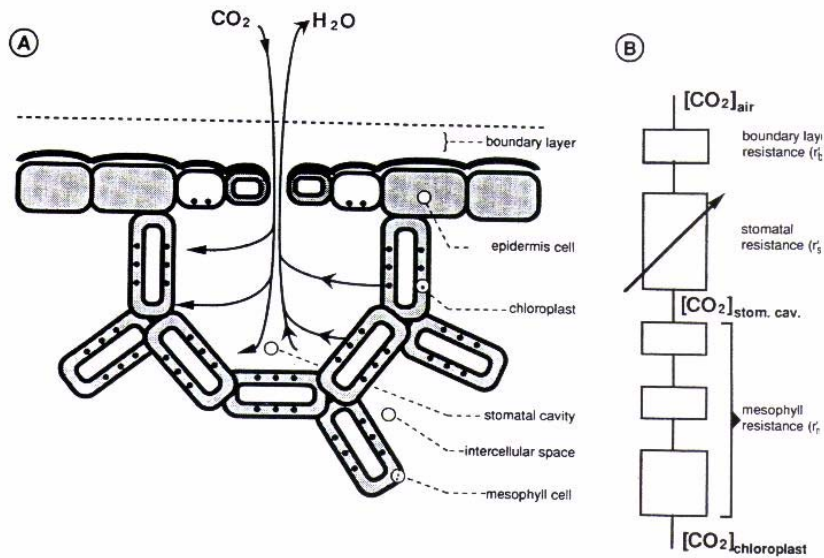


figure 2.1 Cross-section of a leaf through a stoma (a), indicating components of resistances to CO₂ diffusion (b).

Figure 3.1. Schematic cross section of a leaf stomata. Source: Lönvenstein et al. (1992)

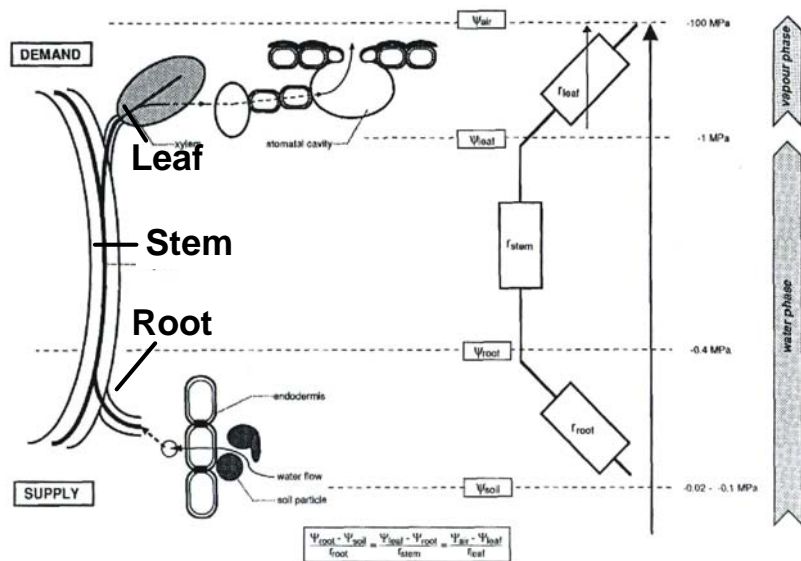


figure 3.1 Schematic overview of water flow in soil/plant/air continuum along a decreasing water potential gradient with ohm analogue

Figure 3.2 Schematic overview of water flow and water tensions in the soil-plant-atmosphere continuum. Adapted from: Lönvenstein et al. (1992)

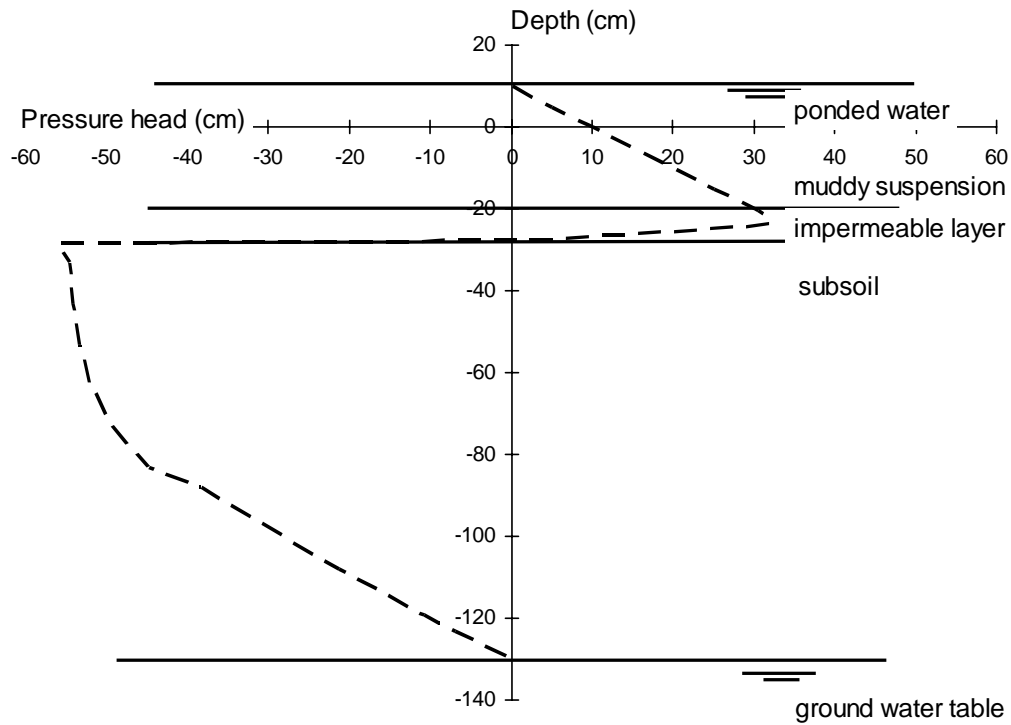


Figure 3.3. Soil water potential (expressed in cm pressure head) at different depths in a paddy soil.

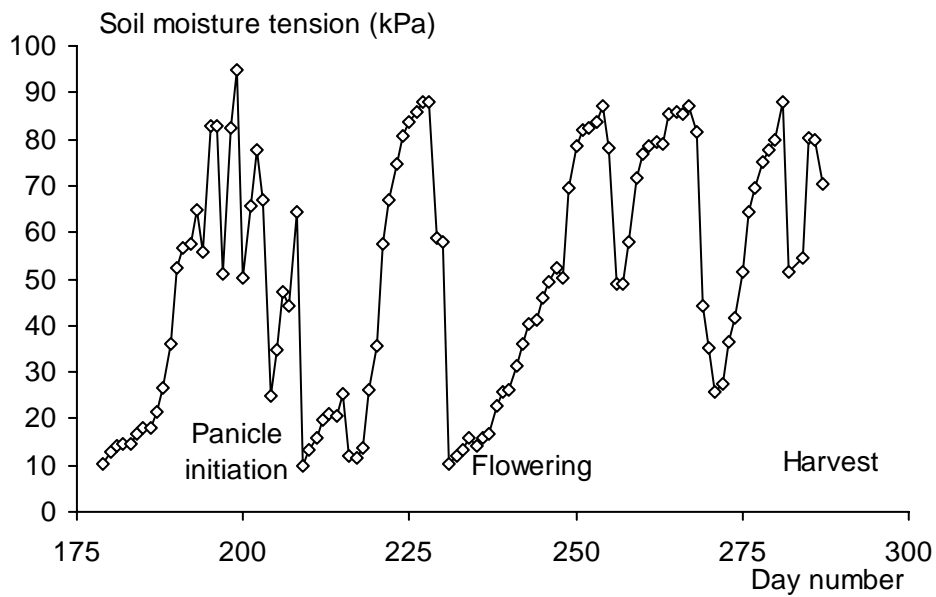


Figure 3.4. Time course of soil water tension in the rootzone of rice grown in a nonpuddled, nonflooded soil (this system is called “aerobic rice”, Chapter 5.4). Adapted from: [Yang Xiaoguang et al. \(2005\)](#).

In each soil there is 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’. 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 3.5** for a typical clay soil and a typical sand soil. There are four important soil water tension values for upland crops: saturation = pF 0, where all pore spaces are filled with water, field capacity = pF 2, which is supposedly the optimal water condition for plant growth, wilting point = pF 4.2, where upland crops usually can not extract any water from the soil anymore, and air dry = pF 7, where the soil is completely without extractable water. The amount of water at each of these four points is different for each soil type. For flooded paddy soils, the pF curve has no meaning. However, when a paddy soil falls dry, the pF curve becomes meaningful as it indicates the amount of water available for plant uptake at each tension level.

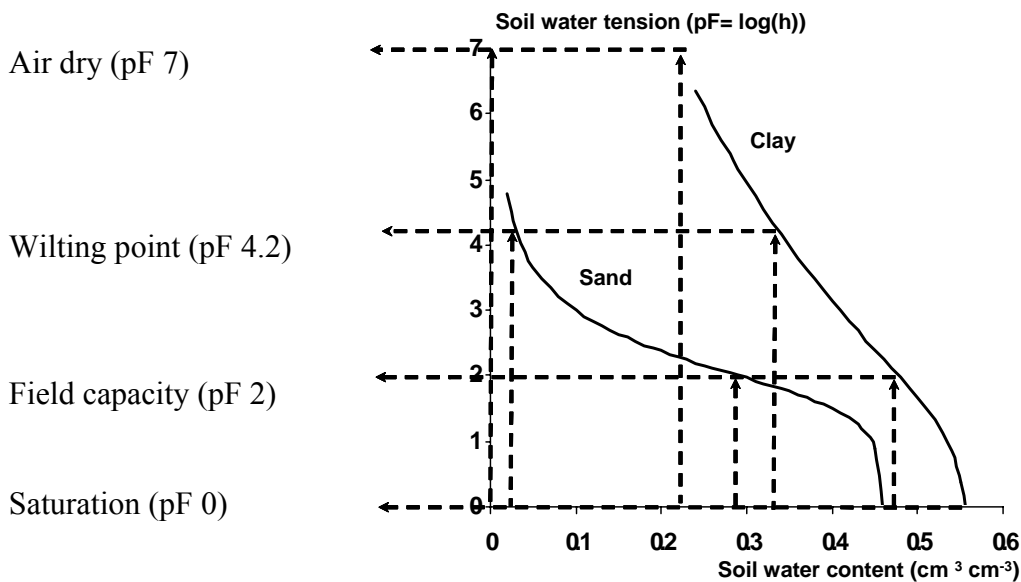


Figure 3.5. Typical soil water retention curve (or pF curve) for a clay soil and a sand soil. Notice the differences in water content at the four critical pF points for the two soil types. Adapted from: [Lövenstein et al. \(1992\)](#)

3.2 The rice plant and drought

Cultivated rice evolved from a semi-aquatic, 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 sensitive 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. Stomatal closure begins at higher leaf water tensions than in other crops, and transpiration declines gradually starting at about 750 kPa ([Dingkuhn et al., 1989](#)). 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 non-sensitive 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 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 1000-grain weight with drought after flowering.

The above processes appear roughly in order of crop development and/or severity of drought, though nos. 2-4 also occur in the reproductive stage. Some effects lead to irreversible processes of yield reduction, such as nos. 4, 9, and 10, whereas others may be restored when drought is relieved, such as nos. 2 and 3, and others may be compensated for by other effects later in the growing season, such as nos. 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 (or duration), and frequency of occurrence. The most sensitive stage of rice to drought is around flowering.

4. Water scarcity in rice-growing areas

Worldwide, water for agriculture is getting 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 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, affecting downstream rice-growing areas (Postel, 1997). Overexploitation of groundwater during the last 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 Phra 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 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.

It is useful to distinguish between different types of water scarcity as these determine the boundary conditions of farmers to respond to it. Usually, response options at the field level to water scarcity are called "water-saving" technologies. For many of us, the term "water saving" suggests an active action or choice to save water. However, this choice is not always in the hand of farmers to make. Usually water scarcity is externally imposed upon farmers, and they just have to cope with it. We draw a parallel with economic descriptions of the concept "savings" to illustrate how water savings work out for rice farmers in irrigated areas.

Saving scenario 1: to reduce the current (way of) expenditures to allow for redirected (different way of) expenditures. In water terms, this translates as "to reduce the use of water for irrigation so that it can be used for another purpose". In agriculture, the motivation for this type of water saving 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 of 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 cutting down the amount of water released for agriculture and redirect 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; Figure 4.1) 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 are just faced with the consequences of these decisions: they receive less water and just 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 industry and cities, is a fallacy. Farmers can be encouraged to voluntarily reduce water use, e.g. by introducing volumetric water pricing, but this is the exception rather than the rule and “enforced water scarcity” is prevalent. Voluntary water saving by farmers for redirected use works 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).

Saving scenario 2: to reduce expenditures because of reduced income. In water terms, this translates as “to reduce the use of irrigation water because there is less of it”. This type of water saving 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, absolute water shortage can also be induced by natural causes. For example, when seasonal rains have failed to fill up reservoirs or ponds, then the amount of water may not be sufficient to keep all rice fields flooded throughout the year. When the reservoir makes part of a large-scale irrigation system, reservoir managers usually respond by reducing the “program area” for irrigation: less farmers will receive irrigation water. However, with smaller reservoirs such as individual ponds, farmers can decide themselves how to cope with the water scarcity. They may decide to reduce their land under irrigation, or they can 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. The way farmers can save water is 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 5).

Saving scenario 3: to reduce expenditures to reduce cost and increase profit. In water terms, this translates as “to reduce the use of irrigation water to cut 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 a flat rate (a fixed sum per unit land area), and water costs can not 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 is a voluntary and deliberate choice of their own. The means to save water is the same as in the scenario above: to reduce water irrigation to their fields.

The examples above 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 (expect in scenario 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”.

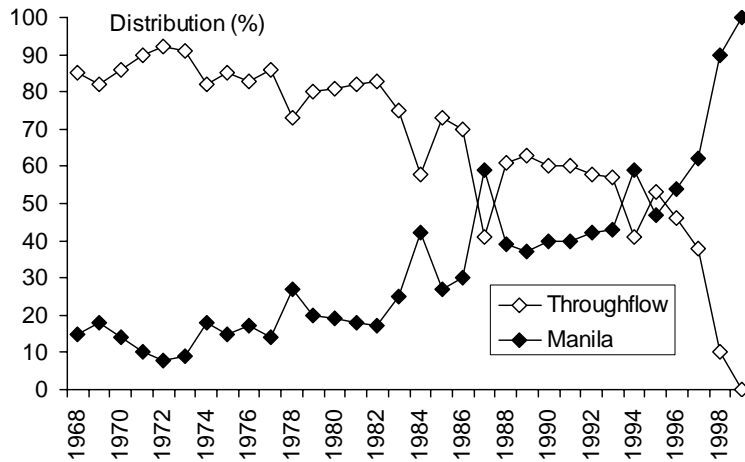


Figure 4.1a. “Imposed water scarcity”: change in relative water allocation from Angat reservoir, Philippines, to through-flow in the river for potential agricultural use downstream and to the city of Manila. Data from: [Pingali et al. \(1997\)](#) and unpublished National Irrigation Administration Philippines.

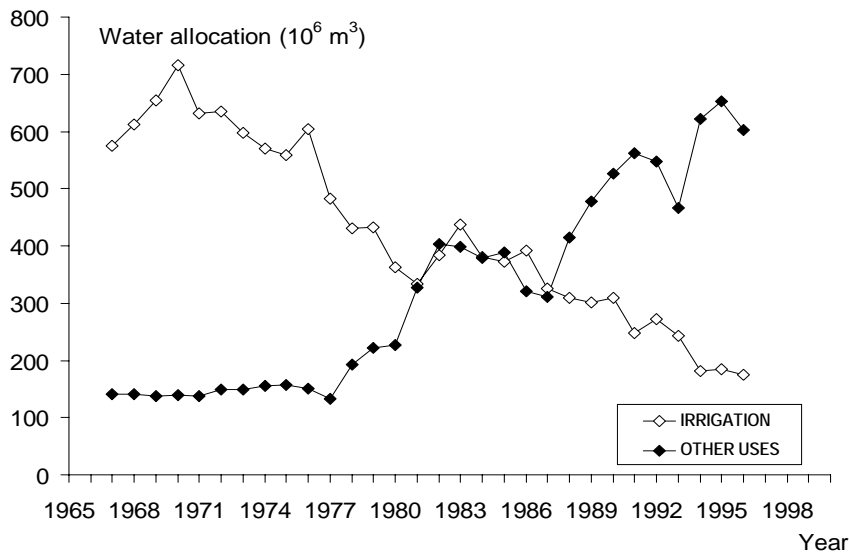


Figure 4.1b. “Imposed water scarcity”: change in water allocation to agricultural and nonagricultural use in Zanghe Irrigation System, Hubei, China, between 1965 and 2002. Data points are 5-year moving averages. Data from: [Hong et al. \(2001\)](#) and unpublished data.

5 Coping with water scarcity

In this chapter, we concentrate on options to assist 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, crop establishment, and during the actual crop growth period.

5.1 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, bund preparation and maintenance).

5.1.1 Field channels

In many irrigation systems in Asia, there are 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 amounts of water flowing in and out of a rice field can not 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 5.5**). Finally, the water that continuously flows through the paddies may remove valuable (fertilizer) nutrients. Constructing separate channels that convey water to and from each field (or to a small group of fields) greatly improves the individual water control water, and is the recommended practice in any type of irrigation system.

5.1.2 Land leveling

A well-leveled field is a prerequisite for good crop husbandry. When field are not level, water may stagnate in the depressions whereas higher parts may fall 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.

5.1.3 Tillage: reducing soil permeability

Seepage and percolation flows from paddy fields are governed by the permeability (hydraulic conductivity) of their soils: their capacity to conduct water downwards and sideways ([Chapter 2.1](#)). A paddy field can be compared with a bath tub: the material of a bath tube is impregnable and it holds water well – however, you only need to have one hole (by removing the plug) and the water runs out immediately. Rice fields just need a few rat holes or leaky spots and they will rapidly loose 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 favour rapid “by-pass flow” to below the rootzone. [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 ([Figure 5.1](#)).

Thorough puddling results in a good compacted plow sole that reduces the permeability and the percolation rates ([Chapter 2.1](#); [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 (semi-)impermeable subsoil layer ([Tuong et al., 1994](#)). 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 5.2](#)).

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 at large scales with government support.

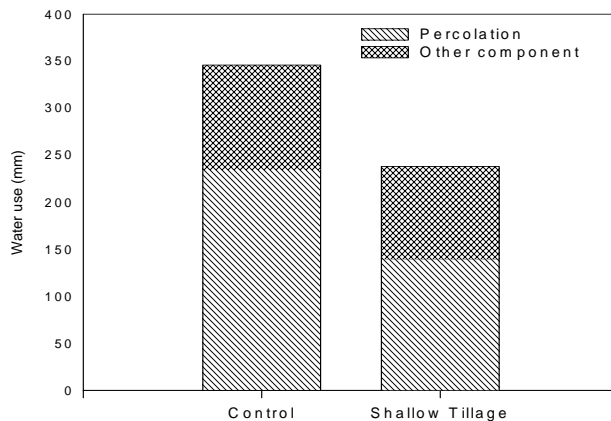


Figure 5.1. Effects of shallow tillage to fill cracks before soaking on water use, Bulacan, Philippines. Data from: [Cabangon and Tuong \(2000\)](#).

5.1.4 Bund preparation and maintenance

Good bunds are a prerequisite to limit seepage flows. 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 the 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 of total water use in a rice field by lining the bunds with plastic ([Figure 5.2](#)). Although such measures are probably financially not attractive to farmers, the author has come upon a farmer in the Mekong delta in Vietnam who used old plastic sheets to block seepage through very leaky parts of his bunds.

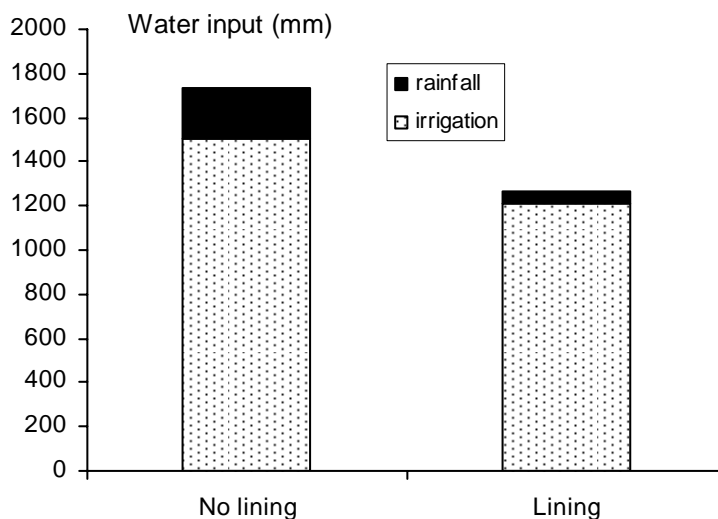


Figure 5.2. Effect on total water input of lining the bunds with plastic in a field experiment at IRRI, los Baños, Philippines. Data from: [Bouman et al. \(2005\)](#).

5.2 Crop establishment

Minimizing the turn-around time between land soaking for wet land preparation and transplanting reduces the period that no crop is present and that the outflows of water from the field do not contribute to production. Especially in large-scale irrigation systems with plot-to-plot irrigation, the water losses during the turn-around time can be very high. For instance, in the largest surface irrigation scheme in central Luzon, called UPRIS (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 turn-around time can be minimized by the installation of field channels, the adoption of common seed beds, or the adoption of direct wet or dry seeding. With field channels, water can be delivered to the individual seed beds separately and the main field does not need to be flooded. Common seed beds, 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 onwards. 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 only possible 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.

5.3 Crop growth period.

5.3.1 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 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 5.1).

Analyzing a data set of 31 published field experiments with a 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%. Borell *et al.* (1997) experimented with raised beds (120 cm wide, with furrows of 30-cm width and 15-cm depth) in Australia to facilitate SSC practices. The water in the furrows just kept the beds at saturation. Compared to flooded rice, water savings were 34% and yield losses 16–34%. More on raised beds is found in Chapter 5.4.1.

Table 5.1a. 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)
Continuous flooding	7.4	694	1.06	7.6	631	1.20
SSC	6.7	373	1.81	7.3	324	2.27

Table 5.1b. Yield, water input, and water productivity with respect to total water input (WP_{IR}) and with respect to irrigation (WP_I) in dry-seeded rice, under continuous flooding and SSC, San Jose City, Philippines, 1996-1997. Data from: [Tabbal et al. \(2002\)](#).

Treatment	Yield (kg ha ⁻¹)	Water input (mm)		Water productivity (g grain kg ⁻¹ water)	
		Irrigation + rainfall	Irrigation	WP_{IR}	WP_I
1996					
Continuous flooding	4,338	1,417	531	0.31	8.16
SSC	4,172	1,330	432	0.32	9.65
1997					
Continuous flooding	4,696	1,920	941	0.25	4.99
SSC	4,546	1,269	355	0.36	12.81

Practical implementation.

Although conceptually sound, SSC will be difficult to practically implement 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.

5.3.2 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. AWD is also the water management practice of the System of Rice Intensification (SRI; [Stoop et al., 2002](#)). Though 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 5.2](#)), even for SRI ([Sheehy et al., 2004](#); [McDonald et al., 2006](#)). 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 that 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.

Table 5.2. Yield, water use, and water productivity 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
		AWD	4.0	880	0.46
Tabbal et al., 2002	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, Hubei, China.	1999	Flooded	8.4	965	0.90
		AWD	8.0	878	0.95
Belder et al., 2004	2000	Flooded	8.1	878	0.92
		AWD	8.4	802	1.07
Munoz, Philippines.	2001	Flooded	7.2	602	1.20
		AWD	7.7	518	1.34
Belder et al., 2004					

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 were reduced by around 15-30% without a significant impact on yield. In all these cases, groundwater depths were extremely shallow (between 10-40 cm), and ponded water depths hardly dropped below the root zone during the drying periods ([Figure 5.3](#)), thus turning the AWD effectively into a kind of near-saturated soil culture. Even without ponded water, plant roots still had access to “hidden” water in the rootzone ([Chapter 2.2](#)). More water can be saved and water productivity further increased by prolonging the periods of dry soil and imposing slight drought stress on the plants, but this comes usually 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](#)).

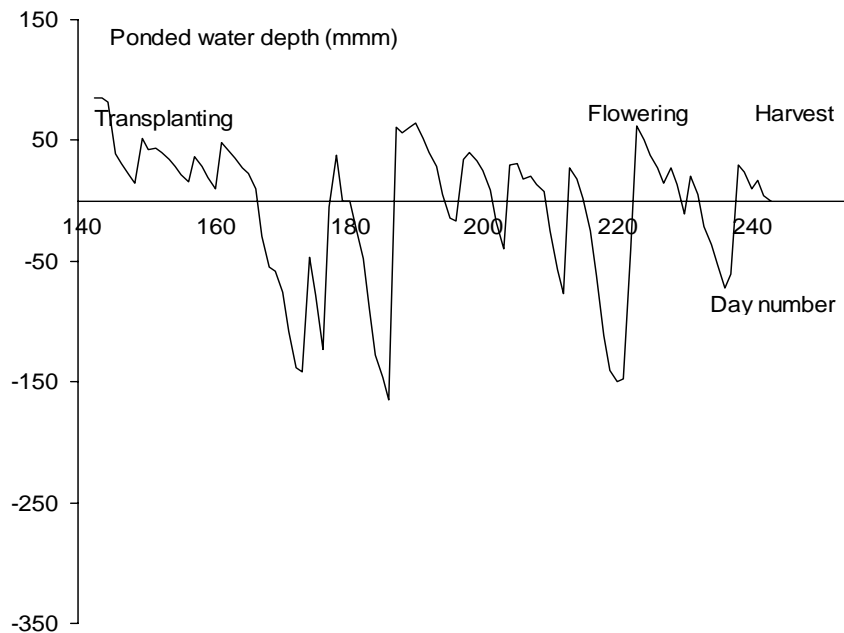


Figure 5.3. Depth of ponded water on the soil surface (above the drawn horizontal line) and below the soil surface (below the drawn horizontal line) in an AWD experiment, Tuanlin, Hubei, China. Adapted from: [Belder et al. \(2004\)](#).

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. [Figure 5.4](#) gives an example of yields and water inputs obtained by farmers in central Luzon, the Philippines, who practiced AWD irrigation ([Lampayan et al., 2005](#)). The farmers used communal deepwell pumps or own shallow tubewell pumps to irrigate their fields. They divided their fields into two, one with AWD management and one with continuous flooding. [Table 5.3](#) gives an economic comparison among the 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 paddy fields: evaporation, seepage, and percolation. The little work done so far suggests that AWD mostly reduces the 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 were reduced by 2-33% compared with fully flooded conditions.

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

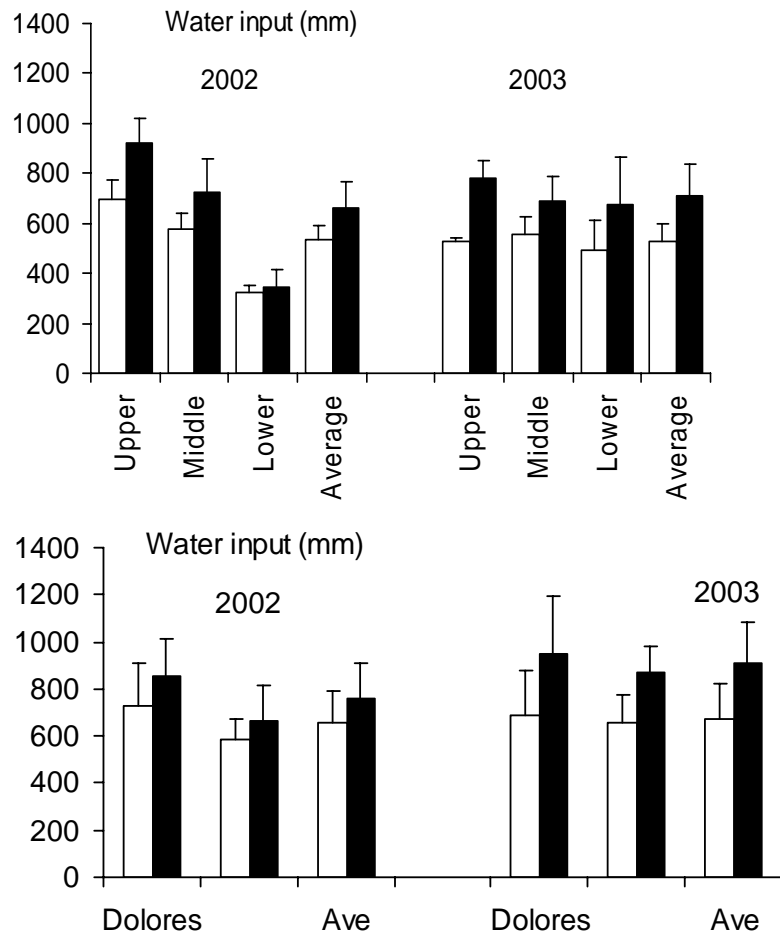


Figure 5.4a. Total water input (mm) under AWD (white bars) and continuous flooding (black bars) in farmers' fields in Tarlac (top panel) and Nueva Ecija (bottom panel), Philippines, 2002 and 2003 dry seasons. Data from: [Lampayan et al. \(2005\)](#).

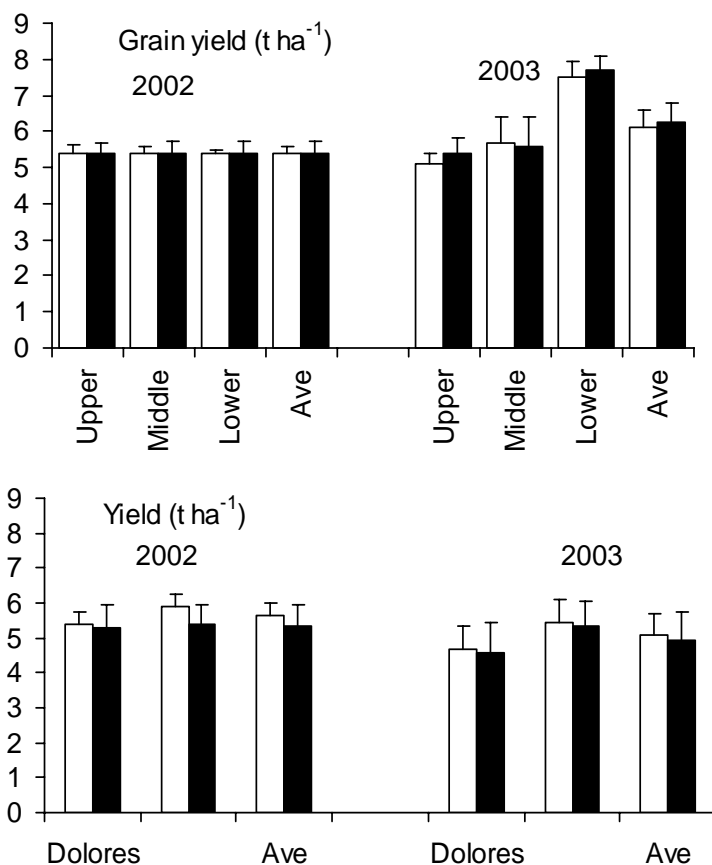


Figure 5.4b Average yield under AWD (white bars) and continuous flooding (black bars) in farmers' fields in Tarlac (top panel) and Nueva Ecija (bottom panel), Philippines, 2002 and 2003 dry seasons. Data from: [Lampayan et al. \(2005\)](#).

Table 5.3. 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 return (\$ 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 return (\$ 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.

A practical way to implement AWD is to monitor the depth of the water table on the field using the ‘field water tube’ described in [Chapter 8.1](#). After an irrigation application, the field water depth will gradually decrease in 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 one week after the peak of flowering, ponded water should best be kept at 5 cm depth to avoid any water stress that would result in potentially severe yield loss ([Chapter 3.2](#)). 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 rootzone. The use of the field water tube makes this “hidden” source of water visible to the farmers! In Safe AWD, water savings may be relatively small, in 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, 25, 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 4 and 5.5](#)).

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 a week before flowering. In the period of one week before to one 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.

5.4 Aerobic rice

A fundamentally different approach to reduce water outflows from rice fields is to grow the crop like an 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 Pruitt, 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 5.5). 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.

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-resistant 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 total (irrigation plus rainfall) water input (Table 5.4). For comparison, the aerobic varieties yielded 5.4-6.8 t ha⁻¹ under flooded lowland conditions, receiving about 1300 mm 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 of 6.0 t ha⁻¹ with 705 mm of water input in 2004 (Table 5.5). 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 rootzone was mostly between 50% and 80% of saturation, and soil moisture tensions went up to 90 kPa (see Figure 3.4 in Chapter 3.1). In field experiments near Kaifeng in the North China Plain, Feng Liping et al. (2007) obtained relatively low yields of 2.4-3.6 t ha⁻¹ with 750-1000 mm 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 total water input, with only one or two supplementary irrigation applications (Table 5.6). Table 5.7 compares performance indicators of aerobic rice, lowland rice, and maize obtained by the same farmers. Simulation model predictions even suggested that no irrigation would be needed for high yields with some 400-600 mm 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 (Pirão *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 relative 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 2500 to 4500 mm annual rainfall in the Philippines. Yields of 6 t ha⁻¹ and more, however, were only realized incidentally in 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 rice varieties in farmers' fields in rainfed uplands in the Philippines. Though the amount of rainfall was not reported, the conditions of the trails 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 1240-1880 mm in flooded fields and 790-1430 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 adoption of aerobic rice by farmers in the tropics are in some rainfed uplands in Batangas province, the 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).

Table 5.4. Water input (I = irrigation; R = rainfall) and yield of two aerobic rice varieties 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
		350	644	5.3	4.7
	Aerobic	283	577	4.6	4.3
		292	586	4.3	4.2
		225	519	3.5	3.4
		175	469	3	2.5
2002	Flooded	900	1,255	4.6	5.3
		522	917	5.7	5.3
	Aerobic	374	769	4.8	4.7
		225	620	4	3.9
		300	695	4.3	4.6
		152	547	3.6	2.9

Table 5.5. 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	3.7	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 5.6. Performance of aerobic rice grown by farmers around Kaifeng, northern China, in terms of yield and water use, 2002-2003. 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	566	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	818	842	820	836	

Table 5.7. Average performance of aerobic rice, lowland rice, and maize near Kaifeng, northern China, 2002-2003. Data from: [unpublished data China Agricultural University, IRRI](#).

Item	Lowland rice	Aerobic rice	Maize
2002; number of farmers:	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 cost (\$ 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
2003; number of farmers:	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

Practical implementation.

Temperate environment/China. Promising aerobic rice varieties in northern China are HD277, HD297, HD502. Before sowing, the land should be dry prepared by ploughing and harrowing to obtain a smooth seed bed. Seeds should be dry seeded at 1-2 cm depth in heavy (clayey) soils and 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. The sowing of the seeds can be done manually (eg 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 seedling can't take up N so fast, so it will easily leach out).

Second and third split applications may 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 depend on the rainfall pattern, the depth of groundwater, and on the availability and/or cost of irrigation water. No concrete indicators for the application of irrigation water have been developed so far. Irrigation can be applied by any 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! Main problems to overcome in the development of tropical aerobic rice are listed in [Chapter 6.1](#).

5.4.1 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 permanent 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 the irrigation water is coursed (in irrigation engineering terms, the system of raised beds is called “furrow irrigation”). Though dimensions may vary, beds are quite often 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. Tractor-pulled equipment has been developed that shape the beds and drill seed (sometimes together with fertilizers) in one operation. In raised beds, the soil of the beds can be kept close to saturation (see [Chapter 5.3.1. Saturated Soil Culture](#)) or “aerobic” as in any other crop under furrow irrigation. In the latter case, specially adapted aerobic rice varieties may give best results.

Among the suggested benefits of raised beds are improved water 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, [Kukul 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 non-puddled 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 1600 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.

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 (<http://www.rwc.cgiar.org/index.asp>). Problems to overcome are listed in **Chapter 6.1**.

5.4.2 Ground cover systems

With aerobic rice, resource-conserving technologies, 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 6000 ha of farmer adopters. The proclaimed

advantages are: earlier crop establishment by three weeks (rice is established in early spring when temperatures are still low, and the plastic sheet increases 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 left-over plastic after harvest may cause environmental degradation if not properly taken care of.

Practical implementation.

Specific information on minimum tillage and resource-conserving technologies can be obtained from the Rice-Wheat Consortium (<http://www.rwc.cgiar.org/index.asp>).

5.5 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 4), on the irrigation infrastructure (or the level of control that a farmer has over the irrigation water), and on the socio-economics of their production environment.

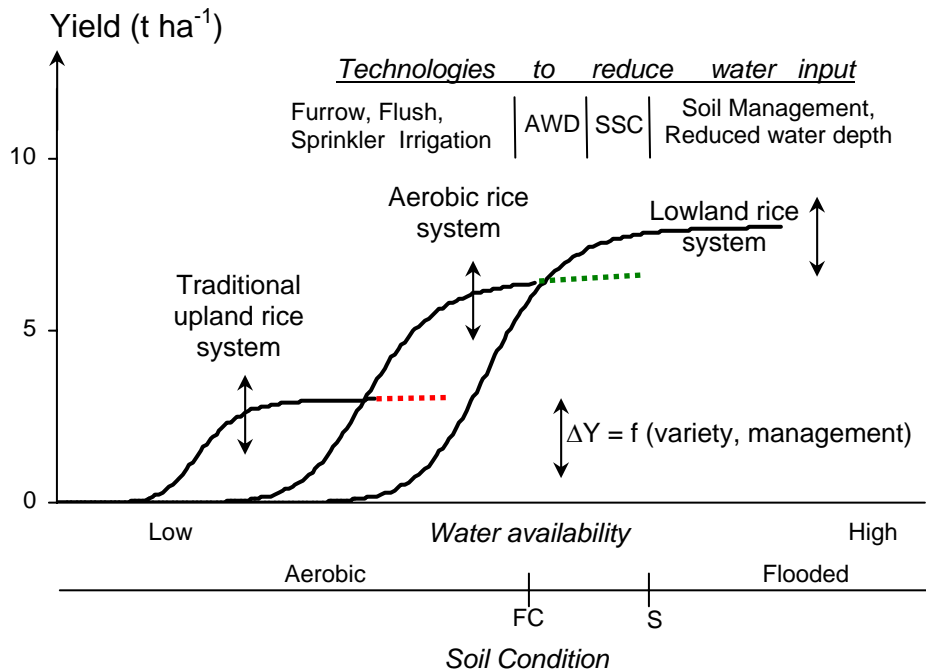


Figure 5.5. Schematic presentation of yield responses to water availability and soil condition in different rice production systems and their respective technologies to reduce water inputs. AWD = alternate wetting and drying, SSC = saturated soil culture, FC = field capacity, S = saturation point, $\Delta Y = f(\text{variety, management})$. Adapted from: Tuong et al. (2005).

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 5.5 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.

With sufficient water available, even having ‘the basics right’ will contribute to good crop growth and development and high yields: good land leveling, bund maintenance, presence of field channels, and thorough puddling (in case of puddled systems). “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 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, 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 3 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) 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 first be to check ‘the basics’. The amount of water loss that can be reduced depends on the initial condition of the paddy field; if the basics are right from the start, there is not much that can be done anymore. With progressing water scarcity, alternative establishment options to transplanting can be considered if the turn-around time between soaking and transplanting is relatively large, such as in some large-scale irrigation systems. If community seed beds, or a commercial provider of seedlings could be organized, then 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 the 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 only be effective in relatively clayey and impermeable soils that don’t need puddling to reduce the permeability anymore.

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 one 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 requires 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 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 larger (letting the water in the 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 7).

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 paddy fields are given in Table 2.1 in Chapter 2.1. 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 Pruitt, 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 5.8). 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 foregoing the wet land preparation. An example of the cross-over point in terms of water availability where aerobic rice gives higher yields than flooded lowland rice is given in Figure 5.6 for field experiments close to 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 1300-1400 mm water input at the right-hand side of the horizontal (water) axis, the lowland variety JD305 gave 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 1100 mm water

input, and under aerobic soil conditions, the aerobic rice varieties HD297 and HD502 outperformed the lowland variety.

Table 5.8. Comparison of water use in a hypothetical aerobic rice crop with that of lowland rice on different soils 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

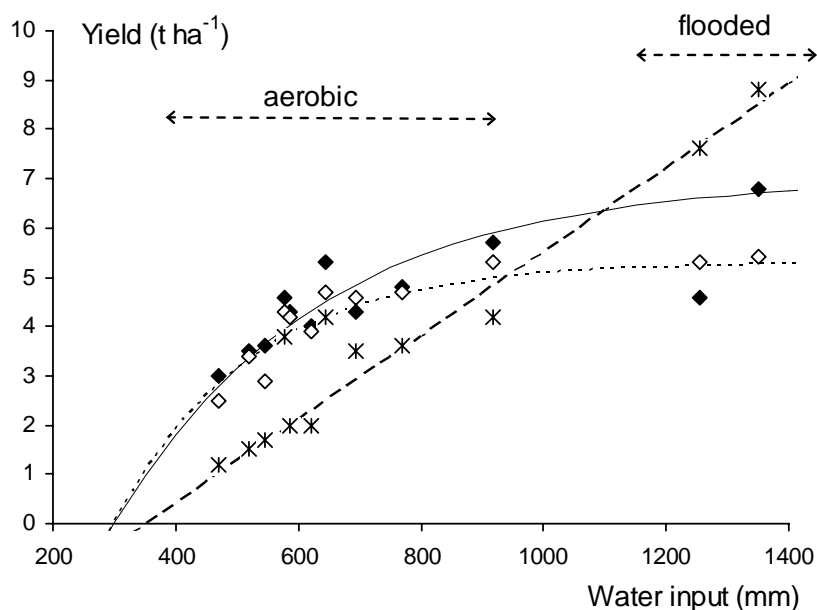


Figure 5.6. Yield of the aerobic rice varieties HD297 (\diamond) and HD502 (\blacklozenge) and of the lowland rice variety (JD305; \times) at different levels of water input. Data from: [Yang Xiaoguang et al. \(2005\)](#)

When water is physically available, but has a high cost, then 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 5.7** 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 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 it 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 P₂O₅ ha⁻¹ and 40 kg K₂O ha⁻¹. The soil SP rate was 9-14 mm d⁻¹. Going from right to left on the horizontal axis, water use was reduced with adopting increasing intervals between irrigations in AWD. Yields were initially not affected, but after a certain point, yields went down with less water use. This happened somewhere below 1750 mm in the top curve, and somewhere below 1000 mm in 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.

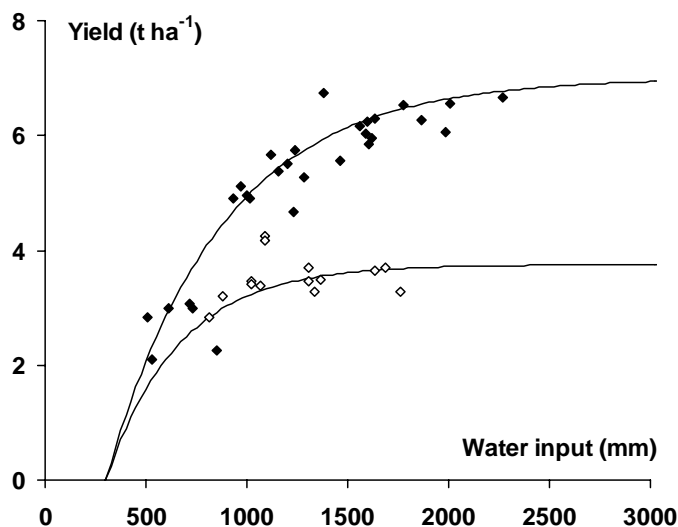


Figure 5.7. Yield versus water input in two experiments in India. Top curve data (♦) are from Cuttack, Orissa, (Jha *et al.*, 1981), and bottom curve data (◇) are from Pantnagar, Uttar Pradesh (Tripathi *et al.*, 1986). The curved lines are fitted production functions of the shape $[\text{yield} = a*(1 - e^{(b*(\text{water input} - c)})}]$. Adapted from: Bouman and Tuong (2001).

6 Environmental concerns

Water scarcity does not only affect the ability of paddies to produce food, but will also affect the environment and the other ecosystem services of paddies.

6.1. Sustainability

While relatively much work has been done on the development of technologies to maintain crop productivity under water scarcity ([Chapter 5](#)), little attention has been paid to 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 a 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 can not be continuously flooded anymore because of water scarcity, these beneficial affects 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 fully aerobic conditions, whether in flat land or on raised beds, problems with micro-nutrient 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 rice-rice cropping (Roland Buresh, pers. comm.).

There are indications that soil-borne pests and diseases such as nematodes, root aphids, and fungi occur more in nonflooded 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 can not be grown continuously on the same piece of land each year (as can be successfully done with flooded rice) without yield decline ([George *et al.*, 2002](#)). [Figure 6.1](#) presents recent data from a continuous aerobic rice cropping experiment at IRRI ([Bouman *et al.*, 2005](#); [Peng *et al.*, 2006](#)). Since 2001, the 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, the 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 *Meloidogyne graminicola* are found in the aerobic rice fields (up to 3000 counts g⁻¹ fresh root) compared with the flooded fields (6-400 counts g⁻¹ fresh root; unpublished data).

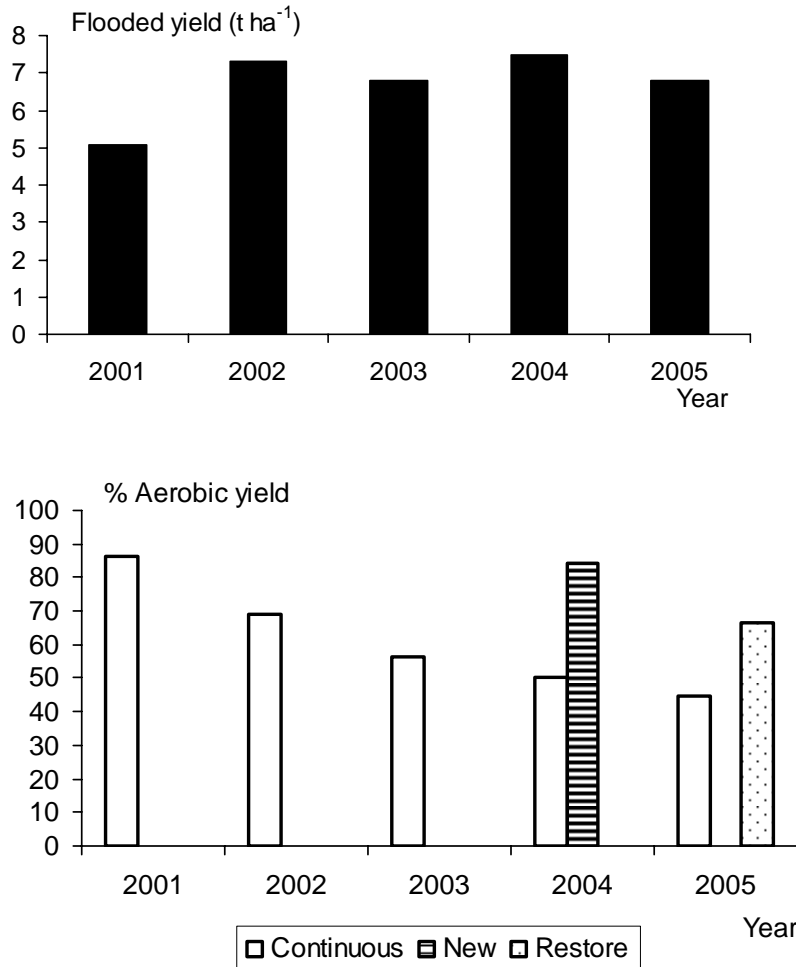


Figure 6.1. Yield of aerobic rice variety Apo under flooded conditions (top panel) and relative yield of Apo under aerobic conditions (as % of the Apo yield under flooded conditions) (bottom panel). In the bottom panel, the white columns indicate continuous aerobic conditions, the striped columns indicate yield under new aerobic conditions after conversion of flooded fields, and dotted columns indicate yield under restored aerobic conditions after one year of fallow or flooded conditions (average is given). Data from: [Bouman et al. \(2006a\)](#).

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 (**Figure 6.2**). Usually, such fields had a light soil texture and had 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 to these soil sicknesses.

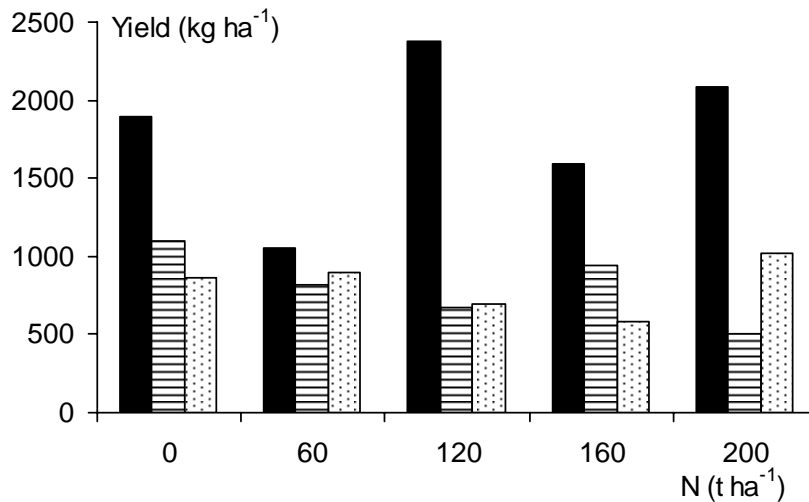


Figure 6.2. Yield of aerobic rice variety Apo under aerobic soil conditions at IRRI in 2004, at 4 levels of fertilizer N supply, and under three levels of water input (black bar = 1,147 mm; striped bar = 772 mm, and dotted bar = 632 mm). Unpublished data IRRI.

6.2 Environment and ecosystem services

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, are 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 than under flooded conditions, but higher nitrous oxide emissions (Bronson *et al.*, 1997a,b). However, the relative emissions of these greenhouse gases vary with environment and management practices (Dittert *et al.* 2002). The overall impact of adoption of water-saving management practices in rice

production on global warming is unknown. 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 1.2](#). 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.

7 Irrigation systems

7.1 Water flows in irrigation systems

Irrigated rice fields are characterized by large volumes of outflows by surface drainage, seepage and percolation (Chapter 2.1). 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 (Figure 7.1). Surface drainage and seepage water usually flow into downstream fields and are only 'lost' at the bottom of a toposequence when they flow into drains or ditches. However, farmers can use small pumps to lift water from drains to irrigate fields that are inadequately, or not, serviced by the irrigation canals. In many irrigation systems in low-lying deltas or flood plains with impeded drainage, the continuous percolation of water has created shallow groundwater tables close to the surface (Chapter 2.2). 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.

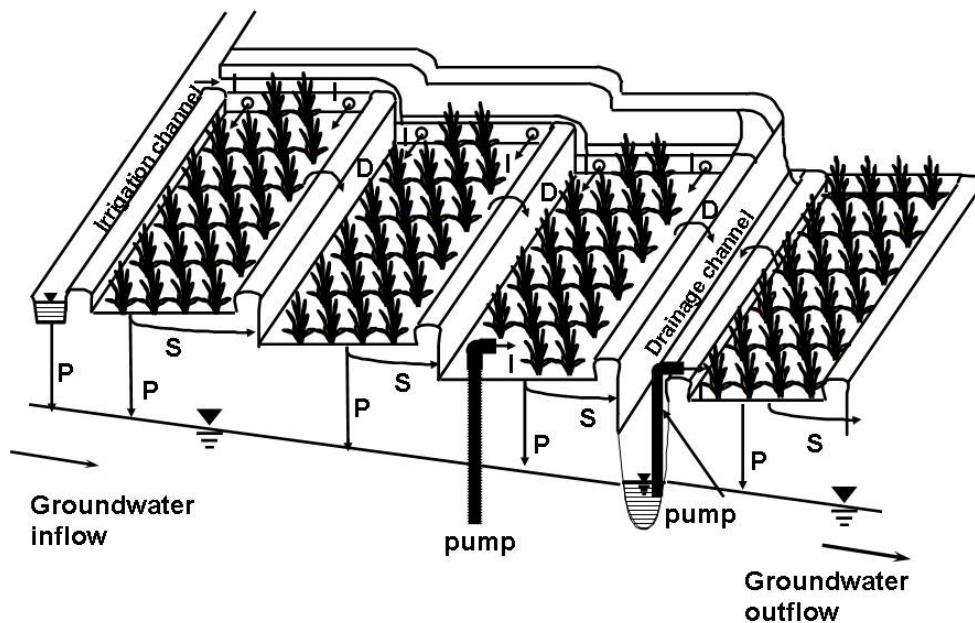


Figure 7.1. Surface and subsurface water flows across a toposequence of rice fields. D = drainage (over-bund flow); I = irrigation, P = percolation; S = seepage.

Recent studies of rice-based irrigation systems in China and the Philippines indicate that the irrigation efficiency improves 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 initiatives 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 in 18,000 ha of District I of the rice-based Upper Pampanga River Integrated Irrigation System (UPRIIS) in central Luzon, Philippines (Figure 7.2). 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 7.3 presents the amount of water reuse by the check dams and by pumping as function of spatial scale in the area.

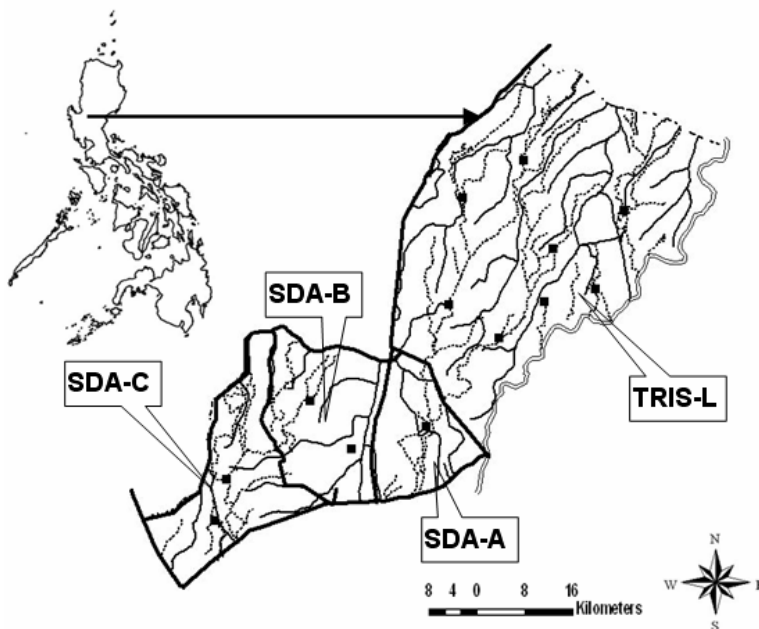


Figure 7.2. Location map of District I, UPRIS. The dots indicate the location of check dams for reuse of surface drainage water. Source: Hafeez (2003).

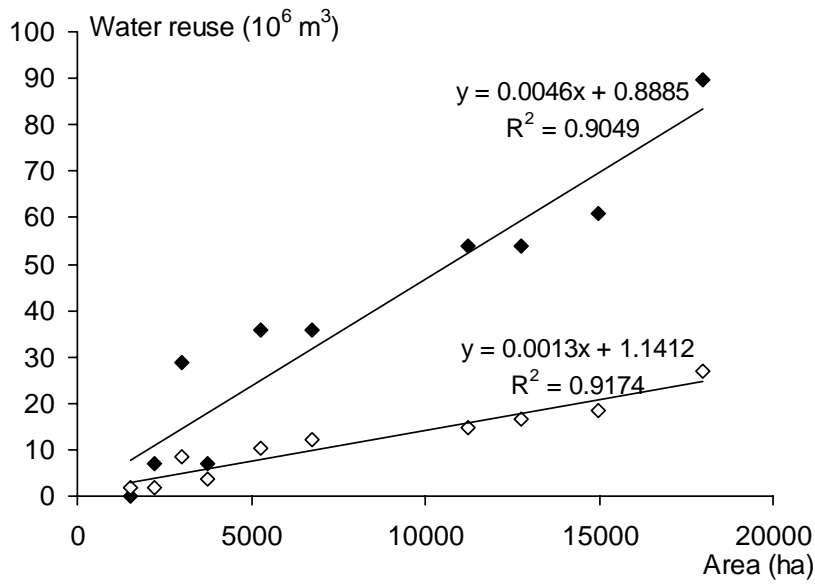


Figure 7.3. Volume of reuse of surface water by check dams (◆) and volume of pumped water (◇) versus spatial scale. The lines are linear regressions. Data from: [Hafeez \(2003\)](#).

Although water can be efficiently reused this way, it does, however, come at a cost, especially to the 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, e.g., 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 requirements is met from rainfall. This is especially true in large irrigation systems with considerable lag time 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 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](#)).

7.2 Field versus irrigation-system level

The relationships between water use at the field and at the irrigation-system levels are complex and involve hydrologic, infrastructural, and economic aspects. At the field level, farmers can reduce water losses by adopting water-saving technologies ([Chapter 5](#)). 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 2.2; 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 farmer. 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 brings about an economic cost.

7.3 Integrated approaches

Approaches that integrate agronomic measures, improved policies, institutional reforms, and infrastructural upgradings may have the best changes of successfully responding to water scarcity. A recent success story is the Zanghe Irrigation System (ZIS) in the middle reaches of the Yangtze Basin, 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 seventies, the amount of water released to agriculture has been steadily reduced in favor of increased releases to cities, industry and hydropower (Figure 7.4). Since the mid-nineties, the amount of water received by agriculture has been less than 30% of the amount received in the early seventies. In the same period, however, total rice production has increased, with a production peak of around 650,000 tonnes 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 tonnes 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; 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.

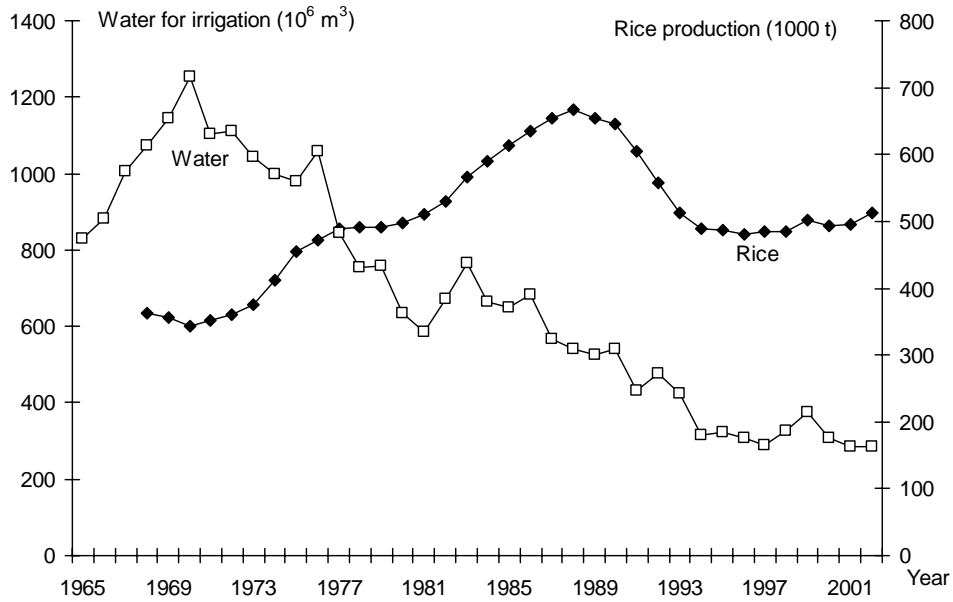


Figure 7.4. Total rice production and irrigation water supply in Zanghe Irrigation System, Hubei, China, between 1965 and 2002. Data points are 5-year moving averages. Data from: [Hong et al. \(2001\)](#); plus unpublished data

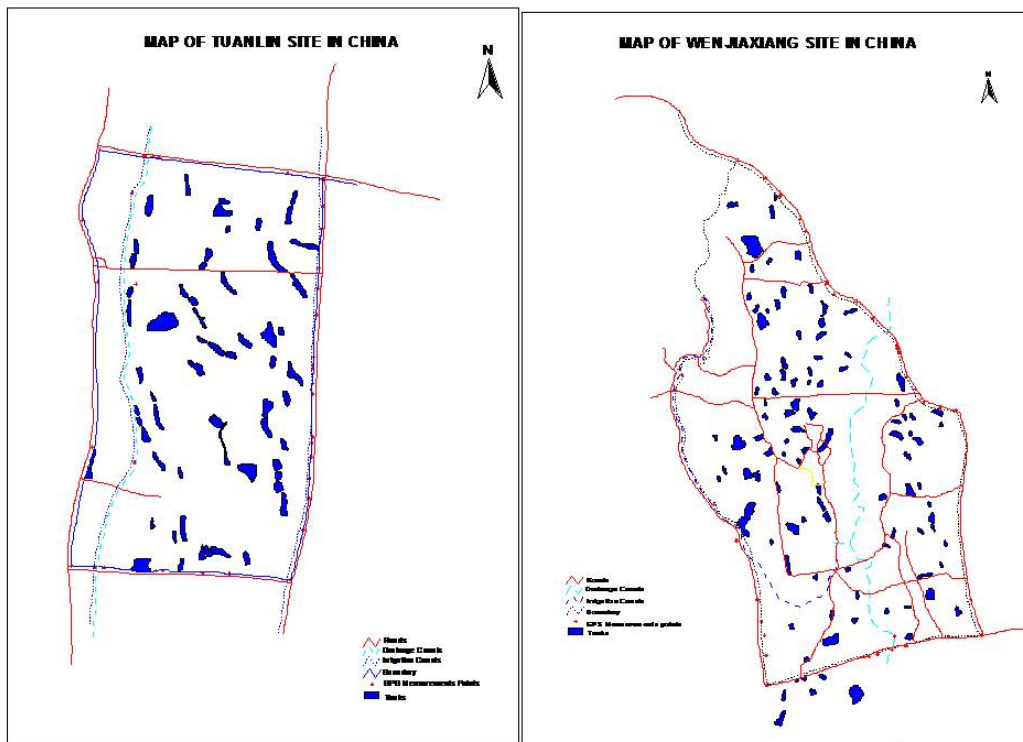


Figure 7.5. Secondary storage reservoir and ponds in 287 ha Tuanlin (left) and in 606 ha Wengjiaxiang (right) in Zanghe Irrigation System, Hubei, China.

- 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 (Figure 7.5).

The ZIS case study suggests that win-win situations can exist where rice production can be maintained, or even increased, while freeing up water for other purposes.

7.4 Optimizing water productivity

When water is scarcer than land, it may be beneficial to maximize water productivity rather than land productivity (which is yield). 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 the 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 7.1 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 5.1.a, and are expressed in units of kg and m in Table 7.2. 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 $69 \times 10^6 \text{ m}^3$. With a full reservoir, this amount of water is sufficient to have 10,000 ha of flooded rice. Suppose there is water scarcity and that the reservoir is only filled for 80%, storing $56 \times 10^6 \text{ m}^3$ 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, 57% of the command area receives the “full” amount of water, allowing these farmers to grow flooded rice, and the remaining 43% receives a reduced amount that is sufficient to grow rice under AWD. In scenario I, the total rice production in the irrigation system is 59×10^3 tonnes, and in scenario II, it is 71×10^3 tonnes. Moreover, there is more equity among the farmers in scenario II than in scenario I.

Table 7.1. 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 $56 \times 10^6 \text{ m}^3$ of water available.

Land use	Area (ha)	Water use (10^6 m^3)	Production (tonne)
Scenario I			
Flooded	8,000	55.8	59,200
AWD	0	0	0
Fallow	0	0	0
Sum	8,000	55.8	59,200
Scenario II			
Flooded	5,680	39.6	42,032
AWD	4,326	16.0	28,987
Fallow	0	0	0
Sum	10,006	55.7	71,019

Table 7.2. Yield, water productivity with respect to total water input (WP_{IR}), and water input of flooded rice and rice grown under AWD.

	Yield (kg m^{-2})	WP_{IR} (kg m^{-3})	Water use ($\text{m}^3 \text{ m}^{-2}$)
Flooded	0.74	1.06	0.69
AWD	0.67	1.81	0.37

Our example also illustrates the effect of taking AWD irrigation as starting point in the development of a new irrigation system. Suppose that a hypothetical reservoir can be constructed with a capacity of $69 \times 10^6 \text{ m}^3$, and that a command area will be designed for rice farmers getting 1 ha each. If AWD irrigation is the design criteria rather than flooded rice, the irrigated rice area and total rice production are larger, and more farmers will benefit from irrigation development (**Table 7.3**).

Table 7.3. Area under rice production, and total water use, rice production, and number of farmers, with flooded rice and with AWD as design criteria.

Design criteria	Rice area (ha)	Water use (10^6 m^3)	Production (tonne)	Farmers (number)
Flooded	10,000	69	74	10,000
AWD	18,649	69	125	18,649

The above examples are quite simple (and ignore complexities of diversified cropping and of systems operation to allow farmers to practice AWD) but illustrative of the effect of including the concept of water productivity (beside yield) in irrigation system design and management.

8. 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 very simple tools that are practical in characterizing the water status (hydrological conditions) of rice fields and can help guide the implementation of some water-saving technologies.

8.1 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 is just below the surface ([Figure 8.1](#)). Perforate a hollow and bottomless PVC-tube of about 20 cm 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 everyday. 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 the water is standing on the field, a positive value means the water level is below the surface. [Table 8.1](#) gives the interpretation of some readings. 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 it is 15 cm.

Table 8.1. Example readings and interpretations of water depth in the field water tube, for a tube that is 35 cm long and protrudes 15 cm above the soil surface.

Water level	Water depth	Interpretation
5 cm above top of tube	-20 cm	20 cm depth of standing water on the field (tube is overflowing)
5 cm below top of tube	-10 cm	10 cm depth of standing water on the field
15 cm below top of tube	0 cm	Water level exactly at the soil surface
30 cm below top of tube	15 cm	Water level is 15 cm below the surface
35 cm below top of tube	20 cm	Water level is 20 cm below the surface,
No water in the tube	Unknown	Water is deeper than 20 cm below the surface

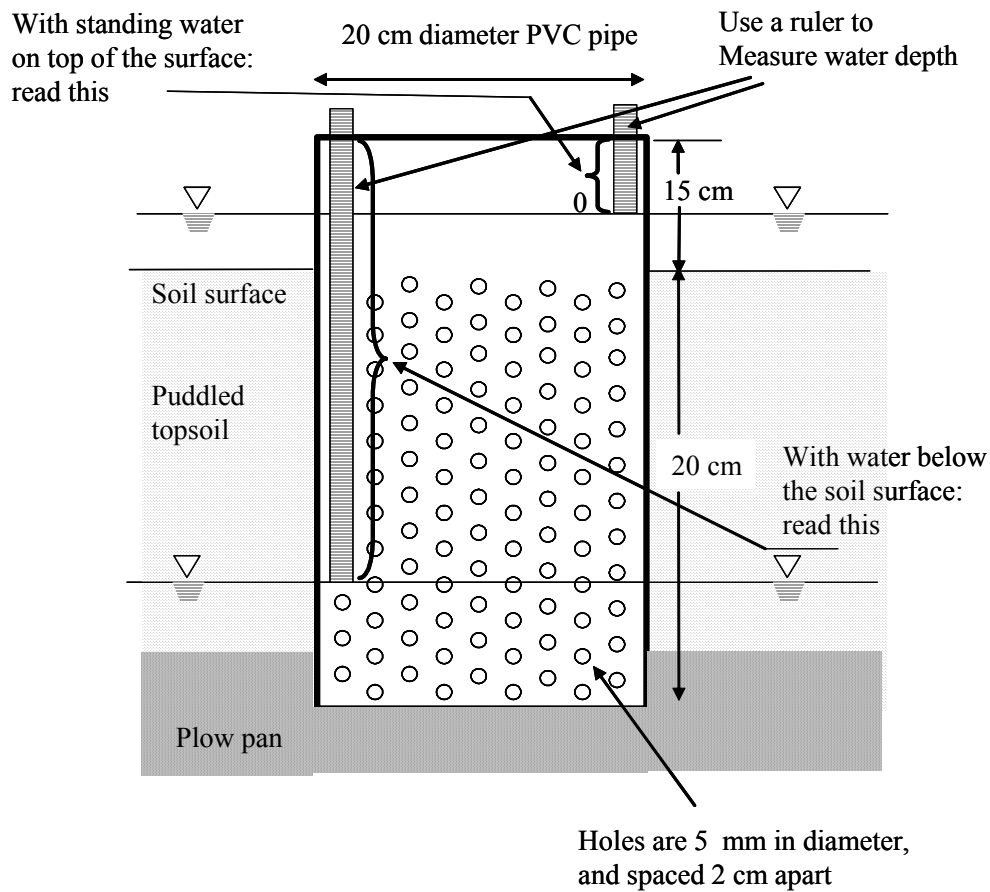


Figure 8.1. Field water tube for monitoring the depth of standing water on a rice field.

8.2 Groundwater tube

The groundwater tube is used to measure the depth of the groundwater below the rice fields (Figure 8.2). Cut a length of 175 to 250 cm of hollow and bottomless PVC-tube of about 5 cm 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. 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 installed, any groundwater water will flow through the holes into the tube, so that the water level inside the tube indicated 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 bambu. 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! Table 8.2 gives the interpretation of some readings. 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 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.

Table 8.2. Example readings and interpretations of water depth in the groundwater tube, for a tube that is 175 cm long and protrudes 50 cm above the bund.

Water level	Water depth	Interpretation
5 cm above top of tube	-55 cm	55 cm depth of flood water above the bund (tube is overflowing)
10 cm below top of tube	-40 cm	40 cm depth of flood water above the bund
50 cm below top of tube	0 cm	groundwater exactly at the level of the bund
150 cm below top of tube	100 cm	groundwater is 100 cm below the bund
175 cm below top of tube	125 cm	groundwater is 125 cm below the bund
No water in the tube	Unknown	groundwater is deeper than 125 cm below the bund

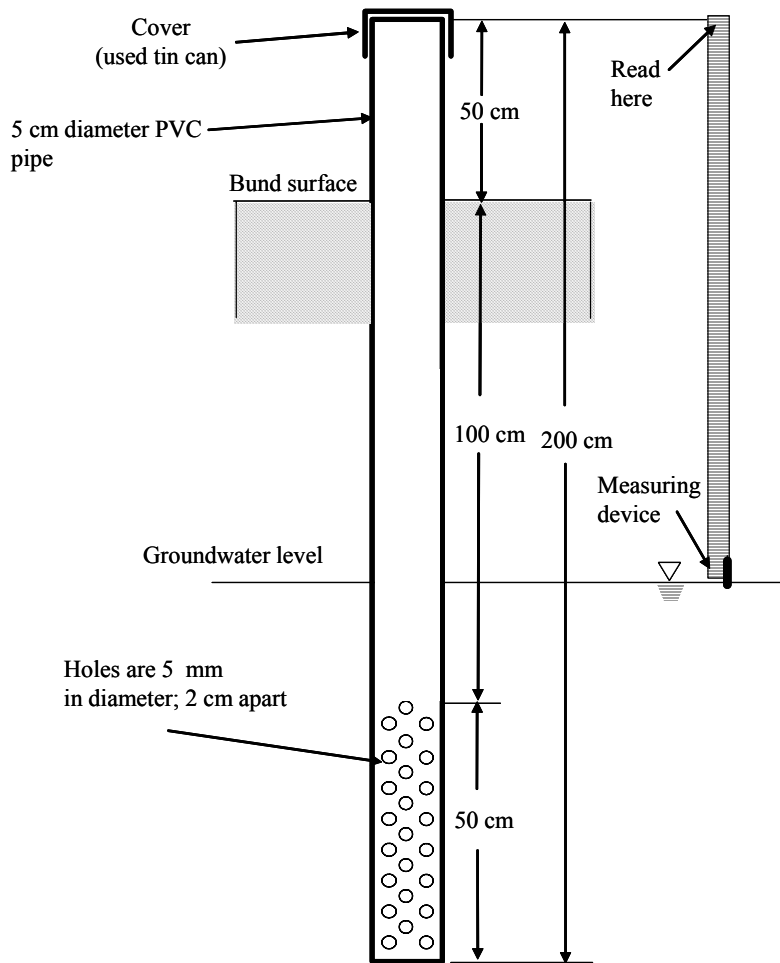


Figure 8.2. Groundwater tube for monitoring the groundwater depth below rice fields.

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