CHAPTER FIVE

HALTING THE GROUNDWATER DECLINE IN NORTH-WEST INDIA—WHICH CROP TECHNOLOGIES WILL BE WINNERS?

E. Humphreys,[*,1] S. S. Kukal,[†] E. W. Christen,[‡] G. S. Hira,[†] Balwinder-Singh,[§] Sudhir-Yadav,[¶] *and* R. K. Sharma[‖]

Contents

[*] International Rice Research Institute, DAPO 7777, Metro Manila, Philippines
[†] Punjab Agricultural University, Ludhiana, Punjab, India
[‡] CSIRO Land and Water, PMB 3 Griffith, NSW, Australia
[§] Charles Sturt University, Locked Bag 588 Wagga Wagga, NSW, Australia
[¶] The University of Adelaide, Adelaide, SA, Australia
[‖] Directorate of Wheat Research, Karnal, Haryana, India
[1] Corresponding author: *E-mail address:* e.humphreys@cgiar.org

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Abstract

Increasing the productivity of the rice–wheat (RW) system in north-west India is critical for the food security of India. However, yields are stagnating or declining, and the rate of groundwater use is not sustainable.

Many improved technologies are under development for RW systems, with multiple objectives including increased production, improved soil fertility, greater input use efficiency, reduced environmental pollution, and higher profitability for farmers. There are large reductions in irrigation amount with many of these technologies compared with conventional practice, such as laser land leveling, alternate wetting and drying (AWD) water management in rice, delayed rice transplanting, shorter duration rice varieties, zero till wheat, raised beds, and replacing rice with other crops. However, the nature of the irrigation water savings has seldom been determined. It is often likely to be due to reduced deep drainage, with little effect on evapotranspiration (ET).

Reducing deep drainage has major benefits, including reduced energy consumption to pump groundwater, nutrient loss by leaching, and groundwater pollution. The impacts of alternative technologies on deep drainage (and thus on irrigation water savings) vary greatly depending on site conditions, especially soil permeability, depth to the watertable, and water management. More than 90% of the major RW areas in north-west India are irrigated using groundwater. Here, reducing deep drainage will not “save water” nor reduce the rate of decline of the watertable. In these regions, it is critical that technologies that decrease ET and increase the amount of crop produced per amount of water lost as ET (i.e., crop water productivity, WP_{ET}) are implemented. The best technologies for achieving this are delaying rice transplanting and short duration rice varieties. The potential for replacing rice with other crops with lower ET is less clear.

1. INTRODUCTION

The irrigated rice–wheat (RW) cropping system of north-west India is fundamental to India’s food security (Timsina and Connor, 2001). The small states of Punjab and Haryana produce 50% of the rice and 85% of the wheat procured by the Government of India (Singh, 2000). The productivity of these systems needs to increase to keep up with population growth in India, which is predicted to increase from 1.12 billion in 2008 to 1.35 billion by 2025 (UNESCO, 1995). Over that time, agricultural production needs to increase by about 25% on the same or less land, but in fact yields of rice and wheat are declining or stagnating (Ladha *et al.*, 2003). Furthermore, production must increase in the face of severe soil degradation, increased incidence of pests and diseases, increasing labor scarcity, salinity, and waterlogging in some regions, and perhaps of greatest concern, groundwater depletion in large areas where the RW system prevails (Chhokar and Sharma, 2008; Pingali and Shah, 1999; Sharma *et al.*, 2004a,b, 2007; Singh, 2000).

Since the early 1970s, there has been a steady increase in the depth to the groundwater in most of the RW area of north-west India (Ambast *et al.*, 2006; Hira, 2009; Hira and Khera, 2000; Hira *et al.*, 2004; Rodell *et al.*, 2009). The increase in depth has accelerated alarmingly in some areas in recent years; for example, in parts of Ludhiana District in central Punjab, the rate of change increased from about 0.2 m/yr during 1973–2001 to about 1 m/yr during 2000–2006 (Fig. 1). A similar trend was reported in Kurukshetra in Haryana (Sharma *et al.*, 2008a). In 2009, 103 out of 138 administrative blocks were overexploited in Punjab, while 55 out of 108 blocks were overexploited in Haryana (http://cgwb.gov.in/gw_profiles/st_Haryana.htm). Using satellite-based estimates of groundwater depletion, Rodell *et al.* (2009) found that groundwater is being depleted at a mean rate of 4.0 1.0 cm/yr across the states of Rajasthan, Punjab, Haryana, and western Uttar Pradesh. Over a period of 6 years (August 2002–October 2008) with close to normal rainfall, they estimated that the volume of groundwater had declined by 109 km^3 (109 10^9 m^3), double the capacity of India's largest surface reservoir. The maximum rates of groundwater depletion appeared to be centered on Haryana and western Uttar Pradesh.

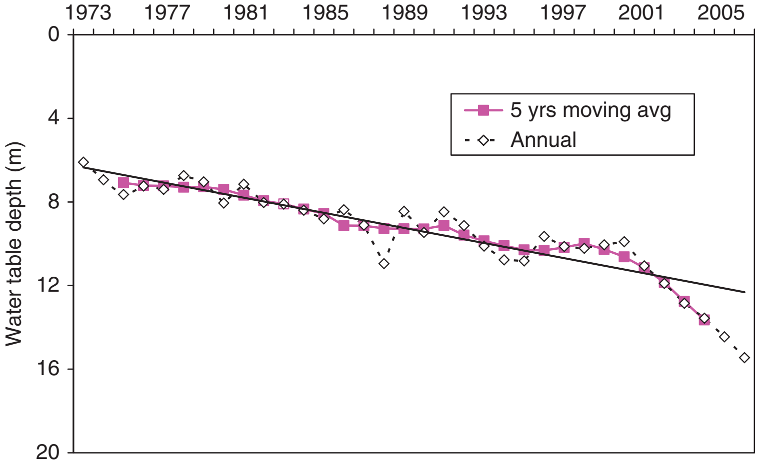

Figure 1 Depth to the watertable in June in Gujjarwal, Ludhiana District, Punjab, India, 1973–2005 (data source: Groundwater Cell, Punjab Department of Agriculture).

The increase in depth to the groundwater in north-west India has three major negative effects (Hira, 2009): (1) increasing energy requirement and cost of pumping groundwater; (2) increasing tubewell infrastructure costs; and (3) deteriorating groundwater quality, which will ultimately be to the degree that the groundwater becomes unusable because of upwelling of salts from the deeper native groundwater (AICRP, 2009; Kamra *et al.*, 2002), and because of saline groundwater intrusion into fresh groundwater (as a result of reversal of groundwater flows due to the lowering of groundwater levels in fresh groundwater regions below levels in areas with saline groundwater).

In an attempt to solve the various problems of RW systems in the Indo-Gangetic Plain (IGP), many improved technologies referred to as "Resource Conserving Technologies" (RCTs) and "Integrated Crop and Resource Management" (ICRM) have been developed over the past couple of decades (Chauhan *et al.*, 2001; Gupta and Seth, 2006; Ladha *et al.*, 2009; RWC-CIMMYT, 2003; Sharma *et al.*, 2005; Sidhu *et al.*, 2007). These technologies are targeted at increasing the productivity, sustainability, and profitability of rice-based cropping systems through reducing and reversing soil degradation, reducing air pollution, and increasing nutrient, labor, and water use efficiencies. Examples of these technologies include laser leveling, reduced and zero tillage, dry seeding of rice, raised beds, retention of crop residues, balanced fertilization, and crop diversification. Many of the technologies involve adoption of one or more of the three fundamental principles of conservation agriculture—reduced or zero tillage, soil surface cover, and crop rotation (FAO, 2008; Hobbs *et al.*, 2008). The importance of integrated management of the crop and all resources, and of considering the performance of the total cropping system, as opposed to that of individual crops in isolation, is also being increasingly recognized (Jat *et al.*, 2009; Ladha *et al.*, 2009).

This chapter explores the potential of many on-farm technologies to save water and to increase productivity with respect to both irrigation amount and total water depletion (water no longer available for productive use due to its loss from the system or pollution), and to highlight gaps in knowledge and future research needs. The focus is on the IGP of north-west India, where RW systems prevail, and where the problems of groundwater decline are most severe. The analysis commences with a brief description of the hydrogeology of the RW areas of north-west India and the causes of groundwater decline in this region (Sections 2 and 3). Section 4 then examines 12 on-farm technologies with regard to their potential to contribute toward increasing food production and reducing water use.

2. THE HYDROGEOLOGY AND DEVELOPMENT OF IRRIGATION IN NORTH-WEST INDIA

The main rice and wheat producing states of north-west India are Punjab (5.0 Mha), Haryana (4.4 Mha), and western Uttar Pradesh (8.1 Mha). They are largely located in the IGP, a flood plain which is the surface expression of a structural depression located immediately south of the Shiwalik Foothills of the Lower Himalayas and filled with alluvium. The topography is gentle (e.g., average slope of 0.3 m/km in Punjab). Most of Punjab and Haryana are underlain by the Indus River plain aquifer, a 560,000 km^2 (56 Mha) unconfined to semiconfined porous alluvial formation that also underlies Rajasthan and eastern Pakistan (Zaisheng *et al.*, 2006 as cited in Rodell *et al.*, 2009). The Ganges plain starts in eastern Haryana.

The hydrogeology of the IGP is described by Tanwar and Kruseman (1985). The structural depression forms a deep (>3000 m) trough, but south of a line extending north east from Delhi the basement is at much shallower depth (200–1000 m). The underlying geologic formation is of marine origin (Asghar *et al.*, 2002; Kulkarni *et al.*, 1989). The trough is filled with alluvial material deposited by rivers from the Himalayas. Coarse to fine sediments overlay a thick deposit of clay starting at 50–150 m below the ground surface (Kulkarni *et al.*, 1989). In the north, clayey layers are intercalated in medium sand and gravel deposits (Bowen, 1985), while in the south clay and silt layers predominate, although intercalated with fine sand layers. Despite its large number of clay layers, *the whole of the aquifer system can be considered as a single heterogeneous unconfined aquifer*. Sometimes the clay layers create semiconfined conditions (leaky aquifers) locally, but the clay layers may also be pervious, especially when they contain large amounts of calcium carbonate nodules (often the case).

Annual rainfall declines from around 1000 mm in the hilly north-east portions of Punjab and Haryana to 200 mm in the south west of each state. Average rainfall is higher in western Uttar Pradesh (1000 mm) than in Punjab (780 mm) or Haryana (615 mm). Eighty-five per cent of the rain falls during the monsoon season, from late June to early September, the period when rice is grown. Potential evaporation exceeds rainfall except during the peak of the monsoon in July and August (e.g., Fig. 2). Winters are dry, with only the occasional light shower during the period of wheat growth (November to March).

Much of the native groundwater of the Indus basin is saline because of its marine origin, but most of the shallower aquifers were flushed of their salt content in the past. Prior to the introduction of irrigation, the depth to the watertable was 20–50 m. In Punjab, groundwater flows from north east to south west. The groundwater quality changes from good quality in the

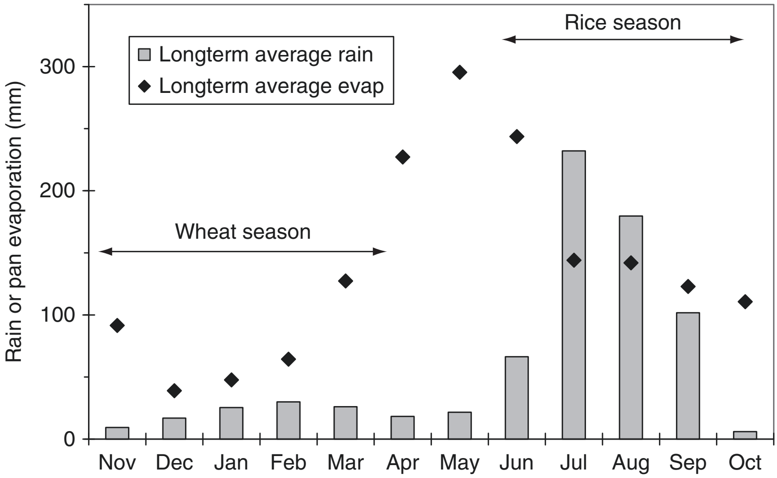

Figure 2 Longterm (1966–1995) monthly mean pan evaporation and rainfall at Ludhiana, Punjab.

north east to poor quality (highly saline and/or sodic) in the south west, and quality also deteriorates with depth (Hira *et al.*, 1998). The northern foothills region (0.65 Mha) and central plains region (2.5 Mha) have fresh and marginal quality groundwater, respectively, which can be used for irrigation. The groundwater in the south-west region (1.9 Mha) is generally unsuitable for irrigation. In Haryana, the groundwater flows from the north east and south toward the center, and from the center toward the west. The north eastern part of the state is underlain by fresh groundwater, and the remaining 2.8 Mha is underlain by brackish to very saline groundwater. The central basin of 1.7 Mha has no proper surface drainage. As in Punjab, the salinity of the groundwater increases with depth (Kamra *et al.*, 2002). The salinity in shallow aquifers, where this occurs, is a result of mixing with deeper saline water and/or evaporation (Kulkarni *et al.*, 1989).

Canal irrigation was introduced by the British in the middle of the nineteenth century, but without provision for proper drainage, and watertables rose rapidly due to deep drainage from the canals, irrigated fields, and rainfall (e.g., Fig. 3). In normal monsoon years in the 1970s, vertical recharge from rainfall was about 90 mm/yr in Punjab and Haryana, and higher (215 mm/yr) in western Uttar Pradesh where rainfall is higher (Datta and Goel, 1977; Datta *et al.*, 1973; Goel *et al.*, 1977). As a result, fresh groundwater lenses now overlie the deeper saline groundwater (Hira and Murty, 1985; Qureshi *et al.*, 2008; Sufi *et al.*, 1998). The thickness of the lenses varies depending on the microtopography, hydrogeology, and proximity of channel distributaries, and is greatest near rivers and canals where the depth to the watertable is least (e.g., Fig. 2 in Qureshi *et al.*, 2008).

Transmissivity values from well tests range from 170 to 2600 m^2/d, and specific yield in the depth range affected by water level fluctuations is 10–15%. The rise in the watertable eventually resulted in waterlogging in large parts of Punjab and Haryana in the mid twentieth century. In 1964 most of the present state of Punjab (except the south west) had a watertable within 3 m of the soil surface, and significant areas had a watertable within 1.5 m (Hira and Khera, 2000). Significant secondary salinization occurred in areas with saline groundwater due to mixing with the overlying fresh water and high evaporation (Ritzema *et al.*, 2008; Uppal, 1966). The salt-affected area in Punjab increased from 0.03 Mha in 1950 to 0.68 Mha in 1965.

In the second half of the twentieth century there was rapid expansion in groundwater pumping from tubewells due to the inability of the supply-driven canal system to meet the needs of farmers growing the new high yielding, input-responsive rice and wheat varieties, and strongly supported by many institutional and policy factors (Raina and Sangar, 2004). This led to the rapid increase in rice and wheat production known as the "Green Revolution." In Punjab, the area of rice increased from 0.39 to 2.48 Mha between 1970–1971 and 2001–2002, while the area of wheat increased from 2.29 to 3.42 Mha over the same period (Takshi and Chopra, 2004). Rice and wheat are now grown in rotation on 1.8 Mha (Abrol, 1999). In Haryana, the rice area increased from about 0.3 to 0.9 Mha between 1970–1971 and 2000–2001, and the wheat area increased from 1.1 to 2.2 Mha over the same period (Ambast *et al.*, 2006), with 0.6 Mha of RW systems (Abrol, 1999). In the whole of Uttar Pradesh there are now

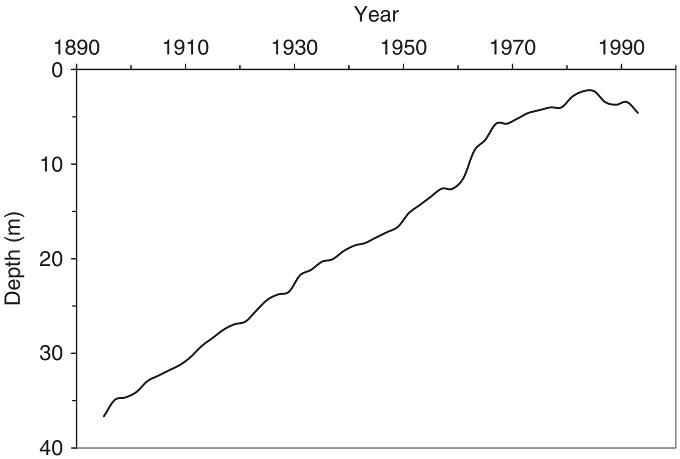

Figure 3 Groundwater rise at Ran Singh Wala village, Faridkot district in south-west Punjab following the introduction of canal irrigation in the nineteenth century (adapted from Hira *et al.*, 1998).

about 5.6 Mha of RW systems (Abrol, 1999). Across north-west India, the RW cropping system prevails in regions where rainfall is more than 500 mm and the groundwater has fresh or marginal quality, and in these regions district average tubewell density ranges from 15 to $30^{+}/\text{km}^2$ (Ambast *et al.*, 2006).

The number of tubewells in Punjab increased from 0.1 million in 1960 to 0.9 million in 1997 (Hira and Khera, 2000), and to about 1.2 million in 2008. In Haryana there were more than 600,000 wells and tubewells by 2005 (Sharma *et al.*, 2008a). By 1994 there were 2 million tubewells in the whole of Uttar Pradesh (Chadha, 2004). About 85% of the land area in Punjab is now cultivated with a cropping intensity of 189%, and 97% of this land is irrigated. Two-thirds of Punjab's rice and wheat are produced in the central zone, where the cropping intensity is 201%. In this region, groundwater is used to irrigate 90–97% of the irrigated area of each district (Sarkar *et al.*, 2009). Across the international border in Punjab, Pakistan, groundwater also provides 70% of the requirements for RW systems (Arshad *et al.*, 2008). In Haryana, cropping intensity in the RW area is 215%, and the state average is 182%. Groundwater supplies 46% of the total irrigated area (Kumar, 2004) and is the main source in the RW areas (Ambast *et al.*, 2006). In western Uttar Pradesh, with a cropping intensity of 157%, 4.2 Mha are irrigated using groundwater (79% of the irrigated area) (Rai, 2004). In the most intensive RW regions, almost all irrigation is now by groundwater (Erenstein, 2009; Sarkar *et al.*, 2009).

The rapid increase in groundwater pumping in the RW areas led to a rapid decline in groundwater levels. For example, there were declines of 5–15 m in the past 20 years in 11 districts across Punjab and Haryana (Ambast *et al.*, 2006). The average depth to the watertable in districts of the central zone of Punjab had increased to 15–28 m by 2006 (Hira, 2009). With no interventions, it is predicted that the watertable will fall below 10 m in 75% of Punjab by 2020 (Takshi and Chopra, 2004). Hira (unpublished data) predicts that by 2025, 42 of 134 blocks (30% of Punjab) will have watertables deeper than 30 m, making it impossible to pump out groundwater using hand pumps or small submersible pumps. Of these 42 blocks, the watertable will fall beyond 40 m in 30 blocks, beyond 50 m in 6 blocks, and to 60–90 m in 4 blocks. In western Uttar Pradesh, the groundwater is declining at 0.1–0.75 m/yr (Rai, 2004).

In addition to the problem of groundwater decline in the major RW areas, parts of Punjab, Haryana, and western Uttar Pradesh continue to be prone to waterlogging and salinization, caused by rising watertables in canal irrigated areas where the groundwater quality is too poor for irrigation. However, the waterlogged area in south-west Punjab had declined to just a few thousand hectares by 2003 (Jose *et al.*, 2004), largely as a result of increased use of the fresh groundwater lens (tapped using skimming wells and shallow tubewells, Hira, 1994), and partly due to the installation of surface drains which drain floodwater from submerged areas to the Sutlej

River. Almost 50% of Haryana has rising watertables and poor quality groundwater (Kumar, 2004), but with potential to greatly alleviate the problem through reducing canal irrigation and increasing the use of the fresh, shallow groundwater overlying the saline groundwater.

3. WATER SOURCES, SINKS, DEPLETION, AND SAVINGS

Keller *et al.* (1996) used the concepts of sources, sinks, and recycling as a means of understanding water in river basins. The *sources* of water in a river basin are present precipitation, past precipitation (snow, ice), surface stores (river channels, dams, canals, rice paddies, lakes, ponds), subsurface stores (soil profile, aquifers), diversions from other basins, and desalinization of seawater (Seckler, 1996). The *sinks* are destinations for water, or conditions of water, from where or which it cannot be reused in the basin; the sinks include the atmosphere, oceans, inland seas, saline aquifers, and water that becomes too polluted for further use. When water is withdrawn from a source and used to irrigate a crop, part of it is lost to the atmosphere sink—by plant transpiration and by evaporation from the soil or from water lying on the soil surface. The remainder drains to surface and/or subsurface storages which may be sources or sinks depending on the condition of the water. Water *depletion* is loss of water to sinks. *"Real" water saving* occurs when flows to sinks are reduced.

3.1. Why is the watertable going down in the rice–wheat belt of north-west India?

Using a water balance model and 10 years (1989–1998) of Ludhiana, Punjab, weather data, Jalota and Arora (2002) estimated annual average crop ET of 964 mm from the irrigated RW system, exceeding average annual rainfall by 128 mm (Table 1). Deep drainage was 1110 mm, 83% of which occurred during the rice phase. As indicated above, deep drainage in the main RW areas flows to the groundwater system from where it can be reused. Assuming that all of the irrigation is from groundwater, and that all of the deep drainage can be reused, the annual net depletion of the groundwater due to the RW system is equal to ET-rain, or 128 mm. Given an aquifer specific yield of 10–15%, annual water depletion of 128 mm is equivalent to a decline in the groundwater level of 1.28–0.83 m/yr. The actual rate of watertable declines at Gujjarwal (Fig. 1) over that period was much less (0.2 m/yr) as there was some irrigation from the canal system (Arshad *et al.*, 2008), because of recharge across the landscape from rainfall, rivers, canals and canal irrigated fields, and because of net subsurface lateral inflow in the groundwater system.

Table 1 Simulated evaporation and transpiration (mm) for an irrigated rice-fallow–wheat-fallow cropping system in central Punjab, on a sandy loam soil

Period	Rainfall	Evaporation	Transpiration	Surplus/Deficit (Rain-ET)
Rice	650	217	292	+141
Short fallow	22	38	–	16
Wheat	122	83	237	198
Long fallow	42	97	–	55
Total	*836*	*435*	*529*	*128*
Annual water requirement (E+T)		964		

Extracted from Jalota *et al.* (2002).

The ET water depletion in the study of Jalota and Arora (2002) was due to transpiration from rice and wheat, evaporation from the soil or water lying on the soil surface during these crops, and soil evaporation during the long and short fallow periods (Table 1). Total rainfall during the rice season exceeded total ET by 141 mm, while total rainfall during the wheat, long fallow and short fallow periods was much less than ET.

There are few published measurements of the amount of irrigation water that farmers apply to their fields in the RW systems of north-west India. Based on a survey of 398 farmers using groundwater only in Haryana (Erenstein, 2009), average estimated applications to rice and wheat were 1890 and 220 mm, respectively. On a loam soil in central Punjab, Humphreys *et al.* (2008a) measured irrigation amounts of 2300–2400 mm to continuously flooded rice, 1400–1800 mm to rice with various forms of alternate wetting and drying (AWD) water management, and 290 mm to wheat. In Punjab, Pakistan, mean irrigation amounts over three seasons ranged from 1100 to 1500 mm for rice, and 150 to 260 mm for wheat (Jehangir *et al.*, 2007). The data indicate that irrigation of rice is very inefficient given that rainfall usually balances or exceeds crop water use requirement (ET) in north-west India, even after allowing for the fact that the monsoon does not start until 2–3 weeks after the crop is transplanted, an estimated water requirement of 250 mm to saturate the rootzone and meet ET demand during that dry period. Thus irrigation water is currently applied to rice at an order of magnitude higher than the theoretical requirement, due to the physiological requirement of near saturated soil for maximum yield (Bouman and Tuong, 2001), the management and fertility advantages of ponding (for weed control and availability of P and micronutrients such as Fe on coarse textured, alkaline soils), and the use of the paddy field as a water storage to buffer against unreliable water (electricity) supply. In contrast to rice, the amount of water applied to wheat is much closer to the theoretical requirement (average ET-rain = 198 mm), however, there will also be some residual soil water available to wheat after rice, reducing the irrigation requirement. These calculations suggest that there is considerable scope to increase the irrigation efficiency of rice in this region, and some scope to increase the irrigation efficiency of wheat, and that the potential gains are far greater for rice. But an even more important question is *"what is the potential to reduce water depletion due to flows to sinks from where the water cannot be recovered, and to reduce or halt the decline in groundwater levels?"*

3.2. How much water do we need to save to arrest the decline in the watertable?

The amount of water that needs to be saved from RW systems depends on the rate of groundwater decline, which varies across the region depending on many factors such as hydrogeology, climate, landuse, and management. From a biophysical perspective, the amount of groundwater extraction should not exceed the amount of recharge to maintain an equilibrium water level in the aquifer at the desired depth. The optimum depth for the RW zones has been suggested to be around 6–7 m (Ambast *et al.*, 2006) and 10 m (Hira and Khera, 2000). The reasons for this depth are not reported, but it is shallow enough to minimize the cost of pumping and avoid the need to dig the deep pits needed to lower the electric motors (which results in many fatalities due to collapse of the pits), and deep enough to avoid loss of groundwater by evaporation and problems of waterlogging and salinization.

The amount of water that needs to be saved is equal to the net depletion from the aquifer over the time period of interest, and can be calculated from the product of the rate of decline in the groundwater level and the specific yield of the aquifer. Using Gujjarwal, central Punjab as a theoretical example, with a recent watertable decline of 1 m/yr and specific yield of 15%, the net loss from the aquifer is equivalent to 150 mm/yr. This implies that to stabilize the groundwater at Gujjarwal at the 2005 level (16 m below the land surface), annual water depletion across the landscape needs to be reduced by 150 mm, which is about 15% of the estimated ET. What is the potential for improved on-farm technologies to save this much water?

3.3. Methods for reducing groundwater depletion

Many methods have been proposed for arresting the decline in the watertable in north-west India (Hira, 2009). These involve decreasing withdrawal of groundwater by reducing on-farm irrigation requirement and/or increasing recharge.

3.3.1. Methods for simultaneously reducing withdrawal of groundwater and increasing recharge

These methods involve increasing surface water supplies, by measures such as:

- Increasing the canal water supply to central Punjab through the construction of new headworks on the Sutlej River to capture some of the $1 \quad 10^9$ to $10 \quad 10^9$ m^3 of water going to Pakistan during the monsoon, and reviving the old canal watercourses (now ploughed in) in central Punjab; this would reduce reliance on groundwater through increasing surface supply, and increase recharge from the canal system
- Construction of small and medium dams in the Shiwalik Hills to increase recharge and provide water for irrigation in Punjab; Grewel and Dar (2004) estimated that 15–20% of the groundwater depletion could be met by such measures

By how much these methods would reduce net water depletion from the Indus basin as a whole is an important question. For example, if all the water that flows down the Sutlej River to Pakistan during the monsoon ultimately flows to sinks (such as the ocean), then capture and retention of that water in Punjab, India would indeed reduce water depletion from the basin. However, if some of the water that flows to Pakistan is used directly from the river system, or if it recharges fresh groundwater systems, then retention of that water in India would not save water in the basin. Only about 20% of the annual flow in the Indus Basin in Pakistan now reaches the sea (Qureshi *et al.*, 2008). The Indus Basin is considered to be a closing basin, with most of its water already used, and with increasing demand for water from nonagricultural sectors in the future (Qureshi *et al.*, 2008). Therefore, politics aside and allowing for environmental flow requirements, the potential for reducing net depletion from the Indus Basin by retaining more water in India is questionable and requires further in-depth analysis.

3.3.2. Methods for increasing recharge of groundwater

Methods for increasing recharge have been proposed at landscape, village, and urban levels, and include:

- Construction of recharge wells in areas where the groundwater is declining, and where there is a thick restricting layer below the soil surface (Ambast *et al.*, 2006; Kamra, 2004)
- Adoption of soil conservation practices in the Shiwalik Hills to reduce runoff and increase infiltration, for example, contour trenches, vegetation barriers, bunding of fields
- Rainwater harvesting in cities through the use of grass saver tiles
- Renovation of village ponds, which are often silted, to increase infiltration

Methods for increasing recharge by capturing runoff have been shown to have local impacts on groundwater levels, with benefits to local water pumpers. However, the effect on water depletion at larger scales is less clear, and depends on the amount of runoff that is captured and used elsewhere in the system. Analysis at larger scales is needed.

3.3.3. Methods for reducing withdrawal of groundwater

Hira (2009) proposed a range of on-farm technologies that would reduce withdrawal of groundwater:

Delaying transplanting of rice
Diversification from rice to other crops
Increasing the efficiency of irrigation water use with technologies such as AWD for rice, laser land leveling, raised beds, and mulching

These and other on-farm technologies are discussed in greater detail in Section 4. There are many anecdotal reports and published papers in the popular and scientific literature indicating lower irrigation requirement (thus reduced withdrawal of groundwater) and higher irrigation water productivity (WP_I) with many improved technologies in comparison with conventional practice in RW systems (Erenstein *et al.*, 2008; Humphreys *et al.*, 2005, 2008b; Ram *et al.*, 2005; Sharma and Singh, 2002). However, whether these technologies reduce water depletion and/or increase crop productivity with respect to water depletion, and by how much, are not known.

3.3.3.1. Reducing run off and deep drainage

Practices that reduce surface runoff and deep drainage to sinks such as saline groundwater and the sea are important ways of reducing water depletion. This is especially the case in regions such as south-west Punjab and southern Haryana, India, and in parts of Punjab and Sindh, Pakistan, where deep drainage water flows into aquifers that are too saline for use (Qureshi *et al.*, 2008). However, even here the fresh drainage water tends to overlie the saline water in thin freshwater lenses. About 50–75% of the freshwater can be captured and reused using technologies such as skimming wells (Ambast *et al.*, 2006; Asghar *et al.*, 2002; Hira, 2009). Of course, the extraction of the fresh water needs to be done with care to extract as little as possible of the deeper saline water (Kamra *et al.*, 2002). The design of the skimming well, depth of the well (distance from the intake to the fresh/saline water interface), and pumping rate and duration are all important factors in this (Sufi *et al.*, 1998). Furthermore, the amount of salt in the freshwater lens will increase over time, mainly due to the salt in the irrigation water (e.g., addition of 1000 mm of fresh river water with a salinity of 0.3 dS/m adds the equivalent of 19 t/ha of sodium chloride). The rate of salinization of the aquifer can therefore be slowed by management practices that minimize the amount of irrigation water applied. Keeping the watertable deep is critical to enable leaching of salt from the root zone. Therefore deep drainage needs to be reduced to an amount lower than the rate of dissipation of the groundwater (by leakage to deeper depths, and/or evaporation in the case of shallow watertables, and/or shallow groundwater pumping). Thus, in areas underlain by saline groundwaters, it is critical to employ technologies that reduce deep drainage.

The effects of improved technologies on the amount of deep drainage will vary greatly with site conditions (soil type/permeability, presence of a hard pan, degree of soil cracking, depth to the watertable) and with irrigation system design (size of irrigation bays relative to irrigation flow rates, which affects the duration of irrigations). It will also vary depending on water management of the current practice (e.g., whether rice is grown with continuous flooding or AWD).

Where surface runoff from individual fields can be captured and reused "downstream," and where deep drainage can be used by groundwater pumpers, these losses from individual fields are actually flows to water sources and not losses from the system at larger spatial scales (Hafeez *et al.*, 2007; Loeve *et al.*, 2004). This is the case in much of the RW belt of north-west India, because the whole of the IGP is underlain by a single, unconfined aquifer (Section 2). Furthermore, in canal irrigated areas, deep drainage to groundwater protects the water source from loss by evaporation, provided that the watertable is not shallow (Hafeez and Khan, 2006; Khan *et al.*, 2006; Young *et al.*, 2007), and is often the source of water for farmers with inadequate or no canal supply. The evaporative loss of water from the groundwater depends on the depth to the watertable and soil type (Raes and Deproost, 2003; Rasheed *et al.*, 1989).

Reducing deep drainage in farmers' fields will reduce pumping costs, pollution of groundwater, and leaching of nutrients, and should be strongly encouraged. However, it will not halt the decline in groundwater levels in the major RW growing areas of north-west India. Here it is critical to develop and adopt technologies that also increase production per unit of evapotranspiration (WP_{ET}).

3.3.3.2. Reducing ET and increasing WP_{ET} Reducing ET and increasing WP_{ET} is beneficial in all water-limited situations. In groundwater irrigated areas where ET is the only source of water depletion and food production needs to be increased, it is critical. There are several ways that WP_{ET} can be increased:

i. increase yield and reduce ET

The ideal would be technologies that increase WP_{ET} by simultaneously increasing yield and reducing ET, providing the means to both increase food production and reduce water depletion. This is possible with improved technologies in some situations, as was the case with subsurface drip irrigated maize in south eastern Australia (O'Neill *et al.*, 2008). However, in general, it is difficult to increase yield without increasing ET because of the strong, positive linear relationship between transpiration and dry matter production (e.g., Farquhar and Richards, 1984; Haefele *et al.*, 2008), together with the fact that dry matter production is an important determinant of yield of cereals up to some optimal level of biomass (e.g., Akita, 1989; Reynolds *et al.*, 2007; Tollenaar, 1991). When yields are at or above about 50% of their potential, yield gains come at a near proportionate increase in ET (Molden *et al.*, 2010). Thus, unless starting at very low yield levels, technologies that increase yield are generally likely to result in higher transpiration and higher ET, unless the yield increase is simply a result of increased harvest index due to factors such as avoidance of heat or cold damage at sensitive reproductive stages.

ii. maintain yield and reduce ET

Examples of technologies that increase WP_{ET} by reducing ET while maintaining yield in north-west India include delaying rice transplanting date (Section 4.2), and growing shorter duration varieties (Section 4.3). As most of the cultivable land in the major RW areas of north-west India is already used, there is little scope for increasing food production with such technologies alone.

iii. increase yield and increase ET, but with a proportionately larger increase in yield

Technologies that increase WP_{ET} by increasing both yield and ET, but which increase yield by more than ET, can also be used to increase food production and reduce ET by reducing the cropped area to the optimum level, but this would be difficult to implement in north-west India for socio-economic reasons. Furthermore, the impact on water depletion from the noncropped land (and which will be affected by management of that land, e.g., weedy fallow vs. bare fallow vs. cultivated fallow) also needs to be considered, in a landscape scale analysis of WP_{ET}.

iv. increase yield and maintain ET

Technologies that increase WP_{ET} by increasing yield while maintaining ET could also serve the dual purpose of increasing food production and reducing water depletion if the total cropped area is reduced, but would be difficult to implement as above (iii).

v. reduce yield and reduce ET, but with a proportionately larger reduction in ET

Technologies that increase WP_{ET} by reducing both yield and ET, with higher reductions in ET, are undesirable if food production is to be increased.

4. EFFECTS OF IMPROVED TECHNOLOGIES ON YIELD, THE NATURE AND AMOUNT OF WATER SAVINGS, AND WATER PRODUCTIVITY

This section reviews the findings to date on the effects of a wide range of technologies on yield, components of the water balance, and water productivity. The components of the water balance considered are irrigation, deep drainage, and ET (partitioned into evaporation and transpiration where possible). The measures of water productivity discussed here are with respect to irrigation (WP_I) and ET (WP_{ET}). Where available, field data are presented. However, it is difficult in field studies to separate most components of the water balance, and few researchers have attempted this. In some cases, the separation has been done using crop models, usually calibrated and validated for the relevant environment and application, and with the advantage of being able to assess performance of the technology over a range of seasonal conditions. The review shows that while there is a considerable amount of data on the impacts of many technologies on yield, irrigation amount and WP_I in comparison with conventional practice, this is not the case for all technologies. Furthermore, there have been very few attempts to determine the nature of any irrigation water savings, and in particular, to determine ET and WP_{ET}. The main findings of the review are summarized in Table 2.

Before discussing the potential benefits of the "improved" technologies, it is important to recognize that there is considerable scope to increase land and water productivity of the RW system through improved agronomic management while retaining current cultural practices (PTR followed by wheat grown using zero till or conventional tillage). District average farmer yields of rice and wheat in Punjab, Haryana, and western UP are considerably below achievable yields on research stations, and 40–70% below potential yields (Pathak *et al.*, 2003; Timsina *et al.*, 2004). The yield gap between the best practice and the farmers' practice was 18.6% in the north western plains under the frontline demonstration program (Anonymous, 2009a). The gaps between research station and farmer yields indicate considerable scope for increasing food production simply by greater adoption of recommended crop management practices. This would also result in large increases in water productivity with respect to both irrigation and ET. In particular, improved management of continuously flooded PTR is likely to have small or negligible effects on irrigation amount and ET, while increasing yield and thus WP_I and WP_{ET}. The situation with regard to WP_I and WP_{ET} of wheat is less clear, and will depend on whether the increase in yield as a result of improved management is greater than any increases in irrigation amount and ET. There is also considerable scope to increase yields of rice, wheat, and alternative crops in the medium term through varietal

Table 2 Estimated impacts of improved technologies on components of the water balance and water productivity in comparison with conventional practice (see Section 4 for explanation)

Section 4 location	Technology	Irrigation	Deep drainage	Yield	ET	WP_{ET}	Effect on rate of groundwater decline
Rice							
4.1	Laser leveling	↘100–200 mm[a]	↘ as for irrig[a]	+0–6%	*Negligible*	*Small increase*	*Negligible*
4.2	Delayed transplanting[b]	↘ 75 mm 20 May–20 Jun ↘ 75 mm 20 Jun–20 Jul	*Negligible*	Negligible	↘ 75 mm ↘ 75 mm	+15% +15%	*Large reduction*
4.3	Short duration rice[b]	↘ up to 270 mm[a,c]	↘ up to 200 mm[a,c]	*Negligible or decrease*	↘ 70 mm	+20%	*Large reduction*
4.4	Alternate wetting & drying	200–800 mm[a]	as for irrig[a]	Negligible	Negligible	Negligible	*Negligible*
4.5	Zero till transplant[b]	?[a]	?[a]	Negligible	*Negligible*	*Negligible*	*Negligible*
4.6	Dry seeding[b]	↘ 200–500 mm[a]	↘ as for irrig[a]	↘ 0–20%	*Negligible*	↘ 0–20%	*Negligible*
4.6	Aerobic rice	↘ 500–800 mm[a]	↘ as for irrig[a]	↘ 30–40%	Decrease	?	*Negligible*
4.7	Transplanted rice on fresh beds	↘ 300–500 mm[a]	↘ as for irrig[a]	↘ 10%	*Negligible*	*Small decrease*	*Negligible*
Wheat							
4.1	Laser leveling	↘ 50–100 mm[a]	↘ as for irrig[a]	+0–20%	?	?	*Small reduction*
4.8	Zero till	↘ 30–100 mm[a]	? low rainfall so little deep drainage	+5%	?	?	*Small reduction*

(*continued*)

Table 2 (*continued*)

Section 4 location	Technology	Irrigation	Deep drainage	Yield	ET	WP_{ET}	Effect on rate of groundwater decline
4.9	Mulching of wheat	↘ 0–40 mm	Negligible	Negligible unless water limiting (increase)	Negligible	Negligible unless water limiting (increase)	*Negligible*
4.10	Wheat on beds	↘ 100 mm	↘ as for irrig[a]	+5%	? *Small increase*	*Negligible*	*Negligible*
Alternatives to rice–wheat							
4.11	Sugarcane	↘ 200 mm	↘ as for irrig[a]		230–240 mm		*Large increase*
4.11	Cotton–wheat	↘ 250 mm	↘ as for irrig[a]		210–250 mm		*Large increase*
4.11	Maize–wheat	↘ 450–500 mm	↘ as for irrig[a]		↘ 50–70 mm		*Medium reduction*

Numbers in the tables should be regarded as indicative only, and are derived from the limited available data reported in the text. ↘ 50 mm indicates a decrease of 50 mm; + 50 mm indicates an increase of 50 mm; ? indicates insufficient data or knowledge to estimate the impact. *Comments in italics are suggested impacts based on current understanding, but for which no data are available.*

[a] Magnitude of the reduction will depend on many factors, especially soil permeability, depth to watertable, and water management.

[b] Same irrigation scheduling criteria/water management as conventional practice.

[c] Data for a loamy sand—more permeable than a typical rice soil.

improvement. For example, by breeding for higher yield potential, improved disease and insect resistance, and tolerance to heat during the reproductive stages. However, neither improved varieties nor improved management using current cultural practices address the sustainability problems of resource degradation, labor scarcity, pollution, and water scarcity. Hence there is a need for technologies which seek to address these and other problems, and also the need for the development of improved varieties suited to these improved technologies.

4.1. Laser leveling

Despite the fact that fields for RW systems are puddled and leveled every year prior to rice transplanting, the soil surface is often very uneven, resulting in excessive water application to enable the highest portions of the field to be flooded for rice, or wetted during irrigation of wheat. In a recent survey of 300 farmers' fields in Punjab, India, the difference between the highest and lowest parts of the fields ranged from 8 to 25 cm (H.S. Sidhu, unpublished data). Jat *et al.* (2006) reported leveling indices (LIs) of up to 13 cm in farmers' fields in Ghaziabad, where LI is the mean deviation between the desired elevation and the actual elevation. LI increased rapidly with field area up to 1 ha. In 50 m 5 m replicated irrigation blocks on a reclaimed sodic soil, Tyagi (1984) found that the irrigation amount required to cover the block increased from 42 to 95 mm as LI increased from 1 to 7 cm. Average wheat yield decreased from 3.1 to 2.2 t/ha as LI increased from 1 to 7 cm, and the decline in yield was attributed to increased waterlogging (the estimated time for the surface water to disappear was 7 d with LI=5 compared with 2 d for LI=1).

In 71 farmers' fields in Punjab, Pakistan, laser guided leveling gave an average reduction in irrigation amount of 76 mm (21%) and an average yield increase of 0.6 t/ha (15%) for wheat (Kahlown *et al.*, 2006). In 71 farmers' fields in western Uttar Pradesh, India, laser leveling gave reductions in irrigation amount of 50–100 mm in wheat and of 100–150 mm in rice (Jat *et al.*, 2006). Assuming irrigation applications of 300 mm to wheat and 2000 mm to rice with conventional leveling, this represents irrigation reductions of 17–30% for wheat, and 5–8% for rice. Mean $\mathrm{WP_I}$ in both crops was increased by about 20% with laser leveling due to reduced irrigation amount and higher yield (by 9% in wheat, 6% in rice). In a small plot replicated experiment on a sandy loam soil in western Uttar Pradesh, laser leveling did not result in significantly higher yields of rice or wheat, however, the total crop system yield with lasering was significantly higher (by 7%) in the second year (Jat *et al.*, 2009), demonstrating the importance of considering the total system as well as individual crops in the rotation. Total irrigation was lower in the lasered treatment compared with conventional leveling, by about 200 mm (12–23%) in rice and 40 mm (9–13%) in wheat.

Studies to explain the effects of laser guided leveling on either crop performance or components of the water balance are lacking. The higher wheat yields are probably due to improved soil water status (reduced water logging and/or reduced water deficit stress due to removal of low and high spots). The net effect on ET is likely to be negligible in both flooded rice and wheat. The higher wheat yields probably reflect improved crop growth and thus greater transpiration, while evaporation is likely to be reduced due to reduced duration of free water on the soil surface (due to faster irrigation time and removal of depressions where water would pond after rain or irrigation). It is likely that much of the irrigation water saving in the above studies was due to reduced deep drainage. In that case, the size of the irrigation water saving will depend greatly on soil type, depth to the water-table, and duration of irrigation (which depends on irrigation flow rates in relation to field size). There are no reports of the effects of these factors on the irrigation water savings due to laser leveling in the RW regions.

In addition to large reductions in irrigation amount and higher yields, laser leveling has many other benefits including increase in the cultivable area and greater efficiency of machinery operations and inputs (due to reduced overlap of machinery passes and reduced "misses") (Jat *et al.*, 2006). Large areas are likely to be laser leveled in the RW systems of the IGP over the next decade, based on initial adoption rates. Laser leveling commenced in western Uttar Pradesh in 2003, and by February 2006, 37 farmers owned laser levelers, and 10,000 acres had been leveled across 10 districts (Jat *et al.*, 2006). However, the most rapid rates of expansion are now occurring further west. In 2005, about 70,000 ha had already been leveled in Punjab, Pakistan, using laser technology (Jat *et al.*, 2006). A project was implemented by the Punjab provincial government in 2006–2008 which was to provide 1500 laser units (50% subsidy) with the goal of leveling 0.3 Mha during the life of the project, and Jat *et al.* (2006) projected that within 10 years about 1.8 Mha would have been laser leveled. Laser leveling is just beginning in Punjab, India, with more than 2000 laser units in that state in August 2009, subsidized by the government (25% in 2008, 33% in 2009) (H. S. Sidhu, personal communication).

4.1.1. Summary—Laser leveling

Large reductions in irrigation amount and increases in WP_I as a result of laser assisted land leveling have been reported from many farmers' fields in the north-west IGP, with irrigation water reductions of the order of 100 mm in both rice and wheat, but results are variable. The irrigation water savings are likely to be due to reduced deep drainage, and will therefore vary with site conditions, irrigation system design, and water management. There is no information in the literature on the effects of site conditions on the effects of laser leveling on irrigation water use and WP_I, nor on the effects of laser leveling on ET and WP_{ET}—WP_{ET} could increase or decrease depending on effects on crop biomass and harvest index. Laser guided land leveling provides many important benefits for farmers, however, it is unlikely to reduce water depletion and groundwater table decline in the major RW areas where groundwater is used for irrigation. On the other hand, in canal irrigated areas, laser leveling will be very beneficial in reducing the rate of watertable rise and thus the amount of waterlogging and secondary salinization. The reduced irrigation requirement will make more canal irrigation water available for other uses.

4.2. Planting date

Shifting planting to a date when a crop can grow under reduced evaporative demand while maintaining yield, and without jeopardizing the ability to sow the next crop at the optimum time, can significantly reduce ET and increase WP_{ET}. This is especially the case in north-west India for crops planted prior to the onset of the monsoon. Many field and modeling studies and Department of Agriculture Statistics show that the yield of transplanted rice is relatively stable over a wide range of transplanting dates from early May to mid June or later, although some studies show a yield decline for transplanting after mid June (Arora, 2006; Chahal *et al.*, 2007; Hira and Khera, 2000; Jalota *et al.*, 2009; Khepar *et al.*, 1999). Many studies also show large reductions in ET by delaying transplanting in north-west India from early May to early July. Using 36 years of weather data at Ludhiana and potential ET calculated by the modified Penman method and crop factors as suggested by Doorenbos and Pruitt (1977), Khepar *et al.* (1999) estimated that ET of rice between transplanting and harvest (duration 110 d) declined from 700 to 490 mm as the date of transplanting was delayed from 1 May to 1 July. Irrigation amounts were least with 1 July transplanting, the date which resulted in the greatest rainfall interception and relatively low ET during the cropping season. Using ORYZA2000 on a sandy loam at Ludhiana, Arora (2006) found that ET of continuously flooded rice decreased from 758 to 569 mm as transplanting date (PR114) was delayed from mid May to 1 July. Jalota *et al.* (2009) found a reduction in ET of PR 118 (120 d transplanting to maturity) of about 70 mm by delaying transplanting from 25 May to 25 June with safe AWD water management (irrigation 2 d after floodwater dissipated), using the CropSyst model on a loamy sand. Using the CROPMAN model, Chahal *et al.* (2007) found that delaying transplanting to mid June or later provided more favorable temperatures (reduced heat stress) and reduced risk of rain during flowering. Later rice planting also widens the window between wheat harvest and rice planting and thus increases the ability to include a third crop, such as a short duration pulse, in the RW system (Section 4.12).

Until recently, the recommended practice in Punjab was to transplant around mid June to save water and electricity. However, in reality, farmers staggered transplanting from early May to the end of June because of limited labor availability, increased pest pressure on later planted crops, and limited availability of electricity for pumping (Hira and Khera, 2000; Singh, 2009). Between 1990 and 2004, 24–64% of the rice crop was transplanted before 31 May, and 49–66% by 15 June (Singh, 2009). During 2006 and 2007, a mass campaign was begun to educate farmers to delay rice transplanting to June 10 or later, and to appeal to the Punjab State Electricity Board to provide 8 h of electricity per day to tubewells from this date onwards (and several hours of electricity were provided every day). The Punjab Preservation of Sub Soil Water Ordinance was implemented in 2008, on the initiative of the Punjab State Farmers' Commission (Singh, 2009). The Ordinance prohibited planting seedling nurseries prior to 10 May, and transplanting rice prior to 10 June. Farmers who did not comply had their crops ploughed in and were required to pay for the cost of the diesel used to do this. The Ordinance was converted to an Act in March 2009, and a similar Act was passed in Haryana. As a result, the area transplanted by 31 May in Punjab decreased to 1.2% in 2008, while the area transplanted before 15 June decreased to 23%. Based on one year's data and historic transplanting patterns, rainfall, and groundwater levels, Singh (2009) estimated that implementation of the Act reduced the long-term rate of decline in the groundwater level by about two-thirds, or 30 cm/yr. The saving in electricity due to the Act was estimated to be 1.22 10^{9} Rs/yr (\$24 million/yr) (Singh, 2009). Hira (2009) predicted that further delaying the transplanting date from 10 June to 15, 20, 25, and 30 June would reduce the average watertable decline rate from 64 cm/yr to 51, 39, 29, and 20 cm/yr, respectively.

4.2.1. Summary—Rice transplanting date

Delaying the transplanting date to mid June will significantly reduce water depletion as ET, while maintaining yield, with important benefits in both groundwater irrigated areas (reduced depletion of the groundwater) and canal irrigated areas (more canal water available for water short areas). The effect of delaying transplanting on deep drainage will be small unless crop duration is significantly affected. As current rice varieties in north-west India are not or only slightly photoperiod sensitive, there will be little effect of changing transplanting date on crop duration. Major constraints to further reducing water depletion by delaying the transplanting date from 10 to 30 June are lower yields for transplanting after mid June, and the lack of labor to transplant millions of hectares of rice over a much shorter time period than has been the case in the past. Mechanical transplanting could potentially solve the latter problem, however, to date attempts to mechanize transplanting in puddled fields have not been successful in north-west India, with negligible farmer uptake. However, mechanized transplanting in nonpuddled fields is a promising new technology (Section 4.4), and would help solve the problem of labor shortage.

4.3. Varietal duration

Reducing varietal duration reduces irrigation water use through decreasing both ET and deep drainage. Using CropSyst on a loamy sand (not a typical rice soil), Jalota *et al.* (2009) found that ET was reduced by about 70 mm with a short duration hybrid (RH257, 90 d from transplanting to maturity) in comparison with the longer duration PR 118 (120 d), while deep drainage was reduced by about 200 mm. The recently released rice variety PAU 201 matures 15 d earlier than many of the current popular long duration varieties, and yields 20–25% more. Thus shifting to varieties with shorter duration, with similar or higher yield, is a real possibility to reduce both irrigation amount and ET while increasing WP_I and WP_{ET}. The reduction in ET will reduce groundwater depletion in groundwater irrigated areas, and the reduction in deep drainage will reduce watertable rise in canal irrigated areas.

4.4. AWD in rice

Traditional lowland rice production involves flooding, puddling, and transplanting, and the fields are normally kept flooded until shortly before harvest. Rice performs best when grown under continuous flooding or in saturated soil, and yield declines as the soil dries below saturation, with a critical threshold of around 10 kPa (Bouman and Tuong, 2001). AWD (also known as "intermittent irrigation") involves flooding the field with a shallow depth of water, say 5 cm, and then waiting for a few days after the floodwater has dissipated before irrigating again. AWD reduces seepage and deep drainage losses, more so on more permeable soil (Tuong *et al.*, 1994). With careful management ("safe AWD"), there is no yield loss compared with continuously flooded rice. Safe AWD incorporates shallow ponding for the first 2 weeks after transplanting, and during flowering, to avoid water deficit stress during these sensitive stages. Yield is maintained if the perched watertable is not allowed to fall below about 15 cm below the soil surface the rest of the time. The actual safe depth varies with soil type, but this has not been quantified, and 15 cm is the upper threshold across all soils. Safe AWD is a proven technology for the tropics and subtropics, with practical guidelines for its application using a simple, low-cost "field water tube" (Bouman *et al.*, 2007a) now known as the "panipipe" in Bangladesh and India. It is widely practised in regions of China where there is now irrigation water scarcity (Li and Barker, 2004), and is also the recommended practice in many countries or regions including the IGP of India and Bangladesh (e.g., Anonymous, 2009b; Sandhu *et al.*, 1980; Sattar *et al.*, 2009), the Philippines, and Vietnam. There are many reports from small plot studies in the IGP showing large irrigation water savings (15–40% of the applied water or up to 840 mm) with AWD in puddled transplanted rice

(PTR) in comparison with continuous flooding, and with no or only small effects on yield (e.g., Choudhary, 1997; Hira *et al.*, 2002; Humphreys *et al.*, 2008a; Sandhu *et al.*, 1980; Sharma, 1989, 1999). The reported irrigation water savings from north-west India are likely to be overestimates in comparison with the situation in farmers' fields because of disproportionately high underbund seepage from small plots where measures to reduce seepage were not implemented (Humphreys *et al.*, 2008a; Tuong *et al.*, 1994). The irrigation water savings are much larger on the permeable soils with deep watertables in north-west India than on soils of low permeability and/or where watertables are shallow (Belder *et al.*, 2004, 2007; Cabangon *et al.*, 2001).

There are a few modeling studies, but very few field studies, which have attempted to determine the nature of the irrigation water savings as a result of AWD in comparison with continuously flooded PTR. On a clay loam in Punjab, Sudhir-Yadav *et al.* (2010a) observed a consistent trend for declining ET as water management changed from continuous flooding to irrigation scheduled at 20, 40, and 70 kPa, however, the differences were not significant. The main causes of the 50% reduction in irrigation amount in going from continuous flooding to AWD were reduced deep drainage and seepage, plus reduced runoff in one year, and reduced ET in the other year. Arora (2006) used the ORYZA2000 model to compare continuous flooding and AWD for PTR on a sandy loam for 12 years of weather data at Ludhiana, Punjab. The AWD treatment involved continuous flooding for 2 weeks after transplanting, and thereafter irrigation (50 or 75 mm) 2 d after the disappearance of free water from the soil surface. AWD reduced the average (over 12 years) irrigation amount by about 350 mm or 25–30%, but ET was only reduced by about 30 mm. Average water productivity with respect to ET (WP_{ET}) was about 5% lower with AWD, while input water productivity (WP_{I+R}) was about 8% higher with AWD due to reduced deep drainage. Belder *et al.* (2007) and Bouman *et al.* (2007a,b) also found only very small effects of safe AWD on ET and small to large effects on irrigation amount and deep drainage for PTR in the Philippines and China using ORYZA2000. The reduction in irrigation with AWD was due to reduced drainage, and was highly dependent on rainfall, soil type, and depth to the watertable.

While AWD is the recommended practice in India, in reality farmers irrigate according to the availability of water (in canal irrigated systems) or electricity (which is highly subsidized, or even free to farmers in some states such as Punjab) for groundwater pumping. The availability of electricity to rural areas is unreliable and limited to a few hours every day or so, therefore farmers pump continuously whenever free electricity is available because of the uncertainty as to when it will next be available. Thus there is little incentive, and high risk, with adoption of AWD by groundwater pumpers who have access to electricity. Farmers are concerned that if the soil dries to the degree that it cracks, then irrigation requirement will be greatly increased. However, where farmers are dependent on diesel (for which they have to pay) to pump groundwater, safe AWD would be a useful technology for minimizing irrigation water (and diesel) use while maintaining rice yield. Hira (2009) proposed charging the full price for electricity to provide an incentive to farmers to irrigate more efficiently, and using half of the income from selling electricity to provide bonuses for rice and wheat. If Punjab State Electricity Board is able to supply 6–8 h of electricity per day to tubewells from 10 June onwards (introduced in 2009), this would enable farmers to practice safe AWD.

The distribution of water in the canal systems of north-west India is based on a rotational system known locally as "Warabandi," and described in detail by Khepar *et al.* (2000). The canal water may only be available to individual farmers every couple of weeks. Farmers in the lower reaches get much less water per unit area than farmers in the upper reaches because the duration of supply at each farm outlet is in proportion to the holding size, without considering seepage losses from head to tail of the system. Infrequent, unreliable, and inadequate water supply means that it is logistically impossible for farmers reliant on canal irrigation to adopt safe AWD. Furthermore, the cost of canal irrigation water is low (US$2.7/ha in Haryana, Erenstein (2009); US$8.2/ha in Punjab in 2009, up from US $3.8/ha in 2007), so there is no incentive for farmers with better access to water in the upper reaches to save irrigation water.

The extent of adoption of safe AWD in the IGP is unknown, but it is likely to be small, in both canal and groundwater irrigated areas, for the above reasons. Where AWD occurs, it is likely to be because the farmers have no other choice because of lack of rain and electricity or canal water, that is, it is "unmanaged" AWD and thus likely to result in yield loss due to water deficit stress (Bouman and Tuong, 2001).

4.4.1. Summary—Safe AWD for rice

Safe AWD maintains yield while giving very large irrigation water savings in transplanted rice on permeable soils with deep watertables, in comparison with continuously flooded rice. The reduction in irrigation amount is likely to be due to reduced deep drainage, with little effect on ET and WP_{ET}. Conversion from continuously flooded rice to safe AWD will help conserve irrigation water for other uses and reduce watertable rise in canal irrigated areas, but will have little effect on the rate of groundwater depletion in the groundwater irrigated areas.

In practical terms, adoption of safe AWD is generally not possible for farmers dependent on canal irrigation or electricity for groundwater pumping because of unreliable and limited supply of water or electricity. There is no incentive to adopt safe AWD because of the low prices of water and electricity. However, safe AWD would be beneficial for farmers who purchase diesel to pump groundwater. Areas where diesel powered pumps are commonly used should be identified and the technology could be promoted immediately.

There is a need for institutional and policy changes to encourage farmers to adopt safe AWD. In canal irrigated systems, adoption by farmers upstream would improve canal water supplies for downstream farmers. However, this would result in reduced groundwater recharge in upstream reaches, with potential effects on "downstream" farmers dependent on groundwater for irrigation.

4.5. Zero till transplanted rice

Mechanical transplanting into noncultivated soil (zero till transplanting) has recently been shown to be a very promising technology for establishing rice in north-west India, with major benefits including large savings in energy and labor, and regular plant spacing (Malik and Yadav, 2008; Sharma *et al.*, 2003, 2005). The technology is particularly relevant to north-west India at present because of the rapidly escalating labor scarcity for transplanting as a result of the National Rural Employment Guarantee Act (2007). This Act promises 100 d paid work in people's home villages, while transplanting of rice in north-west India has been dependent on millions of migrant laborers from eastern Uttar Pradesh and Bihar.

Whether zero till transplanting results in water savings in comparison with transplanting into puddled soil, and the nature of those savings, has not been established. Puddling is practised in rice culture for many reasons including weed control, ease of transplanting, and to help maintain standing water in the field by reducing drainage beyond the rootzone. The relative importance of these benefits varies with many factors such as climate, soil type, and local cultural practices. Reducing deep drainage is most important on coarse textured soils such as those in north-west India, where infiltration rates are very high in the absence of puddling (e.g., 30 mm/d on a sodic silty loam at Modipuram, Uttar Pradesh, Sharma *et al.*, 2002; 72 mm/d on a silty loam in Haryana, Sharma *et al.*, 2004b). The reduction in infiltration rate (and thus of deep drainage) as a result of puddling depends on soil type, depth to the watertable, intensity of prepuddling tillage and puddling, and depth of the floodwater (Adachi, 1992; Cabangon and Tuong, 2000; Gajri *et al.*, 1999; Kukal and Aggarwal, 2002; Kukal and Sidhu, 2004; Kukal *et al.*, 2005; Sanchez, 1973). Thus, *with the same water management* from transplanting to harvest, deep drainage from puddled fields during this period is likely to be lower than from nonpuddled fields. The magnitude of the difference will depend greatly on water management and site conditions such as soil type, degree of soil cracking at the time of rice establishment, and depth to the watertable.

While puddling reduces deep drainage after transplanting, it can also require a large amount of water to undertake the puddling operation, typically 150–250 mm to saturate and flood the soil (Tuong, 1999). In some parts of Asia, there is also a long prepuddling soil soaking period for a range of logistical reasons (Cabangon *et al.*, 2002; Tuong, 1999). During this period, large amounts of water can be lost as evaporation and deep drainage. The amount and size of soil cracks has a large influence on deep drainage (Cabangon and Tuong, 2000; Liu *et al.*, 2003; Tuong *et al.*, 1996). Furthermore, the cracks do not necessarily close during soaking and ponding, and may continue to conduct large amounts of water to depth until they are closed by puddling (Ishiguro, 1992; Tuong *et al.*, 1996). Long soaking periods are common in canal irrigation systems where flow rates are inadequate, and where the irrigation water supply is from field to field instead via distributary channels. However, in the major RW regions of north-west India, farmers have installed tubewells to have ready access to water (e.g., an average of 1.8 tubewells per household in Haryana, Erenstein, 2009). Therefore they can normally irrigate and complete puddling within a couple of days, and the irrigation water savings from avoiding puddling for transplanted rice are likely to be small as the field also needs to be soaked prior to zero till transplanting. Furthermore, in both systems, the field needs to be shallow-flooded for a couple of weeks after transplanting for good establishment.

There are few studies comparing water use in puddled and non-puddled transplanted rice. Singh *et al.* (2001) compared zero till and PTR using the same water management—the soil was always saturated, with floodwater depth ranging from 0 to 5 cm. In their 3 year RW experiment in small plots on a sandy loam at Delhi, they found that PTR used on average 125 mm less irrigation water than transplanted rice in nonpuddled soil. Importantly, their irrigation measurements included the prepuddling irrigations, which is not often the case in reports on water use in PTR in north-west India.

Given the large irrigation water savings possible with safe AWD, it is also important to compare puddled and zero till transplanted rice under these conditions. Puddled soils tend to crack upon drying; the rate and size of crack development depends on the rate of drying, the amount of clay with shrink/swell properties, and the potential for consolidation of the puddled layer (Cabangon and Tuong, 2000; Ringrose-Voase and Sanidad, 1996; Ringrose-Voase *et al.*, 2000). The cracks grow as the soil dries, which in turn increases the rate of drying as a result of exposure of the crack faces to the atmosphere. Sanchez (1973) found that topsoil drying and cracking 30 d after transplanting, followed by AWD, greatly reduced root development and yield, whereas topsoil drying and cracking 60 d after transplanting had no effect on root development and increased yield. Irrigation water use and deep drainage losses can be much higher once the soil cracks due to bypass flow (flow through vertically continuous macropores) (Cabangon and Tuong, 2000; Sanchez, 1973; Wopereis *et al.*, 1994). Anectodal evidence from India is that cracking commences much sooner in puddled soil than nonpuddled soil. This implies that the safe AWD irrigation interval for PTR may be less than for zero till transplanted rice, which may result in irrigation water savings with zero till transplanted rice. Bhushan *et al.* (2007) compared these two tillage methods in small plots on a silty loam soil at Modipuram, using the same AWD irrigation scheduling rule for both methods (irrigate to a floodwater depth of 5 cm at the first appearance of hairline cracks). In 2002 (which was very dry for the first 2 months), the total amount of irrigation applied to both the puddled and zero till treatments was similar (3050 mm). In 2003 (rains well distributed), there was an 8% reduction (150 mm) in irrigation water use with zero till transplanted rice. The nature of the irrigation water savings was not determined. Yield and yield components of zero till and PTR were similar in both years, therefore it is likely that transpiration was similar in both treatments. To date there are no other published data on water use in zero till transplanted rice compared with PTR.

4.5.1. Summary—Zero till transplanted rice

There are insufficient data to predict the impact of changing from puddled to zero till transplanted rice on components of the water balance and measures of WP. The impact needs to be assessed based on optimum irrigation management for each system, and the impact on deep drainage is likely to vary greatly with soil type (permeability, tendency to crack), amount of soil cracking at the time of establishment, and depth to the watertable. The impact on ET is likely to be small.

4.6. Dry seeded rice with AWD

Dry seeding provides another mechanical and potentially simpler option for establishment of rice than mechanical transplanting. In dry seeded rice (DSR), the seed is normally drilled into soil tilled in a similar way to conventional tillage for wheat, but it can also be sown using zero tillage (e.g., Bhushan *et al.*, 2007). Water management for DSR can vary from continuous flooding (after establishment) to frequent irrigation (with the goal of similar yield to that of continuously flooded PTR or DSR—that is, DSR with safe AWD) to infrequent irrigation (for situations where lack of irrigation water limits rice yield) to rainfed.

4.6.1. Frequently irrigated DSR

There is currently a lot of interest in DSR in north-west India because of the reduced labor requirement. DSR is also attractive to farmers because of the lower irrigation requirement of DSR with AWD than continuously flooded PTR, especially given the reluctance of farmers to adopt PTR with AWD due to concerns about soil cracking if irrigation water (electricity) is not available as needed. In the central to eastern Ganges Plains, where rice establishment is often reliant on the start of the monsoon, dry seeding can provide the opportunity for timely establishment on the first rains (usually one to two supplementary irrigations are needed after sowing) prior to the onset of the monsoon proper, rather than waiting for sufficient rain to be able to puddle and flood the soil for transplanted rice. Often the monsoon is late relative to the optimum time for transplanting, resulting in transplanting of seedlings older than the optimum age, and terminal drought due to cessation of the rains prior to maturity of late planted crops. The late rice harvest also delays establishment of wheat beyond the optimum date, lowering wheat yield. However, in north-west India, the optimum time for establishment of DSR is a few weeks prior to the normal start of the monsoon, at a very hot time of year when evaporative demand is very high (typical pan evaporation 8-12 mm/d, Fig. 2). Furthermore, the duration of DSR in the main field is longer (by 2–5 weeks) than the duration of transplanted rice (Cabangon *et al.*, 2002; Sudhir-Yadav *et al.*, 2010b), suggesting that ET of DSR will be higher than ET of PTR. On the other hand, anecdotal reports from farmers and researchers are that the safe AWD irrigation interval in DSR can be much longer than in PTR because the puddled soil cracks much sooner and more strongly. On a clay loam soil in Punjab, Sudhir-Yadav *et al.* (2010a) observed that the soil water tension at 17–20 cm depth increased to 20 kPa 1–3 d earlier in PTR than DSR, and that crack formation usually started just 1 d after irrigation during the early growth stage when there was little plant cover and hot, dry weather. The longer irrigation interval may result in lower irrigation water use in non-puddled soil, while the lack of puddling may increase deep drainage and thus irrigation amount. The net result will depend on site conditions, and in the few cases where it has been determined, irrigation amount was reduced with DSR compared with PTR with the same AWD irrigation scheduling (Bhushan *et al.*, 2007; Jat *et al.*, 2009; Sudhir-Yadav *et al.*, 2010a).

Bhushan *et al.* (2007) compared PTR and zero till DSR in small plots on a silty loam at Modipuram. The DSR was sown on the same day as the nursery for PTR. They used the same irrigation scheduling rules for both establishment methods, daily irrigation for the first 2 weeks after transplanting or sowing, followed by irrigation when hairline cracks appeared. There was a 20% reduction in irrigation application with DSR compared with PTR in both the poorly and well-distributed rainfall years. Yields were similar in both treatments in the first year (>7 t/ha), although yield was achieved in different ways—much higher tiller and panicle density and lower floret fertility in DSR compared with PTR. Yield of DSR was significantly lower than of PTR in the second year (by 13%). Sharma *et al.* (2005) also reported similar yields (>6.5 t/ha) for DSR and PTR. On a sandy loam at Modipuram with similar irrigation management to that of Bhushan *et al.* (2007), Jat *et al.* (2009) also found reduced water input (irrigation plus rain) by 9–24% with DSR (zero till or cultivated) in comparison with PTR. The magnitude of the saving was similar in both lasered and nonlasered treatments. Yields of DSR in the second year were significantly lower than yields of PTR (by about 30% or 2 t/ha in both lasered and nonlasered treatments), resulting in similar WP_I in both DSR and PTR in both leveling treatments. The yield loss with DSR was offset by higher wheat yields after DSR than after PTR in the second year, resulting in similar total system yield, and again demonstrating the importance of considering the total system rather than individual crops. At Delhi the best varieties only produced around 4.5 t/ha when dry seeded and irrigated at a soil water tension of 20 kPa, with about a 10% yield decline when the irrigation threshold tension was increased to 40 kPa (Singh *et al.*, 2008). Irrigation at soil water tensions of 20 and 40 kPa reduced input water by 23% and 32%, respectively, in comparison with irrigation to keep the soil close to saturation. How much of the irrigation water savings in the above studies was due to reduction in ET and/or deep drainage is not known. If the lower yield of DSR was associated with lower biomass, at least part of the irrigation water savings would be due to reduced ET, but the effect on WP_{ET} would depend on whether ET was reduced by more than yield.

In small plots on a clay loam at Ludhiana, Punjab, Sudhir-Yadav *et al.* (2010a,b) found similar irrigation water use and yield (>7 t/ha) of continuously flooded PTR and daily irrigated DSR (topped up to 5 cm daily from the time of transplanting the PTR; the DSR and the seedbed for PTR were sown on the same day) (Fig. 4). When irrigations were delayed until the soil water tension increased to 20 kPa at 17–20 cm depth, irrigation amounts in both establishment methods were more than halved, and the amount

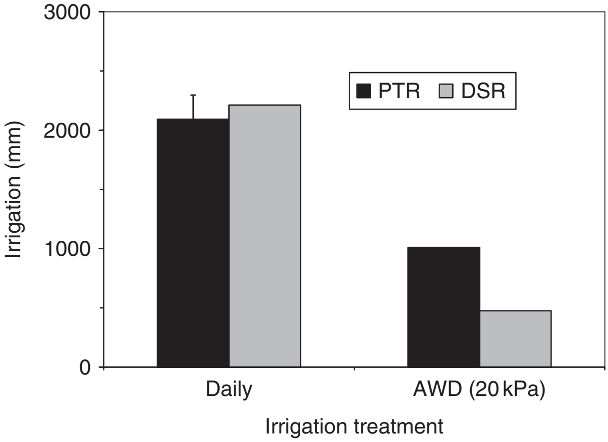

Figure 4 Irrigation water use of PTR and DSR as affected by irrigation scheduling on a clay loam at Ludhiana, Punjab, 2008. Daily = daily irrigation topped up to 5 cm, 20 kPa = irrigated when soil water tension at 17–20 cm increased to 20 kPa. Vertical bar is the least significant difference ($p = 0.05$) for the interaction between establishment method and irrigation treatment. (Adapted from Sudhir-Yadav *et al.*, 2010a.)

applied to DSR was 30–50% lower than that applied to PTR, while yields in both treatments were similar to yields of continuously flooded PTR. The larger irrigation amount with PTR-20 kPa than DSR-20 kPa was mainly due to the fact that the PTR was continuously flooded for the first 15 d after transplanting before the irrigation scheduling commenced, and to a much lesser degree because it also required more frequent irrigation once the scheduling commenced. Deep drainage over the whole season was estimated using tritiated water injected at 60 cm at the time of sowing (DSR) or transplanting (PTR) (Munnich, 1968). Deep drainage under DSR-20 kPa (284 and 453 mm in 2008 and 2009, respectively) was significantly higher than in PTR-20 kPa (170 and 255 mm), probably due to the combination of irrigation and rainfall between sowing and the time of transplanting in 2008, and the lack of puddling (higher infiltration rate) in DSR. However, the deep drainage under PTR in 2008 was probably underestimated as it did not include drainage as a result of the large amount of rain that fell between the time of sowing DSR and irrigation for puddling. ET in both treatments was similar each year (means of 640 and 710 mm in 2008 and 2009, respectively), as was WP_{ET} (1.1–1.2 kg/m^3). The irrigation water saving in DSR was due to reduced seepage and runoff. Whether this is a real water saving would depend on whether the seepage water ultimately flowed to sources or sinks.

Yields of both DSR and PTR declined when the soil was allowed to dry to higher tensions than 20 kPa, and yield of DSR declined more rapidly than yield of PTR as tension increased to 40 and 70 kPa (Sudhir-Yadav *et al.*, 2010b). On a marginally sodic silt loam at Modipuram, yield of DSR declined significantly (by 15%) as the threshold for irrigation increased from 10 to 20 kPa at 20 cm (Sharma *et al.*, 2002). The DSR was affected by iron deficiency in the studies of both Sharma *et al.* (2002) and Sudhir-Yadav *et al.* (2010b), more so as the threshold tension for irrigation increased. Development of improved varieties targeted for dry seeding with AWD water management is needed, as are management guidelines (e.g., irrigation, nutrients, weeds). The IRRI-led Cereal Systems Initiative for South Asia (CSISA) project which commenced in 2009 includes a major effort to develop varieties for dry seeding with safe AWD.

4.6.1.1. Summary—Dry seeded rice with safe AWD

Irrigation amounts of DSR with safe AWD are reduced in comparison with PTR with safe AWD, largely because of the need for continuous flooding during the first 2 weeks after transplanting, and partly because of the shorter irrigation interval to avoid soil cracking in puddled soil. The very limited data available to date (one study) suggest similar ET and WP_{ET} from DSR and PTR with safe AWD management, while the results of several studies show similar or lower yields with DSR than PTR.

4.6.2. Aerobic rice

The System of Aerobic Rice ("aerobic rice") is also a dry seeded system, but one which uses much less irrigation water than well-irrigated DSR. It is referred to as a "System" as it involves the use of both specially developed input-responsive cultivars that are adapted to drier soil conditions than lowland rice varieties, and management practices tailored to maximize input water productivity (WP_{I+R}). Aerobic rice was originally developed for irrigation areas where traditional PTR can no longer be grown due to water scarcity (as a result of physical shortage of water, inaffordability of water to farmers, or policies banning PTR, such as in areas that used to grow PTR around Beijing), and for favorable rainfed upland areas (Wang *et al.*, 2002). The WP_{I+R} of aerobic rice is typically double that of traditional rice culture grown under optimum conditions in the same climate (Bouman *et al.*, 2006; Feng *et al.*, 2007; Yang *et al.*, 2005). In northern China, first-generation aerobic rice varieties have a demonstrated yield potential of 6 t/ha (compared with about 9 t/ha for lowland cultivars) but use only about 50% of the input (irrigation plus rain) water used in paddy rice. While the yield potential of current aerobic rice varieties is only about two-thirds that of lowland varieties grown in saturated or flooded soil, as water input is reduced below that required for continuous soil saturation, yields of traditional varieties fall below those of aerobic rice varieties grown with the same level of water deficit (Fig. 5). Thus aerobic rice is suited to areas where there is insufficient water to grow PTR or high yielding DSR with safe AWD, but where there is a need to continue to grow rice.

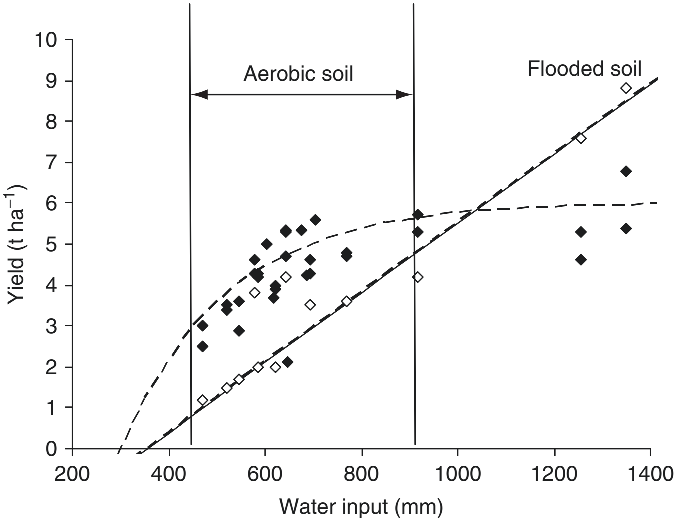

Figure 5 Yield of aerobic rice varieties (black diamonds) and a lowland variety (open diamonds) under flooded and aerobic soil conditions at nearby sites outside Beijing, China, 2001–2004 (source: Bouman *et al.*, 2007a).

It is also an attractive crop for traditional upland areas where crops such as maize and soybeans are sometimes severely affected by waterlogging, as aerobic rice is tolerant of waterlogging. Templeton and Bayot (2008) conservatively estimated that the potential adoption area for aerobic rice in China is about 5 Mha. Preliminary extrapolation domain analysis based on site similarity (climate, topography, rice growing area, availability of irrigation and poverty level) analysis with pilot aerobic rice sites suggested that the potential area for aerobic rice in India is also very large (several million hectares) and includes much of the IGP (Rubiano and Soto, 2008).

Using the ORYZA2000 rice model, Bouman *et al.* (2006) showed that changing the irrigation threshold for aerobic rice from 10 kPa soil tension at 15–20 cm (equivalent to daily irrigation) to 20 kPa had no effect on yield, ET or WP_{ET} with a watertable at 60 cm, in wet and dry years, at Huibei in the Yellow River plain in China. With a deep watertable (1.9 m) in a dry year, both yield and ET declined by about 6% (by 0.5 t/ha, 40 mm, respectively), thus WP_{ET} was again hardly affected. WP_{ET} of aerobic rice ranged from 1 to 1.2 kg/m^3, compared with values in excess of 1.4 kg/m^3 for lowland rice in the same locality, for a range of watertable conditions and irrigation schedules. Xue *et al.* (2008) found higher WP_{ET} of around 1.4 kg/m^3 of aerobic rice for irrigation thresholds of 20–100 kPa using ORYZA2000 in deep watertable conditions near Beijing. Yield declined by about 10% (from 7.5 to 6.8 t/ha) over this range of irrigation schedules, while ET declined by about 6% (from about 510 to 480 mm).

As for frequently irrigated DSR using varieties with higher yield potential, aerobic rice sometimes performs poorly as a result of factors such as micronutrient deficiency and nematodes (Kreye *et al.*, 2009a,b). Further research is needed to produce germplasm with higher yield potential under limited water, and to develop management guidelines for sustainable aerobic rice-based cropping systems.

4.6.2.1. Summary—Aerobic rice Irrigation input can be further reduced beyond that in DSR using safe AWD using the System of Aerobic Rice, and with small reductions in ET, but the tradeoff is lower yield. The very limited data to date (one study) suggest that WP_{ET} of aerobic rice is less than that of well-irrigated PTR. Clearly, further efforts are needed to develop higher yielding aerobic rice systems and to quantify impacts on components of the water balance and water productivity.

4.7. Rice on beds

4.7.1. Transplanted rice on beds

Small plot replicated experiments show reductions in the amount of irrigation water applied to transplanted rice on *fresh beds* compared with PTR (Bhushan *et al.*, 2007; Kukal *et al.*, 2010). In both these studies the same

AWD irrigation scheduling rules were applied to beds and PTR—irrigation on the appearance of hairline cracks on the soil surface of the flat plots or in the bottom of the furrows (Bhushan *et al.*, 2007), or irrigation 2 d after the disappearance of water from the soil surface or furrows (Kukal *et al.*, 2010), and the furrows were filled almost to the top of the beds at each irrigation. Irrigation amount on fresh beds was reduced by 16% on a silty loam in western Uttar Pradesh (Bhushan *et al.*, 2007), and by 11% and 24% on sandy loam and loam soils, respectively, in Punjab (Kukal *et al.*, 2010). At all three sites, there was a reduction in yield on the beds similar to the reduction in irrigation amount, thus WP_I was similar in the transplanted fresh beds and PTR. In a farmers' field on the loam, irrigation was reduced by 15% while yield was reduced by 8%, resulting in a small increase in WP_I. Some of the earliest farmer participatory trials of rice on beds in Ghaziabad, Uttar Pradesh, showed much larger average reductions in irrigation time (around 40%) for transplanted and DSR on raised beds in comparison with farmer practice (PTR), while average yields of all three systems were similar, thus resulting in higher WP_I on the beds (Balasubramanian *et al.*, 2003; Gupta *et al.*, 2003). The reasons for the differences are unknown; however, it is likely that the larger irrigation water savings in the farmers' fields were due to comparison of intermittently irrigated beds with continuously flooded PTR, whereas the studies of Bhushan *et al.* (2007) and Kukal *et al.* (2010) compared beds and PTR with similar AWD water management.

Results of experiments in small plots comparing transplanted rice on *permanent beds* and PTR are quite variable in terms of both grain yield and irrigation water use. In general, rice on permanent beds performs much better in the eastern IGP than in the north west (Humphreys *et al.*, 2008b). Results from Bangladesh, Nepal, and Uttar Pradesh show reduced irrigation amounts of 14–38% on permanent beds compared with PTR, on soils ranging in texture from sandy loam to silty clay loam, for beds up to 8 years old (Bhushan *et al.*, 2007; Jat *et al.*, 2008; Lauren *et al.*, 2008; Talukder *et al.*, 2008). In these studies, Bhushan *et al.* (2007) and Jat *et al.* (2008) irrigated all treatments at the first appearance of hairline cracks in the flat plots or furrows, while Lauren *et al.* (2008) irrigated the PTR and beds on the same day. In contrast, the total amount of irrigation water applied to PTR and permanent beds on a sandy loam at Ludhiana was similar on average over 4 years (Kukal *et al.*, 2010). In this case both treatments were irrigated 2 d after the disappearance of water from the surface/furrows (usually on the same day), and the furrows were also filled almost to the top at each irrigation. On a loam at Phillaur with the same irrigation management, irrigation water application to the permanent beds was significantly higher (by 16–21% over 4 years) than in PTR in the small plots, and by 7% in a large (farmer field) block (one year's data only).

Results from Bangladesh and Nepal consistently show similar or higher yields of transplanted rice on permanent beds than PTR (Lauren *et al.*, 2008;

Talukder *et al.*, 2008), and higher WP_I as a result of both higher yields and lower irrigation amounts. In contrast, results from India and Punjab, Pakistan consistently show lower yields on the permanent beds than in PTR, in both small plots and farmers' fields (Bhushan *et al.*, 2007; Jat *et al.*, 2008; Jehangir *et al.*, 2007; Kukal *et al.*, 2010; Yadvinder-Singh *et al.*, 2008a, 2009), with yield declining as the beds age. The net result in the studies in India was thus similar or declining WP_I on the permanent beds compared with PTR. In Punjab, WP_I declined to about 50% of that in PTR by the 2nd or 3rd rice crop on the sandy loam and loam soils, respectively, in both small plots and in a farmer's field (Kukal *et al.*, 2010).

Kukal *et al.* (2010) also found that total irrigation amount was higher on permanent beds than fresh beds with the same irrigation management in small plots on sandy loam and loam soils (by 11% and 24%, respectively), and by 25% in adjacent farmer blocks on the loam soil. They attributed this to bypass flow as a result of greater macroporosity in the permanent beds due to cracking and biopores. In the farmer field blocks, irrigation application depth also had a large effect on the amount of irrigation water applied to both fresh and permanent beds on the loam (Kukal *et al.*, 2010). Half filling the furrows (instead of filling them to the top of the beds) at each irrigation decreased irrigation water amount in the permanent and fresh beds to 68% and 61%, respectively, of that in PTR with the same AWD irrigation scheduling. However, yield also declined by 20–25% when irrigation depth in the furrows was halved. The net result was higher WP_I in PTR than on both the fresh and permanent beds irrigated with half furrow depth.

4.7.2. DSR on beds

There are only a few reports comparing DSR on beds with DSR on the flat or PTR, all in small plots in north-west India. All these studies show a decline in yield of DSR on the beds relative to PTR, but the results are inconsistent in terms of irrigation amount.

Choudhury *et al.* (2006) compared yield and components of the water balance for DSR on sandy loam and loam soils on *fresh beds* and on the flat at Delhi. The small plots had plastic lined bunds to reduce underbund seepage, and row spacing on the flats was even (20 cm) or with paired rows (20 cm, 47 cm), the same plant row spacings as on the beds. All three treatments were lightly irrigated every 2nd day to keep the root zone close to field capacity. There was a significant (11%) reduction in irrigation amount on the beds in the first year compared with both DSR flat treatments, but no significant difference in the second year. The reduction in irrigation in the first year was due to a 15% reduction in drainage beyond the rootzone, while ET (calculated from the water balance) was similar on beds and flats with paired row spacing in both years, but significantly lower (by about 12% or 75 mm) than with 20 cm row spacing, probably due to the much lower leaf area and biomass production with the paired rows (on beds and flats).

Yields of DSR on beds and flats with paired rows were similar, and significantly lower (by 12–24%) than yields of DSR with 20 cm row spacing. Water productivity with respect to ET was thus similar in all three treatments in 1 year, and significantly lower (by 14%) on beds and flats with paired rows than with 20 cm row spacing in the other year. At Modipuram, irrigation water use of DSR on fresh beds was significantly lower (by 9% and 5% on sandy loam and silty loam soils, respectively) than in DSR on the flat (Bhushan *et al.*, 2007; Jat *et al.*, 2008; first crop on the beds in both these permanent bed studies). Yields on the beds were 17% and 14% lower than on the flat, resulting in slightly but significantly lower WP_I on the beds. At another sandy loam site at Modipuram, yields of DSR and irrigation amount on fresh beds were both about 25% lower than PTR with the same irrigation scheduling rules (appearance of hairline cracks), resulting in similar WP_I in DSR and PTR (Jat *et al.*, 2009).

Yield of DSR on *permanent beds* (3- and 8-year-old beds) was significantly lower (by 46% and 23%, respectively) than yield of PTR, and 16% lower than yield of DSR on the flat, on two sandy loam sites in Modipuram (Jat *et al.*, 2008, 2009). While irrigation input was reduced by about 25% (400 mm) on the 3-year-old beds, WP_I was significantly lower because of the 46% yield decline (Jat *et al.*, 2009). On sandy loam and loam soils in Punjab, yields of DSR on beds also declined greatly relative to yield of PTR as the beds aged, while the amount of irrigation water applied to DSR was similar to or higher than that applied to PTR with the same AWD irrigation management (Humphreys *et al.*, 2008a; Yadvinder-Singh *et al.*, 2008a, 2009). The higher irrigation amounts were partly due to the longer duration of DSR in the main field. Constraints to growth of DSR on beds in north-west India included nematodes and severe iron deficiency which could not be fully overcome by the use of iron sprays (Sharma *et al.*, 2002; Yadvinder-Singh *et al.*, 2008a, 2009).

4.7.3. Summary—Rice on beds

Transplanted rice on *fresh beds* consistently results in irrigation water savings of 15–25% in comparison with PTR with AWD, with irrigations on beds and PTR scheduled using the same rules. However yields on beds in north-west India tend to be lower than yields of PTR, resulting in similar WP_I.

The nature of the irrigation water savings has hardly been investigated, for both transplanted and DSR on beds, apart from the study of Choudhury *et al.* (2006). Where rice growth is similar on beds to that of PTR, there is likely to be little effect on ET, and the savings are probably due to reduced deep drainage and thus their magnitude will depend on soil type and depth to the watertable. The size of the irrigation water savings for intermittently irrigated beds will be much higher if they are compared with PTR with continuous flooding rather than with AWD. The magnitude of the water savings of transplanted rice on fresh beds in farmers' fields in comparison with farmer practice (probably PTR with continuous flooding) appears to be similar to the savings with AWD compared to continuous flooding of PTR.

The performance of *transplanted rice* on *permanent beds* is variable across the IGP. In north-west India yields and WP_I generally decline as the beds age in comparison with PTR with the same irrigation scheduling rules. This is not the case in studies in Nepal and Bangladesh. Results are also variable with regard to irrigation amount on permanent beds compared with PTR. Bypass flow on the permanent beds as a result of soil cracking during the long hot fallow, and the development of biopores, appears to lead to higher irrigation requirement on the permanent beds on some soil types. Yield of *DSR on beds* is consistently inferior to that of PTR, and yield declines greatly as the beds age. Iron deficiency and nematodes are often major problems.

To date there has been negligible adoption of rice on fresh or permanent beds in north-west India. Clearly, further research is needed to develop sustainable, high yielding permanent bed systems for rice.

4.8. Zero till wheat

Traditional establishment of wheat after rice involves removal of the rice residues (predominantly by burning in north-west India, or manually in eastern India), followed by intensive tillage (Gajri *et al.*, 2002). In the north west, this typically involves a pretillage irrigation followed by a couple of discings then harrowings then plankings to prepare the seed bed for wheat. In Punjab, India the seed is normally sown in rows by a seed drill, whereas in Haryana and the eastern IGP it is commonly broadcast. Adoption of zero tillage in the IGP has been rapid since the mid-1990s, increasing to over 3 million hectares by 2006 (Harrington and Hobbs, 2009). The major driver for adoption is increased profitability as a result of lower establishment costs (Erenstein and Lakshmi, 2008). In 2003–2004, zero till wheat (ZTW) was practised on over 1 million hectares in India, using the Pantnagar or “zero till” seed drill (Erenstein and Lakshmi, 2008). This machine is capable of sowing into bare, nontilled soil and into anchored rice residues, but not into combine harvested rice stubbles because the loose residues left by the harvester block the seed drill. Thus ZTW as it is currently practised involves full or partial burning, or removal of the loose rice residues.

In a comprehensive review of ZTW farmer participatory trials and research in RW systems of the IGP, Erenstein and Lakshmi (2008) found that zero till saved one irrigation, and gave average irrigation water savings of 10–30% or up to 100 mm, compared with conventional tillage. This was mainly due to lack of need for a presowing irrigation due the ability to sow sooner after rice harvest while the soil was still moist, and due to the much shorter duration of the first irrigation because of the faster advance of the water over the nontilled soil surface. However, a pre-tillage/sowing irrigation may not always be needed for wheat sown into tilled soil (Sharma and Singh, 2002). Yields of ZTW were similar or higher (by an average of 6%) than yields with conventional tillage, thus WP_I was also higher. Adoption studies in Haryana (Erenstein *et al.*, 2008) also showed that WP_I was significantly (17%) higher in ZTW than with conventional tillage, due to slightly higher yields (by 4%) and slightly lower irrigation amount (by 9%), although the average number of irrigations for both establishment methods was the same.

The nature of the irrigation water savings for ZTW in comparison with conventionally tilled wheat has not been investigated. There are four possible causes: (1) reduced transpiration as a result of earlier planting resulting in the crop growing under a period of lower evaporative demand; (2) reduced deep drainage due to the shorter duration of the first irrigation, and due to fewer irrigations where that is the case; (3) reduced soil evaporation due to reduction in the period between rice harvest and wheat as a result of earlier wheat planting; Humphreys *et al.* (2008a) showed significant drying of the soil profile to depth on sandy loam and loam soils in Punjab between the time of rice harvest in mid October and wheat sowing in early November. As there is often a window of several weeks between rice harvest and the optimum time for wheat sowing in the north west, the use of zero tillage is unlikely to advance the time of wheat sowing significantly, except where rice harvest is late as is the case for basmati rice; considerable areas of basmati are grown in Haryana (0. 4 Mha out of a total rice area of 1 Mha since about 2000, but with a dramatic increase to 0.8 Mha out of 1.2 Mha in 2009), Punjab (20% of the rice area or 0.5 Mha) and Uttar Pradesh; (4) reduced soil evaporation due to nondisturbance of the soil—whether tillage increases total evaporation due to exposure of moist soil aggregates to the atmosphere or reduces it due to breaking of capillarity depends on the time period, soil type, incidence and amount of rain, and evaporative demand (Jalota *et al.*, 2001). Under typical dry, low evaporative demand conditions after rice harvest, Jalota *et al.* (2001) found only very small differences in soil profile water content for untilled and cultivated soil after 2 and 3 weeks on sandy loam soils, but on a loamy sand (not a typical rice soil) water content in the untilled soil was 30 mm higher after 3 weeks.

The optimum time for wheat sowing in north-west India is the first fortnight in November. Given that rice is generally harvested in early to mid October, and the potential for early establishment of wheat using zero tillage, it is important to understand the tradeoffs between on yield, WP_I and WP_{ET} with earlier sowing? Using the DSSAT-CSM-CERES Wheat v.4.0 crop model, Timsina *et al.* (2008) compared yield, components of the water balance, and water productivity of the predominant wheat variety (PBW343) sown at 15 d intervals from 10 October to 10 January. Maximum yield and water productivity with respect to both irrigation (WP_I) and ET (WP_{ET}) occurred with 25 October and 10 November sowings, suggesting sowing can be brought back to at least 25 October, with the potential benefit of capturing residual soil water from rice that would otherwise be lost by evaporation. Yield, WP_I and WP_{ET} were least with sowing on 10 October. The potential for planting between 10 and 25 October also needs to be explored with regard to yield, water depletion and water productivity, given that earlier sowing provides the opportunity for the crop to mature under cooler conditions and with lower evaporative demand.

4.8.1. Summary—Zero till wheat

Adoption rates of zero till wheat are far higher than with any other improved technology for RW systems, with adoption on over 10% of the RW area of India by 2003–2004. A major driver for adoption is increased profitability as a result of lower establishment costs. There is considerable evidence from farmer adoption studies that zero till wheat gives irrigation water saving of at least 10% (at least 20–30 mm) in comparison with conventional practice, while yields are generally slightly higher, leading to higher WP_I. Experimental studies indicate that reductions in irrigation amounts of up to 30% are possible. How much of the irrigation water saving is due to reduced ET or deep drainage, and the effect on WP_{ET}, are not known.

4.9. Surface residue retention and mulching

4.9.1. The effect of mulch on soil evaporation

It is well established from laboratory studies that surface residue retention and mulching decrease soil evaporation, and that the reduction in evaporation depends on the amount of mulch, soil water content, soil type, and evaporative demand (e.g., Bond and Willis, 1970; Gill and Jalota, 1996; Prihar *et al.*, 1996; Steiner, 1989). However, while cumulative evaporation from mulched soil initially lags behind that of bare soil, the difference declines with time (because the mulched soil is wetter) and eventually the total loss from the mulched soil becomes similar to or can even exceed the total loss from the bare soil (Bond and Willis, 1970; Prihar *et al.*, 1996). However, these findings are from laboratory studies in the absence of wetting events after the mulch is applied. Field soils are subjected to wetting by rain and irrigation, and drying by evaporation, root water uptake and drainage, therefore the actual impacts of mulch on evaporation will be site and season specific.

4.9.2. Surface retention of rice residues for wheat

The recent development of the Happy Seeder (Sidhu *et al.*, 2007, 2008) and the Rotary Disc Drill (Sharma *et al.*, 2008b) provides RW farmers in the IGP with the capability of sowing ZTW in the presence of loose and anchored rice residues. The Happy Seeder removes the residues in a narrow strip (7.5 cm) in front of the sowing tynes, and chops the residues which flow past the tynes. This enables zero tillage into bare soil, and leaves standing straw between the seed rows plus a mulch on the soil surface. The Rotary Disc Drill cuts through the residues and makes a slit in the soil for placing seed and fertilizer. Several experiments in Punjab and Nepal show that rice mulch significantly reduces the rate of soil drying and delays the need for irrigation of wheat (Balwinder Singh et al., 2010a; Rahman *et al.*, 2005; Sidhu *et al.*, 2007; Yadvinder-Singh *et al.*, 2008b). Using microlysimetry, Balwinder-Singh *et al.* (2010b) showed that the mulch reduced soil evaporation by 35 and 40 mm on a clay loam soil in both a lower than average rainfall year (89 mm) with poor rainfall distribution, and a higher than average rainfall year (159 mm) with good rainfall distribution, respectively (Fig. 6A and B). However, the reduction in soil evaporation was offset by significantly higher transpiration in both years. In the drier year (three postsowing irrigations), ET, yield and WP_{ET} were unaffected by mulching. In the other year (one postsowing irrigation), mulching significantly increased biomass and yield compared with the nonmulched control which suffered from water deficit stress for about 10 d after maximum tillering. Again ET was similar with and without mulching, but WP_{ET} was significantly increased due to the higher yield.

Whether or not mulching reduces the need for irrigation depends greatly on the incidence and amount of rainfall—in some years mulch reduced the number of irrigations by one when scheduled based on soil matric potential, in other years mulched and nonmulched wheat required the same number of irrigations (Balwinder-Singh, 2010a; Yadvinder-Singh *et al.*, 2008b). The results of Balwinder-Singh *et al.* (2010b) suggest that mulching does not reduce water depletion as ET due to reduced transpiration efficiency in the presence of mulch. This is a disappointing finding which needs further investigation.

In addition to retention of rice residues, the Happy Seeder and Rotary Disc Drill provide the capability of sowing on the day of harvest, maximizing the opportunity for productive use of residual soil water rather than losing it by evaporation. The field studies of Jalota *et al.* (2001) suggest that mulching would result in similar or higher soil profile water content (by up to 50 mm) over a period of 2–4 weeks after rice harvest, in the presence of limited rain. Thus sowing into rice residues immediately after rice harvest could save up to 50 mm of soil water for early use by the crop.

Adoption of the Happy Seeder is at an early stage. In 2008–2009, the Happy Seeder was demonstrated in participatory trials on 930 acres across all districts of Punjab, and in a few trials in western UP. At that time there were four manufacturers and a government subsidy of 33%. Twenty-two machines were sold, 10 to farmers and the rest to government, institutions and cooperative societies (Manpreet Singh, personal communication). In May 2010 there were five manufacturers in Punjab, and the state government announced plans to buy 200 Happy Seeders for the 2010–2011 season, providing 80 machines free to Primary Agriculture Cooperative Societies, and a further 120

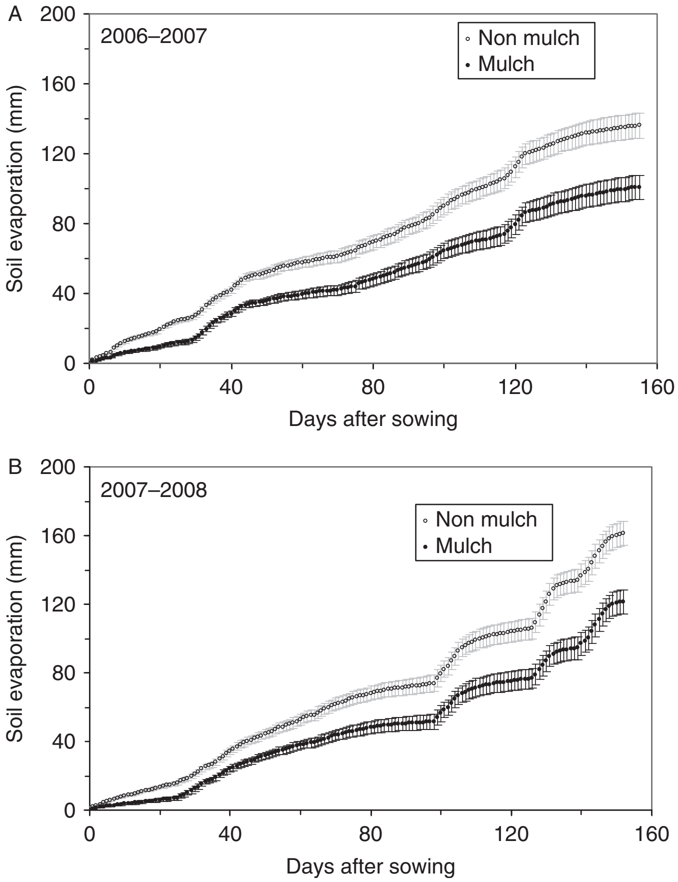

Figure 6 The effect of mulching on soil evaporation from wheat at Ludhiana, Punjab was measured using mini-lysimeters in (A) 2006–2007 and (B) 2007–2008. The standard error of the mean for each data point is plotted, creating an envelope of variability. (Adapted from Balwinder-Singh *et al.*, 2010.)

with a 50% subsidy http://www.tribuneindia.com/2010/20100602/punjab.htm#2. It was anticipated that this would halt burning on at least 20,000 ha in 2010. While there are government bans on the burning of crop residues in Punjab and Haryana, these have not been implemented to date.

4.9.3. Surface retention of residues during the fallow period between wheat harvest and rice planting

Potential evaporation is very high during the 2-month period between wheat harvest and rice planting, with total pan evaporation of the order of 500 mm (Fig. 2); however, the amount of evaporation will depend on soil water content. Results from a sandy loam show that the soil profile was relatively dry at the time of wheat harvest, but that there was further loss of water from the 0–20 and 20–40 cm layers between harvest and preirrigation for rice (Fig. 7). The total loss during this period was about 20 mm. The field studies of Jalota *et al.* (2001) showed losses of around 70 and 40 mm on sandy loam and loamy sand soils during this period, while the modeling studies of Jalota and Arora (2002) predicted higher evaporation (averages of 146 and 97 mm from medium and coarse textured soils, respectively) during this fallow period.

To date, little attention has been paid to management of the fallow period after wheat harvest, apart from the possibility of introducing a green manure crop (Yadvinder-Singh *et al.*, 2004), or a short duration food crop (such as mung bean, Section 4.11) during this period. Most of the wheat in north-west India is harvested by combine (Gajri *et al.*, 2002). The loose straw (about two-thirds of the residue) is normally removed for animal feed, and the remaining straw (2 t/ha) is burnt. Would mulching with that amount of straw in that environment significantly reduce evaporation during the fallow period? In laboratory studies, Steiner (1989) found that stage 1 evaporation from a wetted soil was reduced by 85% with less than 1 t/ha of wheat straw. On deeply wetted soils in laboratory experiments, Prihar *et al.* (1996) found that the introduction of shallow (5 cm) tillage when the cumulative reduction in evaporation due to mulch reached a maximum (a couple of days to about 10 d after mulching, depending on soil type) provided maximum benefit in reducing evaporative loss from a range of soil types. The practical implication of this is that mulching after wheat

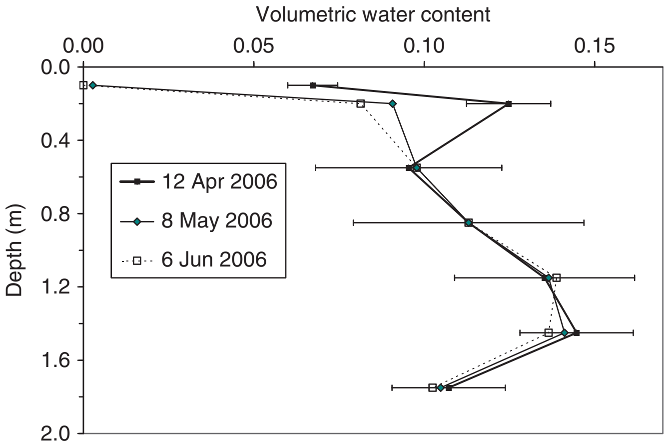

Figure 7 Drying of the upper soil profile between wheat harvest (11 April 2006) and preirrigation for rice on a sandy loam at Ludhiana. Horizontal bars are standard deviations for the data on 12 April (Humphreys *et al.*, unpublished data).

harvest in years when there is significant residual soil moisture (e.g., due to rain close to harvest or late irrigation), followed by shallow tillage a few days later, may help conserve residual soil moisture after wheat. However, the soil profile is normally dry at the time of wheat harvest (Humphreys *et al.*, 2008a), and with little likelihood of rain. In their field experiments, Jalota *et al.* (2001) showed that in the period of high evaporative demand after wheat harvest, and with occasional rains, there was no benefit of mulching (with 6 t/ha of wheat straw) in terms of soil water content.

4.9.4. Summer crops and mulching

The reduction in evaporation of irrigated summer crops as a result of mulching is likely to be larger than for wheat because of much higher evaporative demand, especially prior to the onset of the monsoon. Mulching can greatly increase yield of summer crops in north-west India, but results are variable, depending in particular on weather (Ram *et al.*, 2005; Sekhon *et al.*, 2005). Studies on the effects of mulching summer crops on ET in the region are lacking. Using a water balance model, Jalota and Arora (2002) estimated that mulching maize reduced evaporation by means of 185 and 130 mm on medium and coarse textured soils, respectively, while mulching cotton reduced evaporation by means of 225 and 165 mm, respectively. Based on these results, there may also be considerable potential to reduce evaporation from DSR (with AWD) using mulches, and this needs further investigation.

4.9.5. Summary—Mulching

Mulching offers the potential to reduce evaporation from wheat by 30–40 mm, which will reduce the number of irrigations needed by one in some years. However, initial results suggest that the reduction in evaporation is offset by increased transpiration, and that under well-irrigated conditions transpiration efficiency is reduced, resulting in similar WP_{ET} with and without mulch. Under limited water conditions where mulching reduces water deficit stress and loss of yield, WP_{ET} is increased. Preliminary results suggest that mulching of wheat does not reduce water depletion as ET due to reduced transpiration efficiency in the presence of mulch, and further investigations are needed.

There seems to be little scope for mulching to reduce soil evaporation during the very hot, dry fallow between wheat and rice harvest, unless there is rain shortly prior to the time for establishment of rice. The potential for water savings through mulching of summer crops, including DSR, has not been investigated to date, but maybe substantial based on the results of limited trials with non-rice summer crops. The potential for mulching to reduce water depletion as ET and increase WP_{ET} requires further investigation.

4.10. Wheat on raised beds

There are many anecdotal reports of large irrigation water savings for wheat on beds in comparison with conventional tillage in farmers' fields. The few published data show reduced irrigation time or amount of 35–50% and slightly higher yield (mean 5%) on the beds (Hobbs and Gupta, 2003; Kahlown *et al.*, 2006; Singh *et al.*, 2002). It is likely that most of these reports from farmers' fields are for *fresh beds*. Despite these positive results, there has been negligible adoption of wheat on beds in RW systems. The reasons have not been analyzed, but are likely include the need to purchase a bed planter (although a simple potato ridger can be used) and to knock the beds down after wheat harvest for conventional rice cultivation.

Permanent bed RW systems would probably be more attractive to farmers if yields of both rice and wheat could be maintained or increased, because this would greatly reduce establishment costs. However, to date, poor yields of rice on permanent beds in north-west India have discouraged adoption (Section 4.7). Results of replicated experiments generally show similar or higher yields of wheat on permanent beds compared with conventional tillage, and reduced irrigation amounts (Bhushan *et al.*, 2007; Jat *et al.*, 2008; Lauren *et al.*, 2008; Talukder *et al.*, 2008; Yadvinder-Singh *et al.*, 2008a, 2009). The reduction in irrigation amount on permanent beds from replicated experiments is usually smaller than that reported from farmers' fields (probably fresh beds), perhaps because of the longer duration of irrigation in farmers' fields and/or increased macroporosity of the permanent beds in comparison with fresh beds, and thus more opportunity for deep drainage losses. In some situations, yields were lower on fresh and permanent beds than with conventional tillage—as a result of more rapid drying of the beds on coarse textured soils, accumulation of salt on the beds on a sodic soil, or inadequate tillering associated with late planting (Choudhury *et al.*, 2006; Jehangir *et al.*, 2007; Sharma *et al.*, 2002; Yadvinder-Singh *et al.*, 2009). These problems could generally be overcome by better management, but suggest that beds require more skilled or precise management than establishment with conventional tillage.

There have been few studies to quantify the nature of the irrigation water savings for wheat on beds. In a comparison of zero till wheat on permanent beds with conventionally tilled wheat on sandy loam and loam soils at Delhi, irrigation water use was lower on the beds due to lower ET (Choudhury *et al.*, 2006). The lower ET on the beds was probably due to poorer crop growth (the crop was planted late, and the plants on beds were probably unable to compensate for the wider row spacing on the beds by greater tillering under the cooler weather conditions experienced by late planted crops), and also due to less deep drainage in one of the 2 years of this experiment (Choudhury *et al.*, 2006). The net result was lower WP_{ET} on the beds. It is likely that soil evaporation from beds is higher than from a flat layout during the first part of the crop season, while the soil is bare and until the canopy develops. This is because the formation of beds increases the soil surface area—by about 50% in the case of the narrow beds (30 cm bed top, 37.5 cm furrow width, 15 cm furrow depth) commonly used in north-west India. Prashar *et al.* (2004) and Kukal *et al.* (2008) showed that the beds (10 and 20 cm soil depths) dried more rapidly than conventionally tilled soil after sowing on sandy loam and loam soils, more so on the sandy loam. Model simulations using Hydrus 2D also show substantially greater evaporation from the beds than from the flats with a bare soil surface (F. Cook, personal communication). Mulching of the beds would reduce this loss, and the Happy Seeder approach can provide the capability of direct drilling into crop residues on beds (see cover photo in Humphreys and Roth, 2008).

4.10.1. Summary—Wheat on beds

There is much anecdotal evidence that irrigation amounts are reduced greatly and yields are maintained or increased slightly by growing wheat on fresh beds in farmers' fields in comparison with conventional tillage, and this is also generally the trend in small plot studies. The irrigation water savings are likely to be due to faster irrigation times and reduced deep drainage, and therefore the magnitude of the irrigation savings is likely to depend on soil type and depth to the watertable. Growing wheat on beds is unlikely to decrease ET, and may increase it, especially in situations where beds lead to increased crop growth, such as on soils prone to waterlogging. The effects on WP_{ET} are unknown. Adoption of wheat on beds in RW systems is unlikely to be attractive unless it is in a permanent bed cropping system. Yields of wheat on permanent beds are generally similar to or slightly higher than yields with conventional tillage. However, the performance of rice on beds has been unsatisfactory to date in the north-west IGP, hence there has been no adoption of permanent bed RW cropping systems in this region.

4.11. Replacement of rice, crop diversification

It is sometimes suggested that replacement of rice with other crops would help solve the declining groundwater problem in Punjab, India (e.g., Hira, 2009). Alternative crops to rice, such as maize, soybean and cotton, have much lower irrigation water requirement than rice (e.g., Jat, 2006; Ram *et al.*, 2005). Depending on the distribution and amount of the monsoon rains and soil type, these crops require from none to four to five irrigations after sowing, with total irrigation application to maize and soybeans of the order of one-fifth to one-tenth of that for PTR. Two important questions are: (1) by how much will replacing rice reduce water depletion, and (2) what is the effect on the productivity of depleted water?

Jalota and Arora (2002) used a water balance model to compare components of the water balance for four cropping systems (including fallow periods) using 10 years of weather data at Ludhiana, Punjab. Annual total "losses" (as evaporation, transpiration, and deep drainage) on the medium textured soil were greatest for the RW system, followed by sugarcane, cotton–wheat, and maize–wheat (Table 3). The high losses in the RW system on the medium textured soil were due to much higher deep drainage, which was up to four times the deep drainage in the other summer crops. On the coarse textured soil, annual total losses were highest in sugarcane and again least in maize-wheat. ET was highest in sugarcane, followed by cotton–wheat, RW, and maize–wheat. Ahmad *et al.* (2004) also found higher ET from cotton–wheat than from RW in Punjab, Pakistan, using the SWAP model. The results suggest that simply replacing the RW system with other systems such as cotton–wheat or sugarcane would actually increase water depletion in the major parts of the RW region where most irrigation is from groundwater. The results of Jalota and Arora (2002) also suggest that replacing rice with maize would reduce total annual water depletion by only 50–70 mm. Using the model of Jalota and Arora (2002), Hira *et al.* (2004) also estimated slightly higher ET for soybeans than rice, but much lower ET for other pulses (450 mm) and pigeon pea (300 mm), and lower ET for (winter) oilseeds (280 mm) and black gram (320 mm) than wheat (400 mm), while ET for winter maize was higher (500 mm). However relative ET of all crops, and particularly in relation to rice, depends greatly on the date of planting (Section 4.2), largely because of the effect on the duration of the crop in the field prior to the onset of the monsoon, when evaporative demand is very high.

These modeling results should be regarded as preliminary but indicative, and clearly further work is needed to quantify components of the water balance and water productivity with respect to water depletion for a range of cropping systems. This needs to be done for a range of agroecological (soil type, climate, depth to the watertable) and management conditions (e.g., planting date, irrigation management), using both field measurement and crop modeling.

With minimum government support prices and guaranteed purchase for both rice and wheat, together with a lack of good infrastructure and markets for alternative crops, there is currently no incentive for farmers to replace these crops with alternative crops.

Table 3 Simulated components of the water balance (annual, mm) for a range of irrigated cropping systems (including fallow periods) at Ludhiana, Punjab (adapted from Jalota and Arora, 2002)

	Medium textured soil		Coarse textured soil	
Cropping system	ET	Deep drainage	ET	Deep drainage
Rice–wheat	1130	810	960	770
Maize–wheat	1080	410	890	650
Cotton–wheat	1340	280	1210	500
Sugarcane	1360	210	1340	550

4.11.1. Summary—Replacement of rice, crop diversification

Replacing rice with another summer crop will greatly reduce the amount of irrigation water applied, with many benefits. In canal irrigated areas with saline groundwaters, replacement of rice will reduce water depletion and the rate of watertable rise and associated problems. But replacement of rice with other summer crops will not reduce the problem of groundwater depletion in areas with fresh groundwater, where groundwater is the main source of irrigation water and ET is the only source of water depletion, unless the alternative crop has lower ET than that of rice. Preliminary studies suggest that replacement of RW with cotton–wheat, soybean–wheat, or sugarcane will actually increase ET losses, while the gains through replacing RW with maize–wheat will be large to negligible depending on rice planting date. Further studies are needed to quantify ET for a range of cropping systems under a range of site, seasonal, and management conditions.

4.12. System intensification

Potential evaporation is very high during the long fallow period between wheat harvest and rice planting (Fig. 2, Section 4.9). Wheat planted on 10 November in Punjab reaches physiological maturity around 25 March. Rainfall between 25 March and 25 May is small, and exceeded 50 mm in only 25% of years between 1970 and 2005 at Ludhiana. Inclusion of a short duration crop such as mungbean during this time could make productive use of this rainfall, and also increase productive use of any residual soil water from wheat. Of course this additional crop would also require irrigation and increase total depletion from the system as ET; however, it is the effect on total system production with respect to ET that should be considered. With conventional tillage, mungbean planted after wheat normally requires one presowing irrigation and three to four postsowing irrigations. In 2008–2009, one to two postsowing irrigations were saved by drilling mungbean into wheat residues (after removal of 70% of the wheat straw) which followed wheat drilled into rice residues using the Happy Seeder (Yadvinder-Singh, unpublished data). Furthermore, the residues of the mungbean crop could be retained with other benefits to the total system, including reduction of evaporation from the subsequent rice crop through dry seeding into the residues. Another potential advantage of growing a crop between wheat harvest and rice establishment is reduction or prevention of soil cracking due to the need to keep the soil moist for the crop. This would reduce deep drainage due to crack flow, especially during precultivation irrigation, in the subsequent rice or other summer crop. The impact of crop intensification on productivity of the total system with respect to total water depletion needs to be investigated in field and modeling studies.

5. GENERAL DISCUSSION

In regions where water is limiting (or will become limiting in the foreseeable future), and where food production needs to increase, as in the RW regions of north-west India, two of the objectives of improved crop technologies must be to increase production per unit of depleted water and to reduce water depletion. That is, to achieve real water savings. Our review finds that there are very few data available on the impact of most technologies on water depletion, nor on productivity with respect to depleted water. This is consistent with the observations of Kumar *et al.* (2009) who stated that "*There is effectively no research in India quantifying the real water saving and water productivity impacts of water saving irrigation technologies on various crops, at the field level. An extensive review of literature shows that all the data on water-savings are based on applied water . . .. . .Some of the figures on water saving. . ..are quite high. . . the condition of flood irrigation system chosen for comparison influences the findings on water savings and yield. . ..Poorly managed flood irrigation systems used for comparison could significantly affect the result in favor of. . ..*"

Our review shows that some improved technologies result in reductions in irrigation applications, or "irrigation water savings," and higher WP_I, with major benefits including reduced irrigation/energy costs, and reduced demand on overstretched electricity supplies. The size of the irrigation water saving can be substantial, but is often variable depending on site conditions and the control used for comparison. The choice of control is particularly important in the case of rice—is it PTR with continuous flooding or PTR with the recommended practice, safe AWD? Technologies which generally result in substantial irrigation water savings in RW systems in north-west India in comparison with conventional practice include laser assisted land leveling, delayed rice transplanting, short duration rice varieties, AWD in transplanted and dry seeded rice, aerobic rice, replacing rice with other summer crops, zero till wheat (with and without mulching) and raised beds for wheat. The irrigation water saving can be very large, for example 50–90% (1000–1800 mm) saving by replacing rice with other summer crops, up to 40% or 800 mm for AWD in rice in comparison with continuous flooding, and up to 35% (100 mm) in wheat with laser assisted leveling or zero tillage. The effect of other technologies such as transplanted rice and DSR (on beds or flats, zero till, or cultivated) on irrigation amount in comparison with PTR with safe AWD may be small, but has not been clearly established.

However whether or not decreased irrigation applications are due to real water savings is usually unknown, as very few studies have attempted to quantify this. It is likely that much or all of the irrigation water savings with technologies such as laser leveling, safe AWD, raised beds and replacement of rice with other summer crops in the main RW areas is due to reduced deep drainage which flows to fresh groundwater systems which are pumped for irrigation. To halt the decline in the watertable, the focus in these regions must be on technologies that reduce depletion as ET and increase WP$_{\mathrm{ET}}$. By far the biggest gains in reducing ET come from delaying rice transplanting and growing shorter duration varieties. For example, delaying transplanting in central Punjab from late May to late June reduces ET by about 75 mm while maintaining yield, thus increasing WP$_{\mathrm{ET.}}$ Recent policies and their implementation have resulted in a major shift in transplanting date, with claims of significant impacts on the rate of groundwater decline already. Reducing rice varietal duration provides another important means of reducing ET, for example, by up to 70 mm in central Punjab, and short duration varieties with similar or higher yield potential to the current longer duration popular varieties are now available. The effect of mulching on ET from summer crops, including DSR, may be very large but has not been investigated. The effect of mulching winter crops on ET is less clear, and the recent findings of Balwinder-Singh *et al.* (2010b) suggest that the reduction in soil evaporation as a result of mulching wheat is offset by increased transpiration. It is likely that other technologies such as laser leveling, beds and zero till, will not decrease ET, and in fact may increase ET if crop growth is improved. Whether these technologies lead to higher WP$_{\mathrm{ET}}$ is not known.

Of course, there are also many other benefits of irrigation saving technologies even if they do not reduce ET, and these technologies should be promoted provided they do not decrease WP$_{\mathrm{ET}}$ of the total cropping system. A possible example of a technology that should not be adopted is replacement of the RW cropping system in central Punjab with a cotton–wheat system or sugarcane, based on the ET estimates of Jalota and Arora (2002).

In regions where irrigation water savings can be achieved through reduced drainage to ground or surface waters that are too saline or polluted for further use, such as in south-west Punjab and southern and central Haryana, there is large scale scope for real water savings through technologies that reduce deep drainage (as well as technologies that reduce ET). Here, the biggest potential for saving water is to diversify from rice-based cropping systems to non-rice cropping systems.

While conversion from current practice to technologies that provide real water savings is extremely important, it is also important to consider what happens to the saved water. In situations where water is so limiting that some cultivable land is not cropped, farmers may use the saved water to grow additional irrigated crops, with the net result of increased water depletion. This is the case in Punjab Pakistan, where the introduction of zero till wheat and laser leveling led to increased wheat area, primarily on large landholdings (which account for 50% of the RW area) (Ahmad *et al.*, 2007). They estimated that 60% adoption of zero till wheat would increase water depletion as ET by 5%, or $1.3 \quad 10^{9}$ m^{3}. This is probably less of an issue in the irrigated areas of north-west India where almost all cultivable land is used, such as in central Punjab where cropping intensity is 201%. However, it may be an issue in parts of Haryana and western Uttar Pradesh where lands are sometimes left fallow due to lack of water, especially if the net result is decreased productivity with respect to water depletion.

There have been no studies on the impacts of widescale adoption of improved technologies for RW systems on water depletion and the productivity of that water in north-west India. Widescale adoption of technologies that affect water depletion and deep drainage will have impacts on the depth to groundwater table, demand for water from the canal system, demand for electricity and pollution of groundwater. The impacts will vary depending on site conditions (soils, hydrogeology, climate, source of irrigation water, irrigation and drainage networks) across the landscape. Comprehensive studies using spatial hydrologic models are needed to estimate the likely impacts at higher spatial scales from sub-district to sub-basin and basin. Such studies, combined with the results of field, crop modeling, and economic studies, would be useful to help identify the optimum technology options for local conditions.

6. CONCLUSIONS

This review has focused on the effects of improved technologies for RW systems on components of the water balance, grain yield, and water productivity with respect to irrigation and evapotranspiration (ET). There are many other potential benefits of these improved technologies, such as increased profitability, improved soil properties, reduced labor and energy requirements, and reduced air and water pollution, but these are not the focus of this chapter.

There are clearly many technologies with the potential to reduce the amount of irrigation water applied to RW systems. However, the impacts of the technologies in terms of yield, components of the water balance, and water productivity are often variable and are affected by many factors including climate, soil type, and hydrological conditions. The effects of improved technologies on real water savings is poorly understood at the farmer field scale, and have hardly been considered at higher spatial scales. Very few studies have determined the effects of alternative crop technologies on ET and drainage, and whether the drainage losses at the farmer field scale are losses at higher spatial or temporal scales, and thus the real water savings. The irrigation water savings are often likely to be due to reduced deep drainage, with little effect on ET. More than 90% of the major RW areas are irrigated using groundwater. Here, reducing deep drainage will not "save" water nor reduce the rate of groundwater decline, and technologies that decrease ET are needed. The best technologies for reducing ET are delayed rice transplanting and use of short duration rice varieties. In areas where the groundwater is highly saline and/or sodic, and not suitable for irrigation, reducing deep drainage provides real water savings in addition to other benefits such as reduced waterlogging and secondary salinization.

The performance of the technologies needs to be systematically assessed at the farmer field scale for a range of site conditions, to increase process understanding, and to develop generic knowledge to help target technologies to site conditions. Such targeting needs to be informed by the results of crop simulation modeling. The use of simulation models enables evaluation of technologies over the likely range of seasonal conditions, taking into account soil type, depth to the watertable, and a range of management factors. Crop models also enable estimation of components of the water balance and crop water productivity, parameters which are extremely difficult to measure in the field. Models also allow analysis of risk, and tradeoffs between yield, water depletion, deep drainage, runoff, etc. However, there needs to be significant investment in good data sets for model calibration and evaluation and process understanding to capitalize on the predictive capacity of crop models. This is currently a major gap for RW systems in the IGP.

There is also poor understanding of the amount of reduction in water depletion needed to halt the decline in groundwater levels. This will vary depending on local hydrogeological conditions. There is a need for the development and application of models and other approaches for assessing the impacts of widescale adoption of technologies at a range of spatial scales from sub-district to sub-basin and basin. The ultimate challenge is to design land use strategies, cropping systems and management options that will meet food production needs, and that will be biophysically and socio-economically sustainable in the longer term, appropriately targeted to the variable environments across the IGP.

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