Chapter 5

Water Balance of Flooded Rice in the Tropics

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Additional information is available at the end of the chapter

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1. Introduction

1.1. Rice as a world food

The world human population has been estimated at 7.2 billion in mid-2013 and is projected to reach 9.6 billion by 2050 [1]. There is an urgent need for current world food production levels to substantially be increased in order to avoid hunger and starvation of ever increasing human population. Rice and wheat are important sources of food for people around the world. Moreover, rice is considered as a staple food for about half of the world's population [2]. More than 56-61 per cent of the world's population lives in the Asian Region and the Asian population is growing at 1.8 per cent per year which adds 45-51 million more rice consumers annually [3,4]. Over 90 per cent of the world's rice is produced and consumed in the Asian Region by countries such as China, India, Indonesia, Bangladesh, Vietnam and Japan [4]. It has been estimated that rice production has to be raised by at least 70 per cent over the next three decades to meet the growing demands [5]. The demand for rice and its value-added products is growing steadily, with consumption stretching beyond Asia. For example, annual rice consumption in Australia increased from approximately 5 kg/capita to 10 kg/capita during the past nine years [6].

World rice production in 2013 accounts for 496.6 million tonnes of milled rice and only 37.3 million tonnes (i.e. 7.5% of total production) was traded between countries [7]. Australia produced 1.16 million tonnes of paddy rice in 2013 and usually exports 85% of its rice production to more than 60 countries around the world [8]. Irrigated rice in the world accounts for 79 million hectares (55% of the global harvested rice area) and contributes 75% of global rice production [9]. To keep pace with population growth, rice yields in the irrigated environments must increase by 25% over the next 20 years [9]. Irrigation is the main water source in the dry season and is used to supplement rainfall in the wet season. Inefficient use of irrigation water is one of the main agronomic problems encountered where intensive rice cultivation is practiced.

1.2. Features of tropical regions

Most of the world's rice is grown in the tropics. The tropical region comprises the area between the Tropic of Cancer (23°27'N latitude) and the Tropic of Capricorn (23°27'S latitude). This region experiences tropical climate which is usually marked by hot and humid weather conditions. Vast amount of sunshine along with extremely heavy rainfall is the distinct feature of this climate. The season is marked with two wet and two dry seasons in areas close to equator. Further away from the equator, the climate becomes as monsoonal which has one wet season and one dry season. Wet seasons in the Northern Hemisphere occur during May to July and in the Southern Hemisphere during November to February [10].

The tropical regions of Australia are in the north of the country and include the equatorial and sub-tropical zones (Figure 1) which experience hot temperatures and very high relative humidity values. The wet season which is sometimes referred as the monsoon season starts in November and finishes in March next year. It is usually hot where the temperature varies between 30 and 50 degrees Celsius. Large amounts of water vapour in the atmosphere create high humidity during the wet season. Frequent flooding may occur due to heavy rain events during the wet season. The dry season starts in April and finishes in October. Low temperatures and clear skies are the main characteristics during the dry season. Average temperature in the dry season is about 20 degrees Celsius [11].

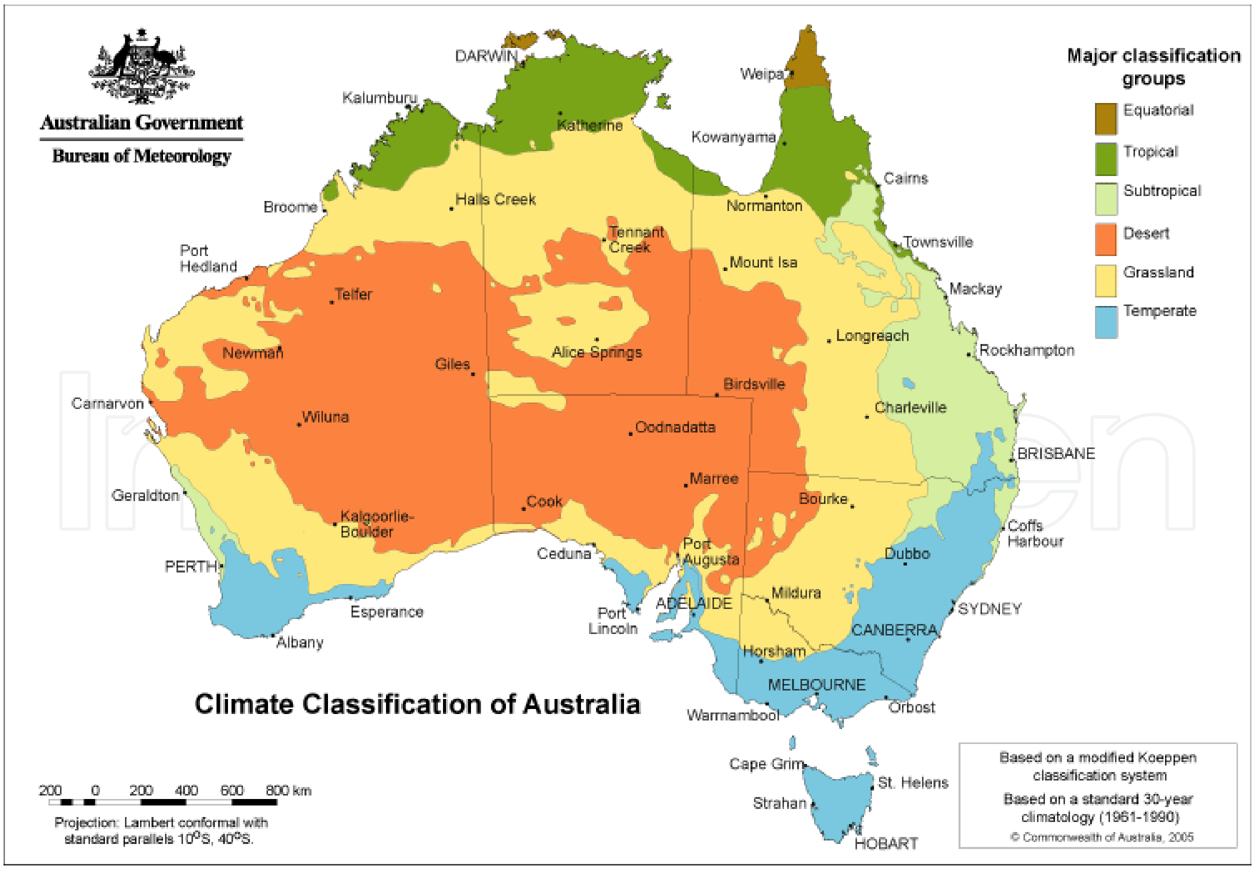

Figure 1. Tropical regions of Australia. Source: [12].

The tropical region in Australia covers 5 to 17 million hectares of arable soil. It is important to realise that the run-off from this region is roughly 152,000 GL and less than 6 per cent of this run-off is currently being used. In contrast, the total amount of water used for agriculture in the whole country is about 12,200 GL [13]. Therefore, it is predicted that by increasing the usage of available water resource in the tropical regions of northern Australia, it would be possible to double Australian agricultural output and make a significant contribution towards combating global hunger and supporting food security [13]. For example, suitable soil types, a warmer climate, and availability of irrigation water make the Ord River Irrigation Area in north-eastern Western Australia ideal for growing rice. Potential yields up to 14.3 t/ha have been demonstrated in this environment [14].

1.3. Rice cultivation

Rice belongs to the family *Gramineae* and genus *Oryza*. The genus *Oryza* comprises about twenty species distributed through tropical and subtropical regions of Asia, Africa, Central and South America and Australia. There are only two species of cultivated rice, *O.sativa* and *O.glaberrima*. *O.sativa* is a common rice widely grown in the tropical and temperate zones, and *O.glaberrima* is endemic to West Africa. Cultivars of *O.sativa* are divisible into three types or races: *Indica*, an elongated, thin and slightly flattened grain which stays separate in cooking; *Japonica*, a broad, thick, short, rounded grain which tends to soften if over-cooked; and *Javanica*, a long and sticky variety which possibly originated in Indonesia.

Rice is a remarkable semi-aquatic plant which has been cultivated for at least 8,000 years in widely different agro-climatic regions of the world. *O.sativa* grows at latitudes from 36° south in Australia to 49° north in Czechoslovakia at altitudes from sea-level to 2,400 metres in Kashmir. *O.sativa* is grown extensively in tropical and temperate regions, normally in water (lowland) but also as a dry-land (upland) crop. It is believed that rice cultivation must have begun at several different locations in Asia between 7,000 and 8,500 years before present time. *O.sativa* probably spread from India to Egypt, Europe, Africa, the Americas and Australia in that order.

First likely introduction of rice seed into southern Australian gold fields was by Chinese prospectors in the 1850s cultivating it in marshy areas or in ponds using effluent from mining. In the 1860s, a small rice industry using upland varieties and Chinese labour emerged in the northern Queensland to supply local demand in the North Queensland gold fields. In 1906, a Japanese ex-parliamentarian, Isaburo (Jo) Takasuka, began cultivating rice using Japanese (Japonica) varieties near Swan Hill in Victoria. In 1924, a commercial rice industry began around Leeton and Griffith in New South Wales.

1.4. Water management of rice

Rice requires more water than most other crops. Most rice varieties achieve better growth and produce higher yields when they are grown under flooded conditions than under aerobic conditions. In addition, the ponded water helps to suppress the weeds, especially broadleaf types. The ponded water provides protection against low night time air temperatures at some locations where the problem of cold damage to crop exists [15,16]. Paddy rice is usually grown in level basins which are flooded with water throughout most of the growing season. In general, areas of irrigated agriculture are prone to rising groundwater, waterlogging and salinity under poor irrigation practices when excess groundwater recharge rates occur. Under extreme circumstances, these negative effects may lead to loss of arable land and/or create additional crop or land management practices for which the grower may need to cover the extra costs. It is believed that flooded rice systems may have contributed to excess groundwater recharge rates at some locations [17,18].

It has been estimated that up to 62% of the world population will be facing water scarcity by 2030 [19]. Currently, there are many countries experiencing water scarcity for food production, for example, China [20]. Hence water will be a major constraint for agriculture in coming decades. The actual water availability in Asia, for example, decreased from 9.6 ML/year.capita in 1950 to 3.37 ML/year.capita in 1990, due to the increase in population [21]. In Asia, about 90% of fresh water diverted from water resources is used for agricultural purposes and more than 50% of this water is used to irrigate rice [22]. World population increase will likely further reduce the availability of water per capita in many countries. Hence, an appropriate response to water scarcity is to focus on the improvement of the overall productivity of water (i.e. the output of goods and services in physical or monetary terms per unit of water applied or consumed) to feed an ever-increasing world population.

With increasing water scarcity for irrigation, productivity of current rice production systems has to be improved substantially. Attempts have already been made at the International Rice Research Institute in Philippines to improve the water productivity of irrigated rice-based systems in Asia [23,24]. Modern rice varieties and advanced water management techniques warrant new estimations of water losses from flooded rice crops. This study reports on a water balance approach taken to determine the evaporation, transpiration and deep percolation losses from flooded rice bays in a tropical environment using a set of lysimeters and lock-up bay tests. Deep percolation under ponded rice culture should be within acceptable leakage rates and should not unduly affect growers or environmental managers in terms of rising groundwater levels, waterlogging and salinity.

1.5. Water balance of rice fields

The term 'water balance' refers to the accounting of water going into and out of an area. The quantity of water added to, subtracted from, and stored within a set volume of soil during a given period of time is considered. It is assumed that in a given volume of soil, the difference between the amount of water added W_{in} to the soil and the amount of water removed W_{out} from the soil during a certain period is equal to the change in soil water content ΔW during the same period of time [25]:

$$\Delta W = W_{in} - W_{out} \tag{1}$$

For this study, it is most appropriate to consider the water balance of the root zone per unit area of field. Thus the root zone water balance is expressed as [25]:

$$(\Delta S + \Delta V) = (RF + IR + UP) - (RO + DP + E + T) \tag{2}$$

where

ΔS is change in root zone soil moisture storage

ΔV is increment of water incorporated in the plants

RF is rainfall

IR is irrigation water

UP is upward capillary flow into the root zone

RO is runoff

DP is downward drainage out of the root zone

E is direct evaporation from the soil/water surface

T is transpiration by plants

All quantities in Equation (2) are expressed in terms of volume of water per unit area of soil (that is equivalent depth units) during the period considered. Thus the components of the water balance equation are expressed in units of water depth (mm), assumed to be spread uniformly across the paddock:

$$1 \text{ mm on 1 hectare} = 10 \text{ m}^3 = 10{,}000 \text{ L} = 0.01 \text{ ML} \tag{3}$$

The various items entering into the water balance of a hypothetical rooting zone for a flooded rice system are illustrated in Figure 2. The principal moisture losses from the rice paddy may be grouped into vapour losses and losses in liquid form. The vapour losses are loss by transpiration from the leaf surface and by evaporation at the water surface. The liquid losses are the downward movement or vertical percolation of free water and the runoff of excess water over the field levees. The combined losses of water resulting from plant transpiration and surface evaporation are called evapotranspiration (ET). It is also commonly referred to as consumptive water use. The ET rate is affected by solar energy, temperature, wind or air movement, relative humidity, plant characteristics and soil water regime [26].

A direct method for measuring field water balance is using a set of lysimeters. A lysimeter is a container filled with soil and installed in the field so that it will represent the prevailing soil and climatic conditions. It allows accurate measurement of certain physical processes occurring in the field. In terms of the field water balance, these lysimeters allow continuous measurement of both evapotranspiration and percolation. The change in water level in square or circular tank lysimeters is measured to refer to evapotranspiration [27,28].

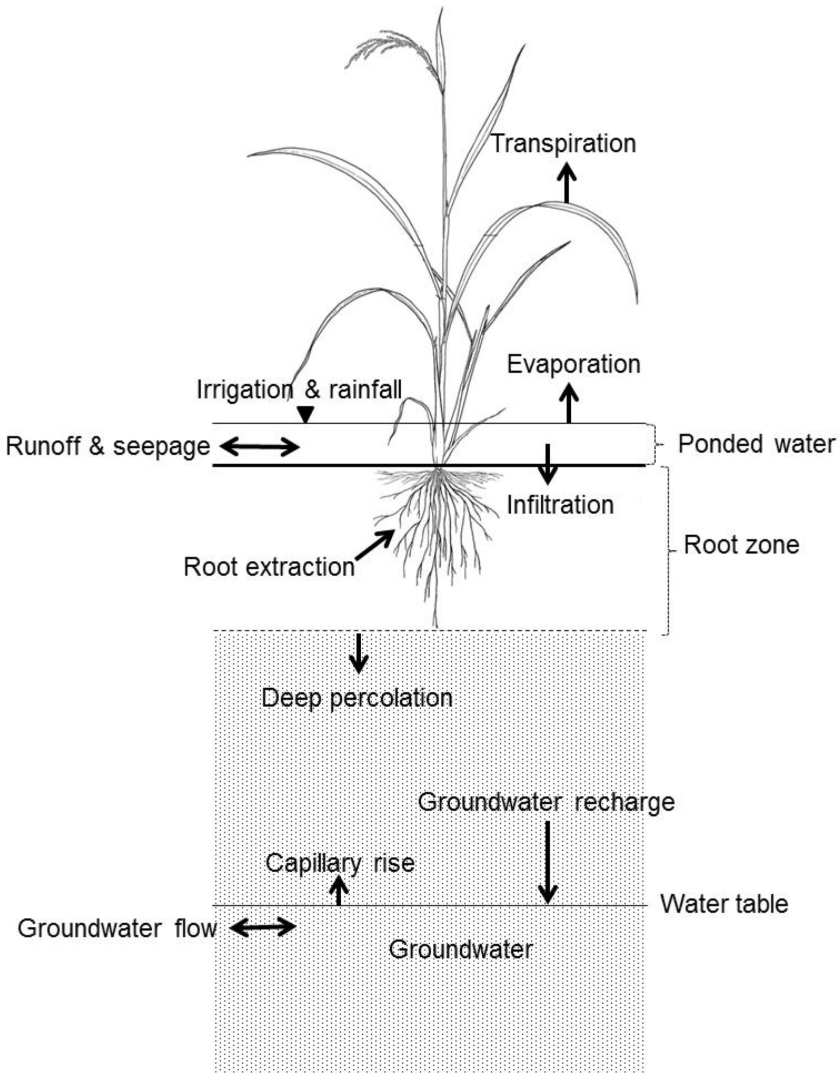

Figure 2. Schematic representation of the water balance of a flooded rice field.

2. Materials and methods

2.1. Site description

The study was conducted at a site (15.65ºS latitude, 128.72ºE longitude, 31 m altitude), located within the research facility of the Frank Wise Institute of Tropical Agriculture in Kununurra in Western Australia. The Frank Wise Institute of Tropical Agriculture is the regional office of the Department of Agriculture and Food, Western Australia (DAFWA) to provide service to the local growers in the Ord River Irrigation Area (ORIA) to improve their farming business. The study site is located within a region which has a tropical monsoonal climate and most of the mean annual rainfall (about 825 mm) occurs during the period from October to April (Table 1). The warm climate (average annual maximum temperature is 35ºC) of the region enables rice to be grown twice (during the wet and the dry seasons) in a year. In addition, it is possible that the monsoonal rains during the period from November to March can provide more than half of the water required for a wet season rice crop. Since cloud cover can reduce the sunshine hours during the wet season, this might be a hindrance to achieve high rice yields. In addition, high humidity experienced during the wet season might favour the occurrence of certain pests and diseases (for example, the devastating rice blast disease).

Month	Air temp min(°C)	Air temp max(°C)	Humidity average (%)	Rain (mm)	Total solar (kJ/m²)	Wind max (km/h)
January	21.6	41.0	70.2	91.2	806586.6	52.56 E
February	22.8	41.3	75.2	146.4	666768.2	35.64 WSW
March	20.4	39.1	75.1	67.4	724862.3	43.56 ENE
April	12.8	38.7	67.4	89.6	685514.2	25.56 NNE
May	9.9	37.8	61.5	5.0	609878.9	34.56 NNE
June	8.9	35.3	54.9	3.0	605294.8	32.76 SSW
July	3.9	35.4	47.1	0.0	708597.7	25.20 SE
August	4.7	37.7	50.2	0.0	813523.3	29.16 ESE
September	14.0	40.5	54.3	0.0	814916.5	38.52 ESE
October	14.6	42.4	52.2	23.4	829273.6	47.88 NW
November	18.1	42.4	61.2	111.4	792809.0	48.60 NE
December	22.8	40.9	72.8	192.2	712451.7	48.60 NNE

Table 1. Local weather data from a meteorological station located near the study area during 2013 (source: [29]).

2.2. Soil characteristics

The study was conducted on Cununurra clay soil which is the major soil type in the region. This soil is classified as the great soil group of the Grey, Brown and Red Clays of Stace et al. [30]. It belongs to fine montmorillonitic typic chromo usterts in Soil Taxonomy (USDA) and Ug5 class of Northcote [31]. Typical Australian Soil Classification (ASC) for this soil type is self-mulching Vertosol [32]. The Cununurra clays could be referred as black soils, black earths or gilgai soils. These soils occur on the black soil plains. These soils were derived from parent materials formed by Riverine deposits. Typical soil profile description of Cununurra clay is given in Table 2 where relationship between approximate field texture and clay content is for loams 20%, clay loams 30%, light clays 40%, medium clays 50%, medium heavy clays 60%, and heavy clays 70% [33].

Horizon	Depth	Characteristics
A-11	0-5 cm	Very dark greyish-brown (2.5Y 3/2); light to medium clay; dry and loose (self-mulching); granular structure; smooth-ped to rough-ped fabric; and pH 7.5.
A-12	5-25 cm	Very dark greyish-brown (2.5Y 3/2); medium to heavy clay; dry and extremely firm; medium blocky structure; smooth-ped fabric; pH 8.0; traces of carbonate nodules; some manganiferous concretions; some indistinct slickensides; shrinkage cracks very evident; and peds approximately 4 × 8 cm.
A-13	25-125 cm	Very dark greyish-brown (2.5Y 3/2); heavy clay; dry and extremely firm; coarse blocky structure evident in the drier parts with prismatic peds 15 × 30 cm; smooth-ped fabric; pH 8.5; traces of carbonate nodules; some manganiferous concentrations; some lenses of fine sand; and shrinkage cracks sometimes penetrate the top of this horizon.
AC-1	125-140 cm	Dark brown (10YR 3/3, 7.5YR 3/2); medium to heavy clay; slightly moist and extremely firm; smooth-ped fabric; pH 8.6; 2-5% carbonate nodules; traces of manganese concretions; some weakly bound concretions of soil material and inclusions of AC-2 horizon material.
AC-2	More than 140 cm	Dark reddish brown (5YR 3/4); medium clay; slightly moist and very firm; pH 8.5; up to 5% large carbonate nodules; smooth-ped faces evident but fabric may be earthy; and increasing micaceous material.

Table 2. Soil profile description of Cununurra clay (source [34]; Copyright © Western Australian Agriculture Authority).

The most important characteristic common to all swelling clays including the Cununurra clay is the high content of clay size particles with expanding clay minerals such as montmorillonite. Cununurra clays are referred to as self-mulching due to formation of a thin surface layer consisting loose dry granules after repeated wetting and drying cycles [35]. Tillage is often very difficult on these heavy clays. The optimum moisture range for tillage is narrow. If the soil is too wet, moist soil will stick to implements. When the soil is too dry, it has considerable strength and will result in high implement draft, wheel slip and high fuel consumption. It will also accelerate wear on implement points and tractor tyres. These soils are normally cultivated dry to achieve a better tilth. Even a little moisture causes large clods to be turned up during ploughing. Generally, infiltration rates in swelling clay soils are low. The magnitude of subsoil conductivity is about 10^{-7} m/sec [34].

2.3. Water management

The trial was undertaken during the dry season under ponded rice culture (flooded system) covering the period from 12 June 2013 to 2 October 2013 (112 days). The crop was established by dry seeding (drill sown into cultivated seedbed) at a rate of 152 kg/ha to a depth of 2-3 cm and intermittently irrigated (flushing) twice, the first - immediately after sowing and the

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second - 14 days later. With intermittent flushing irrigation, the irrigation water was applied enough to cover the soil surface and quickly drained off after 2-3 hours. When the seedlings were 5-10 cm tall and at the 3-5 leaf stage, permanent water to a depth of 3-5 cm was applied, on 31 days after planting. A shallow water depth of 5-10 cm was maintained through the vegetative phase. As the crop approached the panicle initiation (PI) stage, water level was raised to 10-15 cm, and then further increased to achieve a depth of 20-25 cm at early pollen microspore (EPM) stage. Water level was raised to protect the developing panicle from cold temperatures. Once flowering commenced, the water level was allowed to drop to 5-10 cm. Water level of at least 5 cm depth was maintained through grain filling until lockup the bay for the remaining water to be used by the crop at physiological maturity.

In terms of water management of the experimental site, 'Lockup bay tests' as proposed in reference [36] were adopted. For a lockup bay test, the water flow between the bays is prevented and the change in water depth each day over a period of several days is recorded. In this trial, no inflow or outflow within the bay is maintained. This means applying water (top-up) to the paddock as required and then sealing the inlet to prevent further entry of water until the next irrigation event, usually in about 7 days. The outlet was kept sealed throughout the trial period. Since ponded rice culture was undertaken in adjacent bays in both sides, the lateral seepage from the test bay was considered minimum. Just before commencement of the experiment, the tail-end bank was sealed using a plastic barrier to prevent lateral seepage. With the application of permanent water to the crop on 10 June 2013, lockup bay tests were started and continued until the water in the bay disappeared on 2 October 2013 before harvest.

2.4. Setup of Lysimeters

A modified lysimeter experiment [26-28] was conducted to estimate water losses due to evaporation, transpiration and deep percolation under ponded rice culture. Three steel lysimeter rings (two with open-end and one with closed-end) were used. Each lysimeter ring was 50 cm in diameter, 70 cm in height and 5 mm wall thickness. The open-end type lysimeters were installed by pushing the cylinder vertically into the soil up to 35 cm below ground level using heavy machinery. Moist soil from previous flush irrigations made this process easy with minimum disturbance to the soil located inside and outside of the lysimeters. A 50 cm diameter and 35 cm deep hole was dug in the ground and the closed-end type lysimeter was pushed vertically into the hole. This lysimeter was filled with the same soil up to 35 cm. All three lysimeters had 35 cm of the ring protruding above the ground surface. Each lysimeter had a 10 mm diameter hole at 2 cm above ground level to facilitate entry of water into the lysimeter during irrigation events. This allowed the water level inside the lysimeter and that of the surrounding field be same at the end of irrigation. Immediately after irrigation, these holes on the lysimeters were closed using rubber stoppers and industrial lubricant. The holes were kept closed until the start of the next irrigation event when this procedure was repeated. All three lysimeters were installed in the cropped area (Figure 3) but only one open-end type lysimeter had undisturbed rice plants representative of the plants in the surrounding field. Any rice plants found in the rest of the lysimeters were removed.

Figure 3. Field setup of lysimeters and Class A Evaporation Pan for two planting configurations.

It was possible to measure the evaporation (E), transpiration (T) and deep percolation (DP) components by comparing losses from each lysimeter (Figure 4). During each irrigation event (i.e. topping up the bay), the side valve on each lysimeter was opened to allow water inside. Automatic water level recorders were installed in each lysimeter to monitor the water level at 30 minute intervals. Water losses were calculated within each irrigation cycle. Evaporation was the water loss measured in Lysimeter A. For comparison purposes, a Class A Pan was also installed at this site to measure the actual evaporation. Evaporation data from Lysimeter A was primarily used to separate the evaporation component from Lysimeters B and C. Transpiration was the water loss measured in Lysimeter C minus water loss measured in Lysimeter B. Deep percolation was the water loss measured in Lysimeter B minus water loss measured in Lysimeter A. In a flooded system, generally 90% of roots are located in the top 10 cm of the soil [37] and the internal drainage beyond the root zone has been referred to as deep percolation [25]. For this trial, water moving downward from open-end of the lysimeters at 35 cm depth was considered as deep percolation. A 10 cm diameter polyvinyl chloride (PVC) cylinder with a hole at ground level was also used to monitor the water level of the surrounding field. This PVC pipe allowed to remove the effect of ripples, that formed in the surrounding water in the field, on measurement of the water level by the recorder. The effect of different water levels within lysimeters compared with that of the surrounding field towards the end of the irrigation cycle, as shown in Figure 4, will be discussed later.

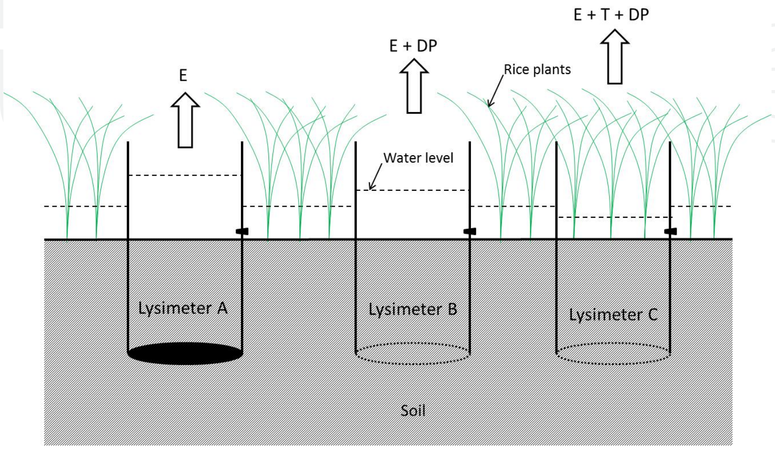

Figure 4. Diagram of lysimeters to measure evaporation (E), transpiration (T) and deep percolation (DP) losses in a paddy field, where the arrows indicate combined water losses.

2.5. Description of Class A pan

A Class A Evaporation Pan (Figure 5) was installed at the experimental site to measure the actual evaporation losses under a paddy field situation and to compare with evaporation observed in Lysimeter A described above. The pan was constructed according to FAO recommendations [38]. The Class A Evaporation pan was circular, 120.7 cm in diameter and 25 cm deep. It was made of galvanized iron (22 gauge). The pan was mounted directly on the ground surface within a cropped area and ponded water. The pan was made level before it was filled with water from the surrounding field to 5 cm below the rim. The water level was not allowed to drop to more than 7.5 cm below the rim by filling the pan whenever required. Few granules of Copper Sulphate were added to the water in the pan to prevent slime build up. The site was located within a large cropped field (Figure 3). An automatic water level recorder was used to monitor the changes in water level within the pan at 30 minute intervals. Measurements were made in a stilling well that was situated in the pan near one edge (Figure 5). The stilling well is a metal cylinder of 10 cm in diameter and 20 cm deep with a small hole at the bottom which allowed the water levels within the stilling well and the pan to remain the same. Usage of a stilling well removed the effect of ripples on measurement of the water level by the recorder. Ripples occasionally formed within the pan when the wind velocity was high.

Figure 5. Class A Evaporation Pan with a stilling well located near one edge (also shown is a Baro-Diver to measure variations in atmospheric pressure).

2.6. Automatic water level recorder

Cera-Diver® and Baro-Diver® manufactured by Schlumberger Water Services in the Netherlands were used in this study to monitor water level fluctuations in lysimeters, evaporation pan and the surrounding field. The Divers consist of a pressure sensor designed to measure air/water pressure, a temperature sensor, memory for storing measurements and a battery. Both Cera-Diver and Baro-Diver measure the absolute pressure and temperature. Note that the absolute pressure is the pressure of the water column above the Diver plus the atmospheric pressure. Therefore measurement of atmospheric pressure is required to determine the water level. Cera-Divers establish the height of a water column by measuring the water pressure using the built-in pressure sensor. The height of the water column above the Diver's pressure sensor (Figure 6) is determined on the basis of the measured pressure. Baro-Diver measures atmospheric pressure and is used to compensate for the variations in atmospheric pressure measured by the Cera-Divers. To measure the variations in atmospheric pressure, a Baro-Diver was installed at the experimental site (Figure 5).

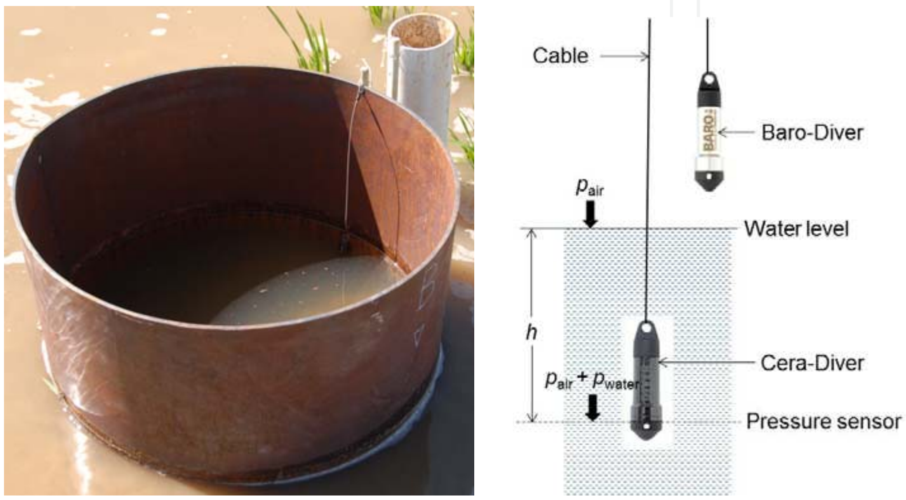

Figure 6. Installation of a Cera-Diver to measure the height of water.

The Baro-Diver measures the atmospheric pressure (p_{air}) and the Cera-Diver measures the pressure exerted by the water column (p_{water}) and the atmospheric pressure (p_{air}). Thus

$$p_{Baro-Diver} = p_{air} \tag{4}$$

and

$$p_{Cera-Diver} = p_{air} + p_{water} \tag{5}$$

When data from Baro-Diver are subtracted from corresponding data from Cera-Diver, it results in pressure exerted by the water column above the Cera-Diver at any point in time. The pressure exerted by the water column can be expressed as the height of water (h) above the pressure sensor [39]:

$$h(cm) = 9806.65 \frac{p_{Cera-Diver} - p_{Baro-Diver}}{\rho \times g} \tag{6}$$

where

p is the pressure in cm of water

ρ is the density of the water (1,000 kg/m^3)

g is the acceleration due to gravity (9.81 m/s^2).

3. Results and discussion

3.1. The water balance

A water balance technique was used to measure the amount of added water and its loss components, as stated in Equation (2). Since the measurements were made on a weekly basis between irrigation events after the permanent water was applied to the field, the change in root zone soil moisture storage (ΔS) and increment of water incorporated in the plants (ΔV) were assumed to be negligible. No precipitation (RF) occurred during the experimental period. The ground water table was more than 15 m below ground level at this site, therefore upward capillary flow into the root zone (UP) was zero. The procedure of lockup was adopted within a measurement cycle, therefore the influence of runoff (RO) or drainage out of the field became negligible. Seepage losses were minimised by lining the bank with plastic barrier and filling the adjacent bays with water. By considering the above and rearranging the parameters, the water balance Equation (2) becomes as:

$$IR = E + T + DP \tag{7}$$

where

IR = amount of irrigation water

E = direct evaporation from the water surface

T = transpiration by plants

DP = downward drainage out of the root zone

No attempt was made to measure the amount of irrigation water applied, but it was estimated from the measurement of other components (evaporation, transpiration and deep percolation) using the lysimeters. It is vital that better estimates of evaporation, transpiration and deep percolation are necessary because they play an important role to accurately determine the crop water requirements. Thus crop water requirements which are directly related to crop evapotranspiration (ET) vary depending on crop grown and its different growth stages.

3.2. Evaporation

Evaporation is the moisture lost in vapour form from the free water surface where rice is grown. Shading of the water surface by rice plants reduces evaporation. Therefore daily evaporation losses are less for rice planted at close spacing. Similarly, evaporation losses also decrease as a crop approaches maturity. Trials elsewhere have shown that over the entire rice-cropping season, evaporation accounted for about 40 per cent of total losses to the atmosphere, with transpiration providing the remainder [40]. In this study, average evaporation losses from Lysimeter A and from evaporation pan are shown in Figure 7. Readings from the Lysimeter A were obtained within an irrigation cycle (that is, between topping-up the bay). Readings from the evaporation pan were obtained between two consecutive re-filling processes. These dates for both measurements were not common in most circumstances. Therefore direct comparison of losses from Lysimeter A with those of evaporation pan using individual data was not possible in this case.

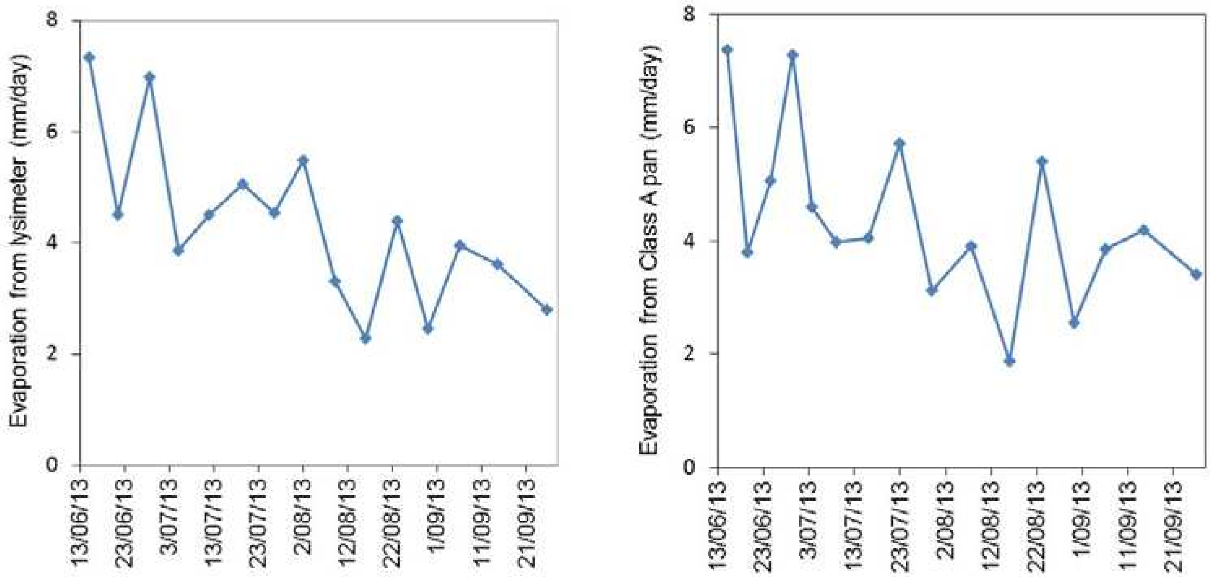

Figure 7. In-situ measurements of evaporation from Lysimeter A and Class A Evaporation Pan.

The data from this study shows that evaporation losses were high at 4-7 mm/day at the beginning when the rice plants were small. But it decreased to 3-4 mm/day when the crop developed full canopy. The shading effect of the crop canopy reduced the evaporation losses. The evaporation was not affected when the air temperature increased in August and September (Table 1). It should be noted that the shading effect was much greater than the air temperature effect on evaporation. Also note that the evaporation losses measured by the Lysimeter A and Class A Pan were close. Total evaporation losses obtained from Lysimeter A over a period of 90.5 days were 375.7 mm. Readings from Class A Pan over a period of 91.2 days resulted in 377.9 mm. Therefore, it can be concluded that for the purpose of reporting evaporation losses from a flooded rice bay, data from either Lysimeter A or Class A Pan could be used.

3.3. Transpiration

Transpiration is a process by which plants release water vapour to the atmosphere. It occurs through stomatal openings in the plant foliage in response to the atmospheric demand. The amount of water lost as transpiration usually reaches a maximum value during the day and the minimum value during the night. Crop transpiration losses were measured in this experiment as the difference in water lost between Lysimeter C and Lysimeter B and the results are shown in Figure 8.

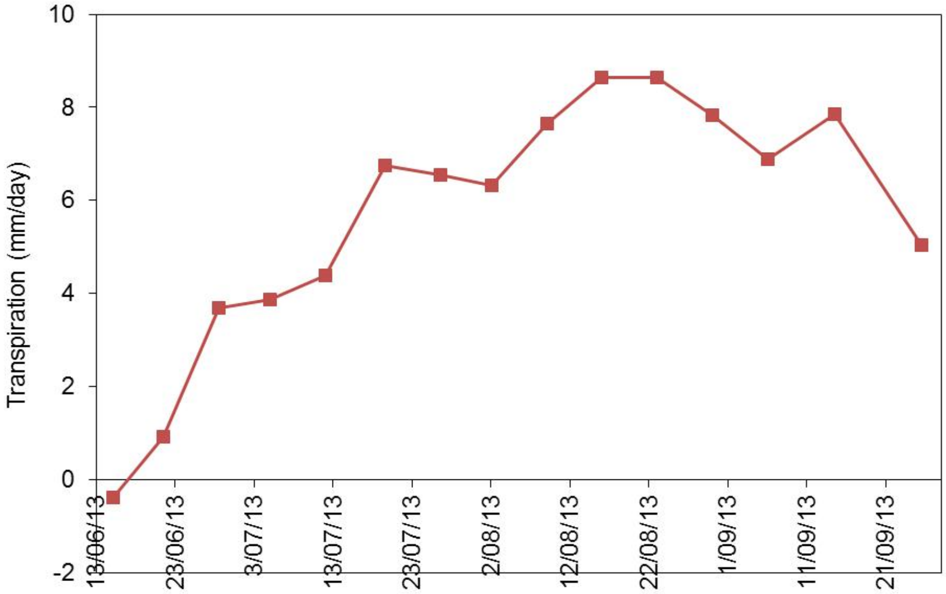

Figure 8. Transpiration losses as measured by the lysimeters.

Transpiration losses at the beginning were lower due to small size of the rice plants at that time. The crop was first irrigated on 12 May 2013. Permanent water was applied on 12 June 2013. Therefore the plants were 31 days old when the experiments started. Slightly negative value for transpiration during the first irrigation cycle was unexpected. The negative value indicated that the average losses from Lysimeter B were slightly higher than that of Lysimeter C. The only difference between these two lysimeters was that Lysimeter C contained rice plants at an early stage whereas no plants were left in Lysimeter B. Because the losses recorded at this stage were very small, this deviation in results (negative value) was ignored.

Transpiration losses increased rapidly as the plants reached full canopy and then started to decline when the plants approached full maturity. The increase in transpiration was mainly due to more leaf surface area contributing to more stomata openings for water loss. At full canopy, transpiration losses (8.6 mm/day) were almost double of evaporation losses (4.4 mm/day). Over the period of 90.5 days, the total transpiration losses were 523 mm. Over the period of measurement, evaporation accounted for about 41.8 per cent of total losses to the atmosphere, with transpiration providing the remainder of 58.2 per cent, similar to the results reported in [40]. The transpiration losses reported in this study are for rice variety IR 72 at plant population of 200-300 plants/m^2. Note that the transpiration losses might be different for another rice variety and for different plant densities.

3.4. Deep percolation

Percolation in a flooded rice field is considered as the downward movement of free water through saturated soil due to gravity and hydrostatic pressure exerted by the ponded water.

Percolation losses are a function of the local soil conditions and the depth of water over the soil surface. When the texture of the soil is heavy (about 70% clay), percolation losses are low (<1 mm/day). Field studies in the Philippines in the dry season have shown mean percolation rates of 1.3 mm/day on alluvial and elastic soils with shallow water tables (< 2m), and 2.6 mm/day when the water table was deeper (> 2m) [41]. The seasonal-average percolation rate as measured in percolation rings was 1.7 mm/day in the dry season and 0.7 mm/day in the wet season at Los Baños in the Philippines [42]. The deep percolation losses as measured in this experiment using Lysimeter B and Lysimeter A are shown in Figure 9.

Figure 9. Deep percolation losses as measured by the lysimeters.

Over the period of measurement, the deep percolation losses varied between approximately 0 and 2 mm/day. This variability in measurement might be due to the nature of measurements carried out in Lysimeters A and B. A total of 87.9 mm deep percolation losses occurred over a period of 90.5 days. This indicates that the average deep percolation loss over the period was 0.97 mm/day. These findings are supported by studies conducted by [43] who found that surface water infiltrated no deeper than 1.07 m into Cununurra clay after surface ponding for 54 hours. Similar results were reported by [44] who found no evidence of upward or downward movement of soil water below a depth of around 1.65 m in Cununurra clay. Much more recently, [45] concluded there was negligible deep drainage below furrow-irrigated sugar cane grown on Cununurra clay. However, higher infiltration rates reported by others [44,46,47] may be attributed to the presence of well-developed slickensides and shrinkage cracks (Table 2) that penetrated the transition zone between Cununurra clay and the underlying lighter textured soil at some locations [48]. Previous flooded rice systems in Cununurra clay in areas where a shallow clay layer overlying a more porous sandy profile were attributed to have contributed to excess groundwater recharge rates [49].

The average deep percolation of 0.97 mm/day as determined in this study was less than previously reported in Cununurra clay, perhaps reflecting improved crop and water management practices used with modern rice varieties. With ponding, the clay swells and the cracks are resealed. Thus irrigation water is unable to infiltrate further than a few metres into Cununurra clay soil under extended period of ponding. However, under furrow-irrigation, soil tends to crack between irrigation events and this phenomenon may have contributed to high infiltration rates. Leakage rates under furrow irrigation were estimated to be 160 to 250 mm/irrigation season for cotton in Queensland [50], 11 to 101 mm/season for maize and between 190 and 340 mm/crop-cycle for sugarcane, both in the Ord River Irrigation Area [51]. Thus the leakage under ponded rice culture compares well with irrigated cotton or sugarcane in the Ord River Irrigation Area.

Climatic conditions can impact on processes such as evaporation and transpiration, but have no effect on deep percolation. If this low level of deep percolation can be replicated at the paddock and farm scale, it is predicted that recharge of groundwater under extensive rice cultivation using the traditional flooded system in Cununurra clay soil should be within manageable limits. If these experimental results can be translated to paddock and whole farm scales, the deep percolation rates under flooded rice system would not be a problem for the growers or environmental managers, regarding rising groundwater levels, waterlogging and salinity.

3.5. Total water use

In the early stages of the rice crop, immediately after ponding, most water lost from rice field was evaporation. Once the crop developed a full canopy cover, transpiration accounted for most of the water used. The combined losses of water from evaporation and transpiration (referred as evapotranspiration) averaged 9.93 mm/day over the period of measurement of 90.5 days. In most of the tropics, the average evapotranspiration during the dry season was found to be 6-7 mm/day [23]. The higher value for evapotranspiration reported in this study might be due to not including the data during the first 31 days of the crop. Data during the first 31 days were not collected in this study. The maximum value of evapotranspiration (13.04 mm/day) was reached at heading time and it was found to be 2.96 times of the evaporation at this site during 2013.

Evaporation pans provide measurements that integrate the effect of climatic factors such as solar radiation, wind, temperature and humidity on evaporation from open water surfaces. Thus, in several countries, data from Class A Evaporation Pan (installed in the rice field) have been correlated with measured actual evapotranspiration. In this experiment, over a period of 90.5 days, the average evapotranspiration was found to be nearly 2.4 times higher than the average evaporation from Class A pan. Trials elsewhere have found that over the whole rice crop growth period, the evapotranspiration from rice field was 1.2 times more than open pan evaporation [52]. In the present study, evaporation losses during the initial period of 31 days were not measured. Even assuming a highest value of 7 mm/day of evaporation during this initial period and negligible transpiration, the adjusted average evapotranspiration could still be 1.9 times more than the average evaporation.

The sum of evaporation, transpiration and deep percolation losses as measured by the lysimeters is considered as total water losses. This is compared with the total field losses as measured outside the lysimeters (i.e. field water level) in Table 3. The total water loss reached a maximum value of 14.3 mm/day for the lysimeter measurements. However the field losses reached a maximum of 10.1 mm/day. This difference in measurement was mainly due to the fact that the lysimeter had 100% cropped area and the surrounding field had only 33.1% cropped area. The trial was established to compare the yield performance of five different rice varieties replicated three times. Hence one metre of bare land was allowed between the plantings in order to separate the treatments. Buffer area around the trial area also followed the same planting configuration. In addition, the head-end and tail-end of the bay had some bare land without any crop planted. Note that the difference in cropped area between lysimeters and surrounding field had a direct effect only on the amount of transpiration losses. Based on the cropped area, this translates into the total transpiration losses from the surrounding field were only a third of that measured in the lysimeters. The initial two readings obtained from water level fluctuation of the surrounding field (that is 9.40 and 10.08 mm/day in Table 3) were possibly due to seepage losses to the neighbouring bay which had its permanent water only on 26 June 2013.

Date	Total water loss in lysimeters (mm/day)	Total water loss in field (mm/day)
15/06/2013	8.88	9.40
21/06/2013	6.33	10.08
28/06/2013	10.96	6.49
05/07/2013	8.16	3.90
12/07/2013	9.64	5.75
19/07/2013	12.25	3.28
26/07/2013	10.60	4.98
02/08/2013	13.63	6.34
09/08/2013	10.59	5.18
16/08/2013	11.05	4.60
23/08/2013	14.31	9.95
30/08/2013	11.26	5.46
06/09/2013	13.36	9.77
14/09/2013	12.35	9.60
25/09/2013	9.97	9.05

Table 3. Total water losses from flooded rice system within lysimeters and outside in the field

The difference in water level within lysimeters and outside as shown in Figure 4 may have created a hydraulic difference (applicable to open-end type Lysimeters B and C only). At the end of irrigation (topping-up), water levels in and out of lysimeters remained at the same level. However, towards the end of the irrigation cycle, water levels inside the Lysimeters A and B remained higher than outside water level. But water level inside Lysimeter C remained lower than outside. Lysimeter A had closed bottom and therefore the difference in water level had no influence on measured values. In Lysimeter B, some water might have moved out due to the hydraulic difference created by different water levels in and out of the lysimeter. The implication of this effect was over estimation of deep percolation losses in this experiment and the actual value of deep percolation might be less than the reported value of 0.97 mm/day. On the other hand, water level inside Lysimeter C was lower than outside towards the end of the irrigation cycle. Therefore some water might have moved into the lysimeter due to the hydraulic difference and contributed to under estimation of transpiration losses in these experiments. In other words, the actual transpiration losses might be higher than the measured values.

The error in the measurement of transpiration and deep percolation due to the difference in water levels was calculated according to the procedure outlined by [53]. For Cununurra Clay soil, the value of hydraulic conductivity as 10^{-7} m/sec [34,47] and infiltration rate as 0.02 cm/min [43,47] were assumed in the calculation of error. For the lysimeter conditions that prevailed in this experiment, the error in the measurements of deep percolation and transpiration was found to be about ±2 per cent which was assumed to be negligible. Conditions such as larger diameter (50 cm) of the lysimeters, their deeper penetration (35 cm) into the soil, and smaller difference (<4 cm) in water levels have contributed to the negligible error in measurements in this experiment compared with the results reported by [53].

3.6. Water productivity

The water productivity values depend on the type of cereal crop under consideration and whether the crop evapotranspiration or the irrigation water is used in the calculation. In this study, water productivity was calculated with respect to the amount of water evaporated and transpired (WP_{ET}) and with respect to total water input (WP_{IR}) [54-56].

$$WP_{ET} = \frac{Y}{\sum(E+T)} \left(\text{g grain kg}^{-1}\text{water}\right) \tag{8}$$

$$WP_{IR} = \frac{Y}{\sum(IR+RF)} \left(\text{g grain kg}^{-1}\text{water}\right) \tag{9}$$

where

Y is the grain yield expressed in g m^{-2}

E is the evaporation expressed in kg water m^{-2}

T is the transpiration expressed in kg water m^{-2}

IR is the irrigation expressed in kg water m^{-2}

RF is the rainfall expressed in kg water m^{-2}

Note that no rainfall (*RF*) occurred during the trial period and the amount of irrigation (*IR*) is represented by Equation (7) that includes deep percolation losses as well. Water productivity expressed in different units can be compared using Equation (10) as:

$$\frac{g_{grain}}{kg_{water}} = \frac{kg_{grain}}{m^3_{water}} = \frac{t_{grain}}{ML_{water}} \tag{10}$$

The total water losses as measured by the lysimeters over the period of 90.5 days were 986.6 mm where 38% accounted for evaporation, 53% for transpiration and 9% for deep percolation. Ponded water was maintained for the rice crop in this trial for 112 days. Hence the above reported results were extrapolated to cover the entire duration of ponding of 112 days. This resulted in 1220.5 mm. According to conversion presented in Equation (3), 100 mm of water depth equals to 1 ML/ha, and therefore the total water loss would be approximately 12.21 ML/ha. No drainage occurred before harvest as the last application of irrigation water was allowed to be used by the crop during grain ripening stage. It can be assumed that the two flushings carried out before the permanent water must have used a further 1 ML/ha in total. Therefore the 2013 rice crop total water usage amounts to 13.21 ML/ha. This compares well with the rice crop water use of 18.4 ML/ha for conventional ponded rice grown on a flat layout at Coleambally in New South Wales in Australia [57]. Compared with other crops such as sugar cane in the Ord River Irrigation Area which requires approximately 18 ML/ha of water, i.e. 12 ML/ha during dry seasons and 6 ML/ha during wet seasons [58], rice appears to require less water.

Mean grain yields of five varieties tested at this site during the trial (Figure 10) varied from 5.76 t/ha (for the variety, Doongara) to 12.66 t/ha (for the variety, Viet 1). The average yield of all five varieties was found to be 9.74 t/ha. These five varieties and the buffer shared equal proportions in area for the bay used in this study. No attempt was made to determine the grain yield of buffer (IR 72) where lysimeters were located. However, visual assessment of the buffer area indicated a yield similar to 9-10 t/ha was possible for this variety, IR 72. Hence, the overall average yield of 9.74 t/ha was used to calculate the water productivity values for this experiment.

A value from 0.42 to 0.60 kg/m^3 has been cited for rice water productivity in Australia [59]. In contrast, a trial in south-eastern Australia found that the water use efficiency of conventional ponded rice was 0.68 t/ML [57]. In the Philippines, under flooded conditions, water productivity with respect to total water input (WP_{IR}) ranged from 0.22 to 0.34 g grain kg^{-1} water and WP_{ET} ranged from 1.50 to 2.12 g grain kg^{-1} water [42]. A trial in India indicated that water productivity in continuous flooded rice was typically 0.2–0.4 g grain per kg water [55]. The average water productivity of rice for conventional method (transplanted puddled rice) in Punjab in Pakistan varied from 0.27 kg/m^3 [60] to 0.34 kg/m^3 [61]. In the present study, water productivity as calculated with respect to the amount of water evaporated and transpired (WP_{ET}) was 0.73 t/ML and with respect to total water input (WP_{IR}) was 0.74 t/ML. The value for WP_{ET} reported in this study was lower than that reported by [42]. However, the value for WP_{IR} in this study was significantly higher than those reported in references [42,55,57,59-61].

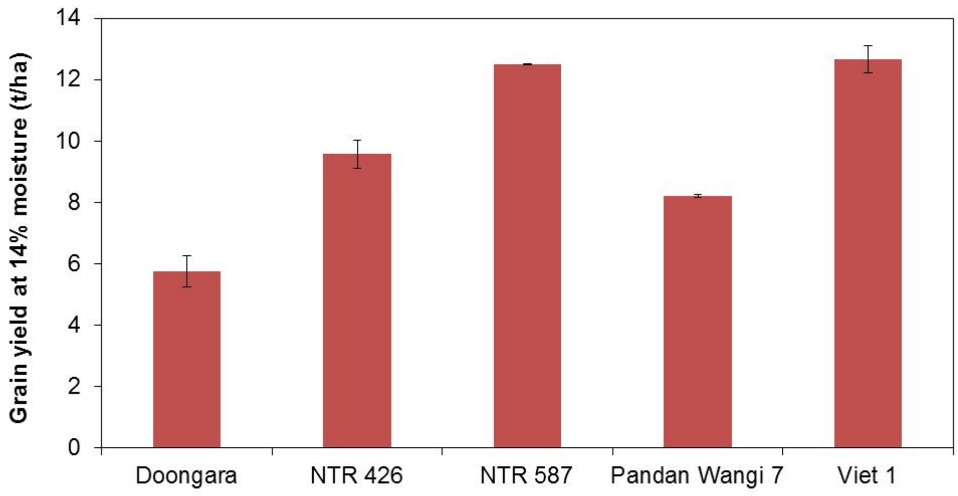

Figure 10. Mean yield of varieties tested at the trial site (error bars indicate standard error).

Hence the conventional ponded rice culture similar to that adopted in this trial was highly efficient for rice production on Cununurra clay in the tropical environment, specifically for the variety IR 72 and for the environmental conditions experienced during the dry season of 2013.

4. Conclusion

Water will be a major constraint for agriculture in coming decades, particularly in Asia and Africa. In densely populated arid areas, such as Central and West Asia, and North Africa, water is scarce and availability of water is projected to be less than 1 ML per capita per year. This scarcity of water relates to irrigation water for food production [19]. To increase crop yield per unit of scarce water requires both better cultivars and better agronomy. Under field conditions, the upper limit of water productivity of cereal crops is estimated to be around 20 $kg.ha^{-1}.mm^{-1}$ (grain yield per water used, equivalent to 2 t/ML) [62]. If the water productivity value is less than this, it can be due to major crop stresses other than water, such as weeds, pests, diseases, poor nutrition, or other soil limitations. Under these circumstances, the greatest improvement can be achieved from alleviating these issues first.

In response to water scarcity and environmental concerns, the amount of water input per unit irrigated area will have to be reduced. Water productivity of rice is projected to increase in many countries through gains in crop yield and/or reductions in irrigation water. Selecting locally adapted modern varieties have potential to lift the yield level in many rice growing areas. For example, a rice variety from Vietnam tested in the tropical climate of the Ord River Irrigation Area achieved a highest yield of 14.3 t/ha in this environment [14]. Saving water is possible by reducing seepage, percolation and runoff losses from fields. This requires that the components of the water balance need to be quantified (similar to the study reported here).

A review of literature which reported on rice water productivity values for the tropical regions shows an average of 0.295 t/ML compared to 0.74 t/ML as found in this study. This difference in water productivity translates into about 2 ML of water saving for every tonne of rice produced in most tropical regions. If the world rice production is about 700 million tonnes and over 90 per cent of the world's rice is produced in the Asian Region, the improved water productivity could save huge amount of irrigation water in the Asian region. With increasing water scarcity for irrigation, productivity of current rice production systems has to be improved substantially to feed an ever-increasing world population. It is vital to use locally adapted high yielding varieties together with appropriate water management techniques to achieve higher water productivity. Although seepage and runoff losses can be minimised, deep percolation losses are difficult to control. Puddling is a technique used to minimise deep percolation losses. However, direct dry seeding techniques are widely used to save labour costs. In this case, more attention must be paid towards choosing appropriate soil types for flooded rice production systems.

Many technologies appear to save substantial amounts of water through reducing irrigation water requirements. For example, a shallow intermittent irrigation saved 32% of irrigation water compared to traditional deep water irrigation without any effect on yield in Korea [63]. Another study in Panjab in Pakistan found that the direct seeding of rice saved 25% water compared to conventional method of transplanted rice and water productivity increased from 0.27 kg/m^3 for conventional method to 0.32 kg/m^3 for direct seeding [60]. Similar improvement of water productivity was reported by [61] for direct seeding method for rice (0.41 kg/m^3) compared with conventional method (0.34 kg/m^3). Note that the present trial reported here used the direct seeding technique to save irrigation water requirement.

It is questionable whether moving away from ponded rice culture to more aerobic rice culture results in improved water productivity. A trial conducted at Coleambally in New South Wales in Australia found that the water use efficiency of the raised bed system (0.55 t/ML) was lower than the conventional ponded rice (0.68 t/ML) [57]. Yield was reduced from 12.7 t/ha in the conventional method to 9.4 t/ha in the furrow irrigated bed treatment in this trial. In terms of irrigation water use, furrow treatment used 17.2 ML/ha while the ponded treatment used 18.4 ML/ha. The increase in length of growing season for the bed treatment also increased the period of irrigation, thus reducing the potential for water savings.

Rice grows well and produces best under flooded conditions but large amount of water is needed for this system. However, reducing water use through an aerobic system of rice production that eliminates maintenance of ponded water is necessary to mitigate a looming water crisis. There is no doubt that increased demand for food will be met by the products of irrigated agriculture. To evaluate the potential of aerobic rice system in the tropics, a field trial on aerobic rice was conducted at the International Rice Research Institute (IRRI) [64]. This study found that aerobic rice saved 73% of irrigation water for land preparation and 56% during the crop growth stage. However, aerobic rice yields were lower by an average of 28% in the dry season and 20% lower in wet season. Yunlu 29 (a tropical variety from Yunnan Province in China which is adapted to aerobic conditions) has shown potential for high yield (10-12 t/ha) in the Ord River Irrigation Area under optimum moisture conditions [15,65]. Further experiments and breeding of varieties better suited to aerobic conditions are needed.

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