University of Southern Queensland

Identifying strategies to improve the water productivity of permanent raised beds

A dissertation submitted by

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ABSTRACT

Permanent raised bed (PRB) farming systems combine several elements (e.g. reduced tillage, controlled traffic, stubble retention) of conservation agriculture. PRB systems have recently been introduced into irrigated areas but there is a lack of information on the agronomic and irrigation performance of these systems under these conditions. Three years of field research into the performance of irrigated PRBs was conducted in south east Queensland, Australia and north west Pakistan. These studies benchmarked the irrigation performance of variously sized PRB systems and explored the impact of bed renovation method (no tillage (NT), shallow cultivation (SC) and blade ploughing (BP)) on soil hydro-physical properties (bulk density, soil moisture storage, infiltration), irrigation performance, crop yield and input water productivity (*WP*). Irrigation management strategies to improve lateral infiltration and irrigation performance were also investigated.

The initial benchmarking study was conducted on two farms with clayey Vertisol (Australia) and three farms with sandy clay loam, Alfisol, (Pakistan) soils. The results showed low irrigation performance with excessive deep drainage potential. The irrigation application efficiency (*Ea*) on the clayey Vertisol and sandy clay loam was as low as 68% and 50%, requirement efficiency (*Er*) 96% and 77% and distribution uniformity (*DU)* 86% and 66%, respectively. However, the majority of the narrow beds (66 cm furrow spacing) were over-irrigated on the sandy clay loam while the wide beds (132 cm furrow spacing) were under-irrigated. Inappropriate renovation and bed furrow dimensions, sub-optimal irrigation management and poor lateral infiltration were the main factors likely to affect *WP* of irrigated PRBs.

The evaluation of bed renovation methods found that BP on the clayey Vertisol reduced (~6%) the average seasonal bulk density of the surface 0-30 cm compared to the NT treatment. BP was found to produce higher lateral infiltration into the beds than either NT or SC. Freshly applied BP and SC produced a higher (~23%) cumulative infiltration than NT but the effect was transient and was not significant in the following season when the PRB renovation treatments were not freshly applied. The SC beds slump more than the BP and NT beds. The soil water content in the beds indicated that there was increased water storage associated with BP.

PRB renovation (i.e. SC or BP) was found to reduce irrigation performance on the clayey Vertisol when the irrigation was farmer managed. The volume of irrigation water applied to the fresh SC and BP treatments increased by up 13% and 55%, and *Ea* was reduced by up to 9% and 29% respectively, compared with NT during the 2010 wheat and 2011 corn seasons. NT produced a higher wheat yield and *WP*, but the lower wheat yield in the cultivated treatments was associated with poor crop establishment from a rough soil surface and inadequate seeder performance in this season. In the subsequent seasons, there was no significant difference in either the crop yields or *WP* between the bed renovation treatments.

Field trials investigating the effect of bed renovation on infiltration were conducted on both soils. Significant differences in the amount of water infiltrated and stored in the bed shoulder and bed middle were found for periods of wetting consistent with normal irrigation practices. This suggests that the general assumption of uniform soil moisture distribution across the beds is not valid for wide PRB systems. The three different renovation methods also significantly affected lateral infiltration, suggesting tillage may be used as a management tool to improve bed wetting in low infiltration soils and subsided beds.

Infiltration and soil-water movement were simulated using Hydrus 2D. The simulations were found to be well correlated with the measured field data and an evaluation for the three PRB renovation methods confirmed that NT had the slowest, and BP the fastest, potential to wet the bed middle of the wide PRBs. Increasing the furrow water head from 4 cm to furrow full of water was also shown to reduce wetting time by more than 30%.

Lateral infiltration was poor in the sandy clay loam. The shortest wetting time (~15 hrs) required to wet the bed middle of a 132 cm wide bed to field capacity occurred when furrow full water head was applied to the BP treated bed. However, even this period of wetting may be difficult to achieve using current irrigation practices in Pakistan. The graphical model outputs developed can be used in developing guidelines to optimise bed width and irrigation management to ensure adequate lateral infiltration with different PRB renovation methods.

Strategies to optimise irrigation management and field design while ensuring adequate lateral infiltration into the bed middle were evaluated using the surface irrigation model SIRMOD. Optimising the inflow rate (*Q*) and the time to cut-off (*Tco*) for the particular field length was found to produce up to a 38% irrigation water saving compared with existing practices. However, the majority of the wide beds on the sandy clay loam required higher inflow volumes than currently applied, which increased *Er* but reduced *Ea*. Optimising furrow length indicated a further improvement in irrigation performance. Similarly, *Q* and *Tco* optimisation together showed up to 35% irrigation water saving and up to 33% improved *Ea* for the most sub-optimally managed BP treatment. Decreased furrow length improved irrigation performance for freshly renovated PRB, while irrigation performance of settled bed furrows tended to increase with increased furrow length. Relating optimum *Tco* to water advance to furrow tail end (*Ta*) was sensitive to furrow length, *Q* and soil infiltration functions. The decision support guidelines developed were helpful in improving existing irrigation performance under both soil conditions.

This research has shown that the existing irrigation performance of PRBs is often low and highly variable. A key constraint is the potential for poor lateral infiltration into the beds and inadequate wetting to the centre of wide beds. However, this work has also highlighted that the adoption of appropriate bed renovation methods (particularly BP) and irrigation management practices (e.g. *Q* and *Tco*) can substantially improve irrigation performance and input *WP*. Although the applicability of the specific decision support tools developed is restricted to the soil types and field conditions encountered, the general understanding and insight into the basic principles of performance optimisation and for agronomic and irrigation interactions is expected to be beneficial in refining understanding and the promotion of sustainable crop production under a wider range of environmental conditions.

CERTIFICATION OF DISSERTATION

I certify that the ideas, designs, experimental work, software, results, analyses and conclusions presented in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Signature of candidate Date

Endorsement:

Professor Steven Raine (Principal supervisor) Date

Dr Allen David McHugh (Associate supervisor) Date

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PUBLICATIONS ARISING FROM THIS RESEARCH

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Akbar, G, McHugh, AD, Raine, SR & Hamilton GJ 2011, 'A preliminary evaluation of furrow inflow rate and cut-off time on the performance of smallholder raised bed farming systems', In: *World Congress on Conservation Agriculture,* September 2011, Brisbane Australia.

Akbar, G, Raine, SR, McHugh, AD & Hamilton GJ 2011, 'A preliminary evaluation of irrigation performance and in season changes under permanent raised beds on Vertisol in Queensland, Australia', In: *World Congress on Conservation Agriculture*, September 2011, Brisbane Australia.

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The following journal papers are in the final stages of review between the authors and are expected to be submitted in the near future:

Akbar, G, Raine, S, McHugh, AD & Hamilton, GJ 'Strategies to improve the irrigation performance of raised beds on small farms in north west Pakistan', will be submitted soon to *Water Resources Management* Journal (Springer).

Akbar, G, Raine, S, McHugh, AD & Hamilton GJ 'Impact on irrigation performance and productivity of permanent raised bed renovation methods on a Vertisol', will be submitted soon to *Crop and Pasture Science* Journal (CSIRO).

Akbar, G, Raine, S, McHugh, AD & Hamilton GJ "Modelling lateral infiltration under different renovation methods of permanent raised beds and furrow water heads in a Vertisol and a sandy clay loam', will be submitted to *Irrigation Science* (Springer).

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LIST OF ABBREVIATIONS

ACIAR	Australian Centre for International Agricultural Research
BD	bulk density
BP	blade ploughing
BW	bottom width of furrow
CA	conservation agriculture
CTF	control traffic farming
D	depth of furrow
DD	deep drainage losses
DU	distribution uniformity
Ea	application efficiency
Er	requirement efficiency
FC	field capacity
MW	middle width of furrow
NB	narrow bed (66 cm furrow spacing)
NCEA	National Centre for Engineering in Agriculture
NT	no tillage
PARC	Pakistan Agricultural Research Council
PRB	Permanent raised bed
Qld	Queensland
SC	shallow cultivation
SD	standard deviation
SM	soil moisture
SMD	soil moisture deficit
Ta	time of irrigation water advance to furrow tail end
Tco	time to cut-off
TW	top width of furrow
WB	wide bed (132 cm furrow spacing)
WP	wetted perimeter
WP	input water productivity

LIST OF SYMBOLS

A	cross sectional area of flow
a	Kostiakov infiltration exponent
D_f	diffusivity
f_o	steady state infiltration rate of the soil
g	acceleration due to gravity
I	infiltration rate
k	Kostiakov infiltration equation coefficient
Q	inflow rate
r	fitted parameter
S	sorptivity
S_f	frictional slope
S_o	furrow slope
v	flow velocity
y	furrow water head
Z	cumulative infiltration
Θ	volumetric soil moisture content
ρ_b	bulk density
ρ_s	particle density
σ_y	surface storage shape factor
σ_z	subsurface storage coefficient
F	scaling factor
φ	boltzman transform
Ψ	soil moisture potential

CHAPTER 1: Introduction

Raised beds may be defined as a farming practice where the beds and furrows are constructed from the cultivated soil that is excavated by furrowers aligned behind the wheels of tractors, and sometimes, as well, with the mid-point the tractor track width. They are raised above the normal level of the soil surface by the soil excavated to form the furrows. The crop is then planted on the surface of the beds and irrigation water is applied to the field via the furrows, with the water absorbed laterally by the soil into the beds (Roth et al. 2005). The furrows are oriented in the direction of the slope and are also used for traffic, and, if need be, bed drainage. Furrow spacing is generally determined by a combination of the track width of machinery, row spacing of the crops and the stability of the soil to rapid wetting, which control the lateral infiltration of water into the centre of the beds. Raised beds are also used under rain-fed conditions to prevent crop waterlogging.

There is a wide variety of cultivation and bed construction methods used around the world, depending on available labour resources, available machinery, farming practice tradition and knowledge of soil and water management. Cultivation methods vary from animal drawn (bullock, horse or camel) ploughing, to tractor drawn chisel ploughing, mould-board ploughing and rotary hoeing. Raised bed construction methods range from animal-drawn single furrowers to tractor drawn, GPS-steered, multiple bed forming implements mounted on hydraulic 3-point linkage arms on the rear of tractors.

Bed and furrow dimensions and field, or furrow length, also vary widely around the world. These vary as a consequence of farm size, slope length, water inflow rates, in-field water distribution infrastructure, proportion of field taken up by unutilised headlands, available machinery, soil type and farmer knowledge. For instance, furrow spacing, or bed width, ranges from 0.5 to 1.0 m in China, India, Pakistan, Bangladesh and Mexico to 1.5 to 3.0 m in Australia (Sayre & Hobbs 2004). Consistent with the variation in bed width/furrow spacing, furrow dimensions range in top width from 40 to 60 cm and furrow depth from 10 to 25 cm.

1.1 Agricultural sustainability and food security

The increasing world population requires greater productivity from existing land, because there is little or no land available to expand agriculture (Hobbs 2007). Simultaneously, climate change is reducing and making less reliable water resources for both agriculture and human consumption (Vörösmarty et al. 2000), and land productivity is declining as a consequence of excessive cultivation, degrading soil structure and the chemical and biological fertility of soils (Beddow et al. 2009). However, with the advent of herbicides to kill weeds the need for cultivation has diminished (Koskinen & McWhorter 1986). This has given rise to reduced tillage and reduced traffic for crop production, known as conservation agriculture (CA).

CA is based on practices that minimally disturb soil, maximise soil cover and rotate crops (Unger 2006). This facilitates the natural soil formation processes of active soil biology and root retention, which enhance the build-up of organic matter and organic nutrients, and combined to increase soil aggregation and the stability of aggregates to wetting (Dexter 1991; Limon-Ortega et al. 2006). In turn, water infiltration and water storage properties improve, and these lead to enhanced irrigation efficiency (Hulugalle et al. 2004). Hence the benefits of CA are twofold: increased irrigation efficiency, and increased productivity (Hassan et al. 2005).

The application of CA farming practices to raised bed irrigation systems occurred because of the operational efficiencies of chemical weed control. However, it brought with it expectations that the soil conditions and fertility improvements, which have been reported where it was practised in rain-fed agricultural areas (Tullberg et al. 2007; McHugh et al. 2009) would ensure that adequate lateral infiltration properties would be maintained. It also brought with it the expectation that all wheel traffic would be confined to the furrows, reducing the loss of water through the base of furrows and avoiding wheel compaction on crop seedbeds. The introduction of CA to raised beds thus enabled the beds to become permanent, and so the term “permanent raised bed” (PRB) was used to describe this way of farming. Hence PRB is a type of soil and irrigation management where the field is divided into two sections: (i) furrows for irrigation application, drainage, and machinery traffic; and (ii) raised beds for growing crops with reduced tillage.

However, notwithstanding the practice of CA on PRB, the expected improvement in irrigation performance failed to eventuate (Akbar et al. 2007; Jin et al. 2007). There are two main reasons for this: one is that some soils used for irrigated PRB are inherently structurally unstable because they have a high exchangeable sodium percentage, which causes soil aggregates to disperse and seal when wet (Smith et al. 2001); and the second is that soils subjected to rapid wetting and drying will disaggregate, subside and consolidate even when they have a stable structure (Utomo & Dexter 1982). Hence, the infiltration properties of soils in PRB, although in better condition than soils in cultivated raised beds (Pagliai et al. 2004), continue to have lateral infiltration rates that are less than desirable (Lucy 1993).

The failure of lateral infiltration to be adequate is a major reason behind conflicting research findings on PRB under variable environmental conditions. Poor lateral infiltration into the bed centre (subbing) has been reported in PRB in many countries e.g. Australia, China, Pakistan and India, where the soils used have poor infiltration properties (Lucy 1993; Akbar et al. 2007; Jin et al. 2007). Thus, additional measures for improving the stability of soil structure to wetting and maintaining a loose friable soil are essential if PRB farming is to gain widespread adoption golbally.

What is needed to achieve these conditions for the soil in PRB is machinery and practices that can renovate beds in a way that loosens the soil with near-zero disturbances, retains all the roots from previous crops in a near undisturbed state and cleans and reshapes furrows and bed shoulders. If achievable, such practices would ensure the benefits of bed-furrow irrigation to be magnified in terms of both irrigation efficiency (lateral infiltration) and productivity. Thus, measures for improving the water productivity (*WP)* of PRBs are central to gaining widespread adoption for the sake of sustainable agriculture.

1.2 Water productivity

The *WP* is a generic term, which can be defined as “the physical mass of production or the economic value of production measured against gross inflows, net inflow, depleted water, process depleted water, or available water” (Molden 1997). This research is focussed on input *WP* because it deals with the physical mass of production (grain or straw yield) measured against water input (irrigation + rainfall). There are many factors that can affect the *WP*, but this research deals with two main areas comprising agronomic and irrigation management. Improving soil structural stability, lateral infiltration, and general soil fertility with better agronomic management (Pagliai et al. 2004) and enhancing irrigation performance with reduced irrigation application losses (Smith et al. 2005) and improved application uniformity are central for enhancing *WP* of PRB farming systems on a sustainable basis.

1.2.1 Agronomic management

Furrow irrigation, no matter how water is applied, depends for its effectiveness on the hydraulic properties of the soil in beds, which for relatively fast lateral movement of soil-water depends on the stability to wetting of the structure of the soil in the beds (Singer & Munns 1999). Despite this dependence and the wide spread scientific knowledge of the deleterious effects of cultivation on the stability of soil structure (Hulugalle & Daniells 2005; McHugh et al. 2009), most irrigation practices in the world still use an unnecessarily large amount of cultivation (Roth et al. 2005). For instance, in most of the under-developed and developing world beds are used only for row crops. In these types of countries, basin irrigation is the preferred irrigation practice for field crops, such as wheat, barley, rice, canola etc., and beds are used for row crops, such as cotton, maize, and vegetables.

The alternate use of beds for every second crop requires an unnecessarily large number of cultivation operations for, firstly, the construction and then, the destruction of beds and levelling of the field for subsequent basin-irrigated field crops. In countries where these practices are the norm, farmers overcome the slow rate of infiltration of water to the centre of beds by overtopping the beds in the first and, possibly, second irrigations (to ensure good germination and establishment of their crops) and/or filling the furrows and maintaining a high water level in the furrows for long periods (Hamilton (pers. comm.)).

Even in countries where beds are used for successive or near-continuous cropping, cultivation exceeds the small number and minimal soil disturbance that is necessary for the creation and maintenance of stable soil structure (Roth et al. 2005). In these countries, various forms of cultivation continue to be practised because of the need to reshape the furrows and beds and to loosen the soil in the beds. Some bed cultivation is considered necessary because of the combined needs of creating a good seedbed, ensuring adequate rates of infiltration into the beds, and for controlling weeds, diseases and pests. With the advent of herbicides to control weeds and a general recognition that soil cultivation is constraining productivity and increasing the cost of production, there is an emerging awareness and desire to find improved ways of managing soil to increase water infiltration, crop production, and farm profitability.

1.2.2 Irrigation management

The Oxford English dictionary (www.oed.com) defines irrigation as “The action of supplying land with water by means of channels or streams; the distribution of water over the surface of the ground, in order to promote the growth and productiveness of plants”. This research deals with furrow irrigation, where irrigation application rate and duration are the main irrigation management factors that affect the efficiency of irrigation application (Raine & Bakker 1996).

Furrow irrigation is one of the commonly used form of surface irrigation throughout the world (Burt et al. 1995). It is generally considered to be a more water-efficient method in comparison with the basin irrigation method because of (i) the speed with which water is conveyed to the low end of a field (Gillies 2008); and (ii) " the relatively small proportion of the soil surface is in contact with the flowing water during irrigation than the flat basin, where whole surface is inundated (Walker 1989).

Although furrow irrigation is more efficient than basin irrigation, it still has challenges. One of the challenges is the knocking down of beds after row crops for the next field crop (wheat, canola, rice etc.) and then reconstruction for the next row crop. Consequently soil in the bed consolidates with wetting and drying and its hydraulic properties deteriorate. Thus, the resulting poor lateral infiltration detracts from the efficiency potentially available by adopting furrow irrigation.

1.3 Research opportunities

Adoption of PRB in developing countries is currently low and existing PRB management is generally inappropriate. Several factors contribute to low adoption rates including uncertainty over the magnitude of crop and water productivity benefits, operational and management factors including lack of availability of suitable machinery and guidelines on appropriate irrigation design and management practices. Anecdotal evidence also suggests that bed subsidence of structurally degraded soils may also limit lateral infiltration into the bed and raises questions of what is an ideal bed width. In these cases, there is a need to identify strategies to enhance lateral infiltration by loosening subsided beds consistent with CA.

The available decision support guidelines on irrigation and soil management practices are limited for improving the *WP* of irrigated PRBs in general and in Pakistan in particular. Soil properties under variable agronomic management of PRB were studied under rain-fed conditions. Similarly, previous research on irrigated PRB has only provided water saving comparisons with traditional flat basin or bay application systems. Hence, there are real research needs to (i) find a way of loosening subsided beds that is consistent with the principles of CA and creates and maintains a stable, loose soil structure with high rates of lateral infiltration; and (ii) develop appropriate irrigation application practices that capture these soil benefits of PRB in the most efficient manner. Combined agronomic and irrigation management strategies need to be explored for improving *WP* of irrigated PRBs.

1.4 Research question and aim

The underpinning research question for this dissertation is: “Can the productivity of current irrigated PRB farming practices be improved by improved soil management (bed renovation) and irrigation management?”

Hence, the aim of this research is to identify and evaluate strategies which improve the input *WP* of irrigated PRB farming systems.

The input *WP* of raised beds may be affected by many factors including plant genetics, external plant environmental characteristics, physical processes, their management and their complex interactions. However, the research reported here deals with the agronomic and irrigation management factors shown in Figure 1.1. In terms of crop management, it deals only with the establishment and yield of crops.

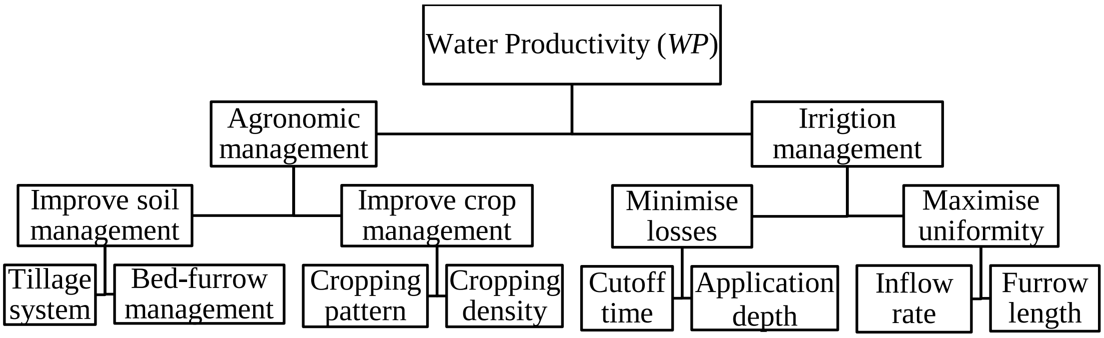


Figure 1.1: Frame work of management factors affecting water productivity of raised beds

1.5 Hypotheses

The key hypotheses for this research are that:

- The input *WP* of irrigated PRB is sub-optimal due to inappropriate soil management, field design, and irrigation management practices.
- The input *WP* of current PRB farming systems can be increased with appropriate bed renovation methods, improved field design (including bed-furrow dimensions) and optimised irrigation management.

1.6 Specific objectives

The specific objectives of this research are to:

- Evaluate the irrigation performance and input *WP* of PRB under commercial Australian and Pakistani farm conditions.
- Evaluate the effect of PRB renovation methods on seasonal changes in soil hydro-physical properties (including lateral infiltration), irrigation performance, crop yield and input *WP*.
- Identify soil and irrigation management strategies to improve input *WP* by increasing lateral infiltration and optimising irrigation performance of PRB.

1.7 Structure of this dissertation

The dissertation structure is outlined in Figure 1.2. This introductory chapter has provided a brief background to the research area including the hypotheses and specific objectives of this study. Chapter 2 reviews existing literature and will provide a rationale for improving input *WP* through keeping in view the prevailing agronomic and irrigation management issues both in Australia and in Pakistan. It reviews the adaptation of conservation agriculture to traditional raised bed farming systems in Australia and Pakistan. Chapter 2 then describes the main agronomic and irrigation performance indicators and provides a background to the evaluation methods that are required to improve the input *WP* of raised bed system.

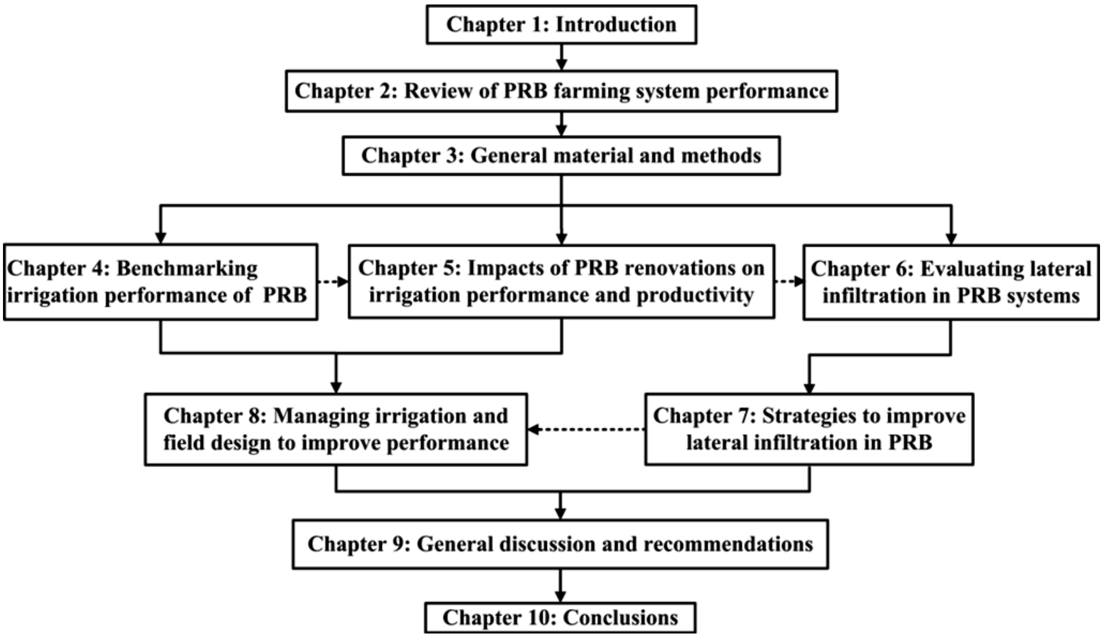


Figure 1.2: Outline of dissertation structure

Chapter 3 is a general material and methods and describes the research plan, study sites, their background information, previous crop and cultivation history and field conditions. It also describes the general assessment methods that were applied across all or most sites during the three field studies and a desktop study components.

Chapter 4 benchmarks the irrigation performance of commercial PRB farming systems in Australia and Pakistan. It provides an assessment of the measured irrigation performance and identifies the main agronomic and irrigation management issues affecting the *WP*.

Chapter 5 evaluates the effect of PRB renovation methods on irrigation performance and productivity. It describes the experiments for the combined implementation of agronomic and irrigation management on a Vertisol. It provides an analysis of seasonal variations in soil hydro-physical properties e.g. bulk density, soil moisture, lateral infiltration and bed furrow configurations with particular reference to crop yield and *WP* during the three cropping seasons under three renovation methods.

Chapter 6 covers detailed field experimentation and analysis of lateral infiltration into the centre of 200 cm wide beds on a Vertisol in Australia and 132 cm wide beds on a sandy clay loam in Pakistan.

Chapter 7 describes strategies for improving lateral infiltration under 200 cm wide PRB on a Vertisol and 132 cm wide PRB on a sandy clay loam using data from Chapter 6 with Hydrus 2D simulation. It provides an assessment of three different renovation methods, variable furrow water head, inflow rate and bed width for improving lateral infiltration and developing management guidelines. It also describes implications of lateral infiltration in irrigation management.

Chapter 8 evaluates various irrigation management and field design strategies using field measured data from Chapters 4, 5 and information from Chapter 7 with SIRMOD simulation. It outlines guidelines for improving the existing irrigation performance in both countries. Chapter 8 also describes alternative solutions and decision support aids for further improvement of the irrigation performance under three PRB renovation techniques.

Chapter 9 is a general discussion and provides a comprehensive overview of the overall research outcomes and their implication in existing PRB farming systems. It also identifies several areas for future research. Chapter 10 concludes the overall key research findings and hypotheses.

CHAPTER 2: Review of permanent raised bed farming system performance

2.1 Introduction

This chapter review the rationale for improving the existing water productivity (*WP)* sustainably using PRB farming system with particular reference to Australia and Pakistan. This review divides the existing challenges and opportunities into two key areas including agronomic and irrigation management. Therefore different agronomic and irrigation factors affecting raised bed *WP* along with their assessment methods has been reviewed. The review concluded a road map to be pursued during this study.

2.2 Need to improve water productivity of raised beds

The world's future food security is uncertain because the population continues to grow at a fast rate, no or little new land is available for agriculture, and water resources are predominantly used inefficiently to produce food and are under threat in terms of the reliability of supply and the quantity available because of the impact of climate change on existing farming areas. The UN (2010) forecasted the world population to reach ~9 billion in 2050, thus water demand will increase tremendously, based on another UN (2005) estimate that ~2700 litres of water per day per single person is required to avoid water scarcity. Expansion in agricultural lands is not viable because of the limited available land and the associated environmental cost. Therefore, improving the production per unit area (Bruinsma 2003) and producing more with less water are the major options available to meet the increasing food demand on sustainable basis.

Production increase with artificial fertilisers may be not sustainable (Tilman et al. 2001). Nevertheless, the use of nitrogen was helpful in improving around 50% of yield levels and according to Gilland (2006) its use at the current level, at least, is forecast as an essential part of the global industrial farming system in the near future. However, the cost of these oil and gas based fertilisers is likely to rise in future as the oil itself will be very expensive due to rapid depletion that will limit its application

(Edgerton 2009). Moreover, soil contaminants in fertilisers like arsenic, cadmium, fluorine lead and mercury and their transfer from soil to food is a matter of concern (McLaughlin et al. 1996). Therefore, there is a need to identify practices that improve productivity without relying on artificial fertilisers.

Traditional methods of farming involve intensive tillage, which is not sustainable. Intensive tillage destroys soil stable bio pores, soil fauna, and biota and exacerbates soil carbon and organic matter loss. Production increase with intensive tillage has been proved as a temporary solution (Tilman et al. 2002; Hobbs et al. 2008). For instance, one of the main reasons for a twofold yield increase in the subcontinent since the 1960s and threefold yield increase in Europe between 1950 and 1990 were attributed to intensive cultivation; however a gradual damage to soil structure and fertility was noted. Consequently, after five decades, a decline in land production potential is obvious (Beddow et al. 2009). Thus, better agronomic management is essential for sustainable production.

Gravity fed surface irrigation systems represent ~90% of irrigation applied globally. According to a UN (2009) report, irrigated agriculture produces ~40% of world food by consuming ~70% of total global water withdrawal for irrigating 20% (~275 million ha) of global cultivated land. Hence, agriculture contributes proportionately more in global water resources losses. The major reasons are frequently attributed to the huge irrigation losses estimated to be ~30% during conveyance (Bos 1985), ~19% during field application (Postel 1993) while only ~10% to 30% of available water is used by plants as transpiration (Wallace 2000). Furrow irrigation is the most common gravity fed surface irrigation method (Burt et al. 1995), but cause higher water application losses under its current management. Water application losses under furrow irrigation have been reported to the extent of 40-70% in Australian cotton and sugarcane industries (Bakker et al. 1996; Dalton et al. 2001; Smith et al. 2005) and up to 40% in Pakistani farm conditions (World Bank 1997). Hence, producing more with less water seems achievable particularly in both countries by controlling the irrigation application losses through better irrigation management.

2.2.1 Extent of agronomic and irrigation management issues

Agronomic and irrigation management issues largely prevail in existing farming systems of Australia and Pakistan, and both countries are the focus of this study. Australia has better farming systems, better farming infrastructure and fertile land resources, but irrigation water is limited, and furrow irrigation management is well short of optimal in all states and across all soil types. Pakistan is a major irrigated country but both land and irrigation management is poor. Both major agricultural countries represent the majority of issues that are generally experienced in the developed and developing countries of the world. A review of agronomic and irrigation management systems in both countries is presented below.

2.2.1.1 Agronomic and irrigation issues in an Australian context

Australian Vertisols have been shown to be very sensitive to poor agronomic management, although it has high natural fertility. The reasons are generally attributed to the existence of low volume of permanent structural pores (Coughlan 1981), which is affected by the shrink swell nature of the soil. Swelling can close unstable macro pores making the soil less permeable (Cook et al. 1992) and more susceptible to runoff and erosion (Smith et al. 1983). In contrast, stable bio pores resist swelling and maintain permeability (Dexter 1991), which can be formed and protected by root channelling, surface residue management, mulching and biological processes (Smith et al. 1983). Existing poor agronomic management involving intensive cultivation, mismatched machinery operations, and random traffic with heavy machines negatively affects these processes.

Vertisol cracks due to wetting and drying processes. Surface cracks are formed due to evaporation and deeper cracks are formed due to soil moisture extraction by plant roots (Dexter 1991). Cracks are beneficial for enhancing lateral infiltration in widely spaced furrows and the wet/dry cycles can also repair soil structure of compacted Vertisol (Samrah et al. 1996). However, during the crop establishment period, surface cracks are more pronounced due to evaporation, while deeper cracks are negligible due to absence of water extraction by plant roots. Generally dry soil profile increase lateral infiltration due to deeper cracking but in case of shallow dry surface layer underlain with wet soil, which generally occur in crop establishment stage, can reduce seed germination in wide bed middle due to limited lateral wetting of irrigation water (Lucy 1993). Similarly, if deeper cracks are present, generally when crops are sufficiently grown, then initial infiltration is very high until the cracks close. The drop is sudden due to declining infiltration into dense soil blocks between cracks. The rapid sealing of cracks by slaking and swelling creates air trapping and zones of low porosity in deeper wetted subsoil, resulting reduced infiltration in Vertisol (Chan 1989).

Vertisol is very sensitive to subsidence, which is caused by slumping due to wetting and compaction due to random mechanical operations (trafficking), especially under moist soil with heavy machinery (McGarry 1993). According to Chan (1989), both these processes generally result in denser and stronger aggregates, which result in the reduction in soil moisture retention properties, sorptivity, and hydraulic conductivity. Thus, water storage of the dense profile could not be substantially improved with prolonged irrigation intervals. Consequently *WP* is adversely affected.

In Australia, surface irrigation (predominantly border and furrow) utilises more than 70% of irrigation water (ABS 2010) under a wide range of fields, pastures and row crops. Unfortunately, irrigation water availability is limited, while the demand for water resources has been constantly increasing due to the development of competing industries. Water is considered one of the key resources for agriculture and economic development in Australia. According to Dalton et al. (2001), improving on farm water use efficiency is part of the solution to the competing demand for limited water resources. Better management of land and water are considered the key factors for improving the existing *WP* sustainably.

Current irrigation performance is poor under most furrow irrigated raised beds and crops. For instance, application efficiencies of 30-60 % were reported by Raine and Bakker (1996) and Dalton et al. (2001) for cotton and sugarcane crops in Queensland and 61% for sugarcane in Ord river irrigation area in Western Australia (Bakker et al. 2006). The major reasons are excessive deep drainage potential and tail drain runoff losses, estimated to the extent of ~43 mm per irrigation in the Queensland cotton industry using modelling, which was estimated to equal ~US$140 million a year at that time (Smith et al. 2005). Poor irrigation management and improper field design were the most common reasons for this (Jensen et al. 1990; Raine & Bakker 1996).

2.2.1.2 Agronomic and irrigation issues in a Pakistani context

Around 80% of cultivated lands in Pakistan (Qureshi & Barrett-Lennard 1998) are irrigated that produce > 90% of its total agricultural production (Barral 1994). The Indus Basin of Pakistan, one of the largest contiguous canal irrigation systems in the world, operates with 25% to 40% water application losses (World Bank 1997). Moreover, pumping groundwater to supplement the canal water resulted up coning of brackish water (Akbar et al. 2001). Consequently, 35% of Indus Basin is affected by waterlogging and salinity causing ~25% loss in productivity (Qureshi et al. 2008).

The government is currently spending billions of rupees on lining the water courses to mitigate the conveyance losses and control the waterlogging and salinity issues. Subsurface drainage systems were installed during the 1980s through salinity control and reclamation programs (SCARP) in many parts of Indus Basin. However, the potential benefits of such curative programs can only be achieved once the preventive measures are strengthened. This is possible through the conjunctive improvement of reducing losses during conveyance and field application.

Irrigated raised bed farming is generally practised for the majority of row crops and vegetables in the Indus Basin. Raised bed farming in Pakistan is characterised by a narrow bed width (65-75 cm furrow spacing), short field length (30-100 m) and blocked furrows at tail ends. Selection of bed furrow configurations is generally based on the farm manager’s understanding of its apparent relationship with land use efficiency, crop type, soil type, lateral infiltration, traditional practices and available machinery (Akbar et al. 2007). Wide beds (132 cm furrow spacing) were recently introduced and are mainly used for research purposes. The main reason for the use of these bed sizes is the 132 cm track width of the commonly available 50 hp tractor.

The non-swelling rigid sandy clay loam soils with a history of intensive cultivation tend to subside and structurally degrade during a cropping season. Thus, the unstable soil structure and reduced hydraulic conductivity adversely affect crop performance, especially in the bed middle (Akbar et al. 2007). The irrigation and crop performance of existing raised bed farming systems in the Indus Basin can be improved on a sustainable basis by adopting soil friendly agronomic management practices involving minimum soil disturbance that improve soil structure by accelerating the natural soil amelioration processes and organic matter build up.

Irrigation water in the Indus Basin is generally available on a weekly schedule from a network of perennial earthen canals and tributaries, which have very poor conveyance efficiency (50%) according to Gill (1994). Flow from the water course to a small temporary manifold type head ditch is generally through a manually controlled outlet called ‘nucca’. The head ditch simultaneously supplies water to several (generally 5 to 10) furrows. Inflow to furrow depends on the number of furrows served, while irrigation application time often depends on flow arrival to tail end and/or furrow filling. Frequent irrigation water overtopping of the bed at the tail end and lack of wetting front penetration into the centre of wide beds (132 cm furrow spacing) are generally obvious during irrigation (Akbar et al. 2007). To achieve uniform application and to fulfil the deficit, the furrow length is generally divided into small (10-15 m long) sections with bunds and each section is irrigated separately in sequence. This practice is highly laborious, time consuming and requires careful monitoring during irrigation, while its impacts on deep drainage losses and contribution to groundwater are largely unknown but seem considerable.

Field design and irrigation management can significantly affect raised bed performance (Raine et al. 1998), but have received only limited considerations in Pakistan. Despite the fact that improved irrigation performance and increased production of raised beds versus flat basin has been reported by Hameed and Solangi (1993) and Berkout et al. (1997), irrigation management of furrow irrigation is still largely sub-optimal (Kalwij 1997; Akbar et al. 2009). The main reasons are uninformed selection of inflow rate and time to cut-off causing over irrigation and sub-optimal bed-furrow configurations causing poor lateral infiltration in wide beds (Akbar et al. 2007).

2.3 Factors affecting water productivity of raised beds

Leaving aside plant genetics and crop husbandry, which are outside the scope of this research, water productivity is affected by the type of soil being used and the manner in which it is managed (Lal 1985), plus the quality, quantity, application method, and frequency with which water is applied. These factors are of importance in all forms of irrigation, but for furrow irrigation they have an elevated importance because of the fact that: (i) water is applied to only a small proportion of the surface area of a field and its lateral movement into the root-zone of plants is dependent on the hydraulic properties of the soil, and (ii) the velocity of water flow in furrows and the rate of advance of water in the furrows needs to be matched to the soil's ability to absorb it for long enough for the infiltrating water to reach the centre of beds.

The bed furrow environment, which the irrigation water and plant encounter during a cropping season, can be illustrated by Figure 2.1 where the bed cross section has been divided into three zones. Zone 1 is the most compact and least permeable, which is a consequence of traffic necessary to farm. By controlling the traffic to defined tracks the compaction of zone 1 can be enhanced (McHugh et al. 2009), which can be beneficial in enhancing lateral infiltration to bed and controlling deep drainage losses. Soil beneath the bed in zone 2 has a density that is a consequence mostly of soil type and partly of prior history of traffic and cultivation. Therefore, better agronomic management can produce long term improvements in zone 2. Soil structure, density, hydraulic properties and bed-furrow shapes within zone 3 can be significantly influenced by farmer operations (Panettieri et al. 2013), and management factors in short term. Therefore, improved water and air movement, organic matter and fertility in zone 3 are the keys for improving *WP*.

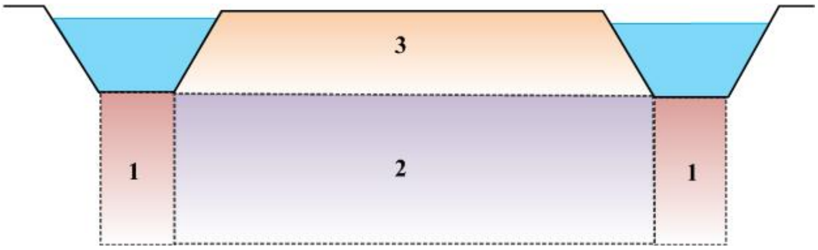


Figure 2.1: Bed cross section with three soil zones affecting irrigation and crop performance

According to the foregoing text the major factors affecting *WP* of raised beds can be divided into two broad groups. They are related to (i) agronomic management and, (ii) irrigation management. Agronomic management is aimed to improve *WP* on sustainable basis by improving soil physical, chemical and biological properties, crop health and land use efficiency. This can largely be accomplished by optimising the soil management techniques, bed-furrow configurations and cropping management under the current raised bed systems. However, this research is focussed on soil management only. Irrigation management involves delivery of water to all parts of an irrigated field, which is an engineering challenge and can be efficiently accomplished by minimising the losses and maximising the uniformity through optimising inflow rate, time to cut-off, application depth and field design.

2.3.1 Agronomic management factors

Because hydraulic conductivity of soil is controlled by the air filled porosity, pore sizes and geometric distribution (Rezanezhad et al. 2010), thus the soil factors important for irrigation are those that affect the pore size distribution and the stability of that distribution to wetting and drying. Some of the differences in these properties between soil types are inherent, resulting from differing types of mineralogy and amounts of clay and the age of the soil profile, all of which are consequences of differing parent material and soil formation processes. Others factors are affected by the way in which the soil is managed. The main agronomic management factors affecting *WP* are listed below.

2.3.1.1 Machinery traffic and tillage

The use of large machinery is an essential part of modern agricultural production systems, because it reduces time, labour and fuel cost of operation. However, intensive tillage under high soil moisture without matching track widths and lack of defined tracks can cause soil compaction (Allen & Musick 1997). According to Soane (1976), around 90% field surface was compacted during seed bed preparation, 25% during combine harvesting and 60% during straw baling. However, by controlling the traffic paths only 15% of the field was compacted, which caused significant improvement in soil infiltration properties. Similarly, up to sixfold increase in infiltration was identified under controlled traffic farming than conventional random traffic farming by Tullberg and Murray (1988), while McHugh et al. (2009) identified up to 45% increase in plant available water and 9% decrease in bulk density in the top 40 cm profile over a 3 year period of controlled traffic farming. Therefore, minimum soil disturbance is helpful in improving soil properties.

Controlling the machinery traffic to fixed tracks can reduce the vertical infiltration into the furrow bottom, which can be helpful in enhancing application uniformity by accelerating the water advance rate in lengthy furrows. Reduced steady state infiltration under compacted furrows was identified to the extent of 20% to 80% in several past studies (Elliott & Walker 1982; Trout & Kemper 1983; Trout & Mackey 1988a; Hunsaker et al. 1999; Li et al. 2001), which can be used to enhance irrigation water advance rate in furrows up to 45% in compacted wheeled furrows in comparison with non-wheeled furrows (Allen & Musick 1992). Using a narrow tyre width can avoid compaction of bed shoulders leading to enhanced lateral infiltration. Reduced vertical infiltration into furrow bottom and enhanced lateral infiltration into the wide bed middle can be helpful in improving *WP*, especially under low infiltration soils.

The severity of tillage impact depends on the environment and the duration of the particular tillage farming system application (Rhoton 2000). Most tillage practices have pronounced effects on soil hydraulic properties following tillage application, but these effects can diminish rapidly (Mark et al. 2008), while porosity and soil infiltration gradually enhances under the no till system (Azooz & Arshad 1996). Comparison of the main cotton pre-planting tillage options indicated a favourable root environment in the direct listed soil, excessive water entered the ripped soil thus caused waterlogging while chisel ploughing indicated intermediate behaviour (Hulme 1987). Similarly, intensive tillage leaves the soil exposed to structural decline, destroys stable bio pores and fauna (Smith et al. 1983) and exacerbates soil carbon and organic matter loss (Boulal & Gómez-Macpherson 2010). Hence, due to effects on soil physical, chemical and biological properties, tillage should be carefully applied.

Tillage is generally applied with the aim of loosening the compacted soil and enhancing soil porosity. Other reasons are control soil borne diseases, pests, pupae and slugs associated with certain crops genetic varieties (McBeath & McBeath 2010). Similarly, shallow rotary cultivation is generally practised in Pakistan to clear the weeds at harvest and to prepare a soft seed bed for facilitation in manual sowing of row crops (Akbar et al. 2007). Blade ploughing with no inversion has been shown to improve *WP* by enhancing lateral infiltration in wide beds (Hamilton et al. 2005; Jin et al. 2007; Akbar et al. 2010) in low infiltration soil. However, studies focussed on the impacts of different soil loosening methods under Vertisol for enhancing soil properties, irrigation efficiency, and crop production sustainably, are scarce.

2.3.1.2 Bed furrow configurations

Bed furrow configuration is variable throughout the world. Bed widths (furrow spacing) of 2 to 3 m are common in Australia, while 0.6 to 1.5 m width is common in China, India, Pakistan, Mexico and Bangladesh (Sayre et al. 2005). Currently selection of bed width depends on available machinery dimensions, soil type, crop type, crop rotation, and farmers’ preferences. Soil infiltration properties, crop row spacing, and crop row distance from furrow centre generally governs the bed width. Bed height and furrow dimensions are generally affected by variable furrower tilt angle, speed of machinery operation, soil moisture at the time of bed construction, tractor power and depth of excavation (Hamilton et al. 2005). In season processes generally modify bed furrow configurations.

Variable furrow dimensions, water depth in furrow and furrow compaction can affect the soil moisture distribution between the wetted furrows (Tabuada et al. 1995). For instance, too deep furrows at early crop stage can reduce furrow water head and lateral infiltration into bed surface, which can be detrimental to densely grown crop establishment (Hassan et al. 2005). Similarly narrow furrows than the tractor tyre width can reduce infiltration due to compaction of bed shoulders (Hao & Yali 2012). Furrow shape has been shown to cause 45% water saving by using compacted V shaped furrows rather than uncompacted U shape furrows by Raine and Shannon (1996). Furrow dimensions change wetted perimeter and surface storage of water, which can affect irrigation performance of short furrows (Trout 1992).

The management of bed furrow dimensions is important in the current raised bed performance. Wide beds have been shown to reduce deep drainage losses, increase the production of land under crop and reduce tractor power requirement per unit area (Jin et al. 2007). Wide beds have also been shown to save irrigation water and enhance yield. However, poor lateral infiltration under low infiltration soil limit adoption of wide beds due to deleterious effects on crops in the bed middle. Moreover, furrow dimensions can affect infiltration due to changes in wetted perimeter (Trout 1992; Oyonarte & Mateos 2003). Wetted perimeter has been shown to affect infiltration evidenced by findings of Izadi and Wallender (1985), who identified a 33% share of wetted perimeter in infiltration variation. However, adoption of optimum bed furrow dimensions is rare under actual field conditions due to lack of knowledge and absence of proper decision guidelines. Therefore, optimised management of bed furrow sizes has the potential to improve the current *WP* of raised beds by reducing the irrigation losses and increasing crop yield through improved lateral infiltration and increased land use efficiency.

2.3.1.3 Cropping management

Crop rotation is one of the important farming considerations for improving raised bed performance. It can affect soil carbon and nitrogen (Edwards et al. 1992; Govaerts et al. 2006) and can increase yield by increasing the root activities (Nickel et al. 1995; Shafiq et al. 2002). It can be used for controlling the microorganism detrimental for root growth (Johnson et al. 1992) and other soil-borne pathogens by adopting non-host crops or pasture species (Gardner et al. 1998) in rotation. However, the cropping frequency and rotation is currently largely driven by market conditions or other farmer preferences.

The soil cover and residue retention tends to reduce the water and wind erosion (Langdale et al. 1991; Ma et al. 2006) thus can also reduce furrow filling and maintenance. It prevents crusting or sealing formation on the surface of the soil (Baumhardt & Lascano 1996) and facilitates improvement in soil infiltration rate (Findeling et al. 2003). Soil cover absorbs excess rainfall energy, thus mitigating the rainfall splash effect leading to enhanced aggregate stability (Pinheiro et al. 2004). The crop residues also tend to enhance the soil organic matter (Yang & Wander

1999). However, retention of straw and crop residues is an economical decision, because of the associated loss in product income. This residue is normally utilised as fodder, fuel or raw material for paper products, especially in the developing countries. Therefore, Halvorson et al. (2002) recommended no tillage while Soon and Arshad (1996) recommended crop choice in rotation for improving organic matter to compensate for the potentially negative impacts of straw removal.

Plant population per unit area can affect crop yields. The land loss due to row spacing and furrow width can affect yield, whose severity depends largely on specific crop species and variety. Fischer et al. (2005) reported 10% yield loss with 45-55 cm furrow width for sensitive wheat cultivars and no loss for least sensitive cultivars, while yield loss of all cultivars of wheat above 60 cm furrow width was confirmed. They also termed light capture as one of the key factors that compensate for the yield loss due to furrow gap. Therefore, the current trend of getting more population per unit area or uncontrolled furrow width can reduce crop production potential levels. Thus, crop row spacing affected by furrow width can affect *WP* if not managed properly.

2.3.1.4 Waterlogging and salinity

Waterlogging is caused when there is insufficient air in the soil for the plant roots to access enough oxygen for them to respire. Waterlogging generally occurs due to upward movement of soil moisture from a high water table. However, excessive rainfall or over-irrigation can also produce a temporary or perched water table, especially under duplex soil conditions (Bakker et al. 2005) that can damage crops due to lack of aeration, while raised beds have been shown to control waterlogging.

Waterlogging and salinity are two different things but are closely related as interconnection has been identified in many regions of the world. Waterlogging can raise a saline water table close to the surface or can mobilise a zone of salinity in a soil where there is no shallow water table. Crops can tolerate a low level of salinity. However, salinity become visible once the concentration of ions in the soil solution exceeds crop threshold levels as reviewed by Tanji (1990). In both cases salt moves to the surface by a combination of convection (i.e. soil water flow) and, if there is a concentration gradient within the soil-water, by diffusion. Convection is always the faster and more influential process. Therefore, waterlogging facilitates the transport of salt to the surface profile or root zone followed by evaporation leaving a concentrated layer of salts at the surface. High concentration of sodium salts in soil for longer period deflocculate soil colloids and degrade the soil structure (Levy & Torrento 1995). The high salinity and sodicity levels make the land surface less productive and in many cases, barren due to their negative impacts on soil structural stability, infiltration rate and drainage rates. Waterlogging and salinity have been identified as the major threat to many fertile lands, especially the Indus Basin (Qureshi et al. 2008). Poor irrigation management and use of poor quality water are the major reasons exacerbating waterlogging and salinity.

Raised beds are generally considered to exacerbate salinity due to large exposed surface areas that enhance evaporation. According to Oster et al. (1984), lateral infiltration is considered to increase the salt content of the centre portion of raised beds. However, a sandy clay loam soil with low salt content failed to show any accumulation in the centre of raised beds during nine years of monitoring salt levels (and nutrients), probably because limited rainfall redistributed any accumulation. Similarly, Bakker et al. (2010) could not identify any increase in salinity build up on raised beds in Western Australia. Therefore, minor salinity variations should not be a major concern in affecting *WP* of raised beds, while proper soil and irrigation management can reduce salinity by the leaching process.

2.3.2 Irrigation management factors

Irrigation performance is the ability of an irrigation system to apply water efficiently and uniformly according to plant and environmental requirements. Generally the term ‘efficiency’ is used as the ratio between input and output. In irrigation terminology it was further subdivided into different performance indicators. For instance, irrigation application efficiency (*Ea*) is the ratio of irrigation water available to the crop in the root zone and water received at field inlet (Purcell & Associates 1999) and requirement efficiency (*Er*) is the ratio of the volume of water stored in the root zone immediately after irrigation to the pre-irrigation root zone soil moisture deficit (Michael 1999; Raine & Smith 2007). The evenness of applied depth across the field is generally indicated by the distribution uniformity (*DU*), which is the average infiltrated depth of water in the lower one quarter of the field, divided by the average infiltrated depth over the whole field (Merriam & Keller 1978).

The irrigation factors important for irrigation performance are those that affect the amount and distribution of water in the field relative to the amount and availability of water and oxygen to plants, and the potential for water to be 'lost' to plants through deep drainage, surface runoff and evaporation. Hence, rate, volume and duration of flow need to be matched to the rate at which the soil is able to absorb water and the quantity that needs to be added to the soil to provide plants with adequate amounts and ease of extraction. The main irrigation factors are the field design factors of slope and length of furrow, as well as flow rates and duration of application that need to match the plant requirements and the soil's ability to absorb the water.

2.3.2.1 Inflow rate

Inflow rate (*Q*) refers to volume of water applied per unit time to a single furrow. Optimum *Q* is considered to be the one which enhances uniformity, minimises losses and suits the field conditions. Generally, *Q* is variable from farm to farm and even within the same farm, while optimum *Q* can hardly be found even in more advanced countries (Renault & Wallender 1992). The reasons for this are generally attributed to the variable delivery methods (e.g. siphons, gated pipes, or bank less channels) used for introducing water to the furrow inlet, which are largely subjected to variations due to variable outlet dimensions and pressure head in the supply channel (Smith 1990). The sensitivity of *Q* to these contributing factors can be illustrated by the investigations, which showed that decreasing the head by 50% resulted in 25% reduction in *Q*, while a 1 to 5 mm change in the diameter of outlets changed *Q* by 25% (Trout & Mackey 1988a). High variations in *Q* can suppress the seasonal trends in infiltration (Mailhol et al. 2005), while Schwankl et al. (2000) attributed up to 50% of variability in uniformity to *Q* variability between furrows. Thus, better management of these factors is essential for achieving optimum *Q*, which is generally constrained by field limitations.

Irrigation performance improvement using *Q* as a management tool can be applied in several ways. These methods are generally referred to as surge irrigation, cutback irrigation, increased inflow, and cablegation. However the majority of these traditional methods are labour intensive and are difficult to adopt under actual commercial farm conditions. Surface irrigation optimisation is another method currently based on using data of previous irrigation's events to calibrate a simulation model and to identify adjustments to *Q* and time to cut-off (*Tco*) for the next irrigation. Optimising *Q* and *Tco* has been successfully demonstrated for improved irrigation performance in many past researches (Raine et al. 1998; Smith et al. 2005; Smith et al. 2009). Nevertheless, it can also provide an opportunity of real time control of irrigation management as mentioned by Khatri (2007) and has raised the prospects of future furrow irrigation automation. This method still has limited field application due to equipment constraints, field limitations, and lack of knowledge due to limited training opportunities, but is suitable for testing and evaluation.

2.3.2.2 Time to cut-off

Time to cut-off (*Tco*) is the time period between switching on and switching off inflow to individual furrow. Optimum *Tco* is the time required to replenish the target soil moisture deficit (*SMD*) with increased efficiency and uniformity. It is generally affected by *Q*, furrow length, furrow slope, irrigation scheduling and soil infiltration characteristics. Lengthy *Tco* causes low *Ea* while reduced *Tco* may result in under-irrigation and can cause plant water stress, especially in tail reaches of the field as pointed out by Khatri (2007) and thus demand more frequent irrigation applications.

The *Tco* decision is generally based on water arrival at the tail end of the field and/or furrow filling, especially under short furrows with blocked ends. However, for lengthy furrows, with open ends, *Tco* is generally affected by the seasonally variable infiltration properties of soil, which govern the water advance rate and consequently affect the *Tco*. Lack of optimum *Tco* under current furrow irrigation management for the majority of crops is affecting the overall raised bed performance. For instance, identification of optimum *Tco* under long Australian sugarcane and cotton fields has been identified as the key in controlling deep drainage and runoff losses (Raine & Bakker 1996; Smith et al. 2005). Similarly, the uncontrolled *Tco* under short

Pakistani blocked end furrows frequently cause over-irrigation and bed over-topping, which have exacerbated the waterlogging issues (Gill 1994). Currently, lack of decision support aids for optimised *Tco* management is affecting irrigation performance in many regions of the world.

2.3.2.3 Application depth and infiltration opportunity time

The depth of application depends on the irrigation deficit prior to irrigation determined by the irrigation schedule, which is generally assumed as fixed. Generally, applying less application depth will result in less opportunity time along the furrows during an irrigation event, thus demanding more frequent irrigation. However, applying less irrigation depth than required will enhance *Ea* (Sepaskhah & Ghahraman 2004) due to reduced potential for deep percolation and runoff losses. In contrast, decline in performance is more pronounced, when achievement of higher *Er* is attempted by applying more application depth (Bautista & Wallender 1993a). Therefore, application depth can affect irrigation performance.

Variability of irrigation application depth from head to tail end of the field largely depends on the *Q*, furrow length, slope and soil infiltration properties. All these factors control the distribution of infiltration opportunity time along the furrow length and the head of water in the furrows. The field head reaches is normally over irrigated to the extent of 30% to replenish *SMD* of major portion (80%) of furrow length (Trout 1990). In contrast, the short furrows, especially at high *Q* and/or with steeper slopes cause larger irrigation application at field tail than at field head reaches. Therefore, irrigation management should account for the spatial variability in infiltration depth for improved *DU*.

Variable infiltration opportunity time is generally held responsible for variable application depth along furrow length. However, variation of infiltration rate during a given infiltration opportunity time can significantly affect irrigation performance. For instance, Bautista and Wallender (1985) admitted the importance of the short infiltration opportunity time in irrigation performance before the steady infiltration rate is achieved while Tarboton and Wallender (1988) also recognised the effects of infiltration opportunity time in field variability of applied depth, but also mentioned greater susceptibility of irrigation performance to variability in the infiltration rate, which is largely affected by the soil properties and soil antecedent moisture content at the time of irrigation.

2.3.2.4 Field design

Field length is one of the important field design components, which can markedly affect the irrigation performance. Theoretically, shorter field length will cause uniform water application and reduced losses provided all other variables remain constant. For instance, a reduction of 42% in irrigation water application was predicted by changing field length from 600 m to 300 m on a highly permeable alluvial soil (Raine & Shannon 1996). Longer furrow lengths, specifically under Australian conditions where the furrow lengths generally range from 600 to 1000 m, necessitate the need for intensive irrigation management to control the large deep drainage losses (Smith et al. 2005). Short furrows, particularly under the Indus Basin field conditions where the furrows generally range from 30-100 m length with blocked ends, are very sensitive to irrigation management factors.

The longitudinal slope of the furrow affects uniformity of water application due to its influence on advance and recession time periods. An increase in slope can slightly enhance the advance and recession rate provided Q and soil infiltration properties are fixed as evident from examining Manning’s equation. Larger infield slope variations have been reported as one of the major contributing factors that negatively affected the existing irrigation performance and exacerbated the waterlogging and salinity issues in the Indus Basin (Gill 1994). Minor infield slope variations can be remedied by land levelling techniques. However, generally field slope is difficult to alter due to the huge cost involved with land forming operations. Therefore, field slope is often regarded as fixed in the design stage.

Furrow spacing can affect irrigation and crop performance. One reason is the rapid completion of the advance phase on wide spaced furrows in comparison with narrow spaced furrows for the same total available field Q. Similarly, total water applied to 132 cm wide spaced furrows was 17% less than 66 cm furrow spacing (Akbar et al. 2010) for wheat and maize crops under sandy clay loam. However, in cracking

Vertisol the effect of wide furrow spacing on water application would be limited due to high lateral infiltration. Experiments conducted under low infiltration soils showed up to 45 times greater root density of maize crop next to the watered furrows in comparison with unwatered furrows (Oliveira et al. 1998). Similarly, poor crop performance of centre rows was reported by Hassan et al. (2005) due to reduced lateral infiltration under sandy clay loam with 180 cm furrow spacing. Therefore, bed width needs to be carefully designed for maximising yield and *WP*.

2.3.2.5 Irrigation scheduling

Irrigation scheduling is a practice that periodically applies sufficient water to maintain the crop root zone near the field capacity for better crop growth (Wichelns & Oster 1990). The soil moisture generally vary between saturation and wilting point (McBride 2004) but it is generally not recommended for the soil moisture to drop closer to wilting point, which can damage crop. Therefore, the lower limit of soil moisture is kept higher than the wilting point, termed readily available water, which generally on crop variety and stage, soil type and water availability.

Irrigation scheduling is generally aimed to minimise irrigation costs, maximise crop yields, optimally distribute a limited water supply and optimise the production from a limited irrigation water (Martin et al. 1990). Irrigation scheduling can influence both irrigation and crop performance. For instance, larger *SMD* prior to irrigation under cracking Vertisols can reduce water advance rate. Similarly, Cavero et al. (2001) identified significant correlation between maize yield and application depth, while Wichelns and Oster (1990) highlighted impact of *SMD* prior to irrigation on cotton crop yield. Therefore, adequate irrigation scheduling can improve *WP*.

Notwithstanding that such advance techniques of irrigation scheduling are present (Jones 1990), implementation of a proper irrigation schedule is still a great challenge due to existing poor irrigation management techniques and field limitation related to unpredictable water availability constraints in many regions of the world, especially the developing countries. Consequently, improper irrigation schedules reduce crop production and exacerbate waterlogging and salinity problems globally.

2.4 Adaptation of conservation agriculture to raised beds

Efforts around the world are underway in exploring innovative ways for ensuring sustainable crop production. Intensive tillage negatively affects soil structure, fertility (McGarry 1993), crop residue distribution, surface roughness, soil temperature and roots distribution (Dwyer et al. 1996), thus enhancing soil erosion, organic matter loss and evaporation losses (Yang & Wander 1999; Six et al. 2000; Kibblewhite et al. 2008). In contrast, minimum/no tillage and crop residue retention enhance productivity on a sustainable basis (Hobbs 2007), because it can protect the soil structure, soil fauna and biota that accelerate biological processes for natural soil amelioration (Tisdall et al. 1978; Govaerts et al. 2008; McHugh et al. 2009). Therefore, agronomic management based on the principles of conservation agriculture (CA) is essential for improving *WP* on a sustainable basis.

CA involves minimum soil disturbance, maximum soil cover and crop rotation with the aim of protecting the soil and water from losses/degradation, to maintain the productivity on an economically, ecologically and socially sustainable basis (Unger 2006). It facilitates soil amelioration by natural processes of wetting and drying without damaging structure, biological processes of root channelling, crop residue reinforcing, and some time by minimum controlled mechanical loosening of soil (McKenzie & Chan 1990; Dexter 1991; Hamilton et al. 2005). It tends to enhance soil structural stability, water absorption, and availability of soil-water to plants. Minimum tillage is better facilitated under the controlled traffic farming (Tullberg et al. 2007), which can also efficiently manage surface drainage and ground cover.

Attempts have been made, particularly in Australia, to improve the management of soils by introducing conservation agriculture practices. These have substantially reduced the amount of cultivation and increased the likelihood of a build-up in soil organic matter and biological activity. The practice of cultivation for weed control has been marginally reduced (Werth et al. 2006) due to chemical weed control and the adoption of minimum tillage crop establishment has further reduced the amount of soil disturbance. Thus the practice of permanent raised bed (PRB) farming has come into vogue. PRB involves distinctly separating the field into cropping zone (bed) and uncropped zone (furrow) and the furrows also serve as a machinery traffic path and water channel for irrigation and drainage.

2.4.1 Permanent raised bed farming systems

PRB farming systems consist of developing a bed-furrow system that is kept in place for several seasons with minor pre-sowing renovation operations (McGarry 1995; McKenzie 1998; Cooper 1999). Generally renovation is performed to restore bed-furrow configuration, to loosen the subsided bed and to control weeds, diseases, insects, slugs, pupae and pests (Wightman et al. 2005). Usually the frequency of remaking ranges from two to seven years (Cooper 1999) at commercial farms to as much as 18 years (Hulugalle et al. 2004) in experiments, which largely depends on soil and crop conditions. Minimum tillage, stable structure and soil cover under PRB conserves soil moisture for longer (Boulal et al. 2012), increase drainage (HulugalleA et al. 2010) and reduces losses, thus enhancing water saving (Jat et al. 2008). By combining several elements of conservation agriculture, PRB systems have been proved useful for controlling erosion, minimising soil structural decline (Verhulst et al. 2011) and reduction of evaporation losses (Hulugalle & Daniells 2005). However, irrigated PRB systems are still largely in their infancy and need to be more productive to achieve the anticipated benefits under wide environmental conditions, according to Roth et al. (2005).

2.4.1.1 Review of permanent raised beds in Australia

PRB system development in Australia gained momentum gradually since the 1970s. Martin Maynard, a pioneer PRB farmer in the Riverina of NSW, found he could increase his farm gross margin by up to 50% by adopting higher value rotation in conjunction with PRB farming system in the 1970s. Similarly, the preliminary work based on investigating the genetic and agronomic approaches for controlling the waterlogging together with the associated zinc deficiency symptoms in soybean in south east Queensland (Mungomery & Byth 1976) provides the initial background for the subsequent development of PRBs according to Borrell and Garside (2005), although this work was not aimed at developing the PRB system. Then, after exploring the benefits with soybeans, the research area on PRB was extended to rice and soybean in rotation (Borrell et al. 1991; Garside et al. 1992). Similarly, in an effort to develop a cropping system that will provide comparable economic return to sugarcane crops in the Burdekin river irrigation area, the double cropping system with PRB was preferred due to its short turnaround time requirement facility between crops in rotation (Borrell & Garside 2005). Studies conducted on double cropping of rice, maize and soybean on PRB in a rotation system from 1986 to 1991 resulted in recognisable advantages of improvement in saving water, nitrogen, phosphorus, timeliness of operation, energy and reduced soil compaction (Garside et al. 1992; Borrell et al. 1999; Ockerby et al. 1999), which acted as stimulus in dissemination of PRB. Similarly, in the Murrumbidgee/Murray valleys all summer non-rice grain cropping systems with an estimated area of 35,000 ha were undertaken using PRBs (Thompson 1995), while now the use of PRBs has been expanded to all irrigated maize, soybean, faba bean and chickpea planting, more than 30% of irrigated canola planting and 25 to 30% of all irrigated wheat plantings (Beecher et al. 2005). The results of a replicated trial on a range of crop sequences in a rice based farming system (Beecher et al. 2006) has shown improvement in ponding water, controlling weeds at crop establishment stage and enhancing *WP* by using lateral PRBs. Therefore, PRBs were adopted due to their inherent benefits, while field research related to improving its performance is scarce.

Cotton is one of the major crops in Australia that is grown largely in the irrigated areas of Queensland and New South Wales. Approximately 80% of the cotton crop is irrigated (Hulugalle & Daniells 2005), while furrow irrigation is the widely used method (> 94%), with a smaller area being irrigated with drip (4%) and sprinkler (< 2%) methods (Raine & Foley 2002). Cotton wheat rotation is followed by ~75-80% of cotton growers, where land preparation varies from intensive tillage (deep ripping, chiselling and bed reconstruction every year) to minimum till PRB systems (Schoenfisch 1999). PRB farming systems with a cotton-wheat rotation under the irrigated grey Vertisol of NSW, Australia, showed improved soil structure, increased number of drainage and aeration pores, which resulted in better drainage and storage (Hulugalle et al. 2010) increased plant available water and oxygen than cultivated raised beds (Hulugalle et al. 2004). Similarly, after reviewing a range of field research, Hulugalle and Daniells (2005) concluded that PRB is a suitable option for cotton crops and the problems related to heliothis pupae control, fertiliser, weeds and water management can be overcome by using appropriate irrigation and agronomic management practices. This study identified benefits of PRBs relative to cultivated beds but did not identify strategies for improved performance of irrigated PRBs.

Sugarcane crops are largely based on monoculture, while excessive tillage with heavy machinery is generally used, which causes severe soil compaction. The fluctuation in prices and yield compels the farmers to think of alternative production methods. Comparison of PRB with traditional methods has shown comparable sugarcane yields and reduced cost of production with improved earth worm activity, infiltration and yields in PRBs (Bell et al. 2003). However, according to Garside (2005) the development of PRBs in the sugarcane industry is still in its infancy but it seems that PRBs will soon become an integral part of the sugarcane cropping system.

The PRB and controlled traffic farming system developed for overcoming the waterlogging and improving the soil structure in high rainfall regions of South East Australia is a recent phenomenon. Around 70000 to 80000 ha of raised bed area was estimated by Wightman et al. (2005) in South Australia. In many parts of south-western Victoria with high water tables adopting raised beds have doubled the crop yields and considerably improved the farm profit (Wightman et al. 2005), while the use of organic amendments with PRB further increase the soil macro porosity and plant available water capacity (Peries & Gill 2011) leading to reduced runoff and greater root proliferation. However, adoption of PRBs is still in its early stage.

Winter waterlogging has been identified as affecting approximately one million hectares each of crop and pasture every year in Western Australia. This causes an average productivity loss of ~25% to 40% (McFarlane et al. 1992) due to perched water table in duplex soil, while PRBs successfully reduced winter water-logging and salinity (Bakker et al. 2005). The reasons were attributed to better PRB management practices that involved bed loosening using horizontal blades without inverting the soil, which resulted in porous and stable soil structure with greater resistance to wetting. These improvements were attributed to a deepened seed bed, increased root mass acting as reinforcing rods, and a significant proportion of larger pores (Hamilton et al. 2005).

The foregoing text showed the farming systems in Australia are still in transition from fresh bed (intensive cultivated) to PRB systems. The majority of the past studies on PRBs provided comparative performance to traditional practices. However, studies focussed on improving the agronomic and irrigation management of PRBs are sparse. Thus, it can be envisaged that performance of current PRB farming practices can be improved with better agronomic and irrigation management.

2.4.1.2 Review of permanent raised beds in Pakistan

The furrow bed irrigation method was introduced in the Indus Basin for growing vegetables and fruits (Berkout et al. 1997) in the late 1960's. The furrow bed system is generally considered a relatively efficient method of irrigation (Kahlown et al. 1998), which has now been adopted in over 40% of wheat-cotton rotation in the Punjab province of Pakistan. Some early work showed ~20% yield increase for wheat (Hameed & Solangi 1993) and ~48% yield increase for cotton (Berkout et al. 1997) just by changing from traditional flat basin to furrow bed system. Notwithstanding that furrow bed system is now being adopted for majority of row crops there are growing concerns about the cost of production (Alberts & Kalwij 1999), weed infestation, soil compaction, lateral infiltration and land degradation because the beds are generally regularly knocked down at the harvest of row crops. Greater interest has been shown to transform the current tillage intensive system.

The concept of PRB farming system is new in the Indus Basin of Pakistan. A joint research study of Pakistan Agricultural Research Council (PARC) and Australian Centre for International Agricultural Research (ACIAR) was conducted during 1999 to 2004 comparing traditional flat basin (intensive cultivated) with 180 cm wide PRB (minimum till: blade ploughing) using maize wheat rotation. Results showed considerable improvement in yield (26% for maize and 15% for wheat), water saving (32% for maize and 36% for wheat), *WP* (65% for maize and 50% for wheat) and reduced weed infestation (24% for maize and 31% for wheat) under PRBs compared with flat basin (Hassan et al. 2005). The reasons were attributed to better crop health on PRB due to improved soil physical properties (e.g. reduced bulk density, increased infiltration) and chemical properties. However, dry bed middle due to limited lateral water movement during normal irrigations was identified. Another study 2004-2009 at the same site using 132 cm and 66 cm furrow spacing in comparison with traditional flat basin showed up to 13% increased yield of maize and ~5% of wheat on PRBs compared with flat basins. This study showed increase of ~126% for maize and 13% for wheat compared with first study. The *WP* was increased by up to 30% for 132 cm and up to 18% for 66 cm PRB than for the flat basins for both crops (Akbar et al. 2010). The subbing issue was partially reduced by smaller bed size but irrigation management issue was still reported.

2.4.1.3 Summary of research needs in both countries

This review of previous work on PRBs in both countries indicated that the majority of the past research compared PRBs with traditional methods and research focussed on improving the renovation methods and irrigation performance of PRB practices was largely ignored. Moreover, the majority of past research used traditional methods of point measurement for field evaluation, which were subjected to variations. Therefore, a comprehensive evaluation of the current performance of PRBs is required using large area measurement methods that should also be helpful in developing strategies for improving soil and irrigation management practices. Evaluation of different PRB renovation methods and their impact on lateral infiltration seems essential for enhancing performance of existing PRBs. Therefore, detailed assessment of the major factors affecting *WP* of PRBs, explored during this review, needs to be critically investigated for identifying strategies to improve the current performance of PRBs.

2.5 Permanent raised beds performance and assessment

Two variables play a major role in controlling the performance of PRBs for improved *WP*. They are the crop yield and the volume of water used during a cropping season. The crop yield can be improved with better soil hydro-physical, chemical and biological properties, a manifest of agronomic management. Irrigation application can be minimised by improving the irrigation performance by reducing the losses with optimised irrigation management. In reality, the complexity of two dimensional infiltrations under furrow irrigation and lack of decision support guidelines has made it hard to manage PRBs properly under actual field conditions. Consequently, irrigation performance is negatively affected.

2.5.1 Agronomic management performance and assessment

2.5.1.1 Soil texture and structure

Soil texture (the relative proportion of sand, silt and clay) strongly affects the infiltration capacity of the soil. The particle sizes of normal soil range from < 0.0002 mm for clay colloids to the larger sand grains that range from 0.5 to 2 mm and even some time large boulders (Singer & Munns 1999). The smaller sized clay particles play an important role by filling the voids between the sand and silt particles, while the charged surfaces bind the particles together. The hydraulic conductivity of a medium with single size particles has been identified proportional approximately to the square of the particle diameter (Iwata et al. 1995). Thus, due to the variable nature of soil type within the same field, regions of soil with sandy texture often have higher infiltration rates (Childs et al. 1993), while clay texture was correlated positively and silt negatively with the initial infiltration rate (Van Es et al. 1991). The soil texture cannot be changed by any agronomic management practices.

Structure is the arrangement of soil particles, generally attributed to soil properties of pore sizes, their distribution, continuity and inter connectivity (McGarry 1993). Soil pores consist of macro pores (> 0.075 mm) and micro pores (< 0.03 mm) (Singer & Munns 1999). The soil pores are variable which largely depend on the biological activities, shrinking swelling, temperature, soil moisture and cultivation effects (Lal 2004). According to Cook et al. (1992), the cohesive forces between particles and the frictional resistance met by the particles impart strength to the soil matrix. Structured soil is more stable, in agricultural terminology, due to flocculation of clay particles and micro aggregates stability, which is enhanced by roots, microbial, fungal and bacterial exudates (Dexter 1991; Tisdall 1994; Czarnes et al. 2000) that also tend to enhance soil infiltration (Flury et al. 1994). The soil structure has been shown to gradually improve with the imposition of PRB farming systems.

2.5.1.2 Soil moisture

Soil management plays a key role in conserving soil moisture. Intensive tillage has been shown to uncover the underlying moist soil thus increase soil moisture loss due to evaporation. Conversely, PRB farming system with good soil cover and minimum soil disturbance conserve soil moisture and thus reduce irrigation requirement. It also helps in protecting the crop from water stress at critical crop stages. Similarly, tillage at low soil moisture level can promote clodding and surface disturbances while moist soil promote smearing and reduced infiltration. Therefore, optimal soil moisture during seed bed preparation is essential for improved performance.

There are two main conventional methods of soil moisture measurement (Jones 2004). The first one is based on the direct measurement of soil moisture status in the root zone and the second one is based on soil water balance calculations, which require detailed methods of estimating evapo-transpiration and water requirements for different crops and environments as reviewed by Allen et al. (1998). Further methods have also been discussed for future development by Jones (2004) that are mainly based on the sensing of plant stress, which include both water status and plant response measurement. However, these methods are generally very sensitive to environmental conditions that can cause fluctuations sometime greater than treatment difference and often require sophisticated and costly equipment.

The thermo gravimetric method is the standard soil moisture measuring technique, which requires oven drying at 105°C for 24-48 hours and determining the weight loss (Walker et al. 2004). However, this method is time consuming, labour intensive, destructive to the soil sampled, and cannot be used for repetitive measurements at the same location, but is still indispensable for calibration and evaluation purposes. There are a wide range of automotive indirect soil moisture measuring techniques including neutron scattering, gamma ray attenuation, soil electrical conductivity (based on electrical resistance and electromagnetic induction), hygrometers (capacitance, infra-red absorption and transmission, psychometers), tensiometers (based on capillary tension or soil matric potential) and that based on soil dielectric constants (including capacitance meters and time domain reflectometer-TDR). Reviews on the use, comparison and suitability of these techniques is given in Topp (2003) and Walker et al. (2004).

There are a wide range of commercially available point soil moisture measurement techniques in Australia. However, the capacitance based technology of (Sentek

EnviroSCAN®), diviner and micro-gopher are used at the National Centre for Engineering in Agriculture (NCEA). The sensors are fitted into a probe at specific desired depth (usually multiples of 10 cm) that is inserted into a specific size access tube installed in the soil profile to the target profile depth. The sensors work on the principle of producing a high frequency electric field around the sensors that extends through the access tube into the soil; the sensors detect the changes in the dielectric constant or permittivity of the soil over time, which varies inversely with the amount of water present in the soil. The scaled frequency readings obtained for a specific soil texture are converted by using a default calibration equation. The output comes in the form of volumetric moisture content in 10 cm profile depth. The sensors can be attached to an automatic solar powered logging facility, which can store a complete record of soil moisture over an extended period of time with the measurements taken at flexible time intervals. These sensors have been successfully tested and used (Mead et al. 1995a, 1995b; Alva & Fares 1998; Starr & Paltineanu 1998; Fares & Alva 2000) but were also identified sensitive to soil type, temperature and soil salinity (Baumhardt et al. 2000) thus require careful installation and calibration.

2.5.1.3 Bulk density

Bulk density is the ratio between mass of the solid material and the volume it occupies, which is generally expressed in (gm cm^{-3}). Thus for soil particles with fixed particle density the bulk density is inversely proportional to the porosity. Mixed results were achieved during attempts to establish a distinct relationship between infiltration properties of soil either with pore sizes distribution (Baker 1979) or with bulk density (Jaynes & Hunsaker 1989; House et al. 2001) due to the complex interactions between other large numbers of soil properties. Increase in bulk density due to compaction caused by grazing animals, machinery traffic and unfavourable agronomic management were reported under wide environmental conditions by Shafique and Skogerboe (1983) and Allen and Musick (1992). Similarly, gradually reduced bulk density were reported (Hassan et al. 2005; Akbar et al. 2009; McHugh et al. 2009) by imposition of PRB farming systems in different soils.

Bulk density variations can affect irrigation performance. The compacted trafficked furrows with high bulk density and non-trafficked loose furrows with low bulk density affect the water advance rates sometimes to the extent of 45% (Allen & Musick 1992) in the same irrigation, which often complicates the traditional irrigation management practices. However, bulk density indicative of variations in organic matter (Gupta & Larson 1979) and soil looseness in the manageable crop root zone under variable tillage systems can be beneficial in illustrating their agronomic performance and in comparing various agronomic management methods. Bulk density results are often inferred to soil porosity, water holding capacity and sometimes plant growth (Arya & Paris 1981).

Bulk density generally varies between less than 1 gm cm^{-3} to 2 gm cm^{-3} for normal soils, which can be determined in the field by oven drying, at 105°C for 24-48 hours, a soil sample of known volume. The ratio between the dry soil weight and initial volume sampled is the bulk density. Volumetric soil moisture can be determined by multiplying the gravimetric moisture content with the bulk density. The relationship between bulk density and porosity can be expressed as follows:

$$Porosity = \left(1 - \frac{\rho_b}{\rho_s}\right) * 100 \qquad 2.1$$

where ρ_b is bulk density in gm cm^{-3} and ρ_s is particle density in gm cm^{-3}.

2.5.1.4 Hydraulic conductivity

Hydraulic conductivity is the ratio of the flux to the hydraulic gradient, which is affected by soil properties such as texture, structure, porosity, pore size distribution, their tortuosities, pore geometry and initial moisture content (Hillel 1982). Intensive farming systems exacerbate the soil subsidence/densification process during a crop season, that tends to convert macro pores into micro pores and the inter-connectivity and/or continuity is considerably reduced, thus hydraulic conductivity also tends to reduce as mentioned by Shipitalo et al. (2000). Therefore, supply of soil moisture to root zone to replenish *SMD* during an irrigation event also reduces. Consequently, crop yields are negatively affected leading to low *WP*.

Minimum soil disturbance under PRB system reduce soil aggregates disintegration (Adem et al. 1984) thus enhance soil hydraulic conductivity. Conversely, intensive tillage and no residue retention accelerates surface crusting/sealing, subsidence, slaking, erosion and silting that negatively affects hydraulic conductivity, infiltration and sorptivity. The hydraulic conductivity of surface seals can reduce up to ~1-8% of the underlying soil and can cause 46% reduced infiltration (Segeren & Trout 1991).

The hydraulic conductivity can be determined in the field, in laboratory or using mathematical models. The field method is more representative but costly and time consuming. Laboratory and mathematical techniques are more convenient but require extensive comparison to field results.

2.5.1.5 Lateral infiltration into bed

Lateral infiltration (subbing) is influenced by the available hydraulic gradient. Hydraulic gradient is a combination of gravity, pressure head, osmotic and matric potentials (Singer & Munns 1999). The soil matric potential/suction plays an important role in soil moisture retention and sorptivity, which is vital for plant growth. The suction causes the beds to wet slowly, thus the pores remain stable for a longer period, while better control is maintained over soil moisture characteristics and biological activities (Adem & Tisdall 1984), which facilitates better root environment and lateral infiltration. However, intensive tillage negatively affects the lateral infiltration process.

Intensive tillage and operation at sub-optimal soil moisture can promote subsidence and compaction leading to reduced lateral infiltration. Poor lateral infiltration problems were reported under loamy soils by Ma and Wang (2005), Jin et al. (2007) and Akbar et al. (2007), under sodic Vertisol by McKenzie and Chan (1990), under red brown soil in the Murray Valley by Thompson and North (1994), and in black Vertisol by Lucy (1993) always where soil is unstable to wetting. Tillage at variable soil moisture content has been shown to affect soil structure and fabric (McGarry 1989) evidenced by up to 17% area of striated clay in wet cultivated soil compared with < 1% area in dry cultivated or land prior to cultivation. Limited controlled mechanical loosening using different kind of cutters/blades, that loosen the surface soil in the bed (zone 3 Figure 2.1) without inversion, have been shown to improve lateral infiltration, surface drainage and *WP* (Hamilton et al. 2005; Jin et al. 2007;

Akbar et al. 2010). Soil loosening using horizontal blade involves slicing, lifting and dropping of soil over a height difference of 1-2 cm, which were shown to opens soil with zero soil inversion and maximum root retention (Hamilton et al. 2005). However, studies on lateral infiltration from furrow to the centre of bed are scarce.

The soil moisture sensors with loggers placed on bed at different distances from the furrow centre and inserted to target depths at desired depth intervals can be used to log the wetting front movement into the bed profile across wide bed widths during an irrigation event (White 2007). Evaluation of the lateral infiltration under variably managed PRB can be instrumental in identifying its impact on PRBs performance.

Lateral infiltration is affected by the sorptive behaviour of soil, which is driven by the capillary forces. Sorptivity is a measure of the capacity of the medium to absorb and desorb liquid by capillarity (Philip 1957a). Philip (1969) defined sorptivity by the following relationship:

$$S = \int \varphi \, d\theta = - 2 \, D_f d\theta / d\varphi \qquad 2.2$$

where S is sorptivity (mm hr$^{-0.5}$), θ is volumetric moisture content (mm^3 mm^{-3}), D_f is diffusivity (mm^2 hr^{-1}), and $\varphi = x \; t^{0.5}$ is the Boltzman transform (mm hr$^{-0.5}$) for describing phenomena that progress in proportion to the square root of time t (hr); and D_f = the hydraulic conductivity at a given moisture content (θ) times the slope of the moisture characteristic (soil moisture potential(Ψ)/moisture content (θ)) at the same moisture content. This analysis of infiltration by Philip (1969) led to the derivation of the simple equation 2.3.

$$Z = S\sqrt{t} \qquad 2.3$$

where Z is the cumulative infiltration, S is sorptivity and t is time.

The soil intake characteristics were shown as the main source of irrigation depth variability (Oyonarte et al. 2002), indicating increased lateral infiltration is possible through increased soil intake using improved furrow bed management.

Apart from field experiments on lateral infiltration, the Hydrus 2D model (Šimunek et al. 1999) can be used to reproduce the results, which can be used for bed-furrow design and irrigation management optimisation. Hydrus 2D is based on the solution of Richards equation (Richards 1931) and has been broadly used in salinity and water movement studies. The Hydrus 2D model satisfactorily quantified soil moisture and solute distribution in PRB of various dimensions in Australia, Pakistan, China, Indonesia and India (Cook et al. 2008), which was helpful in developing guidelines for optimising furrow bed management under different soils. White (2007) described Hydrus 2D is able to adequately predict soil conditions in furrow bed system for short period < 26 days but the prediction capability may decrease due to compounding errors in soil moisture prediction. The Hydrus 2D simulation can be helpful in evaluating the optimum bed furrow dimension, furrow water head and infiltration opportunity time for improved lateral infiltration. It can be helpful in assessing soil moisture distribution under variable PRB renovation methods.

2.5.1.6 Surface drainage and stability during wetness

Removal of waterlogging and improved aeration is necessary for plant growth and better yield. Agronomic management practices affect waterlogging and surface drainage due to its effects on soil structure and infiltration characteristics. Under poor soil structure, which is normally caused by excessive tillage and traffic (McGarry 2003), there are few large stable pores to supply enough oxygen for the plant roots to quickly mitigate the effects of waterlogging. The prolong waterlogging reduces soil aeration and structural stability, which enhance soil subsidence. The subsided and structurally degraded soils are not capable of hosting and flourishing the beneficial microbial, bacterial ecosystem of micro-organisms necessary for achieving improved performance on a sustainable basis. Therefore PRBs are beneficial, because it generally enhance surface drainage (Hamilton et al. 2005), as the furrows can be used to act as drainage channels for disposing of the excess water.

Agronomic practices that strengthen the cohesive forces between soil particles by accelerating soil fungal and bacterial activities and their exudates (Smith et al. 1983) can be helpful in improving the stability of soil structure. A stable soil structure can enhance soil porosity and infiltration for longer. Moreover, the wet/dry cycles can be used for repairing soil structure of compacted Vertisol (Samrah et al. 1996). All these processes can enhance surface drainage and soil stability during wetting.

Soil bulk density variation can be used to indicate soil structure stability but the variable nature of some soil e.g. Vertisol, due to shrink swell properties; can impede the accuracy of measurements, which can be overcome by extensive sampling. Similarly, soil resistance to deformation can also be related to seasonal variations in bed furrow dimensions. The extent of temporal variability in bed furrow dimensions during a cropping season illustrates soil resistance to wetting and deformation, which can also be helpful for comparing different agronomic management methods.

2.5.1.7 Seasonal changes

During a cropping season the land surface is subjected to wetting, flowing water, rainfall hammering, slaking, erosion, silting, sealing and compressive traffic impacts, which affect soil infiltration, aeration and moisture retention properties leading to subsidence (Hillel 2004). Subsidence can largely affect soil hydro-physical characteristics, while large soil fauna entry into small pores is also negatively affected (Brussaard & Van Faassen 1994). The severity of variations in all these processes during a cropping season largely depends on the type of tillage system (Coutadeur et al. 2002) and extent of managing surface cover or crop residues. However, the existence of current poor agronomic management under the majority of raised beds, specifically in developing countries, generally negatively affects the soil hydro-physical and chemical characteristics. Consequently, the productivity potential of soils is at low levels. Therefore, seasonal changes in soil hydro-physical properties need careful consideration in the design and management of raised beds.

Soil infiltration characteristics can vary temporally between irrigations (Rahimi 2011) and spatially between furrows (Gillies et al. 2008). The soil intake characteristics were shown to cause greater variability in infiltrated volume than that caused by variable intake opportunity time from field head to tail sections (Childs et al. 1993); (Oyonarte et al. 2002). Therefore, furrows and beds needs to be carefully managed keeping in view soil infiltration variability in two dimensions and their possible detrimental effect on irrigation performance.

Various soil properties have contrasting temporal and spatial scales of variations. Some soil properties that are responsive to management can easily be measured while others are impractical because of the large spatial variability and cost of measurement. Thus, adopting proper tactics for measurement is crucial to soil property monitoring procedures. Large changes in soil properties within a short spatial boundary have been identified during several studies (Wilding & Drees 1983; Burrough 1993). Selection of a proper method and frequency of soil change measurement depends on the objective of the study, understanding of the system behaviour, pattern of variations, measurement technology and resources (McKenzie et al. 2002). The nature of these highly variable soil properties during a cropping season genuinely requires field measurements recorded during or close to irrigation events using a representative soil sample of the whole field area. The seasonal variability in soil hydro-physical properties can be monitored by employing some inexpensive technologies or can be indirectly predicted by using combination of field measurements and simulation modelling techniques.

2.5.1.8 Crop yield

The ultimate purpose of optimum agronomic management is to get higher crop yield on a sustainable basis. Crop yield is mainly affected by soil fertility, soil structure, organic matter, soil moisture, weather conditions, pests, and diseases. However, agronomic management factors like tillage, bed width, crop variety, row spacing, and amount of inputs can also affect crop yields. For instance, no tillage produced up to 20% enhanced canola seed yield in comparison with conventional intensive tillage (Malhi et al. 2006) while (Phillips et al. 1980; Sayre et al. 2005; Govaerts et al. 2007) identified stubble retaining on PRB to improve organic matter, aggregate stability and reduce salinity leading to increased crop yield. Similarly, evidence of variable impact of *SMD* prior to irrigation on different crop yields has been reported by Wichelns and Oster (1990), Cavero et al. (2001) and Paz et al. (2001), who showed higher crops yields for soil moisture levels between field capacity and the refill points. However, some crops, e.g. cotton, can also enhance yield under stressed conditions (Morgan & Lowery 2003). Therefore, optimum agronomic management can improve crop yield on a sustainable basis.

Limited controlled tillage without causing significant disturbance in the bed can be beneficial in removing compaction, loosening the soil and enhancing the lateral infiltration, particularly in structurally unstable soils. Better crop yields (5%) and improved *WP* (38%) were reported by Jin et al. (2007) by loosening the soil with horizontal blades without inverting the surface soil in comparison with traditional methods of cultivating raised beds. Similarly, up to 13% enhanced wheat yield and 50% enhanced *WP* were reported by Hassan et al. (2005) by using blade plough with horizontal blades in comparison with traditional flat basin systems under sandy clay loam. The reasons were mainly attributed to enhanced lateral infiltration in these soils of low infiltration capacity. However, the impact of blade ploughing on crop yield and *WP* of PRBs under cracking Vertisol soils is unknown. Therefore, crop yield can also indicate the effectiveness of agronomic management, which is easily measurable under actual field conditions.

2.5.2 Irrigation management performance and assessment

Raised beds with furrow irrigations are considered a relatively efficient surface irrigation method, because only the furrow base plus a small portion of the bed shoulders are wet by free water, compared with the whole field surface in basin irrigation. Also, because the surface area of soil in contact with free water is less and the depth of flow is greater, the advance times are much reduced. Notwithstanding these inherently better attributes of raised beds, there have been reports of poor irrigation performance (Gill 1994; Raine & Bakker 1996; Smith et al. 2005). The major reasons were attributed to poor irrigation management. Simulation models have been successfully used to identify optimum irrigation management options.

2.5.2.1 Models to assess irrigation performance

There are several simulation models based on the Saint-Venant equation (Khatri 2007) used to evaluate irrigation performance. These models also help to optimise the design and management factors (section 2.3.2) for enhanced irrigation performance. The Saint-Venant equation is based on the principles of conservation of mass (continuity) and momentum. The continuity part of the Saint Venant equation can be expressed by equation as follows (Walker & Skogerboe 1987):

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}+I_x=0 \qquad 2.4$$

where Q is the inflow rate (m^3 s^{-1}), A is the cross sectional area of flow (m^2), x is the distance (m) and I is the infiltration rate (m^3 m^{-1} s^{-1}).

The expression for the momentum/motion part of the Saint-Venant equation can be expressed by the following equation (Walker & Skogerboe 1987):

$$\frac{v}{g}\frac{\partial v}{\partial x}+\frac{v}{gA}\frac{\partial Q}{\partial x}+\frac{v}{gA}\frac{\partial A}{\partial t}+\frac{1}{g}\frac{\partial v}{\partial t}+\frac{\partial y}{\partial x}=S_0-S_f \qquad 2.5$$

The term v is the flow velocity in (m s^{-1}), g is acceleration due to gravity in (m s^{-2}), y is the depth, S_0 is the furrow slope, and S_f is the friction slope.

Different assumptions were applied to the Saint Venant equations to make it simple. For instance, the zero inertia model neglects the inertia and acceleration terms in the momentum equation 2.5, which reduces the computational requirements (Alazba 1999) and works well under free flow conditions (Schwankl & Wallender 1988). Kinematic wave models further simplify by assuming the change in energy with distance for a constant Q equal to the slope of the furrow. However, it may only work correctly under fields with considerable slope (Gharbi et al. 1993). The volume balance model utilises the continuity equation (2.4) only and neglects the momentum term completely. The full hydrodynamic model is the most accurate, and is based on both continuity and the momentum equation, thus involving rigorous computation. However, the recent development of processor speeds and software has made it a favourable choice for irrigation evaluation and optimisation. Hence, this model is generally preferred for research purposes.

Irrigation performance assessment under furrow bed system is generally complicated by the two dimensional infiltrations that consist of vertical and horizontal components. Gravity forces are dominant in the vertical infiltration, while suction/capillary forces dominate under horizontal/lateral infiltration. There are many physical and empirical equations for describing the amount and rate of infiltration.

However, the Kostiakov-Lewis variant or modified Kostiakov infiltration equation is more widely used, because it can provide adequate prediction of the water advance and cumulative infiltration depth (Hanson et al. 1993). The modified Kostiakov infiltration equation (Walker & Skogerboe 1987) is given by the following equation:

$$Z = Kt^{a} + f_0 t \qquad 2.6$$

$$I = akt^{a-1} + f_0 \qquad 2.7$$

where Z is the cumulative infiltration, I is the infiltration rate, a and k are empirical constants, and f_0 is the empirical parameter that shows a close relationship with final infiltration rate of the soil.

Infiltration characteristics/functions of soil are very important parameters in evaluation, design and management of furrow irrigation. The water advance, depth of infiltration and uniformity of application during irrigation can be identified using infiltration characteristics (Jobling & Turner 1973). There are numerous methods of point infiltration determination including blocked furrow infiltrometer (Bondurant 1957), furrow by-pass infiltrometer (Shull 1961), double ring infiltrometer described by Tricker (1978) and Bouwer (1986) and flow through furrow infiltrometer (Childs et al. 1993). However, due to the spatially and temporally variable nature of infiltration, the point measurement (small area) methods often fail to provide the true overall field infiltration characteristics (Elliott & Walker 1982). One simple method of cumulative infiltration determination can be through determining the difference in pre- and post-irrigation volumetric moisture content by using the gravimetric method or capacitance and neutron probes. One of the drawbacks of such methods can be the inability to determine the water infiltration below the measuring zone (Shepard et al. 1993). Similarly Elliott and Walker (1982) failed to simulate the water advance or runoff using several point infiltration methods. Therefore, point measurement methods are not the preferred options to estimate infiltration in surface irrigation. However, methods involving large areas are considered more representative of the actual field conditions (Esfandiari & Maheshwari 1997), which are largely based on the volume balance approach and were recommended by many (Christiansen et al. 1966; Reddell 1981; Bautista & Wallender 1993b; Gillies & Smith 2005).

Substantial work has been directed recently to determine the spatial average of infiltration characteristics, which has been considered essential for the accurate simulation of surface irrigation. Various methods/models mainly based on the solution of inverse problems for determining infiltration parameters from measuring the water advances during irrigation have been developed. The inverse problems generally use equation 2.6 to determine soil infiltration and full hydrodynamic or volume balance model to determine distribution of water along the furrows.

The empirical constants of the modified Kostiakov equation are generally estimated by matching field measured data obtained during irrigation with the results of a simulation model using the inverse solution approach. Various methods of collecting water advance data in the field have been identified. The two point method (Elliott & Walker 1982) is considered a standard in the irrigation industry, as it performed better for 40 cm to 60 cm wide furrows (Holzapfel et al. 2004). It assumes that the advance curve can be approximated by a simple power function. This method requires separate calculations for identifying f_0. Simulation models like INFILT (McClymont & Smith 1996) based on same basic equations of the two point method, but does not require separate calculation for the steady intake rate term f_0, which was successfully used in the Australian sugarcane (Raine et al. 1998) and cotton (Smith et al. 2005) industries. However, INFILT treats surface storage as a fourth parameter, which causes sometime unreliable results. The IPARM (Gillies & Smith 2005) model is based on modification to the volume balance model to include runoff data and account for Q variability.

IPARM

The IPARM (Gillies & Smith 2005) model utilises the inverse procedure with volume balance model. Equation 2.6 is modified by introducing a constant factor C to account for cracking. Thus the equation 2.6 is modified to equation 2.8:

$$Z = kt^a + f_0 t + C \qquad 2.8$$

The advance distance along the furrow is estimated by rearranging the volume balance continuity equation into the following form:

$$x = \frac{Q_0 t}{\sigma_y A_0 - \sigma_{Z1} k t^a + \sigma_{z2} f_0 t + C} \qquad 2.9$$

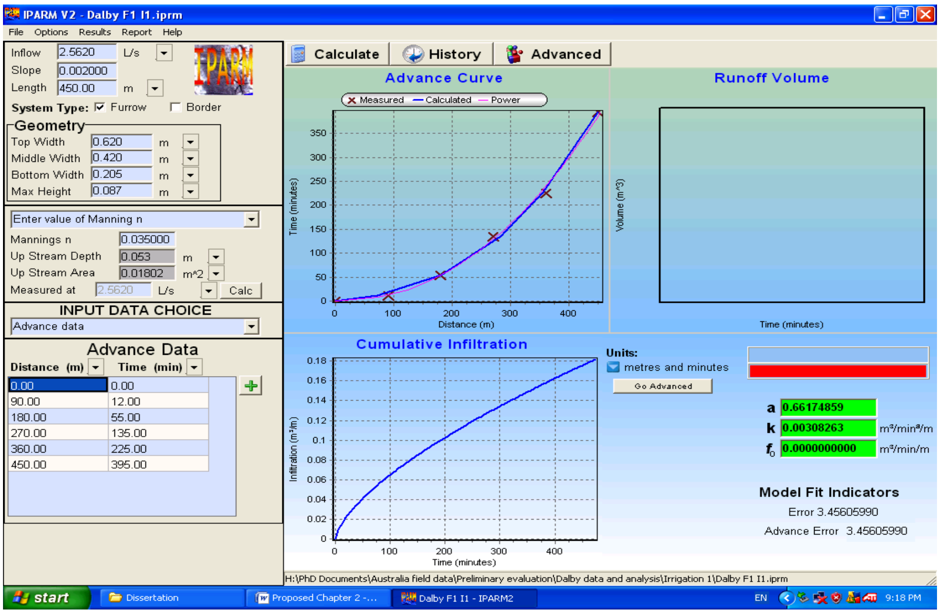
where σ_y is the surface storage shape factor, which was identified to be in the range of 0.7 to 0.8 by different researchers, σ_{Z1} and σ_{Z2} are subsurface storage coefficients for the advance phase (Walker & Skogerboe 1987), where σ_{Z1} was assumed to be equal to 0.8 by Reddell and Latimer (1987). Both coefficients can be calculated as:

$$\sigma_{z1} = \frac{(a + r(1 - a) + 1)}{(1 + a)(1 + r)} \qquad 2.10$$

$$\sigma_{z2} = \frac{1}{(1 + r)} \qquad 2.11$$

where r is a fitted parameter, which can be determined from two advance points by simple logarithmic transformation of the power curve equation.

IPARM replaces the $Q_0 t$ term in equation 2.9 with the integral of inflow hydrograph ($\sum Q(t)dt$) for each advance and runoff time point to account for variable Q. The input data for IPARM includes Q, slope, furrow length, furrow geometry, Manning's n and advance data at multiple points. IPARM can process multiple advance data, which enhances the accuracy of simulation. However, it increases the field data collection requirements. The output consists of infiltration functions (a, k and f_0), advance trajectory (measured and simulated) and cumulative infiltration with time curve. The IPARM version 2 (Figure 2.2) can create automatic SIRMOD (Walker 2003) input files and infiltration parameters. The infiltration functions and other information can be directly exported as a SIRMOD file, which can be retrieved directly by a SIRMOD model for irrigation performance evaluation. The IPARM model was successfully used by Gillies (2008) and Khatri (2007) for Vertisol.


IPARM V2 - Dalby F1 I1.iprm

Inflow 2.5620 L/s
Slope 0.002000
Length 450.00 m
System Type: ☑ Furrow ☐ Border

Geometry
Top Width 0.620 m
Middle Width 0.420 m
Bottom Width 0.205 m
Max Height 0.087 m

Enter value of Manning n
Mannings n 0.035000
Up Stream Depth 0.053 m
Up Stream Area 0.01802 m^2
Measured at 2.5620 L/s

INPUT DATA CHOICE
Advance data

Advance Data

Distance (m)	Time (min)
0.00	0.00
90.00	12.00
180.00	55.00
270.00	135.00
360.00	225.00
450.00	395.00

Units: metres and minutes

a 0.66174859
k 0.00308263 m³/minª/m
f_0 0.0000000000 m³/min/m

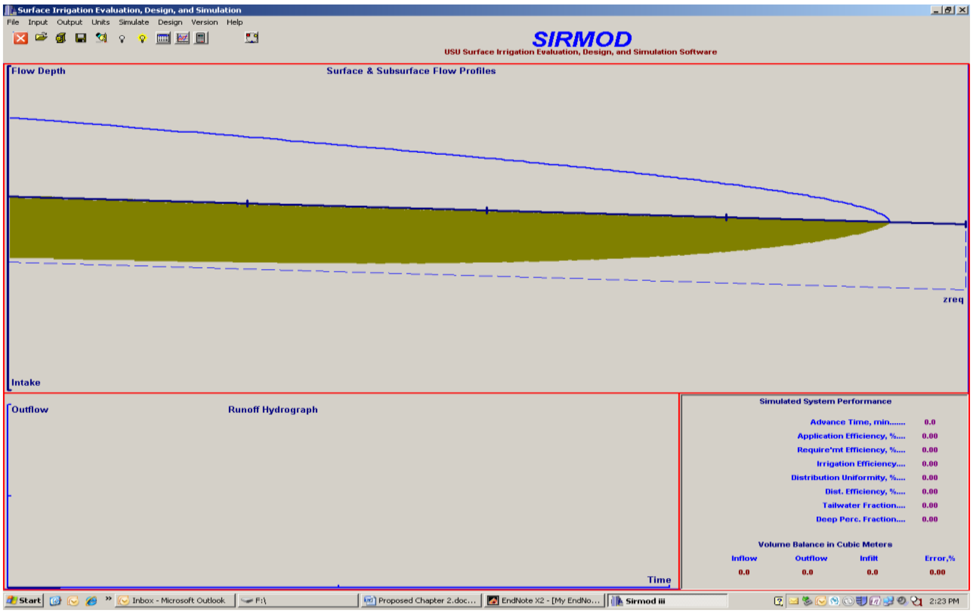
Model Fit Indicators
Error 3.45605990
Advance Error 3.45605990

H:\PhD Documents\Australia field data\Preliminary evaluation\Dalby data and analysis\Irrigation 1\Dalby F1 I1.iprm

Figure 2.2: Screen shot of IPARM version 2 main user interface

SIRMOD

There is a range of available irrigation performance evaluation models but SRFR (Clemmens & Strelkoff 1999) and SIRMOD (Walker 2003) have gained major recognition. The SRFR model employs the zero inertia or kinematic wave models. It is capable of accommodating variations in *Q* and furrow dimensions, field slope and soil infiltration. SIRMOD (Walker 2003) was developed at Utah State University, US, and utilises the full hydrodynamic model i.e. both Saint-Venant equations. In case of unstable solutions with full hydrodynamic model, it also has the additional facility of applying the zero inertia or kinematic wave models. It utilises the modified Kostiakov infiltration equation with an optional term C (cracking factor) for describing infiltration rate. Simulation and evaluation with SIRMOD is event based and its accuracy depends on input data mainly for the modified Kostiakov infiltration parameters. The input data include field length, slope, infiltration functions, *SMD*, *Q*, Manning's *n*, furrow geometry, and furrow spacing. The output includes advance-recession curves, water infiltration along the furrow, run-off hydrograph, *Ea*, *Er*, *DU*, deep percolation fraction and volume balance as illustrated in Figure 2.3.



Simulated System Performance

Advance Time, min....... 0.0
Application Efficiency, %.... 0.00
Require'mt Efficiency, %.... 0.00
Irrigation Efficiency.... 0.00
Distribution Uniformity, %.... 0.00
Dist. Efficiency, %.... 0.00
Tailwater Fraction.... 0.00
Deep Perc. Fraction.... 0.00

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
0.0	0.0	0.0	0.00

Figure 2.3: Screen shot of SIRMOD version III main output screen

SIRMOD can simulate furrow, border, or basin irrigations with open or closed end boundary conditions. It can simulate continuous flow with cutback and surge flow. It can test different management scenarios. For instance, it is capable of evaluating variable Q and modifying the infiltration functions accordingly by using a scaling factor $\mathcal{F}$ based on changes in furrow wetted perimeter, as illustrated below

$$\mathcal{F} = (\frac{\mathrm{WP}_2}{\mathrm{WP}_1})^b \tag{2.12}$$

where WP1 and WP2 are the wetted perimeters (m) when inflow rates are Q_1 *and* Q_2, respectively and b is an empirical constant, which depends on field conditions.

The SIRMOD was extensively used for improving irrigation management and design in the Australian irrigation industry (Raine et al. 1998; Dalton et al. 2001; Smith et al. 2005) and under wide environmental conditions. SIRMOD is commercially available in Australia through IRRIMATE$^{\mathrm{TM}}$, and consists of software and hardware tools developed by the National Centre for Engineering in Agriculture (NCEA) at the University of Southern Queensland (USQ), Australia. However, SIRMOD assume uniform irrigation application between the wetted furrows thus did not account for the lateral infiltration.

2.6 Conclusions

The increasing global requirement for food and fibre demands to produce more with less water on a sustainable basis. PRB farming practices have the potential to enhance productivity but are still in their infancy, while their current management is poor leading to negative impacts on their performance. This review revealed the possibility of improved *WP* of existing PRB farming systems through better agronomic and irrigation management practices. These are the key conclusions:

- Available research on the management of irrigated PRB for improved irrigation performance and *WP* is scarce, especially under Pakistani field conditions. Therefore, evaluation of existing PRB under commercial farm conditions can be helpful to benchmark their current irrigation performance and to refine the key contributing factors to be pursued in this research.
- Improved soil management practices are required to optimise root zone conditions if production is to be increased and sustained. Renovation methods of PRB that offer the best prospects for loosening subsided beds in a way that is consistent with conservation agriculture needs to be investigated by assessing its impact on crop production in PRB.
- Impact of blade loosening without inversion on soil structure stability to wetting and lateral infiltration in comparison with existing methods needs to be investigated in soils of various textures to ascertain its impact on furrow irrigation efficiency and *WP*.
- Furrow irrigation performance models offers the prospect of identifying the optimal application practices for soils of different textures and structures under variable soil loosening practices.
- The quantification of the lateral infiltration into beds with different textures and structures provides an experimental data set that can be used to verify the predicting capability of furrow irrigation performance models.

CHAPTER 3: General material and methods

3.1 Introduction

This chapter provides the research plan, describes all the study sites and details the general field conditions encountered during the experiments. Additionally, the general assessment methods that were applied across all, or most, sites during the three field studies and a desktop study are also presented in this chapter. However, details of the work of each experiment were expanded, as necessary, in their specific chapters.

3.2 Research plan

As per the findings in the foregoing Chapters 1 and 2 this study was planned to evaluate two main factors (irrigation and soil management) for improving the water productivity of raised bed systems. A brief research plan to be pursued in this study is outlined in Table 3.1.

Table 3.1: Research plan for improving water productivity of raised beds

Research plan	**Improve irrigation efficiency and productivity**	
	Irrigation management	**Soil management**
What to do	Optimise inflow rate *(Q)*, time to cut-off *(Tco)* and field length	Improve soil structure stability by practices consistent with conservation agriculture (No tillage and blade loosening and furrow reshaping)
How to achieve it	Quantify existing practices and use modelling (IPARM & SIRMOD) to identify potential improvement possible in irrigation practices with existing soil management	Quantify improvement in irrigation performance, lateral infiltration and *WP* with improved soil structural stability with different renovation methods (no tillage, shallow cultivation and blade loosening)
Analysis	Identify from field matched modelling (a) Best combination of *Q Tco* and furrow length & (b) Assess practical achievability of the optimum set of irrigation practices with existing practices	Identify from field matched modelling (a) Best combination of *Q*, *Tco* and furrow length with no tillage, shallow cultivation and blade loosening & (b) Assess practical achievability of the optimum set of irrigation practices with different renovation methods

3.3 Description of field sites

The three components of this research were conducted on farms in Australia and Pakistan. The first component was related to benchmarking of existing PRB farming systems (objective 1), which was conducted at five sites, two in Australia: sites A1 and A2, and three in Pakistan: sites P1, P2, and P3. The second component was related to evaluation of irrigation performance and *WP* of three PRB renovation techniques (objective 2), which was conducted over three cropping seasons (winter 2010 to summer 2012) at site A1, in Australia. The third component evaluated lateral infiltration under three PRB renovation methods (objective 3) conducted at sites A1 (Australia) and P4 (Pakistan). The different soil properties of site A1 and P1 are given in Appendix A: Table A1 and Table A2 respectively.

The research sites were located in south east Queensland, Australia and north west Pakistan. Both these locations were selected on the basis of resources availability, proximity to working stations, liaison with cooperative farmers and availability of sites where PRB farming systems were actually practised. All field trials were conducted at farmers' fields in both countries. All the trial sites had irrigated PRB farming systems and growers had most farm equipment required for establishing the different treatments for this study.

South east Queensland, Australia is one of the most productive parts of the country, where irrigated agriculture is practised due to available water resources and sub-tropical climatic conditions. The major source of irrigation water in south east Queensland is from rain water harvesting and quite often supplemented by ground water bores. However, irrigation water usage is generally restricted due to tough government rules that vary spatially and temporally according to changing ground water level and quality.

The study sites in north west Pakistan were in the Mardan district of Khyber Pakhtunkhwa Province. Irrigation water in Mardan is from the northern mountains snow melt, which is carried through the Swat River and diverted into canals and then distributed to farms through distribution channels and minor water courses. Part of Mardan district is also served by the Pehur high level canal, which diverts water from the Indus River through the Tarbela Dam. This location was selected because of a research station of Pakistan Agricultural Research Council (PARC), where field research has been conducted on PRB systems since 1999 in collaboration with the Australian Centre for International Agriculture Research (ACIAR), thus the majority of farm equipment needed and support staff to assist in data collection were available. Study locations are shown on world maps in Figure 3.1.

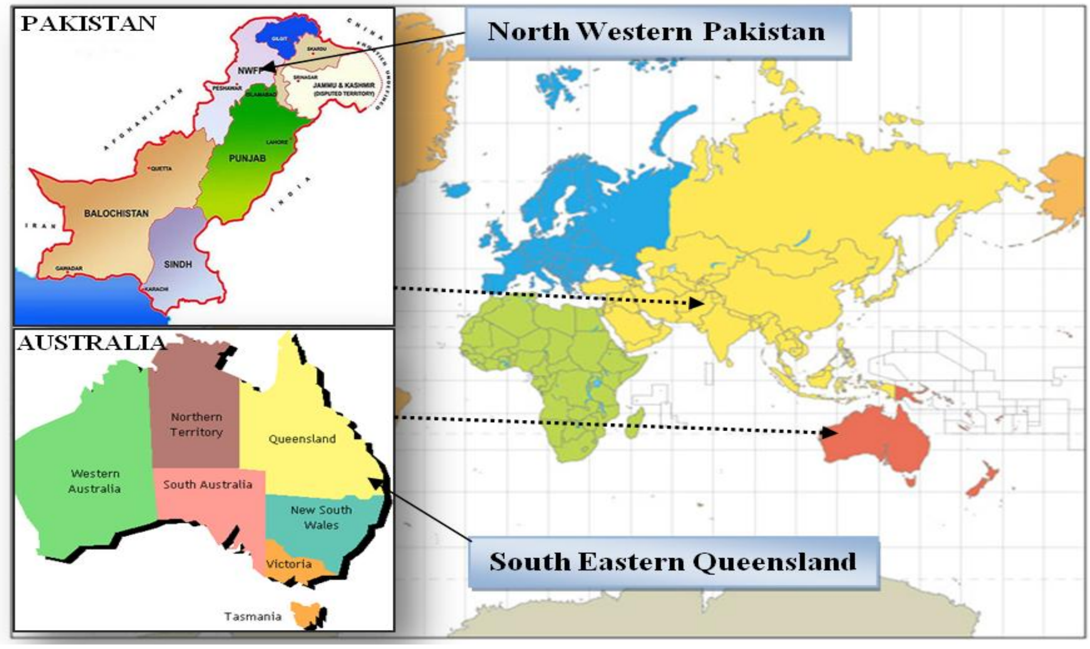


Figure 3.1: **General location of study sites in Australia and Pakistan on World map**

3.4 General field conditions encountered in Australia

3.4.1 Site A1

Site A1 was established on Marinya farm, Karara Road, Cambooya, which is located on the eastern Darling Downs (27.734900°S, 151.828062°E), 30 km south of Toowoomba, Queensland, Australia. Long historical data showed annual mean minimum temperature of ~10°C and the mean maximum temperature at ~25°C, total summer rainfall ~ 466 mm and winter rainfall ~253 mm (www.weatherzone.com.au). However, summer 2010 rainfall was above average (Appendix A: Table A3).

The soil at site A1 was Irving-black Vertisol which is a deep to very deep (100-180 cm), fine self-mulching, brownish black cracking clay with brown or reddish brown subsoils on basaltic colluviums. It generally occurs on mid or lower slopes of low basalt hills and rises (Harris et al. 1999). The soil at site A1 contained a subsoil horizon with about < 10% white calcareous segregations (Tim et al. 2008). Maize, wheat, soybean, barley and millet were the main crops grown on the farm over the last few years, prior to the start of the trial. The crops grown were 2009 soybean, 2010 wheat, 2011 hemp, and 2011 corn during the experimental period from summer 2009 to summer 2012.

The cultivation practice at this farm has been no-till PRB since 1969. The current practice consisted of renovating the beds by furrow cleaning only, either before or after crop sowing. Chisel ploughing was occasionally needed, generally at a frequency of every five years. The aim was to loosen the soil compaction caused due to mismatched machinery track widths and to control pests and diseases according to farmer preferences. Renovation and land preparation methods and their frequency vary from farm to farm in the surrounding locality depending on crop varieties, crop rotation, available machinery, farmer preferences, and weather.

The cultural practices prior to 2009 soybean crop sowing during the benchmarking study, commenced with chisel ploughing to a depth of around 30 cm. Chisel ploughing was followed by a slight (20°) realignment of the furrows as part of recent farm modification processes to improve the water harvesting and surface drainage on the farm. The aim of chisel ploughing was to remove the compaction of previous furrows and to achieve uniform subsurface soil conditions. Furrow spacing of site A1 was 200 cm (Figure 3.2a), which was double that of site A2 (Figure 3.2b). The furrows developed at site A1 were generally shallow (D < 10 cm deep), narrow (TW < 40 cm top width) (Figure 3.2c) and 465 m long with blocked ends. According to the farmer, this was primarily to construct PRB with maximum land use efficiency as well as to prepare a smooth and level surface for the following seeding operation.

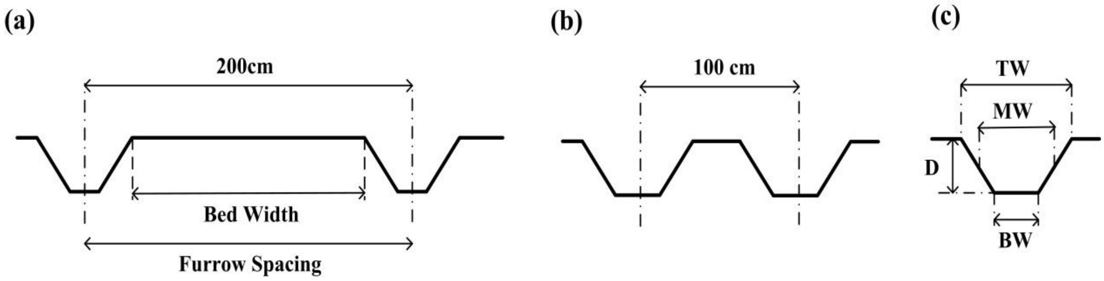


Figure 3.2: Furrow spacing at (a) site A1 (b) site A2 and (c) Furrow dimension (TW: Top width, MW: Middle width, BW: Bottom width and D: furrow depth or bed height)

During the renovation process the farmer used a bed former which consisted of a frame fitted to assist smoothing the bed surfaces from clods with small furrowers to clean the furrows (Figure 3.3a). Stubble at < 5% of plant height were generally retained during the subsequent cropping seasons due to machinery and economic limitations. The available double disc planter (Figure 3.3b), was 600 cm wide, capable of planting seed on the relatively hard seed bed of no till PRB systems. Both the bed former and seed planter covered three beds in one pass.

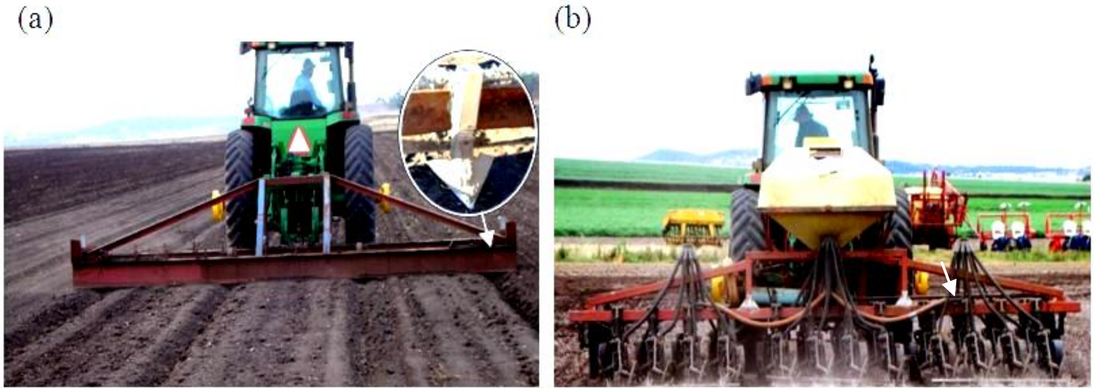


Figure 3.3: Available raised bed machinery (a) bed former; note the smearing of bed surface soil and the shallow, rough furrows (insert show furrower) and (b) no till seeder with 8-rows of crop per bed at site A1 (Marinya farm, Cambooya, Australia)

Irrigation water source at site A1 was from two ground water bores (150 m deep) operated separately or in combination according to supply requirements. Subject to availability of water, additional water was available from the rain water storage dam in the vicinity of the experimental plot. However, water availability on the farm was limited due to water restriction rules for the locality. The farmer also shared water with a vegetable contractor, which further constrained the water availability.

Water supply on the farm was through a distribution channel constructed at the head reaches of the irrigated command area of the farm (Figure 3.4). The distribution channel also served a small dam for the vegetable farmer's irrigation supply. Water supply to the distribution channel was from two bores through a PVC pipe (~20cm diameter). Irrigation water application to furrows from the distribution channel was through siphon tubes (50 mm diameter) 6-7 m long (Figure 3.4). Irrigation *Tco* and *Q* were variable depending on the supply, number of siphons operated at one time and head in the distribution channel. The head height in the distribution channel was adjustable with water release to the small dam. Current farm practice *Tco* was between 18 to 24 hours. This site was used for all three field trials (Chapter 4, 5 and 6) conducted at farming fields in Australia. The data collected, equipment used and specific field conditions during the experiments are discussed in details in the respective chapters.

Figure 3.4: On farm head channel with siphons, flow meters, soil moisture data loggers and weather station at site A1 (Marinya farm, Cambooya, Australia)

The chisel ploughing conducted at site A1, was not the general practice at this farm but was representative of many farms in the vicinity. The furrow dimensions were shallow and narrow as per farmer practice at this farm, which affected water advance in a few furrows during first irrigation in the benchmarking study. Therefore, the furrow dimensions were enlarged before the second irrigation to control water crossing between wet and dry furrows. The available *Q* from the source and the height of distribution channel from fields at this farm was limited, thus offering limited flexibly for variation when required. The blade plough at farm was used during the first season' which consisted of a single horizontal blade (140 cm wide, vertically inclined at an angle of ~25 degrees to the direction of travel and backward rake angle of ~15 degrees). However, due to operational difficulties and soil disturbance during the first season, a new blade plough with two horizontal sharp blades (each 70 cm wide with zero degrees inclination to the direction of travel and a backward rake angle of ~35 degrees) was manufactured, but made available during the last corn season. It was tried to conduct the blade ploughing at optimum soil moisture levels to avoid smearing and soil disturbance.

3.4.2 Site A2

Site A2 was at Bandawing farm, near Dalby (27.150830S, 151.182563 E), 80 km west of Toowoomba, Queensland. The annual mean minimum temperature was 12°C and the mean maximum temperature was 27°C. Total summer season average rainfall was 454 mm and total average winter season rainfall was 172 mm (www.weatherzone.com.au).

This site was selected for the benchmarking study because the PRB management, wheat-cotton rotation and the black cracking clay (Vertisol) at this site truly represented the common farming practices and conditions of this locality. Wheat-cotton rotation was practised at this site for the last ten years. The current agronomic practices in wheat-cotton rotation include annual renovation of PRB by deep ripping involving inversion and bed reforming without relocating the furrows and without disturbing the bed for the next crop. Deep ripping with inversion was to control diseases, pests, slugs and pupae. No stubble were retained at this site. The beds were 100 cm wide with single cotton row planted to the centre of the bed. The bed former was 600 cm wide capable of establishing six beds at a time. The furrow position was kept permanent with tractor mounted GPS. The furrows were ~60 cm wide, alternately irrigated and free draining at tail ends. The benchmarking experiments were conducted in a cotton crop at flowering stage as shown in Figure 3.5.

Figure 3.5: General field conditions and crop stage during measurement at site A2, (Bandawing farm, Dalby, Australia)

The water source was rain water stored in an on-farm storage dam in the vicinity of the experimental field. Water availability was limited in the dam because of the continuous drought conditions over the last few years. Water supply was piped to the distribution channel by gravity. Siphon tubes (50 mm diameter), 4.5 m long were used for irrigating the furrows. The selected experimental site was 455 m long and 24 m wide. Two sets of irrigation data were taken at this site.

This site was used only for the benchmarking study (Chapter 4) due to water availability constraints caused by the drought conditions in 2009-10. The furrows were wide (~60 cm top width), the beds were narrow (~40 cm bed top width) and furrow spacing was 100 cm. Soil cracking was observed to affect irrigation performance of alternate furrow irrigation because water from the wet furrows was able to break through into the dry furrows within soil cracks.

3.5 General field conditions encountered in Pakistan

The study area was located in Mardan (Khyber Pakhtunkhwa Province), in north west Pakistan. All four study sites were located in a radius of 15 km therefore the climatic conditions and soil types were comparable. Mardan lies in the semi-arid zone, where mean seasonal rainfall of 250 mm occurs in summer (April-September) and around 300 mm during winter (October-March). The mean maximum temperature ranges from 27-30°C during June, while the mean minimum temperature ranges from 5-8°C during January. Sites P1 (34.115608 N, 71.595392 E) and P2 (34.115141N, 71.595343E) were located near the Mardan Research Farm (Pakistan Agriculture Research Council (PARC)), a short distance from Mardan-Charsadda Road. Sites P3 (34.054170N, 72.030761E) and P4 (34.081084N, 72.014867E) were located about 30 km and 15 km respectively to the east of site P1. The benchmarking study was conducted at sites (P1, P2, and P3) in summer 2010.

The soil at all experimental sites belonged to Alfisol soil order that have been developed on pleistocene surfaces in subhumid/humid regions of Peshawar valley (Ahmad et al. 1986). The soil texture was sandy clay loam, that belongs to the Mardan soil series, which was classified as fine Usteric Camborthid, a greyish brown, non to slightly calcareous alluvial material of the Holocene age (Shafiq et al. 2002). The soil at these sites has negligible shrink- swell qualities. The subsurface tile drainage system installed in this locality did not allow the water table to rise and generally remains at 350 to 500 cm depth. Sites P1, P2 and P3 were in a low salinity zone and site P4 was in a relatively high salinity zone. No stubbles were retained in this locality. The general field conditions of site P2 (132 cm wide bed) are shown in Figure 3.6.

Figure 3.6: General field conditions of site P2 under corn crop in Mardan, Pakistan (Note that the corn is sown on the edge of the beds to overcome poor penetration of the wetting front, as seen by the wet areas on the surface of the beds)

Experimental plots at site P1 and site P2 were part of a 10 ha farm where water was available on a weekly schedule. The farm manager was able to control *Q* by changing the number of furrows per set. At site P3, *Q* and *Tco* were easily manageable due to the lengthy irrigation turn period for the relatively larger farm size (> 40 ha). The total available maximum *Q* at all four sites was ~28 L s^{-1}. The farm managers had flexibility in using total maximum inflow in any part of their farms according to their needs during the allocated irrigation period at all experimental sites. For instance, during the benchmarking study at site P1 and site P3 the farm manager utilised larger *Q* due to expected slow water advance on high infiltrative soils. However, at site P2 two fields were simultaneously irrigated to reduce the *Q* per furrow due to fast water advance in furrows. The lateral infiltration study was conducted at site P4 situated half way between site P1 and P3. The PRB at this site were two seasons old but the soil was degraded and had mild salinity.

The data for the benchmarking study were collected in the summer season 2010 under cotton crop at site P1 and maize crop at sites P2 and P3. Two bed sizes (NB: 66 cm furrow spacing (Figure 3.7a) and WB: 132 cm furrow spacing (Figure 3.7b)) were tested at each site. The field length at site P1 was 86 m and at site P2 and P3 was 90 m each with a common slope of 0.002 m m^{-1} at all sites. All furrows of WB were trafficked, while only alternate furrows of NB were trafficked.

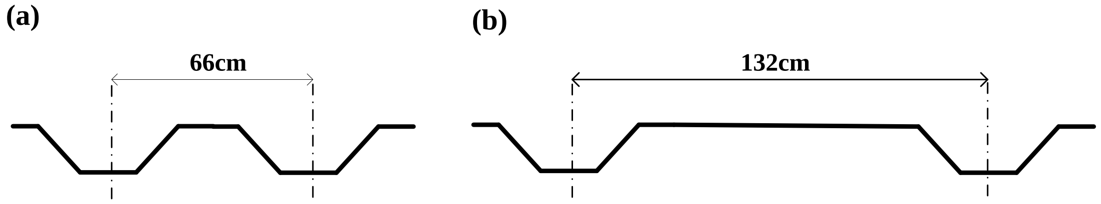


Figure 3.7: Furrow spacing of (a) NB: Narrow bed (b) WB: Wide bed evaluated at three research sites during the benchmarking study in Mardan, Pakistan

Site P1 was under cotton-wheat rotation while site P2 and site P3 were under maize-wheat rotation. The PRB systems at all three sites were renovated by shallow rotary hoeing prior to furrow cleaning, a common renovation method in this locality, while the furrow positions were kept permanent. According to the farmer, the major aim was to control weeds and to loosen the soil for preparing a soft seed bed that facilitates manual seeding of maize and cotton crops.

The observed field conditions at different sites were variable during the benchmarking study. Large weed infestation was observed in the cotton crop at site P1, with an increased number of weeds concentrated in NB furrows in comparison with WB. The crops at all three sites were at different growth stages at the time of data collection. The cotton and maize crops at sites P1 and P3 respectively were at flowering stage, while the maize crop at site P2 was at establishment stage. Third and fourth irrigations were measured at site P1, first and second at site P2, while at site P3 fifth and sixth irrigations were measured. Similarly, manual weeding, a traditional method in the locality, was recently practised at site P3 which increased the furrow surface roughness, but reduced the hindrance caused by weeds to the flow of water. All these field conditions had consequences on results during the analysis.

3.6 Soil and irrigation measurement technique

This research involved field data collection related to soil moisture, bulk density, lateral infiltration, *Q*, *Tco*, irrigation water advance time in furrows at multiple points, bed-furrow configurations, crop establishment, crop height and yield. In addition to field evaluation research components, this study also included a fourth component that involved simulation for evaluation of irrigation performance (*Ea*, *Er*, *DU*, inflow and deep drainage losses) and to identify strategies for improving lateral infiltration and for optimising irrigation management and field design of raised beds. As such, all four components were covered separately in four chapters. However, the common field measurement technique and simulation modelling protocols that were applied across all or most sites for the four research components are discussed below.

Description of all six sites, study objectives, field conditions, measurements, and simulation models used during the analysis are summarised in Table 3.2.

Table 3.2: Summary of experimental sites, objectives, field conditions and measurements (SM = soil moisture , BD = bulk density, SCL= sandy clay loam and three treatments are described in Chapter 5)

Site	[1]Obj.	Experiment period	Field conditions				Measurements		Models used
			Soil type	Cultivation practices	Furrow spacing	Crop & growth stage	Soil	Water	
A1	1	Summer 2009-10	Heavy clay Vertisol with shrink-swell and self-mulching properties	Deep ripping	200 cm	Soybean, full season data	SM, BD & Furrow dimension	*Q*, *Tco*, Water advance time,	IPARM & SIRMOD
	2	Win.2010-Sum 2012		Three treatments	200 cm	Wheat, hemp and corn, full seasons			
	3	Summer 2011		Three treatments	200 cm	Corn, establishment	SM, BD & Lateral infiltration	Water added	Hydrus
A2	1	Summer 2009-10		Annual ripping	100 cm	Corn, flowering stage	SM, BD, furrow dimension	*Q*, *Tco*, Advance time,	IPARM & SIRMOD
P1	1	Summer 2010	SCL with non-swelling properties	Shallow rotary harrowing	WB:132 cm & NB: 66 cm at each site	Cotton, flowering stage	SM, BD & furrow dimension	*Q*, *Tco*, Advance time,	IPARM & SIRMOD
P2	1					Corn, early stage			
P3	1					Corn, late stage			
P4	3	Summer 2011	SCL, mildly saline	Three treatments	132 cm	Corn, establishment stage	SM, BD & lateral infiltration	Water added	Hydrus

[1] *Objective 1: Benchmarking existing PRB performance, 2: Evaluating three PRB renovation methods for irrigation performance and water productivity and 3: Evaluating lateral infiltration under three PRB renovation methods*

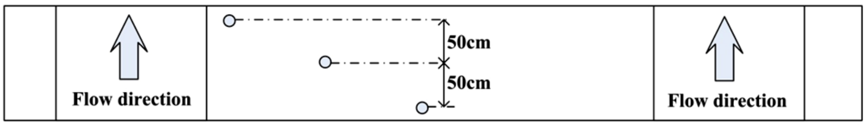
3.6.1 Soil moisture, bulk density and soil moisture deficit

The soil moisture and bulk density was recorded using thermo gravimetric methods according to the procedure described in Marshall and Holmes (1988). The soil cores were collected from 0-30 cm profile depth (rings of 5 cm x 5 cm sizes were used) at 10 cm depth interval. The samples were packed in air tight and insulated containers immediately after collection to avoid any soil moisture loss. The samples were kept in an oven at 105^0C for 48 hours after determining the wet weight. The soil moisture was determined as the ratio of weight lost (water weight) and dry soil weight after 48 hours of drying and bulk density was calculated on dry mass basis as the ratio between dry weight of soil and internal ring volume. Volumetric soil moisture was determined by multiplying gravimetric soil moisture content by mean bulk density for each layer. The root zone soil moisture deficit (*SMD)* was determined as the difference between antecedent and field capacity moisture levels. Field capacity is the upper limit of plant available water or is the soil moisture content after drainage of gravitational water has become very slow and the moisture has become relatively stable, that generally occur after 2-3 days of irrigation (Michael 1999), which was determined at 43% for Vertisol during experiments that closely agreed with values reported by (Hansen et al. 1979; Payero & Harris 2010) and 23.5% for sandy clay loam that closely agreed with values reported by (Shafiq et al. 2002; Hassan et al. 2005).

3.6.2 Lateral infiltration

Lateral infiltration data during the four cropping seasons were collected at site A1, Australia. Automatic soil moisture meters (Sentek EnviroSCAN®, discussed in section 2.5.1) 100 cm deep with sensor slots at 10 cm depth interval, were used. Three probes were placed at 33 cm, 67 cm and 100 cm distances from furrow centre across the bed as shown in Figure 3.8. The holes for the probes were made with a soil auger slightly smaller than the outer diameter of the PVC tube and slightly deeper (120 cm) than the maximum measuring depth of 100 cm. The tubes were then installed by pushing, twisting and hammering at the top of the tube. This procedure reamed the hole to the exact size of the tube while the soil reamed was settled in the extra depth of the hole drilled. This procedure ensured a perfect contact between the tube and the soil. All the sensors were standardised (normalised) by taking free air and water measurements before installations. Initially the commonly used soil properties of Vertisol were used for calibrating the enviroSCAN probes which were latter on readjusted with minor modifications to match the gravimetric soil moisture values on these sites. The EnviroSCAN readings were validated by matching with the calculated volumetric soil moisture obtained from a 0-30 cm profile in a nearby location using the gravimetric method (section 3.6.1). The gravimetrically determined soil moisture values matched well with the calibrated EnviroSCAN readings as given in Appendix C: Figure C1. The soil moisture was logged at 10 minutes interval throughout the cropping season. The probes were removed shortly prior to harvest, and reinstalled shortly after sowing. However, replication of this setup, along with the number and location of sensors per probe, was variable during the experimental period due to equipment constraints. These data collections facilitated in irrigation scheduling and soil moisture deficit (*SMD)* calculations. The number and location of sensors used during the three cropping seasons (2010 wheat, 2011 hemp, and 2011 Corn) are discussed in Chapter 5. The lateral infiltration study during 2011 summer in both soils (Vertisol and sandy clay loam) is detailed in Chapter 6.

(a):Top view



(b):Cross sectional view

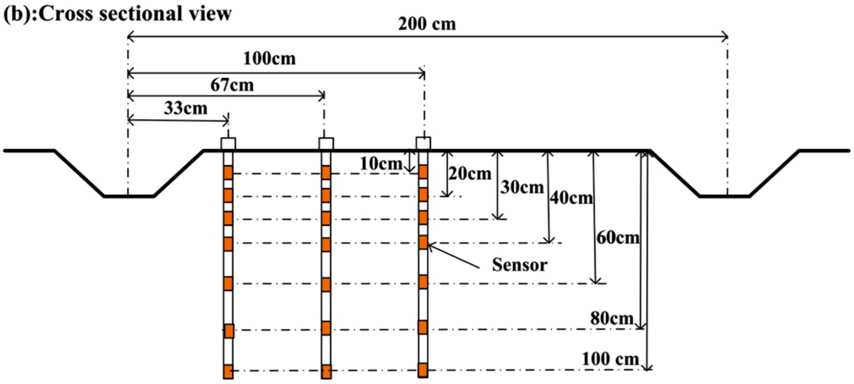


Figure 3.8: Layout of Sentek EnviroSCAN® probes placed across half bed width at given positions of sensors for logging soil moisture variations at 10 minutes interval during 2010 wheat season at site A1, Marinya farm, Cambooya, Australia

3.6.3 Soil infiltration and irrigation performance

The IPARM model (Gillies & Smith 2005) (section 2.5.2.1) was used for identification of Kostiakov infiltration functions (a, k and f_0 of equation 2.6). IRRIMATE^{TM} equipment were used for irrigation data collection in Australia and manual method in Pakistan. SIRMOD III (Walker, 2003) (section 2.5.2.1) was used for evaluation of irrigation performance. The field measured input data and outputs of IPARM and SIRMOD are summarised in Table 3.3. The SIRMOD model was calibrated by adjusting the furrow roughness coefficient (Manning "n") and f_0 in the model until a close match between measured and simulated advance time was achieved. The measured versus simulated advance times was correlated with trend line analysis (Appendix B). Potential for deep drainage due to irrigation excess (DD) was calculated by the equation (Smith et al. 2005);

$$DD = \frac{(1 - Ea)Vi - Vo}{L\,S} \qquad 3.1$$

where Ea is application efficiency, Vi is volume of furrow inflow, Vo the volume of furrow tail-water outflow, L the length of the furrow, and S is furrow spacing.

Table 3.3: Input and output data of IPARM and SIRMOD models

Model	Field measured inputs	Output
IPARM	1- Inflow rate 2- Furrow slope 3- Furrow length 4- Furrow top width 5- Furrow middle width 6- Furrow bottom width 7- Furrow depth 8- Manning's n 9- Water advance at multiple points along furrow 10-Runoff	Infiltration functions of modified Kostiakov infiltration equation 1- a 2- k 3- f_0 4- C and 5-Advance curve 5-Runoff curve 6-Cumulative infiltration curve
SIRMOD	1- All IPARM inputs and outputs except water advance and runoff 2- Time to cut-off 3- Free draining or blocked 4- Furrow spacing 5- Root zone soil moisture deficit (*SMD)*	Irrigation performance 1- *Ea* 2- *Er* 3- *DU* 4- Inflow volume 5- Outflow volume 6-Complete log of advance, recession time and cumulative infiltration along the furrow length

3.6.3.1 IRRIMATE^{TM} equipment for irrigation performance evaluation

The IRRIMATE^{TM} suit of equipment developed at NCEA was used in irrigation data collection. It include siphon inflow meters (Figure 3.9a), which gives a log of Q. The advance sensors (Figure 3.9b) measure the water advance in furrows. The sensor in each furrow triggers when water touches the sensor. The flume flow meter (Figure 3.9c) is installed on flumes specially designed for measuring the runoff volume, which gives a complete log of flow passing through the flume. Data from all equipment is downloaded through a small pocket PC which can communicate using infrared communication with the equipment.

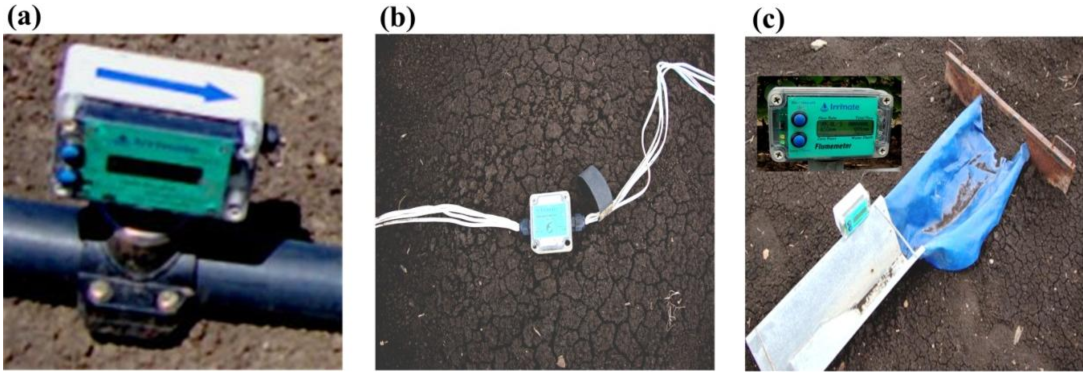


Figure 3.9: IRRIMATE^{TM} equipment for irrigation measurements (a) Siphon flow meter, (b) water advance meter, (c) flume with flow meter

3.7 Statistical methods

Data sets were analysed using Excel and IBM SPSS version 19. All the data sets were checked for compliance with the underlying ANOVA assumption. When normality of data sets was found to violate the ANOVA assumption then data were transformed using SPSS built in functions for improving the symmetry of the distribution prior to analysis. The equal variance assumption was evaluated using the Levene test. If the Levene test showed heterogeneity but the ratio between largest to smallest standard deviation was less than 2, then the data sets were considered fit for ANOVA at $P=0.05$ significance level, otherwise $P=0.01$ was recommended to control the type I error (White 2007). A general linear model (univariate) with Tukey (post hoc) analysis was used to identify significant differences between the treatments (main groups) and plant rows as subgroup for plant data and profile depth as subgroup for bulk density analysis.

CHAPTER 4: Benchmarking irrigation performance of permanent raised beds

4.1 Introduction

Literature reviewed in Chapter 2 illustrated that the existing research on irrigated PRB systems under actual farmer managed conditions is sparse, while the majority of available research largely covers rain fed conditions. The limited field studies focussed on irrigated PRB systems under experimental field conditions, generally used small area or point evaluation methods, which were subject to large spatial variations. Therefore, this dissertation involved preliminary evaluation of existing irrigated PRB farming practices to assess their impact on irrigation performance under both Australian and Pakistani farm conditions. It aimed to benchmark irrigation performance of farmer managed PRB farming systems and identify strategies to improve their *WP*.

Field trials were conducted in Australia and Pakistan on existing irrigated PRB farming systems in farmers' fields. Two sites (A1, A2) were selected in south-east Queensland, Australia. The soil type on both sites was a black Vertisol exhibiting substantial shrinking-swelling, cracking and self-mulching properties as described in section 3.4. Three field sites (P1, P2 and P3) were selected with contrasting environmental conditions in north west Pakistan. The soil type at each Pakistani site was a non-swelling, rigid sandy clay loam with a history of intensive cultivation as described in section 3.5. The measurements were conducted under actual field conditions with full farm manager control.

4.2 Material and methods

The experimental details of measurements of irrigation performance in both countries are summarised in Table 4.1. Irrigation water generally moves to 100 cm and 60 cm depths under Vertisol and sandy clay loam respectively during normal irrigation applications, thus these depths are generally analysed as active root zone depths.

Table 4.1: Experimental details of measurement of existing irrigation performance in Australia and Pakistan (SM-soil moisture, BD- bulk density and *SMD*- soil moisture deficit, FC- Field capacity, NB-narrow bed and WB-wide bed)

Experimental measurement	**Australian sites**		**Pakistani sites**		
	Site A1 (Cambooya)	**Site A2 (Dalby)**	**Site P1 (Mardan A)**	**Site P2 (Mardan B)**	**Site P3 (Mardan C)**
Antecedent SM & BD					
No. of samples & positions	8 – 4 @ head, 4 @ tail	4 – 2 @ head, 2 @ tail	4 – 2 @ head, 2 @ tail	4 – 2 @ head, 2 @ tail	4 – 2 @ Head, 2 @ tail
Sampling depths	0-10, 10-20,& 20-30 cm	0-10, 10-20,& 20-30 cm	0-15, 15-30 & 30-60 cm	0-15, 15-30 & 30-60 cm	0-15, 15-30 & 30-60 cm
Gravimetric SM & BD	Undisturbed cores 5 cm diam. x 5 cm length	Undisturbed cores 5 cm diam. x 5 cm length	Undisturbed cores 3 cm dia x 60 cm long tube	Undisturbed cores 3 cm dia x 60 cm long tube	Undisturbed cores 3 cm dia x 60 cm long tube
Volumetric SM Method	Gravimetric SM x BD	Gravimetric SM x BD	Gravimetric SM x BD	Gravimetric SM x BD	Gravimetric SM x BD
***SMD* prior to irrigation**					
No. of samples & positions	4 – 2 @ head, 2 @ tail	4 – 2 @ head, 2 @ tail	4 – 2 @ head, 2 @ tail	4 – 2 @ head, 2 @ tail	4 – 2 @ head, 2 @ tail
Distance from furrow centre	33, 67, 100 cm	50 cm	44 cm	44 cm	44 cm
Profile depths	10 cm intervals to 100 cm	10 cm intervals to 100 cm	0-15, 15-30 & 30-60 cm	0-15, 15-30 & 30-60 cm	0-15, 15-30 & 30-60 cm
Method	Sentek capacitance probe	capacitance probe	Gravimetric (as above)	Gravimetric (as above)	Gravimetric (as above)
Calculation	SMD= FC -SM in 100 cm	SMD= FC -SM in 100 cm	SMD= FC -SM in 60 cm	SMD= FC -SM in 60 cm	SMD= FC -SM in 60 cm
Water advance in furrow					
No. of samples & positions	5 – @ 100 m intervals	5 – @ 90 m intervals	4 – @ 21 m interval	5 – @ 18 m intervals	5 – @ 18 m intervals
Method	IRRIMATE™ Flow advance meter	IRRIMATE™ Flow advance meter	Manually using measuring tape and staff watch	Manually using measuring tape and staff watch	Manually using measuring tape and staff watch
No of furrows measured	21	20	20 NB & 16 WB	20 NB & 16 WB	20 NB & 16 WB
Inflow rate	IRRIMATE™ Siphon flow meter	IRRIMATE™ Siphon flow meter	Total inflow into 5 NB & 4 WB furrows by broad-crested weir (pipe) flume	Total inflow into 5 NB & 4 WB furrows by broad-crested weir (pipe) flume	Total inflow to 5 NB & 4 WB furrows by broad-crested weir (pipe) flume
Runoff	None- Furrow blocked at tail end	IRRIMATE™ Flume/ flow meter	None- Furrow blocked at tail end	None- Furrow blocked at tail end	None-Furrow blocked at tail end
Treatments					
Furrow spacing	200 cm	100 cm	NB (66 cm) & WB (132 cm)	NB (66 cm) & WB (132 cm)	NB (66 cm) & WB (132 cm)
Bed width	~150 cm	~40 cm	NB(29 cm) & WB (70 cm)	NB(16 cm) & WB (90 cm)	NB(18 cm) & WB (80 cm)
Measured irrigations					
No. & sequence	2 (1st & 2nd)	2 (2nd & 3rd)	2 (3rd & 4th)	2 (1st & 2nd)	2 (5th & 6th)
Dates	Dec 26, 2009; Jan 29, 2010	Jan 7 & 27, 2010	Jul 18 & 28, 2010	Jul 19 & Aug 2, 2010	Jul 20 & 29, 2010

4.2.1 Data collection and instruments used

The site conditions and cultivation practices recorded were already discussed in Chapter 3. The IPARM model (Gillies & Smith 2005) was used to calculate the infiltration functions and the SIRMOD III (Walker 2003) model was used to evaluate the irrigation performance. Both these models are described in section 2.5.2.1 and their input data (Table 3.3) and collection procedure is described in section 3.6.3. Data sets for calibration of both models are given in Figure B1 & B2 (Appendix B). Specific field data collected to parameterise the IPARM and SIRMOD models and instrument used in both countries during this study are summarised below.

4.2.1.1 Australia

At site A1, a field topographic survey was conducted for determining the slope at the commencement of the trials. Weather data were recorded by an automatic weather station on the experimental site. The *SMD* was calculated as the difference of field capacity (43%) and antecedent soil moisture using soil moisture and bulk density data in surface 0-30 cm depth at 10 cm depth interval using the thermo-gravimetric method as discussed in section 3.6.1 and the four replications were in both the field head and tail reaches. Additional soil moisture data were collected prior to irrigation at 0-100 cm depth using automatic soil moisture meters (Sentek EnviroSCAN®), as discussed in section 2.5.1.2 and the method described in section 3.6.2, according to layout shown in Figure 3.8 at site A1. The measurements were replicated twice both at field head (50 m distance from distribution channel) and tail (350 m distance from distribution channel) to account for spatial variability. The capacitance probe accuracy was validated by the gravimetric soil moisture.

Two irrigations (26 December 2009 and 29 January 2010), were applied to a soybean crop at site A1. IRRIMATE™ equipment (section 3.6.3.1) consisting of siphon flow meters were used to record *Q* in three furrows and flow advance monitoring sensors placed at ~100 m intervals along the furrow length were used to measure water advance in 24 furrows. Flow crossing in few furrow affected the water advance during first irrigation thus the furrow sizes were increased before the second irrigation and data of affected furrows discarded.

At site A2, the data collected include furrow slope, agronomic management (including land preparation, crops, inputs and machinery) and current irrigation management as discussed in section 3.4.2 and summarised in table 3.2. The *SMD* and irrigation data were obtained similar to site A1. However, the water advance sensors were placed 90 m apart in this case. Two irrigations (7 January 2010 and 27 January 2010) to cotton were measured at this site. The furrows were free draining and alternate furrow was irrigated. Runoff was measured by flumes with flow recording meters. Collection of two irrigations data was possible on both sites because no third irrigation was applied during the season. However, the replication of data during both irrigations on both sites was sufficient for evaluating statistical significance.

4.2.1.2 Pakistan

Two irrigations were measured at each of the three sites. The number of irrigation events monitored was limited due to time constraint but the number of sites and replication of data during each irrigation event at each site was sufficient for identifying statistical significance. Two bed furrow treatments were evaluated (1-NB: narrow bed at 66 cm furrow spacing and 2-WB: wide bed at 132 cm furrow spacing) at each site, as described in Chapter 3. Data from five furrows per set under NB plot and four furrows per set under WB plot were twice replicated at each site. The *Q* to a group of furrows was calculated from water head measurements over the crest level of broad crested weir type flume at 5 minute intervals. The average *Q* per set was divided by the number of furrows to calculate the single furrow *Q*. Similar *Q* in each furrow per set was obtained through parallel bunds by controlling flow depth near the head by adjusting bund crest height. Water advance data were measured at 21 m interval on site P1 and 18 m interval on site P2 and P3 manually.

The root zone (0-60 cm) *SMD* was determined according to procedure described in section 3.6.1 using field capacity of 23.5% of the local sandy clay loam (Hansen et al. 1979) as determined by Shafiq et al. (2002). The soil cores were collected at 0-15 cm, 15-30 cm and 30-60 cm depth intervals using 3 cm diameter x 60 cm long tube from the shoulders of WB and middle of NB with two replicates in each plot. Data of three sites were averaged for different treatments in majority of cases due to no significant differences between sites.

4.3 Results

4.3.1 Field conditions and soil moisture deficit before irrigation

The topographic survey on both Australian sites (A1 and A2) showed an average slope of ~0.002 m m^{-1}. The *SMD* was ~100 mm before both irrigations on site A1 and before the second irrigation on site A2. However, the average *SMD* was 76 mm before the first irrigation on site A2 (Figure 4.1). Weather data for site A1 are attached in Table A1 (Appendix A).

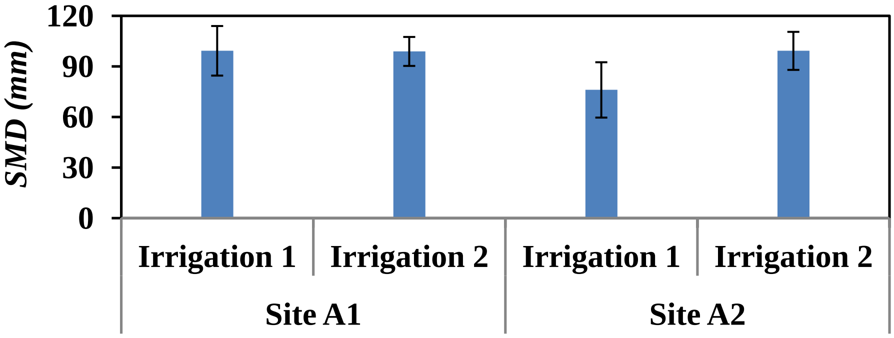


Figure 4.1: Soil moisture deficit *(SMD)* in the root zone (0-100cm depth) prior to two irrigation applications at both sites on Vertisol, Australia (vertical bars show SD)

The fields evaluated in all Pakistani sites were short (< 100 m) and field widths were also less than 100 m. The furrow slopes were ~0.002 m m^{-1}. Field observations of the soil profile up to 60 cm depth showed a fairly uniform soil structure and texture across the field. The average root zone *SMD* was ~60 mm/60 cm depth prior to both irrigations on all sites as given in Figure 4.2.

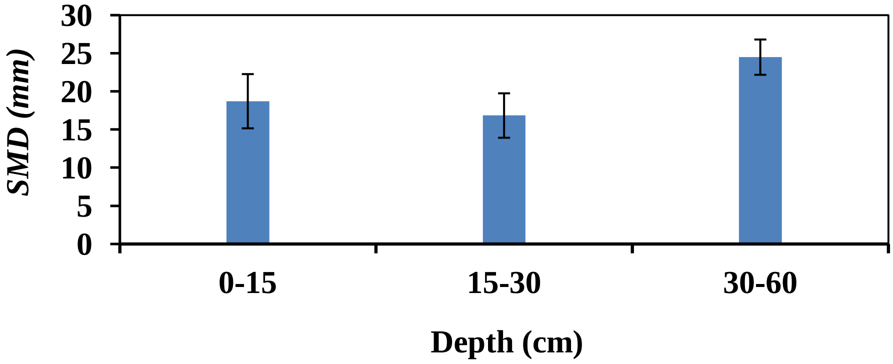


Figure 4.2: Average *SMD* at given depths on three sites, prior to two measured irrigation applications at Mardan, Pakistan (Vertical bars show SD)

4.3.2 Bed furrow dimensions

In Australia, the furrow spacing was 200 cm at site A1 with an initial furrow top width of 42 cm and depth of ~8 cm during the first irrigation. However, due to insufficient capacity for the applied *Q* during the first irrigation, the furrow dimensions were increased by ~26% before the second irrigation (Table 4.2). At site A2, the furrow spacing was 1 m with average furrow top width of ~61 cm (Table 4.2), and bed top width of ~39 cm. The wider furrow width avoided compaction of the furrow sides. However, cracks crossing the bed from wet to dry alternate furrow were obvious during the second irrigation, when *SMD* was high.

Table 4.2: Average furrow dimensions (TW = top width, MW = middle width, BW = bottom width and D = depth) recorded prior to two irrigations at two sites (A1 and A2) in Australia and three sites (P1, P2 and P3) in Pakistan (SD in brackets)

Bed & furrow dimensions	**Australia**		**Pakistan**					
	A1	**A2**	**P1**		**P2**		**P3**	
	200cm	**100cm**	**NB**	**WB**	**NB**	**WB**	**NB**	**WB**
TW	48	61	37	*62*	50	43	48	52
(cm)	*(8)*	*(3)*	*(3)*	*(2)*	*(3)*	*(1)*	*(1)*	*(3)*
MW	27	43	25	52	35	34	31	33
(cm)	*(4)*	*(4)*	*(3)*	*(4)*	*(3)*	*(1)*	*(3)*	*(3)*
BW	13	24	19	38	20	15	14	18
(cm)	*(2)*	*(5)*	*(2)*	*(7)*	*(4)*	*(2)*	*(2)*	*(2)*
D	9	10	10	12	12	11	9	10
(cm)	*(1)*	*(1)*	*(1)*	*(1)*	*(2)*	*(1)*	*(1)*	*(1)*
L *(m)*	465	455	86	86	90	90	90	90

In Pakistan, the furrow dimensions of both NB and WB were different (Table 4.2 and Figure 4.3). The furrow widths were smaller for NB than WB in majority of cases. Conversely, at site P2 the NB furrows were wider due to fresh renovation applied prior to measurements. However, the difference in furrow depth was not significant *(P=0.05)* between the NB and WB. For NB the furrow top width ranged from 37 to 50 cm, while for WB the furrow top width ranged from 43 to 62 cm. Thus, the NB furrow sides were subjected to more compaction by tractor and machinery tyres, as generally tractor and machinery widths range up to 45 cm, during the field operations compared with the WB furrows. Bed furrow sizes at all sites and cropping seasons are summarised in Appendix A: Table A4.

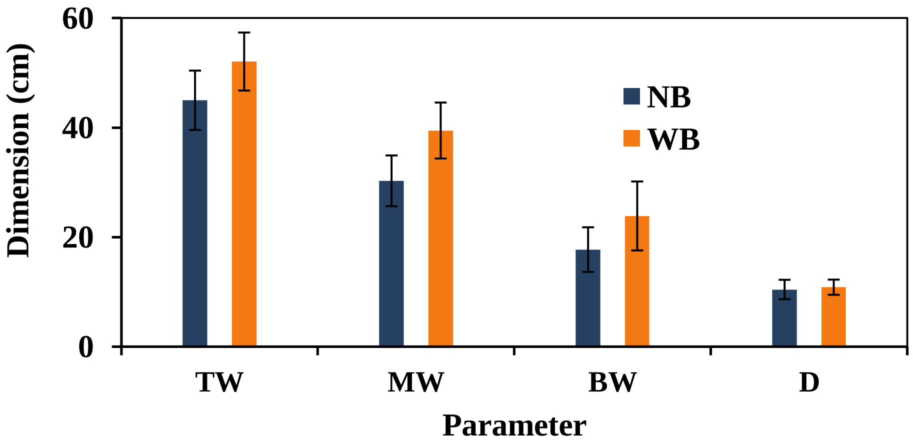


Figure 4.3: Average field measured furrow dimensions (recorded prior to two irrigations at all three sites for narrow bed (NB: 66cm furrow spacing) and wide bed (WB: 132cm furrow spacing) systems at Mardan, Pakistan (vertical bars show SD)

4.3.3 Inflow, water advance and time to cut-off.

In Australia, the field measured *Q* ranged from 1.91 L s^{-1} to 1.98 L s^{-1} with an average of 1.92 L s^{-1} during the two irrigations at site A1 (Table 4.3). The total average inflow volume was 134 mm during the two irrigations with ~12% increased inflow volume during the first (146 mm) than the second irrigation (130 mm) (Table D1: Appendix D). At site A2, the average *Q* ranged from 2.5 L s^{-1} to 2.6 L s^{-}1 with an average of 2.54 L s^{-1} during the two irrigations. The total average inflow volume was 108 mm during the two irrigations with ~12% less inflow volume during the first (101 mm) than for the second irrigation (113 mm).

The average measured advance time to furrow tail end (*Ta*) at site A1 was 13% longer during the first (993 min) than during the second irrigation (862 min) (Figure 4.4a), indicating impact of seasonal changes on water advance along the furrow length, because impacts of *SMD* and *Q* were negligible due to their comparable values. At site A2, the average *Ta* during the first irrigation (387 minutes) was 34% shorter than for the second irrigation (584 minutes) (Figure 4.4b). Wider cracks due to larger *SMD* (100 mm) were observed during the second than for the first irrigation (Figure 4.5a), which reduced the advance rate and all furrows (wet and dry) were equally inundated (Figure 4.5b) till the end of the second irrigation. The advance times at all sites are summarised and attached in Table A5 (Appendix A).

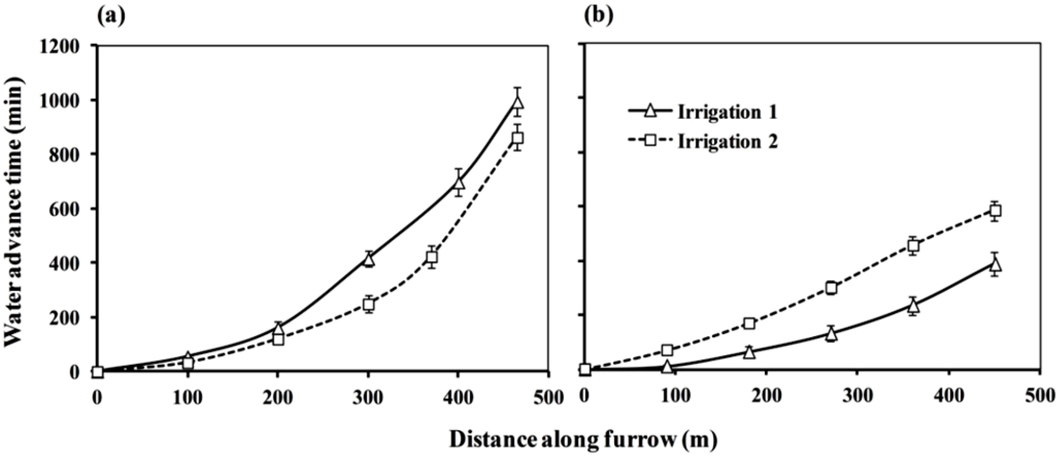


Figure 4.4: Average field measured water advance curves of two irrigations at (a) sites A1, and (b) site A2 in Australia (vertical bars show SD)

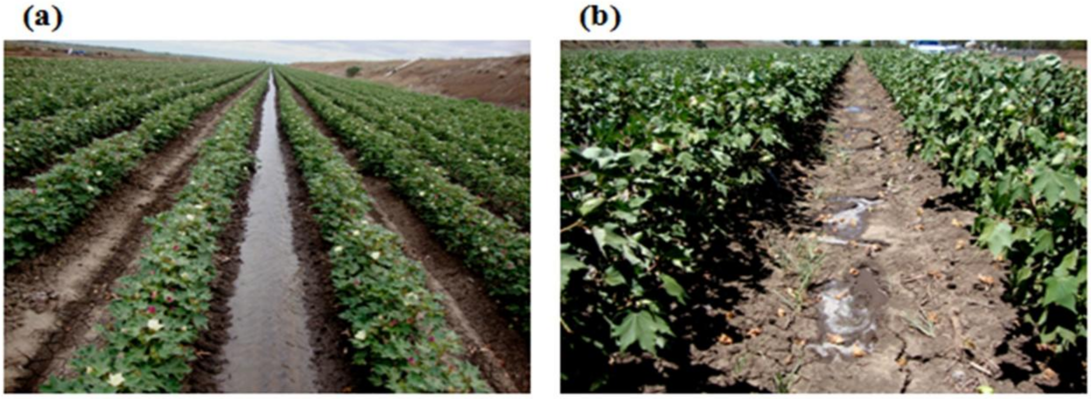


Figure 4.5: Crop and field conditions before (a) irrigation 1 with no cracks; (b) irrigation 2 with flow crossing the bed through cracks at site A2, Australia

The average *Tco* at site A1, was 1078 minutes (Table 4.3) with 7.5% shorter *Tco* during the second (1057 min) than for the first irrigation (1143 min) (Table D1: Appendix D). The average *Tco* at site A2 was 646 minutes during the two irrigations with 15% longer *Tco* during the second than for the first irrigation (590 min).

In Pakistan, the measured Q ranged from 1.55 L s^{-1} to 4.88 L s^{-1} on all sites. The results showed a significantly *(P=0.05)* reduced Q on NB that ranged from 1.55 L s^{-1} to 3.09 L s^{-1} (2.3 L s^{-1} average) than for the WB that ranged from 2.66 L s^{-1} to 4.88 L s^{-1} (3.5 L s^{-1} average). The total inflow volume per single furrow of WB was 36% increased (5.40 m^3 to 9.75 m^3) than for the NB (2.9 m^3 to 7.4 m^3) during all measured irrigations. However, the total inflow volume per unit area was significantly *(P=0.05)* reduced (32%) on the WB (60 mm) than for the NB (Table 4.3).

Table 4.3: Average irrigation performance of two irrigations measured on two sites (A1 and A2 with two bed sizes) in south east Queensland, Australia and three sites (P1, P2 and P3 with two bed sizes) in north west Pakistan (SD in brackets)

Irrigation Performance Parameter	**Australian sites**		**Pakistani sites**							
	A1	**A2**	**P1**		**P2**		**P3**		**Overall**	
	200cm	**100cm**	**NB**	**WB**	**NB**	**WB**	**NB**	**WB**	**NB**	**WB**
Q	1.92	2.54	2.95	4.86	1.62	2.71	2.36	2.96	2.3a	3.5b
(L s-1)	*(0.1)*	*(0.1)*	*(0.2)*	*(0.0)*	*(0.1)*	*(0.1)*	*(0.4)*	*(0.2)*	*(0.6)*	*(1.1)*
Tco	1078	646	39	33	34	35	37	34	37a	34b
(min)	*(40)*	*(51)*	*(2)*	*(2)*	*(3)*	*(1)*	*(1)*	*(1)*	*(3)*	*(2)*
Inflow	134	108	121	83	56	47	88	50	88a	60b
(mm/irrigation)	*(8)*	*(7)*	*(15)*	*(6)*	*(9)*	*(5)*	*(11)*	*(5)*	*(27)*	*(17)*
DD	34	12	61	24	6	4	28	1	32a	8b
(mm/irrigation)	*(8)*	*(6)*	*(4)*	*(2)*	*(1)*	*(1)*	*(2)*	*(0)*	*(24)*	*(6)*
Ea	75	81	50	72	92	99	68	99	70a	90b
(%)	*(4)*	*(6)*	*(6)*	*(4)*	*(8)*	*(1)*	*(9)*	*(1)*	*(18)*	*(9)*
Er	99	97	100	99	83	77	99	83	94a	86b
(%)	*(1)*	*(1)*	*(0)*	*(1)*	*(7)*	*(0)*	*(1)*	*(7)*	*(5)*	*(10)*
DU	91	87	90	77	66	84	73	75	76a	79a
(%)	*(3)*	*(3)*	*(6)*	*(2)*	*(7)*	*(8)*	*(1)*	*(9)*	*(13)*	*(10)*

**Figure followed by same letter in rows are not significantly (P=0.05) different (All table abbreviations defined on page xxviii)*

The average *Q* for the NB (2.95 L s^{-1}) at site P1 was ~39% less than for the WB (4.86 L s^{-1}) during both irrigations. The average total inflow volume per furrow for the NB (6.75 m^3) was ~28% less than for the WB (9.35 m^3) during both irrigations. But the total average inflow volume of the NB (121 mm) was ~46% larger than for the WB (83 mm) during both irrigations (Table 4.3). At site P2, the average *Q* was 1.62 L s^{-1} on NB and 2.71 L s^{-1} on WB. The average inflow volume per single furrow on NB (3.25 m^3) was ~40% less than for the WB (5.45 m^3). In contrast, the average inflow volume per unit area of NB (56 mm) was ~20% larger than for the WB (47 mm). At site P3, the average *Q* of NB (2.36 L s^{-1}) was ~20% less than for the WB (2.96 L s^{-1}), while the average inflow volume per single furrow of NB (5.15 m^3) was ~13% less than for the WB (5.9 m^3). However, the average inflow volume per unit area of NB (88 mm) was ~75% larger than WB (Table D2: Appendix D).

The average *Ta* on the NB treatment was 51% longer, similar and 14% longer than WB treatment during both irrigations at sites P1, P2 and P3, respectively. The data generally showed a significantly *(P=0.05)* longer (19%) *Ta* on NB than WB (Figure

4.6a). All trafficked furrows showed a significantly *(P=0.05)* faster (~21%) *Ta* than the non-trafficked furrows (Figure 4.6b and 4.7) of all sites.

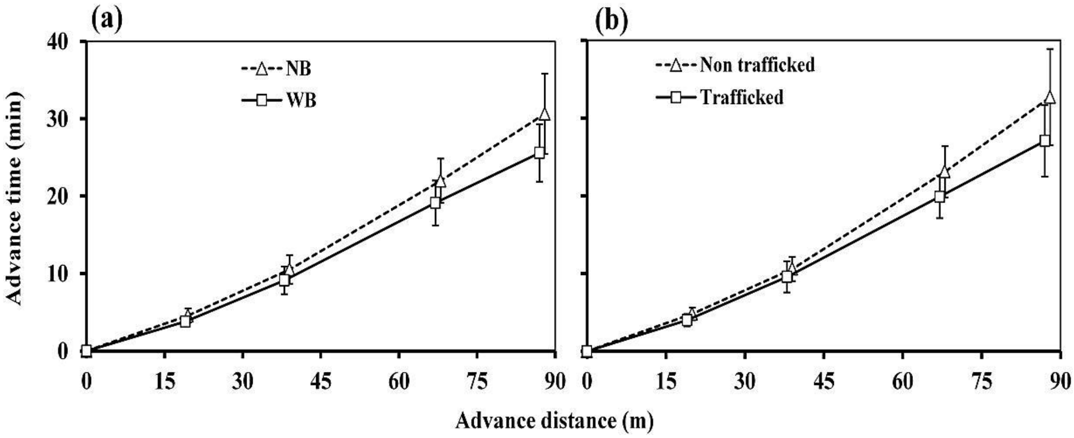


Figure 4.6: Impact of (a) bed size and (b) wheel trafficking on average water advance along furrow for all three sites in Pakistan (Vertical bars show SD)

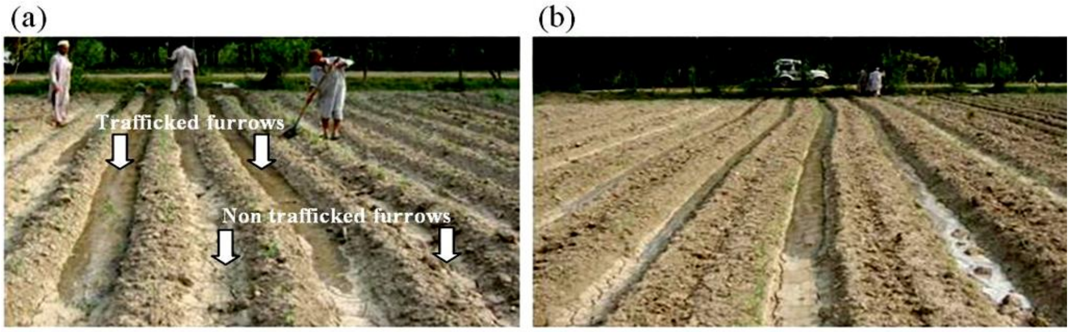


Figure 4.7: Field conditions of site P2 with (a) NB: Fast water advance on trafficked furrows and slow on non-trafficked alternate furrows; (b) WB: Uniform water advance on both trafficked furrows

The average *Tco* for the NB was ~18% longer, similar and ~9% longer than for the WB at site P1, P2, and P3 respectively during both irrigations (Table 4.3). Overall results indicated longer average *Tco* on NB than on WB with current management systems. Field observation showed that the farmer decision for *Tco* on WB was based on furrow filling and avoiding bed overtopping at the tail end of the field, which caused poor lateral infiltration at the head reaches. For the NB systems, the measured *Tco* exceeded the *Ta* with the existing farmer management. The water advance along the furrows showed linear response with the square root of time for both soils as provided in Figure A1 (Appendix A).

4.3.4 Infiltration

In Australia, at site A1, results showed a general tendency of reduced cumulative infiltration during the second than the first irrigation. Comparison of both irrigation results during the 900 minutes of infiltration opportunity time showed ~11% reduced cumulative infiltration during the second (132 mm) than the first irrigation (148 mm) (Figure 4.8). Similarly, the total cumulative infiltration at the time of water arrival to the tail end of the furrow was ~15% increased during the first (155 mm) than for the second irrigation (135 mm), indicating reduced soil porosity due to subsidence.

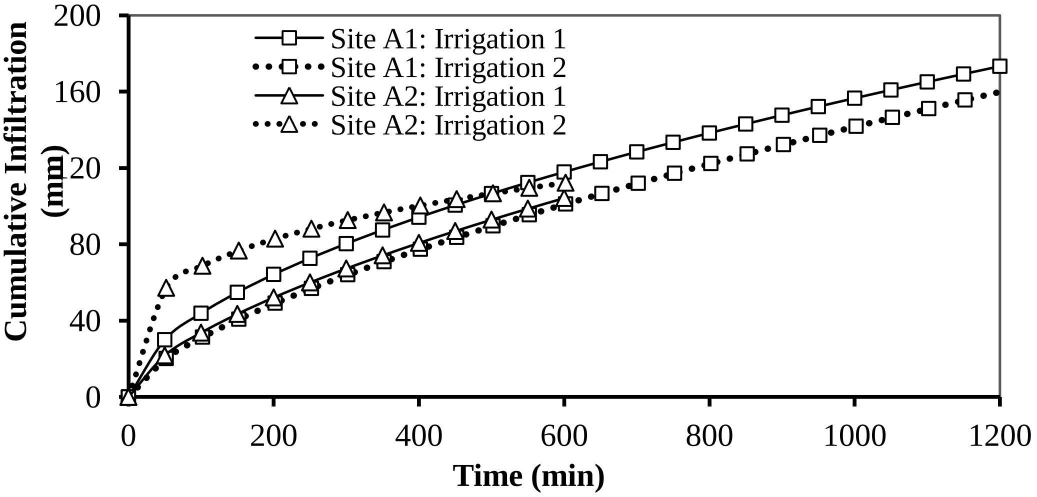


Figure 4.8: Comparison of SIRMOD simulated cumulative infiltration at given times during two irrigations at both sites (A1 and A2) on a Vertisol, in Australia

At site A2, the cumulative infiltration showed 25% increased infiltration during the second (100 mm) than the first irrigation (80 mm), when compared at 400 minutes of infiltration opportunity time (Figure 4.8). Overall data showed ~38% increased cumulative infiltrations during the second (110 mm) than the first irrigation (80 mm) at the time of water arrival to the furrow tail end during both irrigations, indicating the larger *SMD* increased the cumulative infiltration during the second irrigation.

The cumulative infiltration along the furrow length (Figure 4.9) indicated 27% to 40% and 34% to 42% less cumulative infiltration at the tail than at the head reaches on site A1 and A2, respectively. The cumulative infiltration at site A1 was 29% and 33% increased at the head and tail reaches, respectively, than site A2. At site A1, the *SMD* (100 mm) was fulfilled but with excessive *DD*, while at site A2, 11% (50 m) and 33% (150 m) of the field length from field tail end received less than required irrigation application during the first and the second irrigation, respectively (Figure 4.9). The infiltration opportunity time at the tail reaches was 38% to 60% reduced at sites A1 and 58% to 78% at site A2 than at the head reaches.

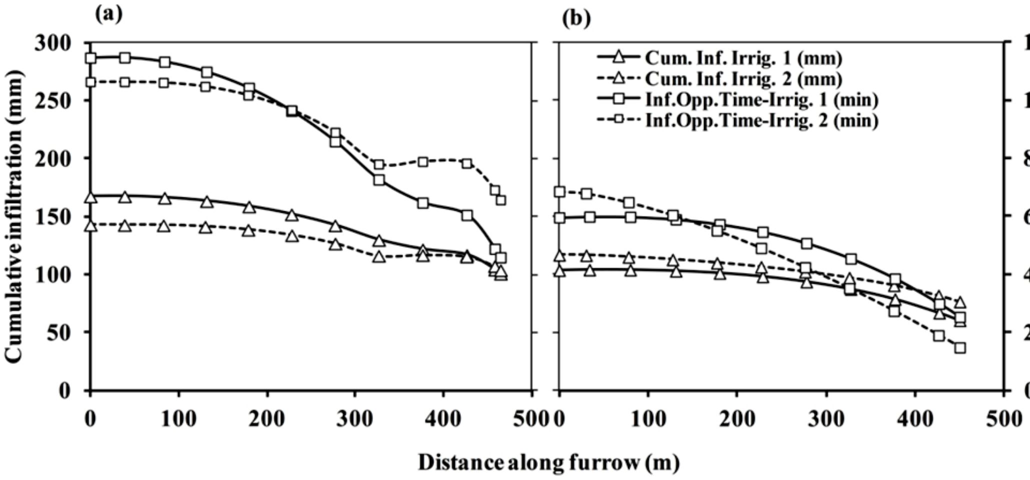


Figure 4.9: Average cumulative infiltration and infiltration opportunity time along the furrow length during the two irrigations at (a) site A1 and (b) site A2 in Australia

In Pakistan, the volume infiltrated per unit furrow length was in the range of 0.04 m^3 m^{-1} to 0.15 m^3 m^{-1} on NB (Figure 4.10a) and 0.08 m^3 m^{-1} to 0.11 m^3 m^{-1} on WB (Figure 4.10b) during the 100 minutes infiltration opportunity time. Overall results showed 12% increased infiltrated volume per unit furrow length for WB than for the NB during the 100 minutes infiltration opportunity time.

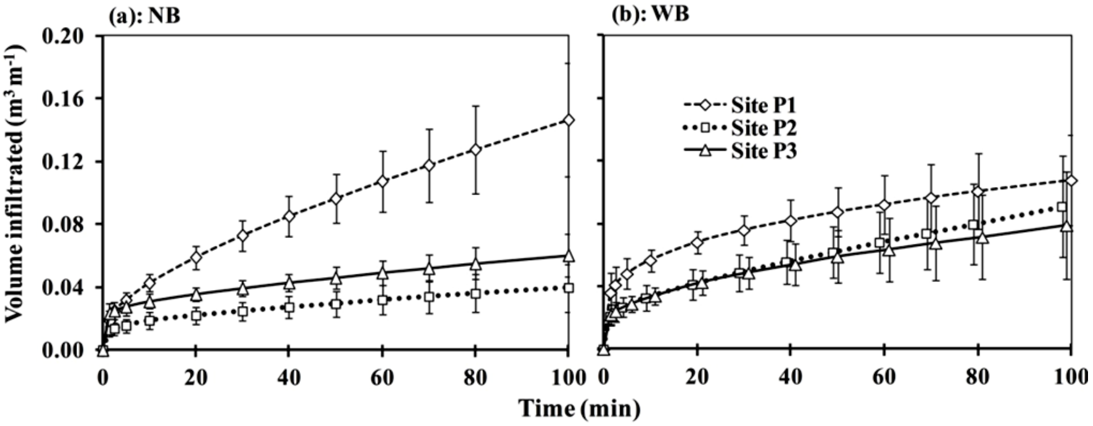


Figure 4.10: Average volume infiltrated per unit furrow length on two bed sizes at three sites during two irrigations in a sandy clay loam, Pakistan (Vertical bars show SD)

The volume infiltrated per unit area ranged from 0.06 m^3 m^{-2} to 0.225 m^3 m^{-2} on NB (Figure 4.11a) and 0.06 m^3 m^{-2} to 0.11 m^3 m^{-2} on WB (Figure 4.11 b) during the 100 minutes infiltration opportunity time. The average volume infiltrated per unit area was ~35% less on WB than on NB during the 100 minutes infiltration opportunity time. Thus the infiltration properties varied from site to site.

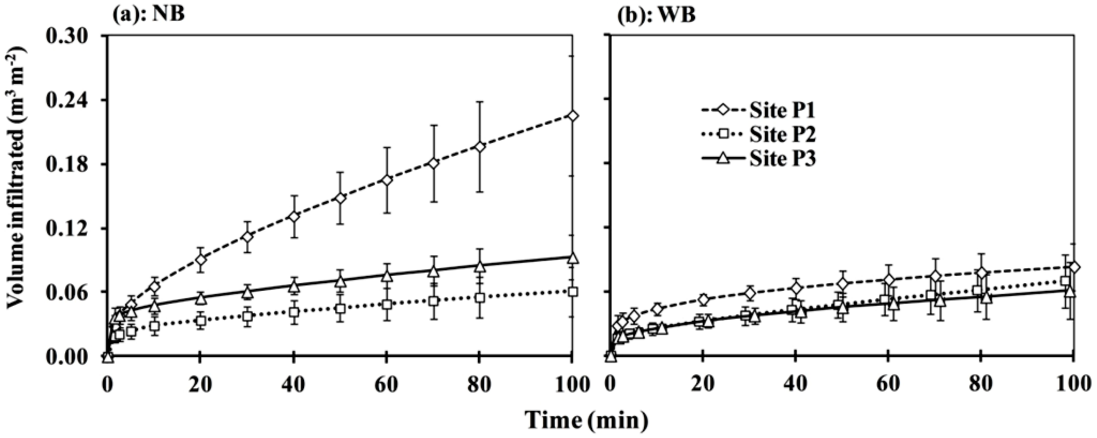


Figure 4.11: Average volume infiltrated per unit area on two bed sizes at three sites in sandy clay loam, Pakistan (Vertical bars show SD)

The spatial distribution of average cumulative infiltration along the furrow length (Figure 4.12) clearly illustrated that 50% of the measured irrigation events were over-irrigated (e.g. site P1 both beds and site P3 NB) and ~50% were under-irrigated (e.g. site P2 both beds and site P3 WB) as shown by the reduced cumulative infiltration at head reaches than the target 60 mm *SMD*.

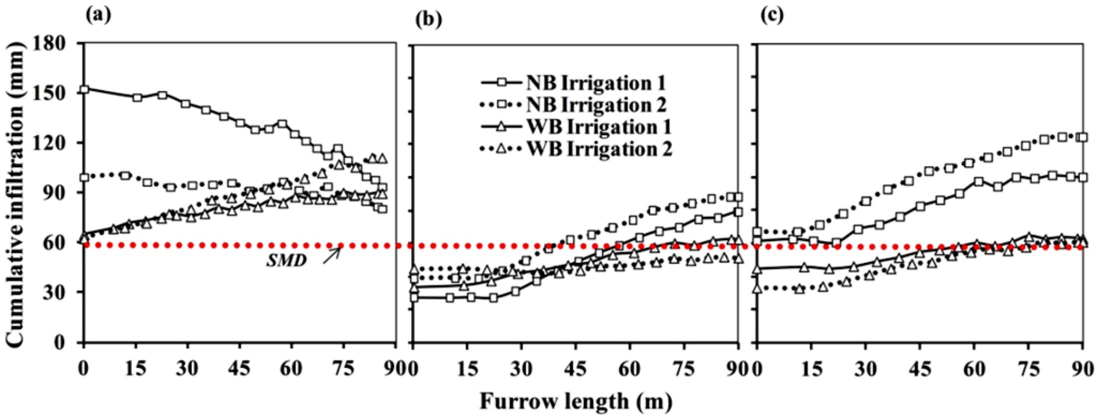


Figure 4.12: Spatial variation in average cumulative infiltration along the furrow length to replenish 60 mm soil moisture deficit (*SMD*) during two irrigations each at (a) site P1, (b) site P2 and (c) site P3 under two bed sizes in sandy clay loam, Pakistan.

4.3.5 Irrigation performance

In Australia, at site A1, the results showed *Ea* in the range of 68% to 77% with 75% average, *Er* above 99%, while *DU* ranged from 88% to 92% with 91% average (Table 4.3). Comparison of two irrigations showed improved *Ea*, *DU* and reduced inflow volume during the second irrigation than for the first irrigation (Table D1: Appendix D). The lower *Ea* caused excessive *DD* that ranged 30 mm/irrigation to 47 mm/irrigation as the furrows were blocked at tail end. The *DU* was increased by 4% during the second than the first irrigation (88%).

At site A2, the average *Ea* was 81% during the two irrigations (Table 4.3) with relatively reduced (74%) *Ea* during the first irrigation, due to excessive irrigation application with ~18% *DD* and ~8% tail drain runoff losses (Table D1: Appendix D). In contrast *Ea* during the second irrigation was increased (85%) resulting in reduced *DD* (6%) and tail drain runoff (9%) losses. The *Er* ranged above 95% while *DU* ranged above 81% during both irrigations.

In Pakistan, at site P1, *Ea* was the lowest at 50% on NB and 72% on WB followed by site P3 at 68% on NB and 99% on WB (Table 4.3). At site P2, *Ea* was the highest at 92% on NB and 99% on WB (Table 4.3). At site P1 excessive irrigation was applied, that resulted in increased *DD* (24 mm/irrigation to 61 mm/irrigation), while at site P2 the *SMD* was not fully met. Overall data showed significantly *(P=0.05)* lower *Ea* on NB that ranged from 46% to 97% (70% average) in comparison with the WB, that ranged from 69% to 100% (90% average) on all sites. At site P1 both bed sizes and at site P3 NB only, the lowest *Ea* was experienced with over-irrigation and large *DD* (up to 61 mm/irrigation). However, improved *Ea* (> 90%) for site P2 and P3 (WB only) reduced *DD* (< 6 mm/irrigation), but *SMD* was not met (Table D2: Appendix D).

Results showed higher *Er* at site P1 that ranged above 99% followed by site P3 at 91% and then site P2 at ~80%. The overall data showed a significantly *(P=0.05)* increased *Er* on NB (94%) than for the WB (86%), thus *SMD* was generally not fully met on the majority of WBs. A comparison of irrigation volume applied indicated a number of over-irrigated events (i.e. *Er* > 99%), especially at site P1 (both bed sizes) and site P3 (NB only), in other words, the *SMD* was met, but with considerable losses below the root zone. While at site P2 (both bed sizes) and site P3 (WB only) *Er* ranged down to 77% and thus crop was mostly under-irrigated. Overall results showed comparable *DU* on WB (79%) and NB (76%) as given in Table 4.3.

The average simulated surface water storage fraction (ratio between surface storage of irrigation water in furrows to the total inflow) at the time of water arrival to the furrow tail end on site P2 was higher (30%) than site P1 (24%). The increased surface water collected at the tail end of site P2 caused dry bed middle at the head reaches. Comparison of results indicated increased surface water storage (Table 4.4) for larger furrows in comparison with smaller furrows at all sites indicating larger impact of furrow sizes on irrigation applications in small farms. For instance, at site P1 the surface storage fraction on the narrow furrow (Table 4.2) of NB was 20% (Table 4.4), which was 8% less than the wide furrow of WB with 28% surface storage at the same site. Similar trends were also identified at P2 (Table 4.4).

Table 4.4: Volume of surface water storage in furrows at the time of water arrival to tail end on three sites with two bed sizes in sandy clay loam, Pakistan (SD in brackets)

Performance Parameter	**P1**		**P2**		**P3**	
	NB	**WB**	**NB**	**WB**	**NB**	**WB**
Inflow rate ($L\ s^{-1}$)	2.95	4.86	1.62	2.71	2.36	2.96
Total inflow (m^3)	6.250 *(1.06)*	6.875 *(0.18)*	2.400 *(0.28)*	4.200 *(0.57)*	4.075 *(0.32)*	4.550 *(0.64)*
Surface storage (m^3)	1.225 *(0.04)*	1.950 *(0.07)*	0.875 *(0.04)*	1.000 *(0.28)*	1.175 *(0.18)*	1.300 *(0.00)*
Surface storage *(%)*	20	28	36	24	29	29

4.4 Discussion

4.4.1 Sites conditions and existing management

The soil moisture deficit *(SMD)* identifies the required irrigation application, which plays a key role in the irrigation performance evaluation and scheduling (Luis S 1999). The *SMD* values of ~100 mm under lengthy furrows of Australian farms are generally considered suitable to ensure irrigation schedules with long gap periods due to higher cost associated with the irrigation and to make effective use of the in-season rainfall. In contrast, the weekly canal irrigation schedules in north west Pakistan and the potential pan evaporation values of ~8 mm day^{-1} (Javaid & Khalid Usman 2009) during the summer season had made the 50 mm to 60 mm irrigation application very common. Our study showed the *SMD* values in the range of 76 to 100 mm in Australia and ~60 mm in north west Pakistan, which well represented the existing irrigation management and scheduling practices, thus contributed in the accurate benchmarking of the existing irrigation performance.

This study showed largely variable bed furrow dimensions spatially from farm to farm, which also indicated a temporal changing trend at different crop stages. For instance, the measured bed furrow dimensions significantly varied between both Australian farms and between two bed sizes on three Pakistani farms. The significantly larger furrow widths of WB in all Pakistani sites were due to the increased space between furrows, which easily accommodated the excavated soil compared with smaller space on NB. Bed furrow dimensions were also variable during the cropping season evidenced by the marginally deeper furrows in the early season (site P2) than for the late season (site P3). Variable bed furrow configurations of PRB have been shown to affect irrigation and crop performance (Hassan et al. 2005; Jin et al. 2007; Akbar et al. 2010), while the variable furrow dimensions of current study further increased its importance in irrigation management studies.

Furrow spacing and compaction by trafficking affected the water advance rate and inflow volume per unit area respectively. For instance, at site A1, the *Ta* during the first irrigation was 13% longer than for the second irrigation due to reduced soil infiltration capacity of relatively wider and compacted furrows that imparted greater momentum to flowing water during the second than the first irrigation. According to Allen and Musick (1992) furrow compaction can enhance the water advance up to 45%. At site A2, the furrows were compacted and wide (~61 cm TW) but the furrow spacing was small (100 cm) with a bed top width of ~39 cm, which caused flow crossing between the wet and dry furrows during the second irrigation, when soil was cracked, thus making the water advance rate slower. The furrow spacing impact on total inflow volume can be evidenced by the 32% larger irrigation application to the NB than for the WB, which closely agrees with the findings of Hassan et al. (2005) and Akbar et al. (2009) under similar short furrows.

This study showed a close relationship of the *Tco* with *Ta* under actual field conditions, as the majority of farmers followed this rule. However, the *Ta* was affected by several factors. For instance the *Ta* was increased at low *Q* and high infiltration capacity soil, which agrees with the findings of Allen and Musick (1992), availability of larger cracks under dry soil conditions (e.g. site A2 irrigation 2 caused 24% larger infiltration than irrigation 1), which agrees with the findings of Bautista and Wallender (1993b) and furrow surface roughness due to abundance of weed (e.g. site P1) and manual weeding (e.g. site P3). Other reasons may be the deeper root penetration of cotton and maize crops as mentioned by Meek et al. (1992) and Mitchell et al. (1995), (e.g. site P1 and P3 that were at flowering stage), which seems to have made the soil more infiltrative. Other evidence was the 34% longer *Ta* caused 15% longer *Tco* during the second than for the first irrigation at site A2. Impact of wheel trafficking on water advance was significant (21%), which can largely affect the irrigation performance under longer furrows as mentioned by Allen and Musick (1997). Thus, a large number of factors affected *Ta*. Therefore, development of guidelines to relate *Tco* to *Ta* under variable field conditions seems to be instrumental in enhancing the irrigation performance.

The observed low *DU* and reduced lateral infiltration under the short furrow lengths in Pakistan is a serious problem. The local farmers generally divide the field into smaller segments (15 to 20 m long) with bunds, which control the downstream flow of water to increase the opportunity time in the field head reaches and to reduce the tail end overtopping. This study revealed low *DU* as a consequence of poor irrigation management, reduced opportunity time, and short *Tco* due to the short furrow lengths. Consequently, the tail end was overtopped, while the head reaches received less irrigation depth, which is contrary to lengthy furrows (Trout 1990), thus the *DU* was negatively affected, and the poor lateral infiltration issue was exacerbated, at head reaches. Therefore, development of guidelines to improve *DU* can be beneficial in saving labour and in enhancing the lateral infiltration.

4.4.2 Renovation methods and irrigation performance interactions

This study showed variable renovation methods in actual practice. Renovation methods largely affect infiltration properties of soil (Akbar et al. 2010), which played a key role in the existing irrigation performance. For instance, the existence of loose soil conditions (during the first irrigation on site A1) due to deep cultivation prior to crop sowing made the furrow surface rough and permeable due to less compaction and trafficking, which enhanced the infiltration capacity of soil (9% increased after 900 minutes of infiltration opportunity time during the first than for the second irrigation), which conformed to the findings of Hulugalle et al. (2007). The loose soil conditions exacerbated the furrow filling with sediment. Consequently, a large area was inundated as a result of shallow furrow sizes, thus the water advance rate was retarded due to bed overtopping, and irrigation performance was negatively affected. On the other hand, shallow rotary hoeing (e.g. site P2) caused quicker *Ta* due to furrow sealing, which forced short *Tco*, and exacerbated the poor lateral infiltration issue. Poor lateral infiltration was also reported by Jin et al. (2007) and Akbar et al. (2007) in the sandy clay loam. Thus, appropriate renovation method seems vital for improving the soil infiltration properties, mitigating the poor lateral infiltration and for improving the irrigation performance.

The water advance along the furrows showed linear response with the square root of time (Philip 1969), which indicates that infiltration was dominated by capillary forces during the whole irrigation events for both soils. Thus the soil properties created by pore size distribution, clay type, soil structure and the stability of soil structure, a manifest of soil management, influenced irrigation performance. The practices that deliver water to the soil will also impact on irrigation performance.

4.4.3 Sites and irrigation performance interactions

This study revealed a poor irrigation performance in the majority of sites. However, the *Ea* identified in the range of 68% to 85% in Australia, was higher than reported in early studies (Raine & Bakker 1996; Smith et al. 2005) under sugarcane and cotton crops, which show improvement by using PRB. In Pakistan, *Ea* ranged from 45% to 99% with the majority of low *Ea* on NB and high *Ea* on WB. The major reasons were the current common over-irrigation practices in Australia and on NB (common bed size) in Pakistan. However, the high *Ea* values of WB were indicative of insufficient irrigation applications in sandy clay loam. The *Er* was above 96% in Australia due to excessive applications, while in Pakistan it was significantly reduced on WB than on NB. Current evaluations showed that the *DU* of all irrigation events in Australia were negatively affected by large cumulative infiltration at head reaches. In contrast, 67% of measured irrigation events in Pakistan (i.e. site P2 and P3) were affected by large cumulative infiltration at tail reaches than at head reaches. Further investigation revealed that *DU* was adversely affected in cases when cumulative infiltration was larger at the tail than in the head reaches. The low *DU* associated with high *Ea* for WB is consistent to Sepaskhah and Ghahraman (2004).

This study showed a higher potential for deep drainage due to irrigation excess that ranged 7 mm/irrigation to 47 mm/irrigation in Australia and up to 61 mm/irrigation in Pakistan, as the furrows were blocked at the tail end, which is consistent to the findings of Raine and Bakker (1996) and Smith et al. (2005). The recent increasing trend of land loss due to accelerated waterlogging and salinity problems in the Indus Basin (Yasin et al. 2002; Qureshi et al. 2008) can partly be attributed to the increased infield deep drainage losses under the most common NBs. Thus, deep drainage losses has a greater role in improving the current irrigation performance.

4.4.4 Irrigation management and performance interactions

This study indicated irrigation management as one of the major factors affecting the existing irrigation performance of PRB farming systems. The inflow volume, a manifest of the effectiveness of irrigation management for replenishing the soil moisture deficit with uniformity and efficiency (Khatri 2007; Smith et al. 2009), was variable at different sites for replenishing 76 mm to 100 mm *SMD* in Australia and

~60 mm in Pakistan, which showed that irrigation management is poor in both countries. The uninformed selection of *Tco*, based on either relative to water arrival to the furrow tail end, furrow filling, or any other farm manager preferences, negatively affected the irrigation performance. The farmer interest on both Australian sites was to replenish the *SMD* and to avoid dry field sections, however irrigation was applied for longer periods than required, which caused excessive deep drainage losses. Similarly, on site P1 in Pakistan fewer plots per turn were irrigated simultaneously, thus more *Q* per furrow was applied. However, at site P2 more plots were irrigated, thus less *Q* per furrow was applied.

The *Q* and *Tco* were revealed as perhaps the most important irrigation management factors. Inappropriate *Q* was also reported as the main reason of inefficiency by Raine and Bakker (1996) and Smith et al. (2005) in Australia and Kalwij (1997) in Pakistan. The selection of *Q* and *Tco* and their appropriate combination according to specific field conditions affected *DU* as mentioned by Raine and Bakker (1996). For instance, the higher *Q* with short *Tco* on WB at site P3 caused increased *DU*, when compared with NB at low *Q* with longer *Tco*. The low *Q* and prolonged *Tco* at site A2 negatively affected *DU* during the second more than for the first irrigation. Nevertheless, the current irrigation management was not capable of meeting the *SMD* for variable furrow spacing evidenced by 32% less irrigation application to WB (60 mm) than NB (88 mm). The reasons were attributed to ~9% larger *Tco* on NB than WB and ~52% larger *Q* on WB than NB under current management. Thus, development of decision support guidelines, especially for selection of *Q* and *Tco*, can be instrumental in improving the current irrigation performance.

Poor lateral infiltration under WB has been shown to adversely affect water productivity of many regions especially under the structurally unstable loamy soils with low lateral hydraulic conductivity (Hassan et al. 2005; Akbar et al. 2007; Jin et al. 2007). The current study revealed that soil moisture distribution was not uniform between the bed shoulder and middle on Vertisol and majority of WB in sandy clay loam. Beside the inappropriate soil management in both soils, one of the reasons was the reduced water application to WB than for the NB, thus the poor lateral infiltration issue was also exacerbated due to sub-optimal irrigation management.

4.4.5 Performance improvement options of existing permanent raised beds

The current soil management of PRB systems was dominated by annual or occasional deep ripping in Australia and seasonal shallow harrowing in Pakistan, which placed the sustainable crop production objective at risk. This study showed that poor soil management/renovation methods adversely affected the irrigation performance of PRB farming systems in both countries. Thus, cultivation practices/renovation of beds seem to be among the current major issues in both countries and therefore need a comprehensive evaluation for developing decision support guidelines according to the changed soil conditions.

This study showed that poor lateral infiltration in wide PRB farming systems is one of the main limiting factors in low infiltration soils and subsided beds constrained by the existing poor agronomic and irrigation management practices, which was also pointed out in several past studies (Lucy 1993; Akbar et al. 2007; Jin et al. 2007). The variable bed furrow configurations and resulting variable irrigation performance further complicate the lateral infiltration issue due to lack of understanding. Therefore, a comprehensive evaluation of lateral infiltration and its interaction with variable renovation methods and irrigation management needs to be undertaken for further refinement of understanding and for developing decision support procedures.

The existing irrigation performance is largely variable/poor in both countries and reasons are generally attributed to poor irrigation management and inappropriate soil management practices according to Gill (1994), Kalwij (1997), Raine et al. (1998), Smith et al. (2005) and Gillies (2008). Irrigation management strategies have been successfully tested by using simulation modelling in many past studies (Kalwij 1997; Raine et al. 1998; Smith et al. 2005) but have received only limited considerations under the actual field conditions of irrigated PRB in Australian farms in general and under Pakistani farms in particular. This study showed that current poor irrigation management seems to be a significant problem on variable soil management in both countries and needs to be evaluated for developing decision support guidelines for the improved performance of existing PRB farming systems.

4.5 Conclusions

The existing soil and irrigation management practices of PRB are sub-optimal in both Australia and Pakistan, thus irrigation performance is poor. Several important conclusions emerged from this benchmarking study as listed below:

- The existing soil management of PRB practices involve intensives tillage, which is destructive to soil structure, thus negatively affecting PRB performance and placing the sustainable crop production at risk.
- The current irrigation performance of PRB is poor demonstrated by *Ea* down to 68% in Australia with up to 47 mm/irrigation deep drainage losses and down to 50% in Pakistan with up to 61 mm/irrigation deep drainage losses and the current irrigation management seems to be largely poor.
- Wide PRBs are more susceptible to poor lateral infiltration, especially under sandy clay loam, while renovation methods and irrigation management seems to have a greater role in lateral infiltration of wide PRBs.
- The water advance showed linear response with the square root of time, which shows that capillary forces dominated in infiltration. Thus, pore sizes and their distribution in the beds, a manifest of soil structure and soil management, either side of the furrow control irrigation performance.
- The SIRMOD evaluation was effective in benchmarking the existing irrigation performance, thus can be instrumental in mitigating the excessive deep drainage losses and in controlling the frequent under-irrigation practices on wide PRBs. However, the uniform soil moisture distribution assumption between the wetted furrows seems detrimental for wide PRBs.

Developing decision support guidelines for selection of appropriate renovation methods, irrigation management and field design of PRBs seems to be very beneficial for improving the current raised bed performance in both countries (Australia and Pakistan).

CHAPTER 5: Impact of PRB renovation on irrigation performance and productivity

5.1 Introduction

Renovation methods of PRB systems vary around the globe (Roth et al. 2005), and depend on traditional practices, farmer preferences, crop type, and available machinery. The effect of renovation methods on irrigation performance has generally not been studied in previous research. Hence, detailed studies on the management of soil structure and the effects on hydraulic properties and performance of PRB in an irrigation environment are sparse. The preliminary evaluation of irrigation performance reported in Chapter 4 suggested that improper renovation of beds is one of the main factors in the performance of existing PRB systems. Tillage has been shown to affect soil hydro-physical, chemical and biological properties (Smith et al. 1983; Hulugalle et al. 2004; Tullberg 2010). Thus, if PRB renovations using tillage affect soil properties then renovation would also be expected to influence irrigation performance, crop yield, and *WP*. This chapter describes field experiments to evaluate the comparative *WP* performance of different PRB renovation methods on an irrigated Vertisol. Chapters 6 and 7 report the investigation of lateral water movement into the beds.

5.2 Material and methods

5.2.1 Site description, treatments and experiment layout

The field trials for this experiment were conducted at the Australian field site A1 (as described in Chapter 3) used in the benchmarking study (Chapter 4) and commenced after the soybean crop. The experiments were conducted over four seasons (from 2010 winter to 2012 summer) with two summers and one winter crop, and with one winter fallow. The crops were consecutively 2010 wheat, 2011 hemp, and 2011 corn.

Three PRB renovation treatments were applied to the one season old PRB after the 2009 soybean season. The three treatments were:

NT: No tillage: The beds were not disturbed and furrows were cleaned with bed former. Only the soil in the sown rows was disturbed by the seeder during planting (Figure 1a).

SC: Shallow cultivation: The whole top of the bed cultivated to a depth of about 10-15 cm without relocating furrow positions using a six metre wide cultivator prior to furrow cleaning with bed former (Figures 5.1b and 5.2a),

BP: Blade ploughing: The furrows were reshaped and the soil in the bed opened by horizontal blades that were passed through the base of the bed at ~30 cm depth opening the soil without disturbing the roots of the previous crop and without causing any soil inversion using a 200 cm wide blade plough (Figures 5.1c and 5.2b).

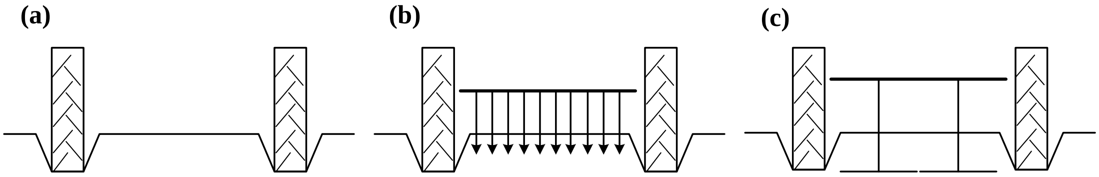


Figure 5.1: Layout of three PRB renovation methods including (a) NT: no tillage, (b) SC: shallow cultivation and (c) BP: blade ploughing treatments

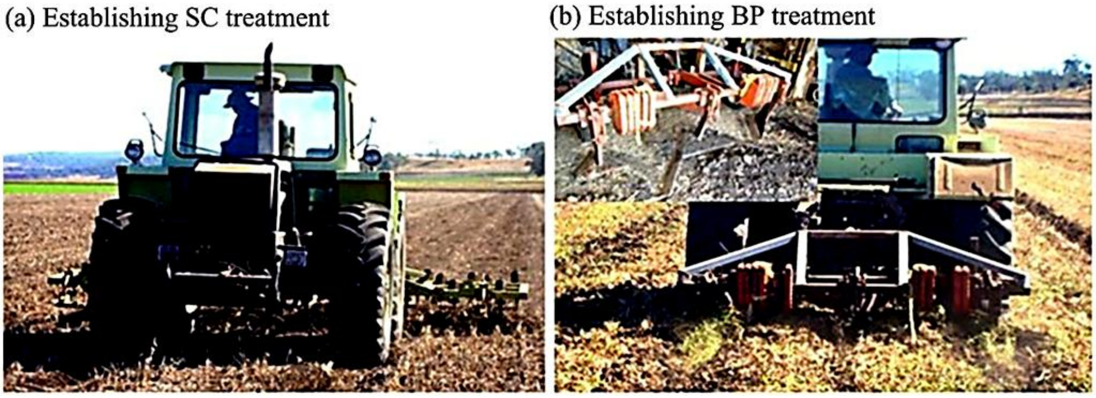


Figure 5.2: Establishment of two renovation treatments for 2010 wheat crop after 2009 soybean harvest at site A1, Marinya farm, Cambooya, Australia

The three treatments were thrice replicated using a randomised block design as shown in Figure 5.3. Each treatment consisted of three beds surrounded by a three bed wide buffer area to avoid interference of treatments. The two beds of buffer area were treated similar to respective adjacent treatments to reduce the influence of edge effects across the treatment furrows and beds.

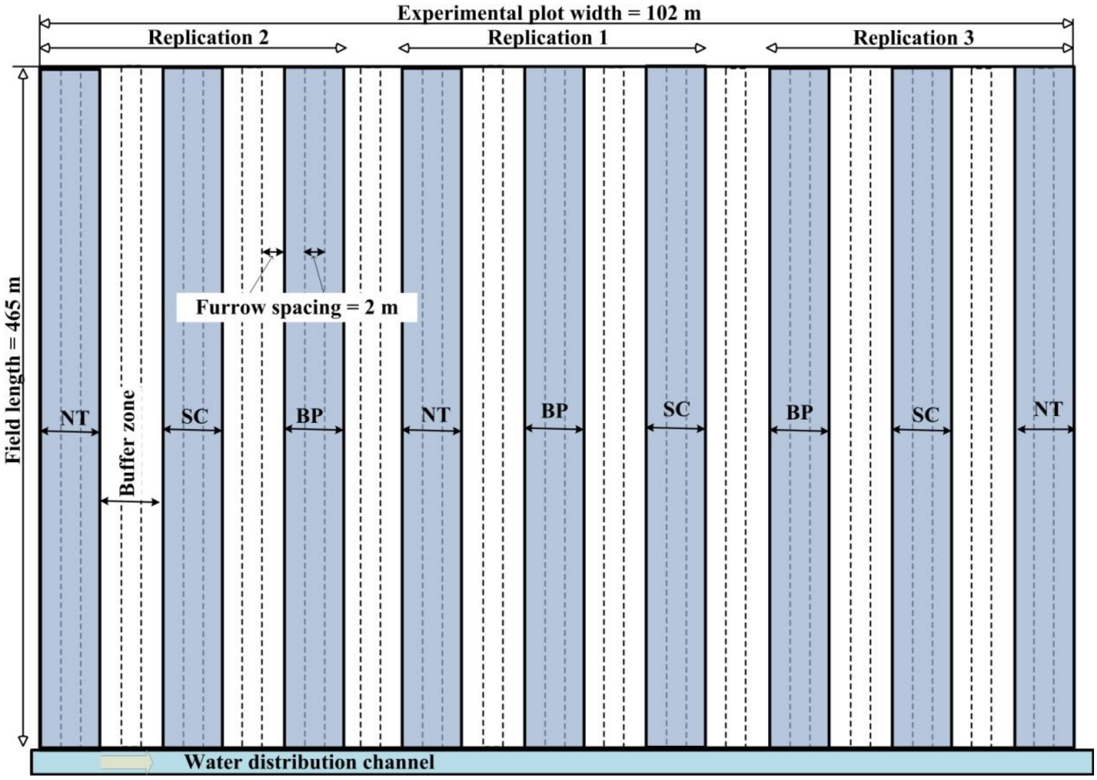


Figure 5.3: Layout of bed renovation treatment plots at site A1, Australia

The various soil tillage treatments applied at the start of each season for each treatment are described in Table 5.1.

Table 5.1: Soil tillage applied to each treatment over three cropping seasons at site A1

Crop	Year	Renovation treatment		
		NT	**SC**	**BP**
Wheat	**2010**	Furrow reshaped Soil in bed undisturbed	Furrow reshaped Beds cultivated to 15 cm depth	Furrows reshaped Beds blade ploughed at 30 cm depth
Hemp	**2011**	Furrow reshaped Soil in bed undisturbed	Furrow reshaped Soil in bed undisturbed	Furrow reshaped Soil in bed undisturbed
Corn	**2011**	Furrow reshaped Soil in bed undisturbed	Furrow reshaped Beds cultivated to 15 cm depth	Furrow reshaped Beds blade ploughed at 30 cm depth

Note: *Blade ploughing for 2010 wheat used blades vertically inclined at an angle ~25 degrees to the direction of travel and backward rake angle of ~15 degrees. Blade ploughing for 2011 corn used blades with a vertical inclination of zero degrees to the direction of travel and a backward rake angle of 35 degrees.*

5.2.2 Agronomic management practices

The first season treatments were established on one season old PRB and wheat was planted on 7 June 2010. Eight rows of wheat per bed on 20 cm row spacing were planted at a seed rate of 74 kg ha^{-1} using a 6 m wide seed drill equipped with double disc openers (Figure 3.3b). The same quantities of inputs (seed, fertiliser, herbicides) were applied to all treatments. Nitrogen was applied as urea at a rate of 74 kg ha^{-1} at sowing and again at 100 kg ha-1 on 10 July 2010. After planting, glyphosate isopropylamine was sprayed at prescribed rate on 9 June 2010 to reduce weeds. Only a single irrigation was applied during the cropping season (on 19 June 2010) due to the wet winter weather. The 2010 wheat crop was harvested as hay at ~5 cm above ground surface on 15 November, 2010.

Summer crop sowing in 2010-11 was delayed due to broad scale severe regional flooding. The hemp crop was planted late on 26 January 2011 without disturbing any treatment, due to wet soil conditions. Furrows of all treatments were cleaned (excavated) after sowing. Urea was applied at the rate of 74 kg ha^{-1} at sowing and 100 kg ha^{-1} on 16 February 2011. Four irrigations were applied during the season. The initial two irrigations were applied quickly at low *SMD* early in the season in response to poor crop establishment observed in the middle of the bed. The third and fourth irrigations were applied at high *SMD*. The 2011 hemp crop was harvested on 15 May 2011 leaving less than 5% crop residues in the field.

The third season corn crop was planted on 3 October 2011 after a winter fallow on freshly renovated beds. The BP treatment was applied with a newly designed bed former with two sharp horizontal blades for reducing soil disturbance. Round up weedicide was sprayed at the prescribed rate before sowing. Two rows of corn were planted on the bed shoulders at 100 cm row spacing and ~20 cm plant to plant spacing. Liquid nitrogen fertiliser was applied at prescribed commercial application rates at crop early stage. Urea fertiliser was applied at 74 kg ha^{-1} before first irrigation and 100 kg ha^{-1} before second irrigation. Two irrigations were applied, the first on 12 November 2011 and the second on 7 January 2012. The 2011corn crop was harvested on 15 February 2012 leaving ~5 cm crop residues above ground surface. All crops in all treatments were sown with the same double disc drill.

5.2.3 Sampling and instrumentation

Weather data including rainfall, temperature, humidity, and wind speed were recorded using a solar powered automatic weather station located adjacent to the experimental area during the three cropping seasons. The furrow dimensions data including TW, MW, BW and D (Figure 3.2c) were recorded at the head, middle and tail sections of each treatment at the time of sowing before irrigation, after irrigation and at harvest of all three seasons. Irrigation data including *Q*, water advance at multiple points along the furrow at 100 m intervals and *Tco* were recorded using IRRIMATE$^{\text{TM}}$ tools including siphon flow meters, advance sensors (shown in Figure Figure 5.4 and described in section 3.6.3.1).

Figure 5.4: Overbank systems and IRRIMATE$^{\text{TM}}$ meters for measuring inflow rate. Insert shows water advance sensors and soil moisture sensors layout during irrigation. Photo taken during 2010 wheat season at site A1, Cambooya, Australia

Volumetric soil moisture content was monitored using three capacitance probes (Sentek EnviroSCAN$^{®}$) per treatment during all seasons from sowing to harvest. These sensors were installed at 50 m distance from head channel in replication 2 only (according to the layout shown in Figure 3.8 and described in section 3.6.2). During the 2010 wheat season the sensors were positioned to record at profile depths of 10, 20, 30, 40, 60, 80 and 100 cm as shown in Figure 3.8. During the 2011 hemp and 2011 corn seasons the sensors were positioned at 10, 20, 30, 40, 70 and 100 cm depths. This set up provided a complete record of soil moisture variation at 10 minute intervals across a half bed width and up to 100 cm depth during all three cropping seasons. Gravimetric soil moisture and soil bulk density were measured in the 0-30 cm surface profile at 10 cm intervals using the thermo-gravimetric method described in section 3.6.1 (Chapter 3). Three replications were collected in each treatment at sowing, before irrigation, after irrigation and at harvest.

During the 2010 wheat season, the plant density (number of plants per metre row length), average plant height per row, and total plant biomass data were collected near maturity stage at harvest using a sample plot size of 2 m x 1 m. Three plant samples, one per each bed in a treatment, were collected from the head, middle, and tail sections of all treatments. The sample size spanned the whole or half bed width to account for possible growth variations across the bed while the 1 m perpendicular length of sample was adequate (Payero & Harris 2010) to cover spatial variability and to make the management possible with limited resources. These samples were packed in paper bags. The green weight of all samples was recorded and the samples were placed in an oven at 45^0C. The oven dry weight of the samples was checked twice daily after 5 days of drying to ascertain any further weight loss. The final dry weight was recorded on the seventh day when no further weight loss was observed.

The plant height, plant density, and dry plant biomass data for the 2011 hemp crop were recorded at crop harvest from each treatment using sample plot size of (1 m x 1 m, spanning half bed width) with three replicates at head, middle and tail sections of each treatment plot. The above data for each one metre row length of the three rows per sample were also recorded separately to identify yield variations across the bed width. The samples were air dried for two weeks and the oven dry weight of samples was recorded.

The 2011 corn plot samples from a 1 m section of row were collected at harvest. Samples were taken at the head, middle, and tail sections of the treatment plots with three replicates per treatment. The number of plants and the three plants height within the one metre row were also recorded. After drying the ears, the grain was separated from the husk and then placed in an oven at 45^0C until fully dried. The dry weight of grain and dry plant biomass were recorded separately. Dry weight of 100 grains per sample, randomly selected, was also recorded.

5.2.4 Irrigation performance and water productivity

Irrigation management was based on controlling *Q* and *Tco.* Irrigation application was stopped when the furrows were filled with water and before the beds overtopped at the bottom end of the field. Irrigation was generally scheduled to occur at 65% depletion level of soil moisture in the 100 cm depth profile during the cropping season. However, due to water restrictions in the locality and demand for water in other parts of the farm, the irrigation scheduling plan was moderately adjusted on occasions. Irrigation management aimed to maximise *WP* with management adjusted based on expertise from previous irrigations results. In particular the inflow rate to the BP furrows was increased relative to the other treatments by increasing the head in the head channel. While field design limitations restricted adoption of optimum *Q*, *Tco* and total volume of irrigation applied (based on calculations of *SMD* prior to irrigation) were monitored and managed through observation.

The irrigation characteristics of four furrows were measured in each replicated treatment plot. The irrigation performance was determined using the procedure described in Chapter 3 and Chapter 4. The infiltration parameters were determined by adjusting both the f_0 and Manning's 'n' coefficient in the IPARM model to ensure that the observed water advance matched the simulated advance. The f_0 ranged from 0.0001 to 0.00005 during the 2010 wheat season and was 0 during the 2011 hemp and 2011 corn seasons. The irrigation performance indicators (*Ea*, *Er*, *DU* and total inflow volume applied) were evaluated using the SIRMOD (III) model. The furrows were blocked at the tail end thus deep drainage was the only source of loss, which was calculated according to equation 3.1 (Smith et al. 2005). Calibration of IPARM and SIRMOD for the three seasons is provided in Figure B3 (Appendix B).

The input water productivity (*WP*) was calculated as the ratio between the dry weight of crop yield (grain or straw) per unit area and total water applied during the cropping season. The total water applied was calculated by adding the seasonal rainfall (assumes all rainfall is effective) and total irrigation water applied during the season. Statistical analysis was conducted according to the procedure described in section 3.7. The experimental details of measurements during the three cropping seasons for three PRB renovation treatments are summarised in Table 5.2.

Table 5.2: Experimental details of measurement of soil properties, irrigation, crop yield and water productivity per each PRB renovation plot during three cropping seasons at site A1, Australia (SM = soil moisture, BD = bulk density).

Measurements	Wheat 2010	Hemp 2011	Corn 2011
Crop sowing date	7 June 2010	26 January 2011	3 October 2011
SM and BD			
No of samples & position	3 – 1 each @ plot head, mid & tail	3 – 1 each @ plot head, mid & tail	3 – 1 each @ plot head, mid & tail
Sampling depths	0-10, 10-20 & 20-30 cm	0-10, 10-20 & 20-30 cm	0-10, 10-20 & 20-30 cm
Grav. SM & BD method	Undisturbed cores 5 cm diameter. x 5 cm length	Undisturbed cores 5 cm diameter. x 5 cm length	Undisturbed cores 5 cm diameter. x 5cm length
Volumetric SM method	Gravimetric SM x BD	Gravimetric SM x BD	Gravimetric SM x BD
Sampling time	Sowing, pre & post irri. & harvest	Sowing, pre & post irri. & harvest	Sowing, pre & post irri. & harvest
SMD prior to irrigation			
No of samples & position	1 – @ 50 m distance from plot head	1 – @ 50 m distance from plot head	1 – @ 50 m distance from plot head
Distance from furrow centre	33, 67 and 100 cm	33, 67 and 100 cm	33, 67 and 100 cm
Profile depth	0-100cm	0-100 cm	0-100cm
Equipment	Sentek EnviroSCAN®	Sentek EnviroSCAN®	Sentek EnviroSCAN®
Method	*SMD*=FC – Antecedent SM	*SMD*=FC – Antecedent SM	*SMD*=FC – Antecedent SM
Irrigation data			
No & position of furrow dimensions	3 – 1 each @ plot head, mid & tail	3 – 1 each @ plot head, mid & tail	3 – 1 each @ plot head, mid & tail
No & position of inflow rate	1-siphon flow meter per treatment	1-siphon flow meter per treatment	1 - siphon flow meter per treatment
No & positions of water advance	5 – @ ~100 m distance along furrow	5 – @ ~100 m distance along furrow	5 – @ ~100 m distance along furrow
No of furrows measured	Four furrows per treatment plot	Four furrows per treatment plot	Four furrows per treatment plot
Time to cut-off reading	One per treatment plot	One per treatment plot	One per treatment plot
No of irrigations measured	one	Four	two
Harvest data			
No of samples & positions	9 – 3 each @ plot head, mid & tail	9 – 3each @ plot head, mid & tail	9 – 3 each @ plot head, mid & tail
Sample size	2 m x 1 m (span whole bed width)	1 m x 1 m (span half bed width)	1 m x 1 m (span half bed width)
Data measured	Tillers density, height and dry biomass	Plant density, height and dry biomass	Plant density, height, dry biomass & 100 grain weight
Crop harvest date	15 Nov 2010	15 May 2011	15 Feb 2012

5.3 Results

5.3.1 Weather conditions

The winter (2010 wheat season) had an average temperature of 13^{0}C, average humidity of 72% and total rainfall of 196 mm. During the summer (2011 hemp and 2011 corn) seasons the average temperature was ~17^{0}C and average humidity was ~69%. The total rainfall was 228 mm and 302 mm during the 2011 hemp and 2011 corn seasons, respectively. The majority of the individual rainfall events applied < 10 mm, but a maximum of 32 mm, 25 mm and 40 mm daily rainfall was recorded once during the 2010 wheat, 2011 hemp and 2011 corn seasons, respectively. The 2010 wheat harvest was followed by severe weather conditions, which delayed the 2011 hemp sowing. A total of 211 mm rainfall was recorded in the last half of December 2010, with 132 mm rain in a two day period (27 to 28 December, 2010). Severe flooding occurred in the surrounding areas and overland flow occurred in the experimental area. A monthly record of weather data is provided in Table A3 (Appendix A).

5.3.2 Observation of machinery operations

The available machinery consumed one extra machinery operation time and energy per bed for the SC and BP treatments compared with the NT treatment prior to furrow cleaning. The draft/energy required per operation was also higher for establishing the BP treatment (according to the farmer), especially during the 2010 wheat season due to inadequate machinery design and set up. Field coverage of the available single bed per pass machinery for the BP treatment was lower compared with the three beds per pass machinery for the SC treatment. Moreover, the operator was comfortable sowing the NT treatment with the available double disc, zero till seeder. In contrast, the loose soil on the SC and BP treatment beds caused hindrance during sowing operations. Thus, machinery design, set up and type of renovation method affected the machinery operation performance at this site.

The major hindrance faced was the frequent seed drill clogging and reduced steering control caused by the loose soil conditions when applying the SC and BP treatments. For the 2010 wheat BP treatment, the cutting edge sharpness and angle on the available thick cutting blade was not appropriate to the soil conditions. This resulted in occasional pulling out and dragging of the previous soybean crop stubble affecting the bed and furrow shapes as well as the bed surface roughness. This issue was resolved for the 2011 corn BP treatment when a new bed former (adequately designed and set up) was used.

Another problem was the insufficient strength of the loose Vertisol soil to withstand the pressure inserted by the double discs, thus making it difficult for the operator to keep a uniform seeding depth and seed rate for the SC and BP treatments. Moreover, the closely spaced (20 cm) discs of zero till seeder did not provide sufficient clearance for the passage of loosely held stubble trash, especially on the SC treatment. This caused occasional accumulation at the front of the disc opener for both SC and BP treatments.

5.3.3 Effect of PRB renovation method on bed and soil properties

5.3.3.1 Furrow dimensions

The furrow dimensions varied between tillage treatments and seasons (Table 5.3). The largest furrows during the 2010 wheat and 2011 corn seasons were on the BP and NT treatments with the smallest on the SC treatment. The difference in furrow dimensions between the tillage treatments was negligible during the 2011 hemp season when no renovation occurred. Furrow top widths were 8 and 12 cm narrower for NT and SC respectively, compared with BP furrows during the 2010 wheat season. Furrows were also 2 cm and 3 cm shallower for NT and SC treatments compared with the BP treatment during the 2010 wheat season. During the 2011 corn season the furrows were wider on BP followed by NT and then SC treatment as given in Table 5.3.

Table 5.3: Average furrow dimensions (according to layouts shown in Figure 3.2c) under three PRB renovation treatments during each cropping seasons (SD in brackets)

Crops	Treatment	Average furrow configurations (cm)				L (m)
		TW	MW	BW	D	
Wheat 2010	**NT**	53	35	15	12	465
		(2)	*(2)*	*(2)*	*(1)*	
	SC	49	32	16	11	
		(3)	*(2)*	*(2)*	*(1)*	
	BP	61	39	19	14	
		(2)	*(3)*	*(3)*	*(1)*	
Hemp 2011	**NT**	47	32	20	13	465
		(5)	*(2)*	*(5)*	*(1)*	
	SC	48	34	22	13	
		(6)	*(3)*	*(3)*	*(1)*	
	BP	49	35	21	13	
		(6)	*(3)*	*(4)*	*(3)*	
Corn 2011	**NT**	54	41	20	13	465
		(3)	*(4)*	*(4)*	*(1)*	
	SC	51	37	25	11	
		(5)	*(4)*	*(5)*	*(1)*	
	BP	58	44	29	11	
		(4)	*(4)*	*(5)*	*(1)*	

The furrow dimensions varied during the 2010 wheat season after fresh renovation (Figure 5.5). In general, the furrow top width and depth decreased over time. In contrast, the furrow middle and bottom widths increased over time. This change continued into the following 2011 hemp season, which was not renovated. The furrow top width was reduced by ~11%, 2%, and 20% for the NT, SC, and BP treatments respectively from the 2010 wheat to 2011 hemp seasons. The full data record of furrow dimensions is provided in Table A4 (Appendix A).

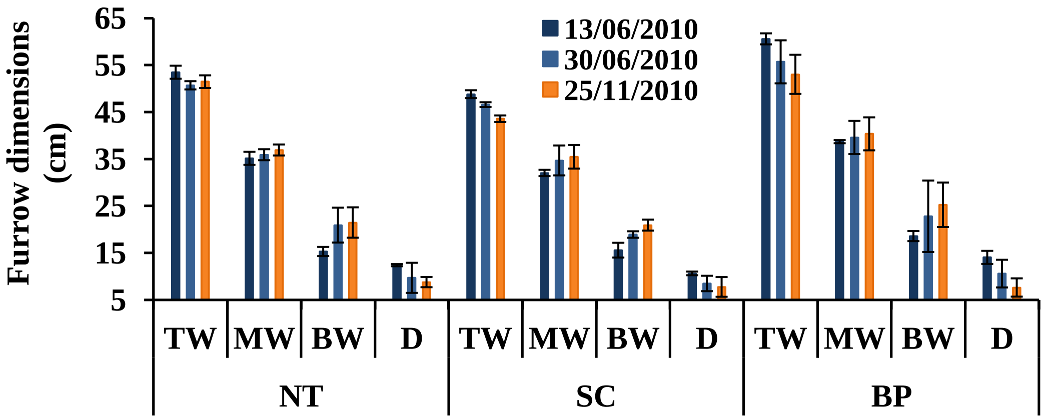


Figure 5.5: In-season variations in furrow dimensions (TW = top width, MW = middle width, BW = bottom width and D = furrow depth) during 2010 wheat season (vertical bars show SD)

5.3.3.2 Bulk density

The average bulk density (gm cm^{-3}) for the 2010 wheat season of one season old PRB over 0-30 cm depth was significantly (*P=0.05*) lower with BP when compared with NT (Figure 5.6). However, the bulk density of the SC treatment was not significantly (*P=0.05*) different from either the NT or the BP treatments.

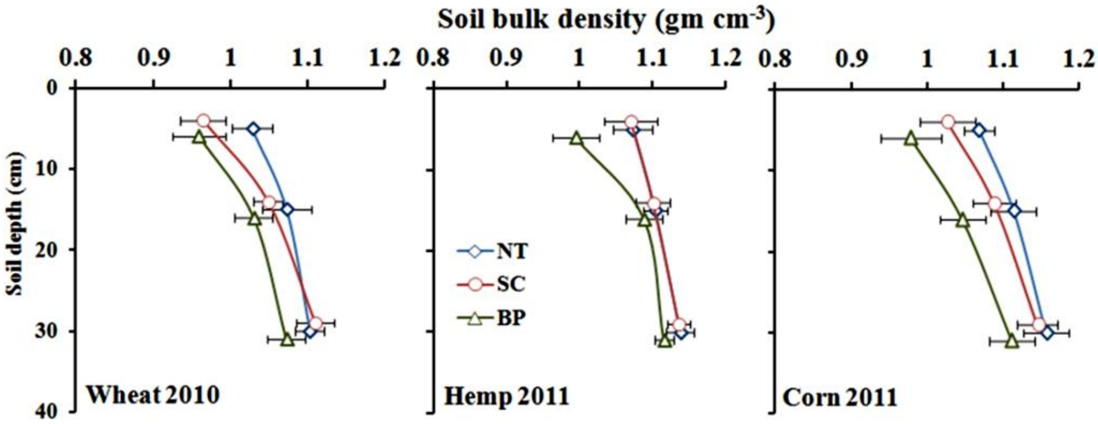


Figure 5.6: Average seasonal bulk density of three renovation treatments during three cropping seasons at site A1, Australia (Vertical bars show SDs)

The average seasonal bulk density over 0-30 cm for the 2011 hemp season of BP was still significantly (*P=0.05*) lower than the NT and SC treatments (Figure 5.6) while this difference was not significant between NT and SC treatments. However, the bulk densities increased up to 6% for SC (~11% increase in 0-10 cm depth), followed by BP (4% increase) and the least with NT (3% increase) from wheat to hemp season.

The average seasonal bulk densities for the 2011 corn season over 0-20 cm depth were significantly (*P=0.05*) lower with BP than for the other two treatments (Figure 5.6). Bulk densities over 0-30 cm depth were similar for SC and BP and were 2% and 6% respectively, lower than NT. The seasonal increase in bulk density during the 2011 corn was more for SC (~8%) than the other two treatments (~5%).

The results showed a significantly *(P=0.05)* higher and similar bulk density in the 0-20 cm depth for the NT and SC treatments respectively compared with BP when renovation was freshly applied (i.e. wheat and corn seasons). However, the bulk density of 20-30 cm depth was similar between treatments during all seasons.

The soil moisture did not confound the treatment effect on bulk density because sampling was done when the soil moisture was not significantly *(P=0.05)* different between treatments. However, the bulk density tended to reduce at high moisture level and to increase at low moisture level during the cropping seasons irrespective of treatment differences Table A6 & Figure A2 (Appendix A).

5.3.3.3 Soil moisture deficit and infiltration properties

The *SMD* was ~100 mm prior to irrigation for all treatments during the 2010 wheat season (Figure 5.7). During the 2011 hemp season the soil was dry at the surface (0-10 cm) and wet at deeper depths in early crop season. The *SMD* was lower (~40 mm) prior to the initial two irrigations and higher (~100 mm) prior to the last two irrigations. The *SMD* in 100 cm depth prior to irrigation during the 2011 corn season was lower (60-74 mm) during the first than the second irrigation (106-134 mm).

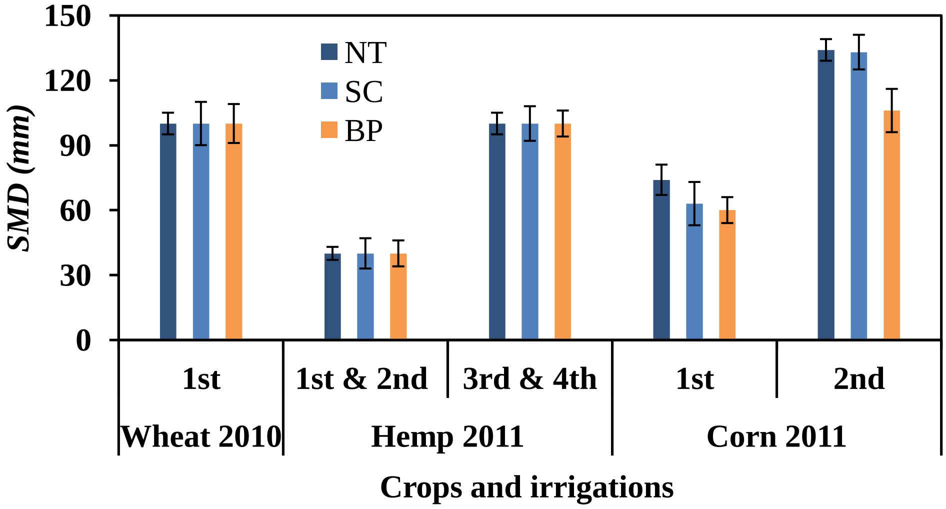


Figure 5.7: Average soil moisture deficit in 100 cm depth prior to irrigations during the three seasons (vertical bars show SD)

The average cumulative infiltration depths were plotted against time for all treatments and crop seasons (Figure 5.8). Infiltration was significantly higher on freshly applied renovation treatments than on un-renovated beds. There were also larger differences between the renovation treatments when renovation was freshly applied. For instance, average total cumulative infiltration after fresh renovation (e.g. 2010 wheat and 2011 corn seasons) was significantly *(P=0.05)* higher for BP than for the other treatments. The BP treatment infiltration after 400 minutes was 23%

higher than the NT (89 mm). The beds were not renovated during the 2011 hemp season and the cumulative infiltration was significantly lower (48-55%) than during the other two crop seasons. The differences in furrow infiltration affected the advance rate of irrigation water in furrows during the three cropping seasons as shown graphically in Figure A3-A4 (Appendix A).

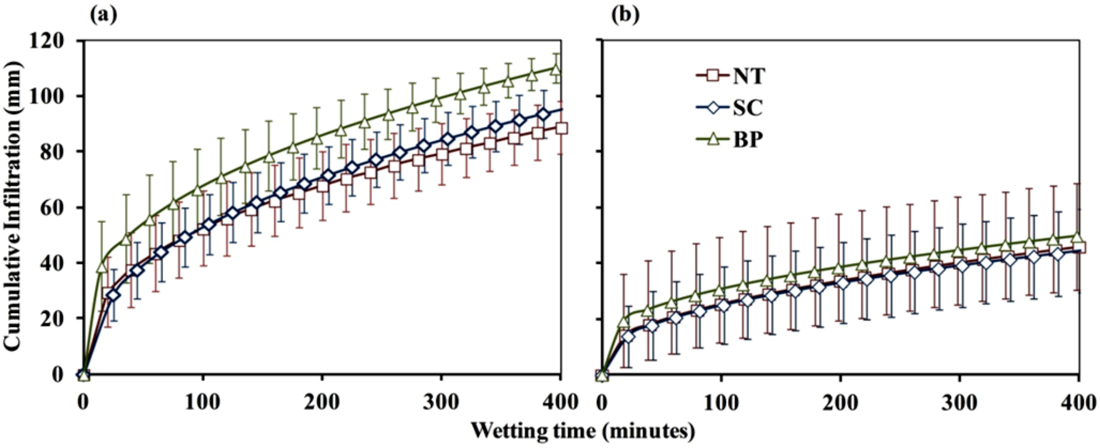


Figure 5.8: Average cumulative infiltration under (a) freshly applied renovation treatments during 2010 wheat and 2011 corn (average of one irrigation to wheat and two irrigations to corn) crop seasons and (b) un-renovated beds during 2011 hemp season (average of 4 irrigations) at given time at site A1 (Vertical bars show SD)

The lateral wetting front movement into the centre of the bed was largely influenced by the renovation methods during the 2010 wheat season. The wetting front took ~10, ~9 and ~6 hours to wet the bed middle to field capacity (FC) for NT, SC and BP treatments respectively (Figure 5.9). The majority of the bed width was wetted above field capacity within 10 hours in all three treatments. However, the wetting of the bed profile continued till irrigation cut-off time.

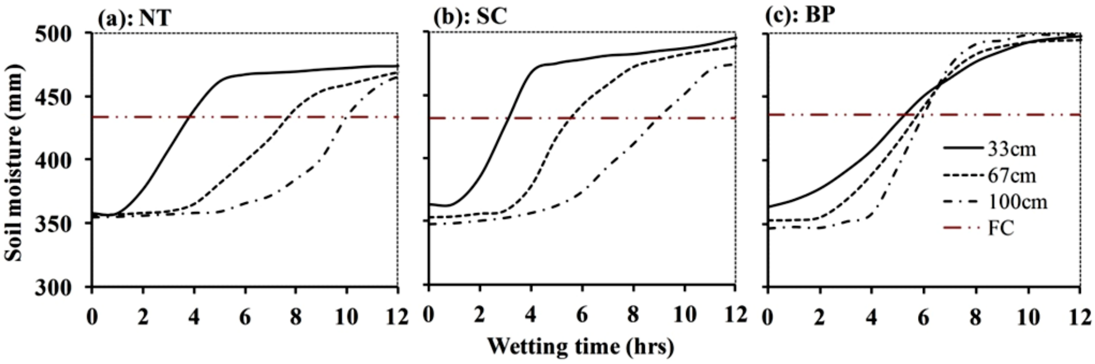


Figure 5.9: Volumetric soil moisture (100 cm depth) at given distances from furrow centre during irrigation to 2010 wheat crop at site A1, Australia (FC = field capacity)

During the 2011 hemp season, the un-renovated beds were settled while compaction and sealing of furrows were obvious and *SMD* was less during the initial two irrigations. Therefore, lateral infiltration was poor and the wetting front could not reach to the centre of the bed during the first two irrigations. The lateral infiltration was marginally increased during the subsequent third and fourth irrigations due to cracking but *SMD* in bed middle was still not fully met (Figure C1:Appendix C).

The first irrigation in the 2011 corn season was applied at a *SMD* of 60-70 mm prior to the first irrigation. Lateral infiltration was slow for the NT and SC treatments. However, the BP treatment indicated faster lateral wetting (~6 hrs) into the middle of the bed (Figure 5.10). The *SMD* was higher (~130 mm) before the second irrigation and the lateral infiltration was quicker due to the presence of soil cracks. More detailed analysis of the lateral infiltration is provided in Chapter 6 and 7.

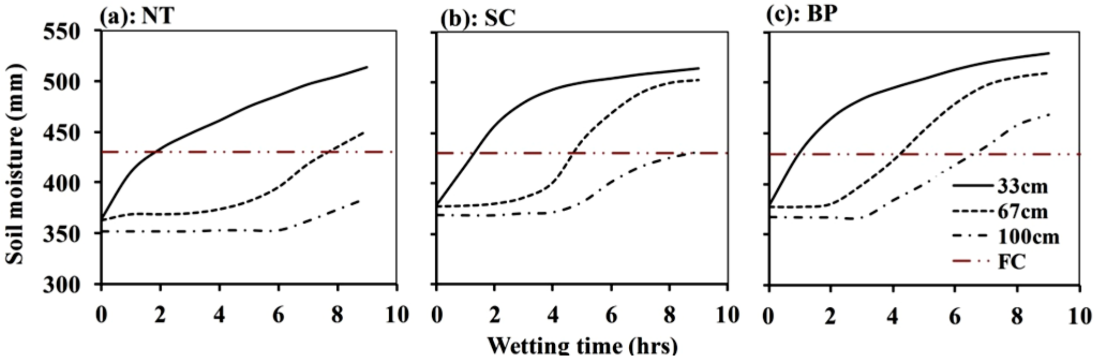


Figure 5.10: Volumetric soil moisture (100 cm depth) at given distance from furrow centre during the first irrigation to 2011 corn at site A1, Australia

5.3.4 Water applied and profile water content

A single irrigation was applied twelve days after sowing (Figure 5.11a) during the first 2010 wheat season. The average irrigation volume applied was 103, 116 and 160 mm to the NT, SC, and BP treatments, respectively (Table 5.4). Four irrigations were applied (Figure 5.11b) during the 2011 hemp season. Total irrigations of 191 mm (29, 31, 68, and 63 mm) was applied to NT, 204 mm (28, 39, 70 and 67 mm) to SC and 212 mm (26, 42, 70 and 75 mm) to BP treatment. Two irrigations (Figure 5.11c) of 224 mm (100 and 124 mm) to NT, 244 mm (107 and 137mm) to SC and 248 mm (126, 122mm) to BP during the 2011 corn season.

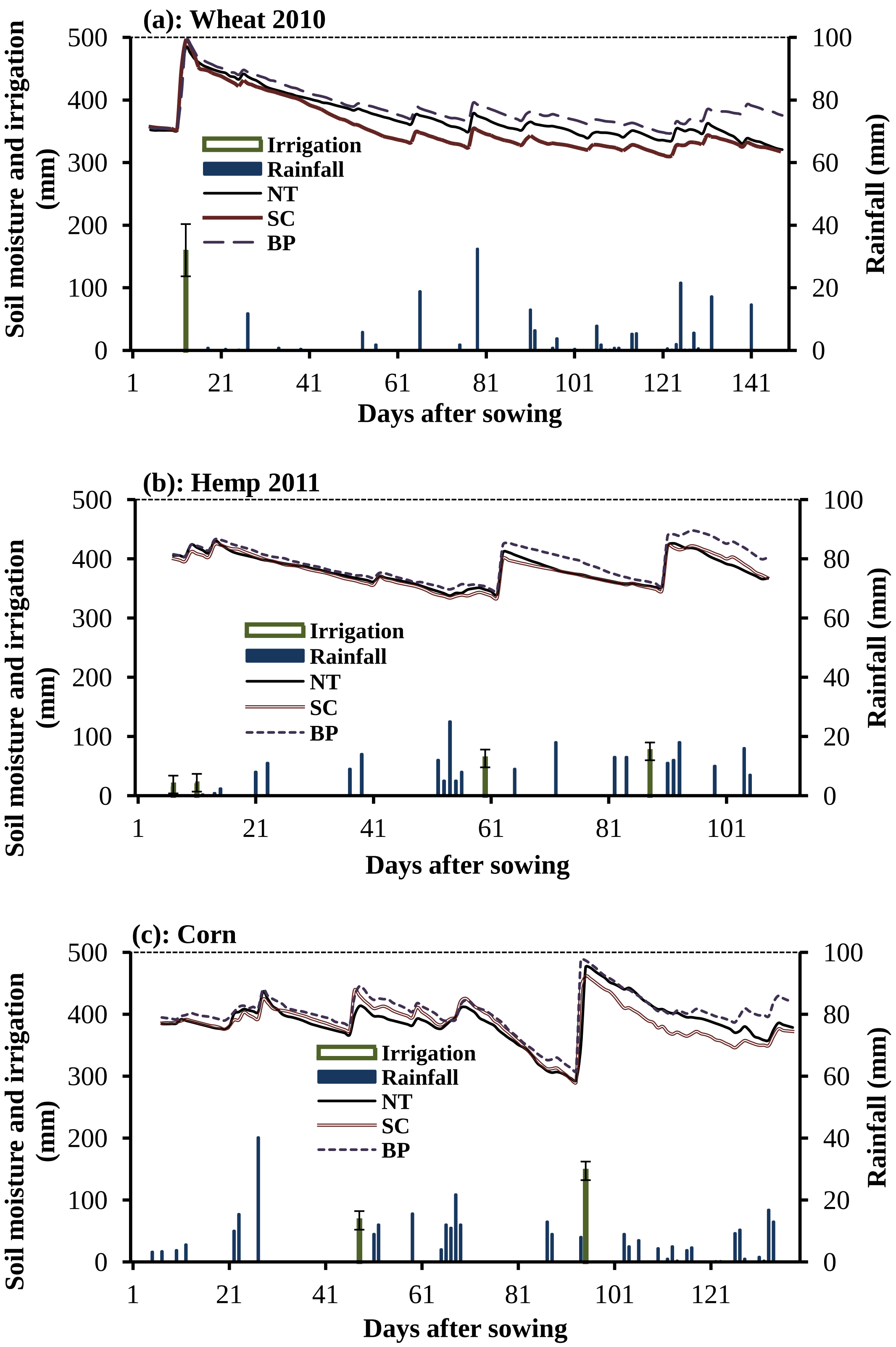


Figure 5.11: Average daily volumetric water content in 100 cm profile, irrigation applied and rainfall during three cropping seasons under three PRB renovation treatments on a Vertisol. (Vertical bars show SD in irrigations applications between treatments)

Table 5.4: Total water applied (*TWA*) during the three cropping seasons in three PRB renovation methods at site A1, Cambooya Australia.

Crop	Treatment	Irrigation (mm)	Rainfall (mm)	*TWA* (mm)
Wheat 2010	**NT**	103 *(6)*	196	299
	SC	116 *(3)*	196	312
	BP	160 *(9)*	196	356
[a]Hemp 2011	**NT**	191 *(16)*	228	419
	SC	204 *(18)*	228	432
	BP	212 *(21)*	228	440
Corn 2011	**NT**	224 *(14)*	302	526
	SC	244 *(16)*	302	546
	BP	248 *(17)*	302	550

[a] *SC and BP treatments were not freshly applied and were only furrow cleaned*

The 2010 wheat was harvested early as hay, therefore it required less irrigation applications. Less irrigation was applied to the 2011 hemp due to large residual soil moisture at planting and low farm irrigation water availability at crop maturity. In 2010 wheat fresh renovation with BP resulted in 19% higher total water input (Table 5.4), SC 5% higher-similar to that for the non-renovated 2011 hemp; in the 2011 corn fresh renovation only resulted in about 5% higher total water input for both SC and BP-similar to that in the non renovated beds for the non renovated 2011 hemp.

The volumetric soil moisture content in the beds was consistently higher for BP than for the NT and SC treatments during the experiments (Figure 5.11). The bed middle (67-100 cm from furrow centre) was relatively drier than the bed shoulder on both NT and SC treatments and vice versa for BP during 2010 wheat and 2011 corn cropping seasons. The average seasonal profile water content in 100 cm depth of the BP treatment was ~4% higher during all three cropping seasons when compared with NT. However, the average seasonal profile water content of SC treatment was ~4% less than the NT treatment during the first season but similar for the last two seasons.

5.3.5 Effect of PRB renovation on irrigation characteristics

5.3.5.1 Inflow

The data for two crops (2010 wheat and 2011 corn) were averaged because the results were not significantly different between both seasons. The inflow rate (*Q*) was slightly lower for NT and SC than for BP over all three cropping seasons, as practical adjustment to the different infiltration behaviour causing variations in the water advance rate (Table 5.5). There was also a trend toward longer *Tco* with cultivation. Thus, the irrigation volume applied to the BP and SC treatments during the wheat and corn seasons was significantly *(P=0.05)* larger than the NT treatment (109 mm) and similar during the hemp crop season.

Table 5.5: Irrigation performance for freshly applied PRB renovation treatments during two cropping seasons (2010 wheat & 2011 corn) and on un-renovated PRB (2011 hemp) treatments at site A1, Australia (SD in brackets)

Irrigation Performance Parameter	Wheat 2010 & Corn 2011			Hemp 2011		
	NT	SC	BP	NT	SC	BP
Q	1.87a	1.97b	2.21c	1.79a	1.79a	2.01b
(L s^{-1})	*(0.1)*	*(0.1)*	*(0.2)*	*(0.2)*	*(0.2)*	*(0.1)*
Tco	904a	942a	963a	406a	438a	406a
(min)	*(90)*	*(99)*	*(135)*	*(124)*	*(126)*	*(145)*
Inflow	109a	120b	137c	47a	51a	53a
(mm/irrigation)	*(12)*	*(13)*	*(18)*	*(17)*	*(18)*	*(17)*
DD	13a	25b	49c	2a	3a	3a
(mm/irrigation)	*(4)*	*(9)*	*(11)*	*(1)*	*(1)*	*(1)*
Ea	87a	78b	66c	94a	92a	93a
(%)	*(10)*	*(15)*	*(16)*	*(11)*	*(11)*	*(10)*
Er	94a	97b	98b	65a	70b	71b
(%)	*(4)*	*(3)*	*(2)*	*(6)*	*(11)*	*(8)*
DU	83a	82a	80a	75a	73a	75a
(%)	*(7)*	*(8)*	*(7)*	*(20)*	*(18)*	*(15)*

**Figures followed by different letters in rows for different treatment in the same cropping seasons are significantly (P=0.05) different between treatments*

5.3.5.2 Irrigation performance

The *Ea* was significantly *(P=0.05)* higher (9% and 21%) for NT compared with SC and BP, respectively, during the 2010 wheat and 2011 corn seasons (Table 5.5). The treatment difference in *Ea* was not significant *(P=0.05)* during the 2011 hemp season. The *DD* were significantly *(P=0.05)* higher on freshly applied BP (49 mm/irrigation) and SC (25 mm/irrigation) compared with NT (~13 mm/irrigation).

The *Er* was highest (> 94%) for the freshly renovated PRBs during the 2010 wheat and 2011 corn seasons (Table 5.5) but there was no significant difference between the treatments. Similarly, the treatment differences in *Er* were negligible during the 2011 hemp season but the *Er* was significantly *(P=0.05)* reduced (65-71%) during the 2011 hemp season. The full results are detailed in Table D3 & D4 (Appendix D).

There was no significant *(P=0.05)* difference between the treatments based on the combined average *DU* results for the 2010 wheat and the 2011 corn seasons (Table 5.5). However, comparing season to season results (Table D3: Appendix D) indicated a significantly (*P=0.05*) lower (~9%) *DU* for the SC and BP treatments compared with the NT treatment during the 2010 wheat season. The *DU* was also higher during the 2011 corn season than during the 2011 hemp season.

5.3.6 Dry biomass yield

The tillers density of the 2010 wheat was significantly (*P=0.05*) lower for BP than for NT and SC treatments (Figure 5.12a), while plant height was similar between treatments (Figure 5.13). The dry plant biomass was significantly (*P=0.05*) higher for NT (9.24 ton ha^{-1}) than for SC (8.71 ton ha^{-1}) and BP (6.88 ton ha^{-1}) treatments (Figure 5.12b & Table 5.6). Results showed reduced (~5%) dry plant biomass on the bed middle (row 3 and 4) for NT and increased biomass for SC (~9%) and BP (~19%) treatments compared with bed shoulder (row 1 and 2). Comparison of rows for different treatments showed significantly lower wheat tillers density and dry biomass for BP on all four rows than NT and SC and for SC on row 1 and 2 than NT. The correlation was positive when tillers density was regressed against dry biomass.

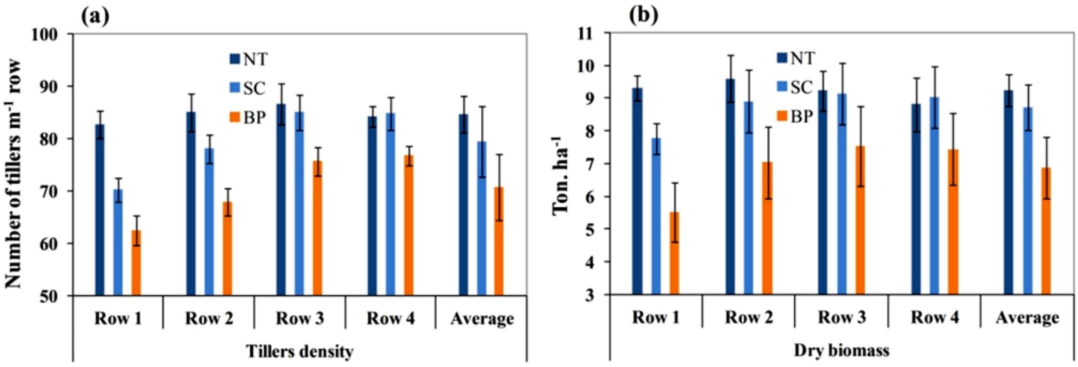


Figure 5.12: Tillers density (a) and dry biomass (b) for four rows (row 1 on bed shoulder and row 4 on bed middle) of 2010 wheat at site A1(vertical bars show SD).

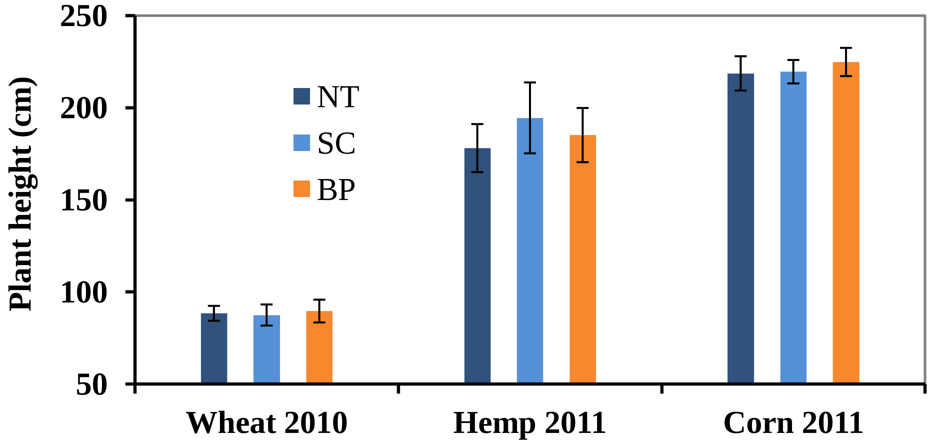


Figure 5.13: Average plant height of three crops on three PRB renovation treatments at site A1, Australia (vertical bars show SD)

Table 5.6: Average dry plant biomass for three crops and dry grain yield for 2011 corn with three PRB renovation methods at site A1, Australia (SD in brackets)

Crop & Treatments	**Biomass Yield (ton ha^{-1})**		
	NT	**SC**	**BP**
Wheat 2010	9.24a *(075)*	8.71b *(0.9)*	6.88c *(0.92)*
Hemp 2011	8.88a *(2.6)*	8.83a *(2.3)*	8.48a *(2.1)*
Corn 2011	14.07a *(2.7)*	14.59a *(2.6)*	15.14a *(1.9)*
Corn 2011 grain	8.94a *(1.7)*	9.13a *(2.3)*	9.24a *(1.9)*

**Figures followed by same letters in rows show no significant (P=0.05) difference between treatments*

The 2011 hemp crop plant density and dry biomass was not significantly different *(P=0.05)* between the treatments (Figure 5.14a & b). But the plant density of row 3 was significantly *(P=0.05)* larger than rows 1 and 2 for SC and BP treatments. The average plant height across the bed width was significantly *(P=0.05)* lower for the NT than for the SC but BP was similar to both NT and SC (Figure 5.13). The plants were physically weaker in the bed middle of all treatments. The dry biomass of row 3 and 2 on the bed middle was significantly *(P=0.05)* reduced by up to 55%, ~35% and ~43% than row 1 on bed shoulder for the NT, SC and BP treatments, respectively. Row to row comparison between treatments for plant density and dry biomass indicated no significant difference between treatments.

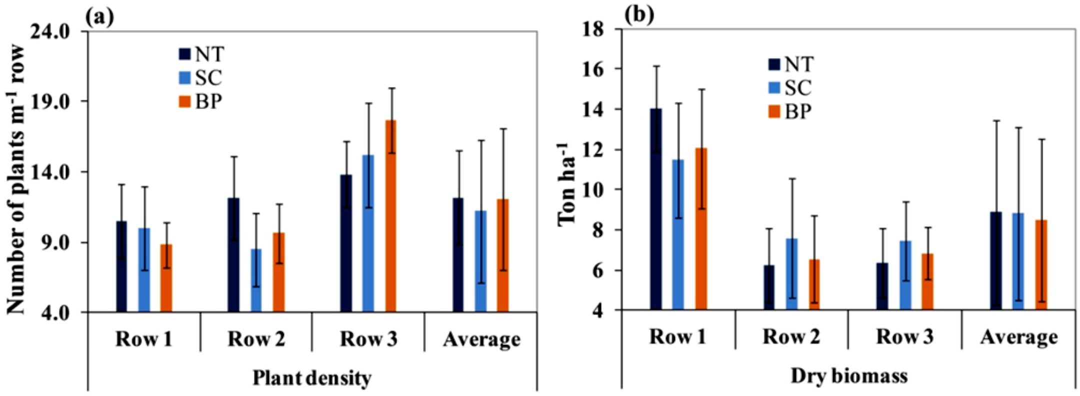


Figure 5.14: Plant density (a) and dry plant biomass (b) for 2011 hemp three rows (row 1 on bed edge and row 3 on bed middle) across a half bed width for three tillage treatments at site A1, Australia (vertical bars show SD)

There was no significant *(P=0.05)* difference in either the dry biomass or dry grain yield for the renovation treatments during the 2011 corn season (Figure 5.15). The difference in grain weight, plant height or plant density between the treatments was not significant (Figure 5.15). However, 2011 corn performance on BP was comparable to NT and SC treatments, which was contrary to the 2010 wheat results.

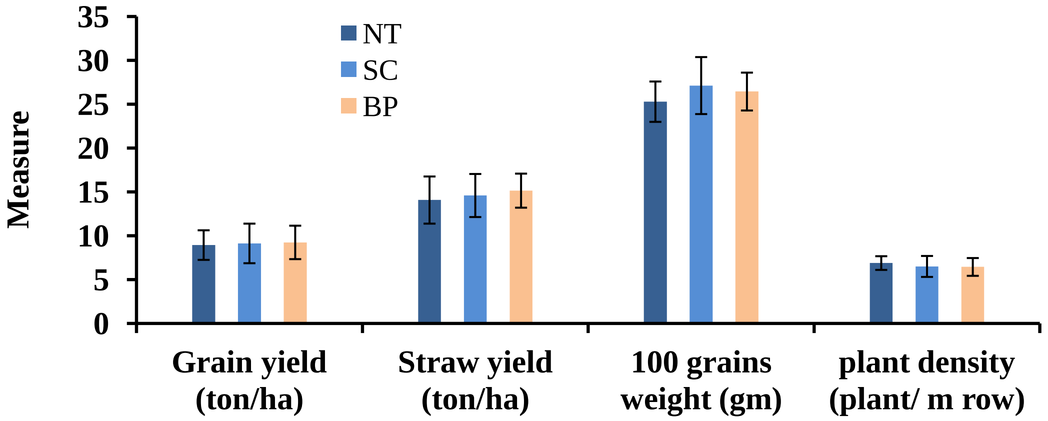


Figure 5.15: Comparative performance of 2011 corn on three PRB renovation treatments at site A1, Australia (vertical bars show SD)

5.3.7 Water productivity

The biomass *WP* of NT and SC treatments were significantly (*P=0.05*) higher than the BP treatment during the 2010 wheat season (Table 5.7). The *WP* was 10% and 39% lower for the SC and BP respectively, compared with NT treatment during the 2010 wheat season. There was no significant (*P=0.05*) difference between treatments for the other two crop seasons (Table 5.7). However, the combined average *WP* for freshly applied treatments during the 2010 wheat and 2011 corn seasons indicated significantly *(P=0.05)* higher *WP* for NT compared with SC and BP.

Table 5.7: Dry biomass input water productivity of three crops under three PRB renovation methods at site A1, Australia.

Crop	Treatment	Water applied (mm)	Dry biomass (ton ha^{-1})	*WP* (kg.ha^{-1} mm^{-1})
Wheat 2010	**NT**	299	9.24a	31a
	SC	312	8.71b	28b
	BP	356	6.88c	19c
Hemp 2011	**NT**	419	8.87a	21a
	SC	432	8.83a	20a
	BP	440	8.48a	19a
Corn 2011	**NT**	526	14.07a	27a
	SC	546	14.59a	27a
	BP	550	15.14a	28a

**Figures followed by different letters in columns for each crop season show significant (P=0.05) differences between treatments within the season*

The dry grain input water productivity of corn (Table 5.8) was comparable between treatments.

Table 5.8: Dry grain input water productivity of 2011 corn under three PRB renovation methods at site A1, Australia.

Treatment	Water applied (mm)	Dry grain yield (ton ha^{-1})	*WP* (kg.ha^{-1} mm^{-1})
NT	526	8.94a	17a
SC	546	9.13a	17a
BP	550	9.24a	17a

**Figures followed by different letters in columns for each crop season show significant (P=0.05) differences between treatments within the season*

5.4 Discussion

5.4.1 Effect of PRB renovation methods on soil physical properties

Furrow dimensions

The furrow dimensions varied between tillage treatments despite the same bed former being used for furrow cleaning in all treatments. For instance, the furrows were largest for the freshly established BP treatment and smallest for the SC treatment during the 2010 wheat and 2011 corn seasons. BP furrow sizes were larger associated with the deeper (30 cm) cutting of the bed with horizontal blades. Another reason was the lifting of the soil in the bed area by the blade without inversion. This caused loosening of the bed soil, thus increasing bed height (Hamilton et al. 2005). The furrow dimensions of the shallow cultivated treatment were smaller as the loose soil in furrows provided less traction for deeper excavation, while the loose soil slid back from the bed shoulder to furrow bottom, thus reducing the furrow dimensions.

The furrow dimensions of SC and BP treatments were largely reduced due to bed settlement and refilling of the furrow bottom with loose soil from bed shoulders transported as sediment during irrigation and rainfall. Bed settlement may also have occurred due to the collapse of unstable macro pores, as soil strength against deformation and subsidence is negatively affected by tillage (Coughlan 1981; Dexter 1991; Cook et al. 1992). Furrow filling (Yang & Wander 1999; Six et al. 2000) caused a reduction in total furrow depth, thus elevating the furrow bottom width (BW) and middle width (MW) making these larger than the initial values. Therefore, PRB renovation methods affect furrow dimensions and need to be applied according to the soil properties and susceptibility to slumping, erosion, and subsidence during the cropping season.

Bulk density of the beds

The treatment effect on soil bulk density was not confounded by soil moisture because soil sampling was done when the difference between treatments was not significant. However, bulk density decreased generally with increase in soil moisture during a season irrespective of treatment differences presumably due to swelling as reported by McKenzie and McBratney (2001) and McKenzie et al. (2002). Average bulk density during the 2010 wheat season was highest for the NT and lowest for the BP treatment, indicating higher soil porosity for the BP. Differences in bulk density due to tillage or removal of tillage were also reported by Cassel (1982) and McHugh et al. (2009). A maximum temporal increase of ~11% in bulk density of the surface profile (0-10 cm) and 8% increase in average seasonal bulk density for the SC treatment identified during two cropping seasons (2010 wheat and 2011 hemp) indicates that subsidence occurred in a short period of time as mentioned by Meki et al. (2012). The smaller seasonal increase in bulk density for the NT and BP treatments (~5%) suggests these treatments have a greater soil structural stability and resistance to deformation, which may favour improved irrigation performance and *WP* leading to sustainable crop production.

Infiltration

The soil infiltration properties were significantly influenced by the different renovation methods and varied throughout the season. This study found a 23% higher cumulative infiltration using BP treatment compared with NT. Similarly, cumulative infiltration was reduced by approximately 50% for all treatments between 2010 wheat and 2011 hemp seasons, indicating the transient nature of the infiltration improvement caused by improper machinery design and setup. The occurrence of heavy rainfalls before the 2011 hemp sowing may have affected the soil structure and porosity due to excessive wetting. This reduction in infiltration properties within two cropping seasons closely agrees with the findings of Dunn et al. (1998), who demonstrated similar changes in soil hydraulic conductivity and soil water retention properties and attributed them mainly to the collapse of larger temporary pores created due to tillage operations. Consequently, the seasonal reduction in soil infiltration properties negatively affected lateral infiltration and irrigation performance. Therefore, soil disturbance caused bed subsidence and sealing leading to poor infiltration and made it difficult to replenish the *SMD*, which negatively affected crop yield in the bed middle.

Wetting front penetration into the centre of wide beds is generally not considered a major issue for the Australian Vertisol with shrink-swell, cracking, and self-mulching qualities. Moreover, long furrows and irrigation times (Raine & Bakker

1996) generally overcome lateral infiltration problems in an Australian context. However, this study showed that under specific irrigation and crop conditions the reduced lateral infiltration due to bed subsidence (e.g. up to ~10 hours to wet the bed middle) may affect the PRB performance. For instance, the lower lateral infiltration to the centre of the un-renovated beds during the 2011 hemp season caused germination problems and reduced crop yield in the bed middle. This conform with the findings of Lucy (1993) and suggests that renovation, especially BP, may be helpful in improving the lateral infiltration under the subsided beds.

Seasonal profile water content and irrigation application

The seasonal profile water content differences between renovations treatments were largely influenced by the irrigation scheduling, soil infiltration, and retention properties. Irrigation scheduling is an important decision-making process (Wichelns & Oster 1990) which has consequences on irrigation performance. However, the limited control over infiltration when using surface irrigation systems makes it difficult to apply a target water volume, while the uncertain weather conditions, water availability restrictions, and management practices further confound the ability to apply an optimal schedule (Mailhol et al. 2011). The soil infiltration properties at the time of irrigation and the selection of Q and Tco (Shafique & Skogerboe 1983) to suit the changed soil properties largely impacted on the irrigation performance. Thus, the field limitations and changed soil conditions due to the different renovation treatments influenced irrigation applications and consequently the profile water content was also influenced for the different treatments.

The BP treatment was identified with larger water absorption and soil water storage capacity (~4%) during all three cropping seasons. The reason was higher lateral infiltration, which enlarged the volume of soil available to store water in the root zone across the bed width and greater porosity of loose soil, which agrees with several studies (Hamilton et al. 2005; Jin et al. 2007; Akbar et al. 2009). Therefore, blade ploughing seemed beneficial for conserving in-season rainfall, which can be enlarge the gap between the irrigation and can avoid in-season water stress. However, the long irrigation times and cracking during the 2010 wheat and 2011 corn seasons mitigated treatment impact on lateral infiltration.

The profile water content largely impacted on the irrigation performance of three PRB renovation methods because the heavy clay Vertisol was prone to affect irrigation performance due to its cracking properties (Raine et al. 1998; Gillies 2008), which were normally developed when *SMD* prior to irrigation was greater. For instance, the larger *SMD* prior to fourth irrigation of the 2011 hemp and second irrigation of the 2011 corn caused deeper and wider cracks across the bed, thus the water advance in the furrow was reduced. Consequently, *Ea* was also reduced and *Er* was increased. In contrast, the severe rainfall before the 2011 hemp season wetted the soil profile to deeper depths. However, the top soil surface turned dry till the 2011 hemp sowing with no cracks as the deep soil was still wet. Consequently the *Ea* was increased but *Er* was reduced during the initial two irrigations. This caused poor lateral infiltration and the two rows in the bed middle were poorly germinated initially, which conformed to the findings of Lucy (1993). Luckily the early season rainfall assisted in seed germination in the bed middle. Therefore, soil moisture at the time of irrigation largely affected the irrigation performance.

5.4.2 Treatment, irrigation management and performance interactions

Irrigation performance varied between treatments and crop seasons. The selected irrigation management criteria worked well in improving the irrigation performance and in controlling the excessive losses identified under farmer managed systems (Chapter 4). However, comparing the overall results showed a significantly different irrigation performance between the tillage treatments (as low as 61% *Ea* on BP and above 86% *Ea* on NT treatment), while field limitations in implementing the optimum *Q* and *Tco* seem to have largely impeded in achieving maximum irrigation performance. However, seasonal changes suppressed the treatment differences, evidenced by the negligible variations between irrigation performance factors during the four irrigations to the 2011 hemp crop. Hence, renovation methods largely matter in irrigation performance of PRB systems.

The potential to deep drainage due to irrigation excess were largely variable between the renovation methods. The higher infiltration capacity increased the deep drainage potential (up to 62 mm/irrigation) on freshly applied BP treatment, which agreed with the findings of Smith et al. (2005) and Raine and Bakker et al. (19996), compared with NT (up to 15 mm/irrigation). According to Raine and Bakker (1996) and Smith et al. (2005) deep drainage is one of the main reasons for poor irrigation performance on Australian farms. However, due to bed settlement and furrow compaction, *Ea* was improved but *Er* was significantly reduced during the subsequent irrigations to 2011 hemp. Thus, inadequate irrigation management for the changed soil conditions reduced the performance of freshly renovated PRBs.

Irrigation management played a key role in the irrigation performance of different tillage treatments. For instance, the improved *Ea* achieved during the 2011 hemp season was due to reduced *Er*, because the fast arrival of water to the tail end of blocked end furrows necessitated the need for shorter *Tco*, at applied *Q*, to avoid excessive tail end bed overtopping. In contrast, *Ea* of freshly applied BP treatment was reduced due to slow water advance caused by higher soil infiltration properties and low applied *Q*. Similarly, the uniformity of NT treatment during the first irrigation to 2010 wheat crop was higher due to the slight backing effect of blocked end furrows, which compensated the less infiltration opportunity time that normally occurs at the tail end (Merriam & Keller 1978). However, the excessive bed overtopping at the tail end during the 2011 hemp season negatively affected the *DU*. In other words, *DU* was negatively affected, when the difference of infiltrated depth between the head and the tail ends of the field was larger. In contrast, *DU* during the 2011 corn season was improved due to three seasons of furrow compaction. Thus, irrigation performance was influenced by the changed soil properties.

The root zone soil moisture largely influenced the irrigation performance. For instance, the *Ea* was reduced during the initial two irrigations to 2011 hemp crop, when the soil was wet and *SMD* was low compared with the last two irrigations, when *SMD* was high, which agreed with the findings of Sepaskhah and Ghahraman (2004). In contrast, a very high *SMD* can also negatively affect *Ea*, as evidenced by the lower *Ea* during the second compared with the first irrigation to the 2011 corn, which agreed with the findings of Bautista and Wallender (1993b). Thus, irrigation performance was largely affected by the increased porosity of renovated beds during the early period and by the *SMD* during the latter period after bed settlement. However, irrigation management did not lose its importance during both periods.

5.4.3 Treatment and crop yield interactions

The maximum 2010 wheat crop dry biomass was ~10% less compared with average dry biomass reported with 100 kg ha^{-1} seed rate by (Khan et al. 2004). Similarly, the 26% higher dry biomass of wheat for NT conform with the findings of (Abu-Hamdeh 2003) and Sayre et al. (2005) who also identified greater yield on NT compared with conventional methods. However, equipment design and set up, its suitability for a particular operation, knowledge of soil properties, soil moisture during machinery operations and expertise in machinery operation for achieving the desired results are important considerations that can affect crop yields. For instance, the grain yield of 2011 corn was up to ~22 % less than the twenty years average reported by (Payero 2008) in the same locality. While, the grain and straw yield were increased by 3% and 8%, respectively on well managed BP treatment compared with NT, which was contrary to the 2010 wheat results due to poor wheat crop establishment.

The three renovation methods caused variable lateral infiltration, thus affecting crop yield, which agreed with the findings of Hamilton et al. (2005), Jin et al. (2007) and Akbar et al. (2009). For instance, the reduced lateral infiltration in NT treatment decreased crop yield in the bed middle by ~5% during 2010 wheat season and up to 55% during the 2011 hemp season (on two season old PRB). Impact of poor lateral infiltration can also be evidenced by the weaker plant height in the bed middle for the 2011 hemp crop. However, during the 2010 wheat season a single irrigation was applied and frequent rainfall during the season mitigated the negative impact of poor lateral infiltration on crop yield in the bed middle. Similarly, impact of treatments on 2011 corn season could not be established as the two rows were on the bed shoulder.

The irrigation performance may affect crop yield as analytical correlations between the crop yield and different irrigation performance parameters were established by Solomon (1984), Holzapfel et al. (1985), Juan et al. (1996) and Zhang et al. (1999), which seemed to have influenced the crop yield in the current study. It can be inferred that the general poor irrigation performance on BP and SC treatments have negatively contributed in their yield compared with the NT treatment. Thus, if achievable, improved irrigation performance through better irrigation management of BP treatment may also contribute to improved crop yield and *WP*.

5.4.4 Treatment and water productivity interaction

The *WP* varied for the renovation treatments and was affected by the irrigation and agronomic management practices, as reported by Playán and Mateos (2006). The results indicated increased *WP* for NT treatment followed by SC (10% less) and then BP (39% less) during the 2010 wheat season. However, seasonal changes due to bed settlement and slumping caused comparable *WP* among treatments during the 2011 hemp season. Despite poor crop performance was caused by bed settlement and subsidence in the bed middle of NT, the yield and *WP* of NT was comparable with the cultivated treatments during the 2011 hemp and the 2011 corn seasons.

The irrigation application and crop yield mainly contributed to the *WP*. The larger soil infiltration and deep drainage losses on BP treatment increased the total water applied, which negatively affected its *WP*. However, the larger soil water storage and increased lateral infiltration compensated for the losses by increasing crop yield in the bed middle. Large soil water absorption and retention with blade ploughing was also reported by Thomas et al. (1990) over seven years of grain sorghum planting in central Queensland, Australia. The yield loss of NT treatment in bed middle was compensated by the improved crop yield on the bed shoulder. Thus the *WP* was similar between treatments during the 2011 hemp and 2011 corn seasons.

This study showed similar *WP* between the three renovation treatments during the last two seasons (2011 Hemp and 2011 corn). Thus the NT treatment seems more beneficial because of its greater consistency with the principles of conservation agriculture and favourable long term impacts on soil structure and biology (Cook et al. 1992; McHugh et al. 2009). However, the reduced bulk density, enhanced lateral infiltration and greater soil moisture retention with less soil disturbance due to no surface inversion by BP (Hamilton et al. 2005) and gradually improved *WP* during the three cropping seasons indicate benefits in using BP compared with SC treatment for the controlled mechanical loosening of subsided PRB on a Vertisol.

5.4.5 PRB renovation options for improved performance on a Vertisol

The NT treatment significantly improved *Ea* while crop yield was not significantly reduced compared with SC or BP treatment. Thus, the NT treatment with no soil disturbance and reduced machinery requirements seems a preferable choice under normal field conditions in the irrigated Vertisol. The NT is also consistent with the principles of CA, which tends to restore the soil hydro-physical, chemical and biological properties through self-regeneration processes (McHugh et al. 2009).

The SC treatment caused greater soil disturbance, poor establishment, accelerated furrow filling and enhanced deep drainage losses. According to Coughlan (1981) the Vertisol is very sensitive to intensive tillage because it destroys the low volume of permanent pores as the shrinking and swelling generally close the unstable macro pores making the soil less permeable (Cook et al. 1992) and more susceptible to erosion and degradation (Smith et al. 1983). Thus SC is not preferable for Vertisol.

This study showed that renovating PRB with the BP method reduced irrigation performance under current management but improved soil physical properties (i.e. bulk density, lateral infiltration and soil water storage) due to non-inversion on the bed surface, thus leading to comparable crop yield and *WP* with the NT treatment in the last 2011 corn season. The closer consistency of BP with the principles of CA makes it a better choice compared with SC treatment for loosening the subsided beds if required. The BP can better manage ground cover because of no inversion (Hamilton et al. 2005) compared to SC treatment which destroy ground cover. It can also be inferred from these outcomes that BP can be beneficial for conserving more water from in-season rainfall, for reducing irrigation application frequency by enlarging irrigation application gaps and mitigating negative impacts of drought and water stress on crop yield, which is very common on Australian farms. However, BP needs careful selection of specialised equipment (right design and set up), correct soil moisture (soil moisture above or below plastic limit can cause smearing or soil disturbance), and operating expertise for improved performance. Additionally, the changed soil infiltration properties with BP require intensive irrigation management optimisation to avoid excessive application losses, while long term impacts of BP on soil structure and its optimal frequency of applications is not known on Vertisol.

5.5 Conclusions

The *Ea* of three freshly applied renovation methods on 2 m wide beds was significantly influenced by the current irrigation management due to the changed soil hydro-physical properties. However, productivity was not significantly affected except for the 2010 wheat season, suggesting that changes may take longer to significantly emerge in *WP* for this site. The key conclusions are:

- Renovation methods did affect bed bulk density, cumulative infiltration, and lateral wetting into the bed. However, the effect was largest immediately after renovation and decreased during the season. There was no difference between the treatments in the second season after renovation.
- While there was some difference between renovation method treatments on the rate of lateral wetting, the long irrigation times and cracking resulted in close to full wetting of beds under the majority of conditions observed.
- The *Ea* was significantly lower for the freshly applied SC and BP treatments during the 2010 wheat and 2011 corn seasons due to the higher soil infiltration rate, larger *Tco* and increased *DD* than with the NT treatment. However, the overall difference in *Er* and *DU* was not significant.
- There was no significant difference in irrigation performance between the treatments for the 2011 hemp crop, when the beds were not renovated.
- Except in the first 2010 wheat season, there was no significant difference in yield or *WP* between the NT, SC or BP treatments.
- First season BP (and possibly SC) yield may have been affected by poor seeding and establishment due to poor machinery performance.
- Reduced yield was observed in the bed middle for all treatments during the 2011 hemp season but full bed width yield was similar on all treatments.
- The increased infiltration of SC and BP treatments suggests that these treatments need to be irrigated more quickly using increased *Q* and reduced *Tco*. If achievable, the *Ea*, *Er* and *DU* of SC and BP should be able to increase substantially. Chapter 8 explores these possibilities.

CHAPTER 6: Field evaluation of lateral infiltration in permanent raised beds

6.1 Introduction

In most countries where water is either in short supply or is costly, wide beds are often preferred to narrow beds because smaller irrigation volumes normally are applied and land available to grow crop is increased (Jin et al. 2007). However, for such irrigation to be effective the soil in the beds needs to be highly sorptive to ensure water is drawn quickly to the centre of the bed. Poor lateral infiltration negatively affects *WP* of wide PRB systems (Lucy 1993; Akbar et al. 2007; Jin et al. 2007). The reasons for water not being absorbed quickly into the centre of beds are that the soil in the centre of the beds is compact or the soil structure is poor or unstable to rapid wetting. In consequence, farmers use a variety of renovation methods to restore the sorptive behaviour of beds in PRB farming systems. No field research has been found that is specifically focussed on this issue. The results of benchmarking studies in Australia and Pakistan (Chapter 4) and poor lateral infiltration revealed in the *WP* study in Australia (Chapter 5) have emphatically illustrated the need for research into renovation practices that embody all the principles of conservation agriculture and build and maintain a soil structure in beds that ensures they are permanently sorptive enough to ensure water reaches the centre of beds as quickly as possible.

Most furrow irrigation research and simulation models assume uniform penetration of water to the centre of the beds. Thus, a secondary need for research into managing the sorptive behaviour of PRB is to reinforce the legitimacy and applicability of this research and the models by ensuring practices exist that validate the assumption of uniform penetration of water to the centre of beds. Therefore, this study evaluated the effect of renovation methods on lateral infiltration into wide permanent raised beds. Three PRB renovation methods were evaluated on two soils in Australia and Pakistan. This chapter reports on the field evaluation of three PRB renovation methods while Chapter 7 evaluates irrigation strategies to improve lateral infiltration.

6.2 Material and methods

The experiments involved using a blocked furrow infiltrometer method (Walker & Skogerboe 1987) and measurements of soil moisture content across the beds to determine differences in lateral infiltration due to renovation methods on two soils. The experiments were conducted at site A1-Vertisol in Australia and site P4-sandy clay loam in Pakistan. The sites details are described in Chapter 3.

6.2.1 Site description, treatment and experimental layout

Two sets of measurements were obtained during the 2011 summer in a Vertisol planted with corn at site A1, Australia. Three renovation treatments with three replicates were applied in a randomised block design. The three renovation treatments were NT, SC and BP as described in Chapter 5 (section 5.2.1) and laid out as shown in Figure 5.3. The centre bed of each treatment was selected for measurement. A total of nine data collection points, one for each treatment, were selected at ~40 m distance from the head end of the experimental plot. The measurements of lateral infiltration were conducted immediately prior to the first and second irrigation of the 2011 corn crop (Chapter 5). The furrow dimensions of the three treatments at the time of the measurements are given in Table 6.1.

Table 6.1: Average furrow dimensions during two irrigations on a Vertisol and a sandy clay loam (furrow dimensions explained in Figure 3.2c), (SD in brackets)

Site/soil	Treatment	TW (cm)	MW (cm)	BW (cm)	D (cm)
A1-Vertisol	NT	62 *(3)*	46 *(3)*	18 *(3)*	12 *(1)*
	SC	52 *(4)*	37 *(4)*	21 *(3)*	10 *(1)*
	BP	60 *(3)*	44 *(2)*	23 *(2)*	11 *(1)*
P4-Sandy clay loam	NT	56 *(1)*	41 *(1)*	22 *(2)*	13 *(1)*
	SC	51 *(1)*	27 *(2)*	14 *(1)*	13.5 *(2)*
	BP	55 *(2)*	34 *(1)*	20 *(3)*	14 *(1)*

Two additional sets of measurements were obtained on a farmer's field at site P4 (north west Pakistan), on a sandy clay loam soil during the 2011 summer corn season. Four randomly selected replications of three treatments NT, SC, and BP were freshly applied to a two season old PRB. The main differences in renovation treatment between the sandy clay loam and Vertisol sites were the furrow spacing (132 cm rather than 200 cm) and the use of a rotavator (for 10-15 cm deep rotary hoeing) instead of a tined cultivator for the establishment of the SC treatment. The data collection points were located at a 20 m distance from the field head.

The sandy clay loam at this site has a badly degraded and inherently weak structure as a consequence of excessive cultivation over many years. It was also marginally saline while analyses of soils in the area showed an exchangeable sodium percentage of 18% (Akbar and Hamilton, unpublished data), which will predispose them to dispersion and sealing when rapidly wet.

Two rows of corn crop were planted per bed on 25 June 2011 using a minimum till planter with 60 cm row spacing and 10 cm between plants in the rows. The measurements were obtained immediately prior to the first and second irrigations of the season. The average furrow dimensions at the time of measurements are shown in Table 6.1.

6.2.2 Bulk density and soil moisture measurements

Bulk density measurements were taken at two positions near each measuring point prior to wetting. Samples were taken in multiples of 10 cm to a depth of 30 cm according to the procedure described in section 3.6.1.

Volumetric soil moisture measurements were taken prior to and during the irrigation by a micro-gopher operated within PVC access tubes installed across the beds. Four access tubes (2 cm internal diameter) for soil moisture measurement were installed according to the layout shown in Figure 6.1. The measuring points were located at the furrow centre, 33 cm, 67 cm from the furrow centre and the bed middle on the Vertisol and at 22 cm, 44 cm and 66 cm distance from the furrow centre on the sandy clay loam. The holes for the access tubes were made with a soil auger slightly smaller than the outer diameter of the PVC access tube and slightly deeper (120 cm) than the maximum measuring depth of 100 cm. The bottom end of all access tubes were sealed with putting plug to ensure full water tightness. The access tubes were then installed by pushing and twisting using a nylon plug at the top of the tube. This procedure reamed the hole to the exact size of the PVC tube while the soil reamed was settled in the extra depth of the hole drilled. This procedure ensured a perfect contact between the access tube and the soil. To further reduce the possibility of vertical preferential flow along the walls of the access tube installed in the furrow centre, bentonite clay was applied around the tube (2 cm wide and 2 cm deep cross sectional ring). The access tubes were then tested for any physical deformation during the installation by placing the micro-gopher sensor head into the access tube and checking the uniformity of physical resistance whilst pushing it slowly from top to bottom through the entire length. After installation, the top of the access tubes were covered with a small plastic cup that ensured free air entry and protected from rain water entry.

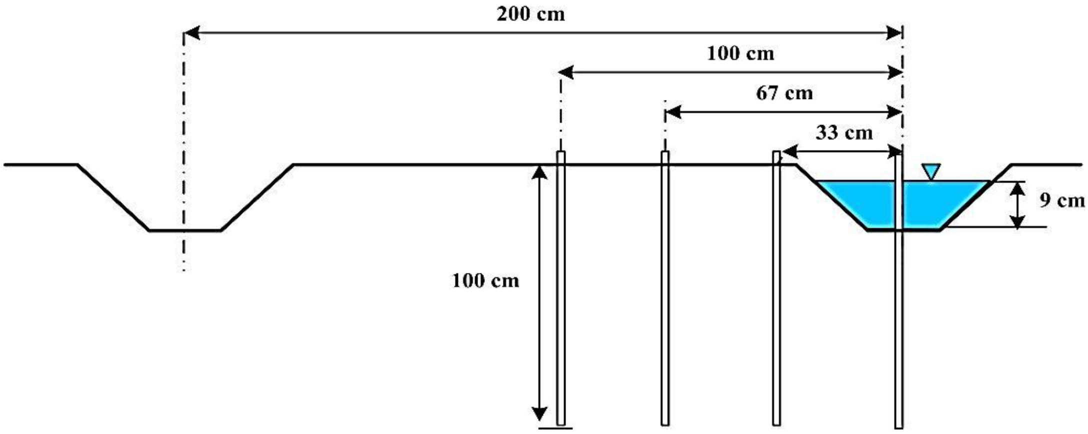


Figure 6.1: Experimental set up showing location of four access tubes for micro-gopher across half bed width installed at nine locations (one/treatment) at site A1-Vertisol.

The micro-gopher was calibrated using the inbuilt volumetric function. The initial field capacity values were set to 43% for the Vertisol and 23.5% for sandy clay loam following the procedure described in the equipment manual. However, the equipment calibration was readjusted latter on for the given field capacity values by taking soil moisture readings at 10-20 cm depth after 2 days of full irrigation. A single point calibration was considered adequate because both soil profiles were uniform over the 100 cm depth being monitored. The micro-gopher readings were validated by matching with the calculated volumetric soil moisture obtained from a 0-30 cm profile in a nearby location using the gravimetric method (section 3.6.1). The gravimetrically determined soil moisture values matched well with the calibrated micro gopher volumetric soil moisture readings as given in Appendix C: Figure C2 for both soils.

6.2.3 Blocked furrow infiltrometer measurements

A one metre long section of the centre furrow in each treatment (Figure 5.3) was isolated at both ends by steel sheets (inserted to a depth of 10 cm into the furrow bottom and 5 cm into both adjacent bed shoulders). The experiment commenced with recording antecedent soil moisture in both soils in all tubes. Then the one metre long furrow section between metal covered with polythene sheet was filled with water to 9 cm depth. The water was released by gently sliding out the polythene sheet and the 9 cm depth was immediately checked and in case of any deficiency additional water was added quickly. The 9 cm depth was kept constant during the experiment and a log of time and volume of water added to each furrow was recorded for a maximum of 9 hours on both soils. The change in soil moisture of 100 cm profile at 10 cm depth intervals was monitored at 15 minute intervals during the first hour and at 30 minute intervals after one hour till the end of experiment.

6.2.4 Lateral infiltration and sorptivity

Lateral infiltration was determined by comparing the soil moisture at the three measured positions from the furrow centre to the bed centre. Cumulative infiltration for each measured position at each time interval was calculated as the increase over the antecedent volumetric soil moisture content for a 100 cm deep profile. Sorptivity was calculated as the slope of the linear regression line of best fit by plotting the sum of the increase in profile moisture content at all three lateral positions against the square root of time.

Sorptivity is not only a descriptor of early-time infiltration, but also of soil structure stability (Collis-George & Laryea 1972), because of its reliance on hydraulic conductivity and the moisture characteristic, both of which vary with moisture content and pore size distribution. Therefore, sorptivity evaluations were conducted to illustrate the effects of different PRB renovation methods on soil structure and the resulting variable lateral infiltration in two very different soil types.

ANOVA analysis was applied on selected data only to determine significant differences as some of the data violated the normality of distribution and equal variance assumption. Thus mean and standard deviations were generally provided.

6.3 Results

6.3.1 Site A1-Vertisol

The average bulk densities of the combined 0-30 cm layer were generally not significantly *(P=0.05)* different between irrigations for all treatments (Figure 6.2). Results showed significantly *(P=0.05)* lower bulk density of the combined (0-30 cm) layer on BP compared with NT. However the average bulk density of the combined 0-30 cm layer on SC was not significantly different (*P=0.05*) from either NT or BP. Treatment comparison showed significantly reduced bulk density for BP compared with NT while bulk density of SC was similar to both NT and BP at all measured individual depths. However, bulk density of the combined 0-20 cm layer was significantly *(P=0.05*) reduced for SC and BP in comparison with 20-30 cm layer.

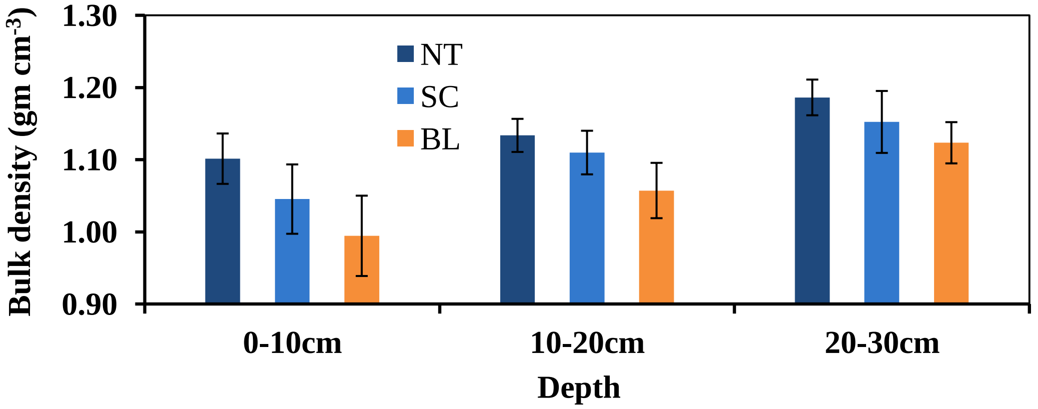


Figure 6.2: Average bulk density (BD) before two irrigations for three PRB renovation treatments at site A1, Vertisol (vertical bars show SD)

Soil moisture variations in 100 cm profile at 10 cm depth intervals across the bed on all three treatments during both irrigations were evaluated by comparing the average antecedent and one, four and nine hours post soil moisture content. The antecedent soil moisture content of all treatments was not significantly *(P=0.05)* different from one to another preceding both the first and second irrigations (Figure 6.3 & 6.4). However, the antecedent soil moisture content of the first experiment was significantly higher compared with the second experiment. Thus, both irrigations were evaluated separately. These moisture content differences caused the rate of infiltration and the amount absorbed over 9 hours for the first and second irrigations to be very different, as was expected from the knowledge of sorptivity.

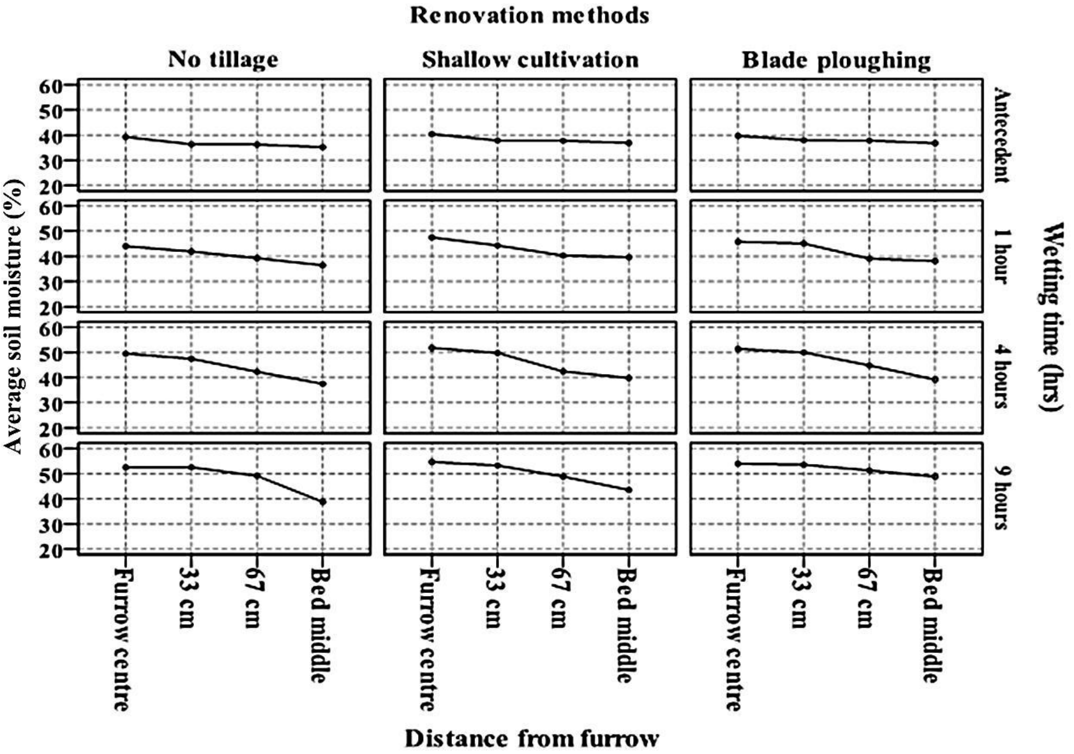


Figure 6.3: Impact of renovation method, wetting time and distance from furrow centre on average soil moisture in 100 cm profile depth during the first irrigation at site A1-Vertisol

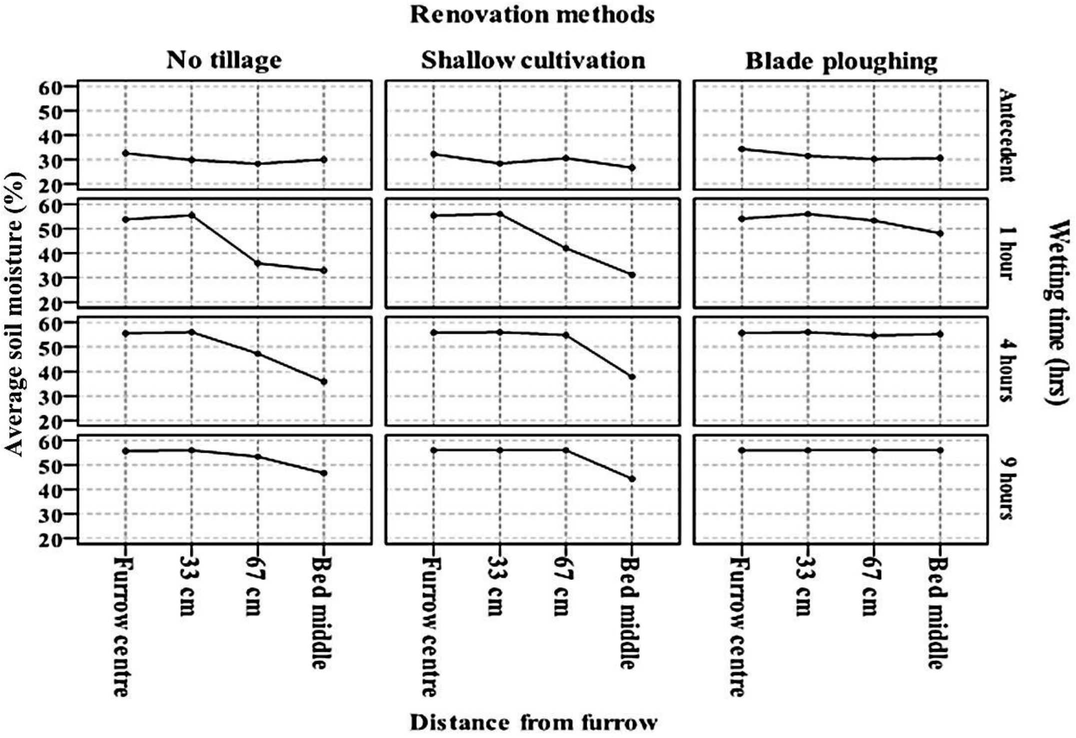


Figure 6.4: Impact of renovation method, wetting time and distance from furrow centre on average soil moisture in 100 cm profile depth during the second irrigation at site A1-Vertisol

Temporal variations in average profile soil moisture across the bed indicated no significant *(P=0.05)* difference between treatments after one hour during the first irrigation (Figure 6.3) but a rapid increase at the 33 cm for NT and SC and 67 cm for BP during the second irrigation (Figure 6.4). However, after four hours NT showed significantly *(P=0.05)* lower soil moisture across the bed than the other two treatments, which were similar. After nine hours of wetting during the first irrigation the average soil moisture at 33 cm was similar between all treatments. However, the average soil moisture at 67 cm and the bed middle was significantly *(P=0.05)* higher for BP and SC compared with NT. During the second irrigation the moisture content at the bed middle was lower for NT and SC than BP after nine hours of wetting (Figure 6.4).

Separate parallel plots for the four measured positions (furrow centre, 33 cm, 67 cm and bed centre) were plotted for all three treatments to illustrate the difference in vertical distribution of soil moisture across the bed (Figure 6.5 & 6.6). The results indicated greater soil moisture variations on the bed surface compared with the deeper depths for all treatments. The vertical soil moisture distribution at 67 cm was similar for all treatments after 9 hours of wetting (Figure 6.5a-c). However, the moisture content was higher in the BP bed centre than the SC or NT during the first irrigation (Figure 6.5d). The total change in soil moisture of 0-100 cm profile in the bed middle was similar during four hours of wetting (Figure 6.5d). The change in profile moisture content was two and three times higher for the SC (Figure 6.5d-2) and BP (Figure 6.5d-3) treatments respectively, compared with NT treatment (Figure 6.5d-1) after nine hours of wetting during the first irrigation.

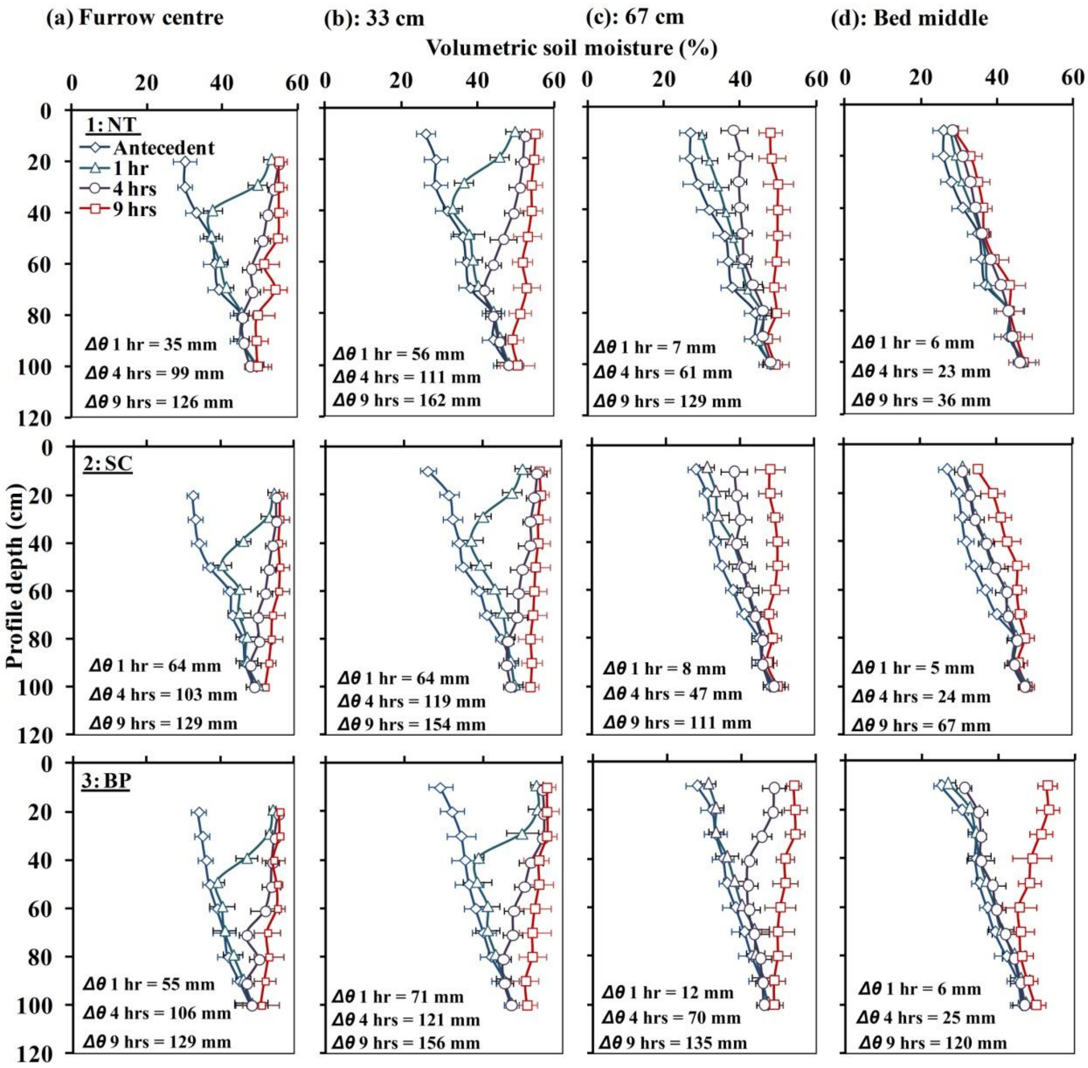


Figure 6.5: Change in soil moisture content *($\Delta\theta$)* across a 200 cm wide bed at given distances from furrow centre and given times with three renovation treatments during the first irrigation at site A1-Vertisol

The larger infiltration (i.e. gap between antecedent and one hour post wetting water content curves) at 33 cm for NT and SC treatments and at 67 cm for BP treatment (Figures 6.6) illustrated increased lateral and vertical infiltration during the second than the first irrigation, as the water moved rapidly through cracks. However, the greater wetting front penetration in BP treatment is more obvious compared with the other two treatments evidenced by a 52% increase in soil moisture of BP treatment than the NT treatment after nine hours of wetting.

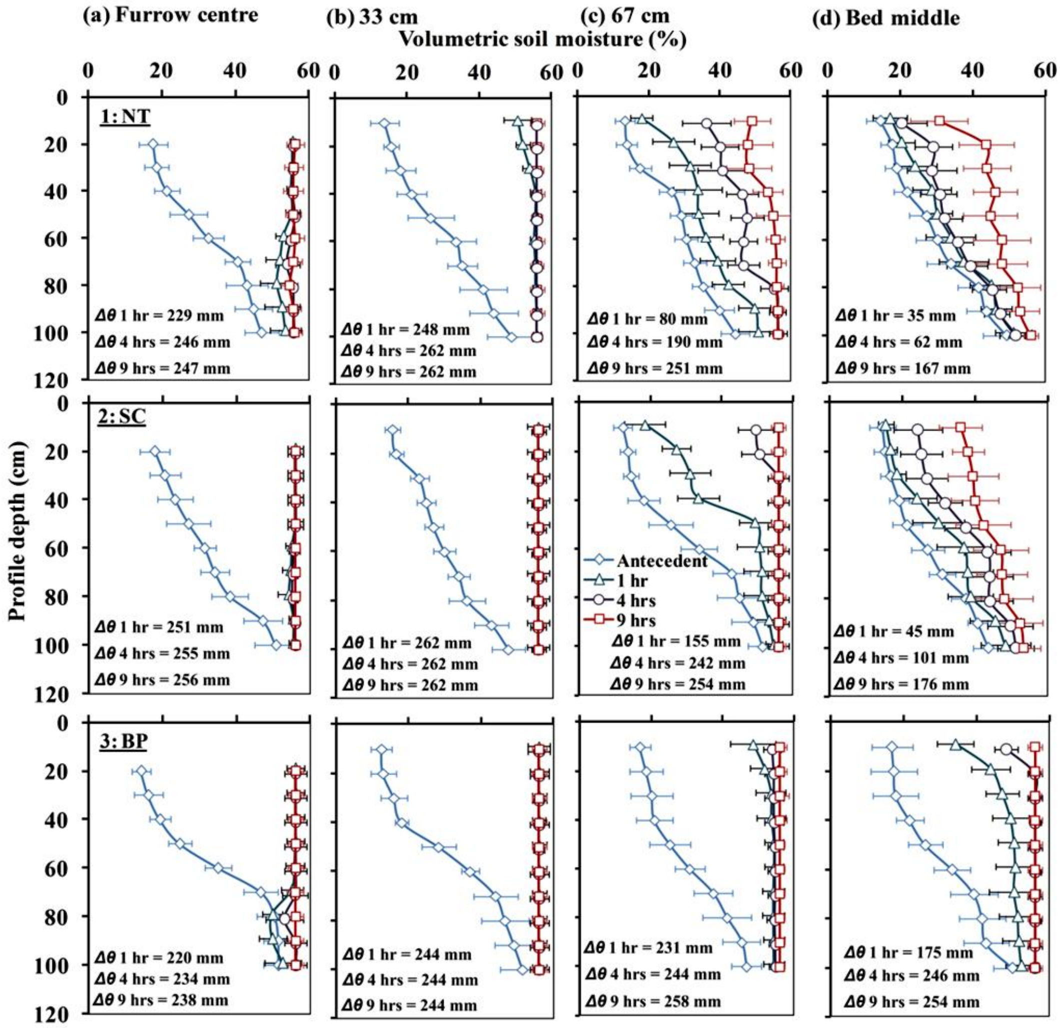


Figure 6.6: Change in soil moisture content *($\Delta\theta$)* across a 200 cm wide bed at given distances from furrow centre and given times with three renovation treatments during the second irrigation at site A1-Vertisol

The comparison of temporal variation in cumulative infiltration (Figure 6.7) for the first irrigation shows the highest values at 33 cm, followed by the furrow centre, 67 cm and the bed middle for all treatments. However, infiltration was similar at 67 cm and the furrow centre after 8 hours for NT and BP (Figure 6.7). The bed middle of SC and BP received 86% and 233% more cumulative infiltration respectively compared with NT (36 mm) after 9 hours during first irrigation. The cumulative infiltration rapidly increased across BP, while the bed middle for NT and SC (Figure 6.8) took longer to wet during the second irrigation.

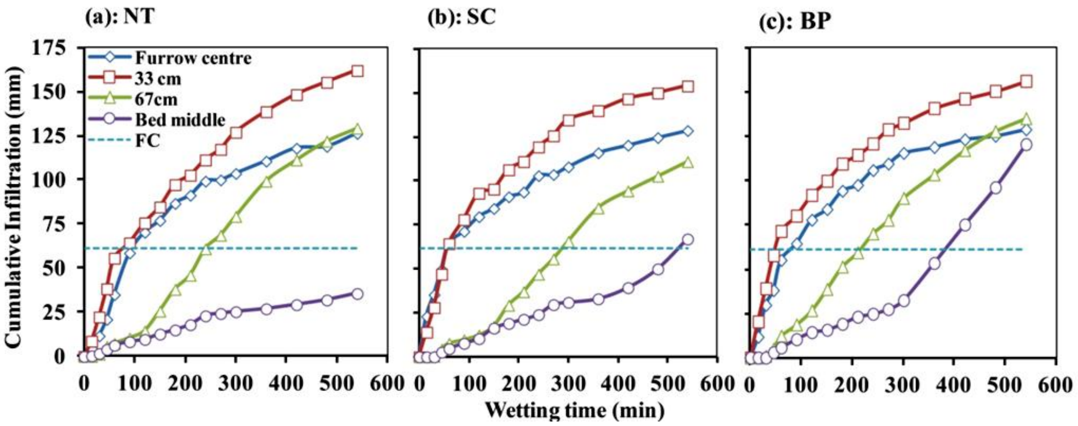


Figure 6.7: Cumulative infiltration across a 200 cm wide bed with three renovation treatments during the first irrigation at site A1-Vertisol

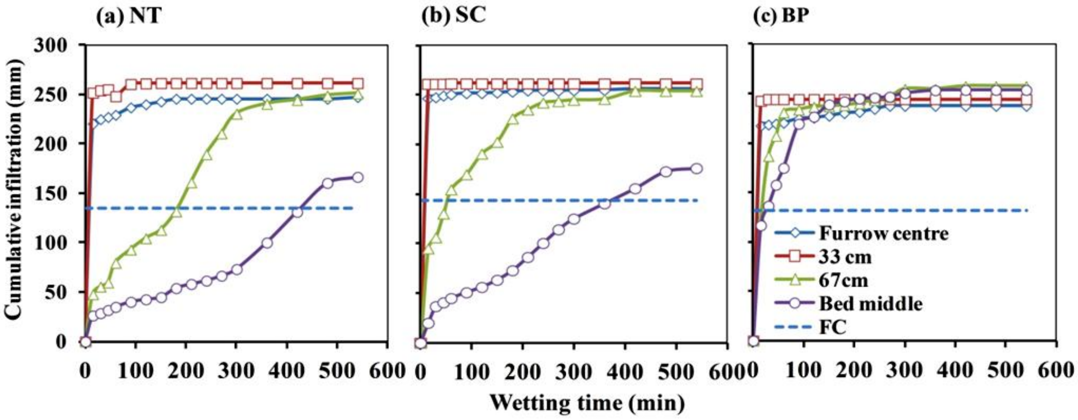


Figure 6.8: Cumulative infiltration across a 200 cm wide bed with three renovation treatments during the second irrigation at site A1-Vertisol

The two dimensional soil moisture profiles (expressed as percent of field capacity) were graphed using the Krigging data interpolation function of software Surfer (version 8). Temporal variations in soil moisture (antecedent, one hour, four hour and nine hour) were plotted separately (Figure 6.9 & 6.10), which shows the substantially higher lateral infiltration for the BP compared with NT and SC (Table 6.2).

Table 6.2: Wetting front penetration (in cm from furrow centre) at the bed surface after 9 hrs of wetting for three treatments during the first irrigation at site A1-Vertisol.

Irrigation	Treatment	80% FC	100% FC	120 % FC
1	**NT**	90	75	46
	SC	> 100	>100	45
	BP	> 100	>100	> 100
2	**NT**	95	78	50
	SC	> 100	90	77
	BP	> 100	>100	> 100

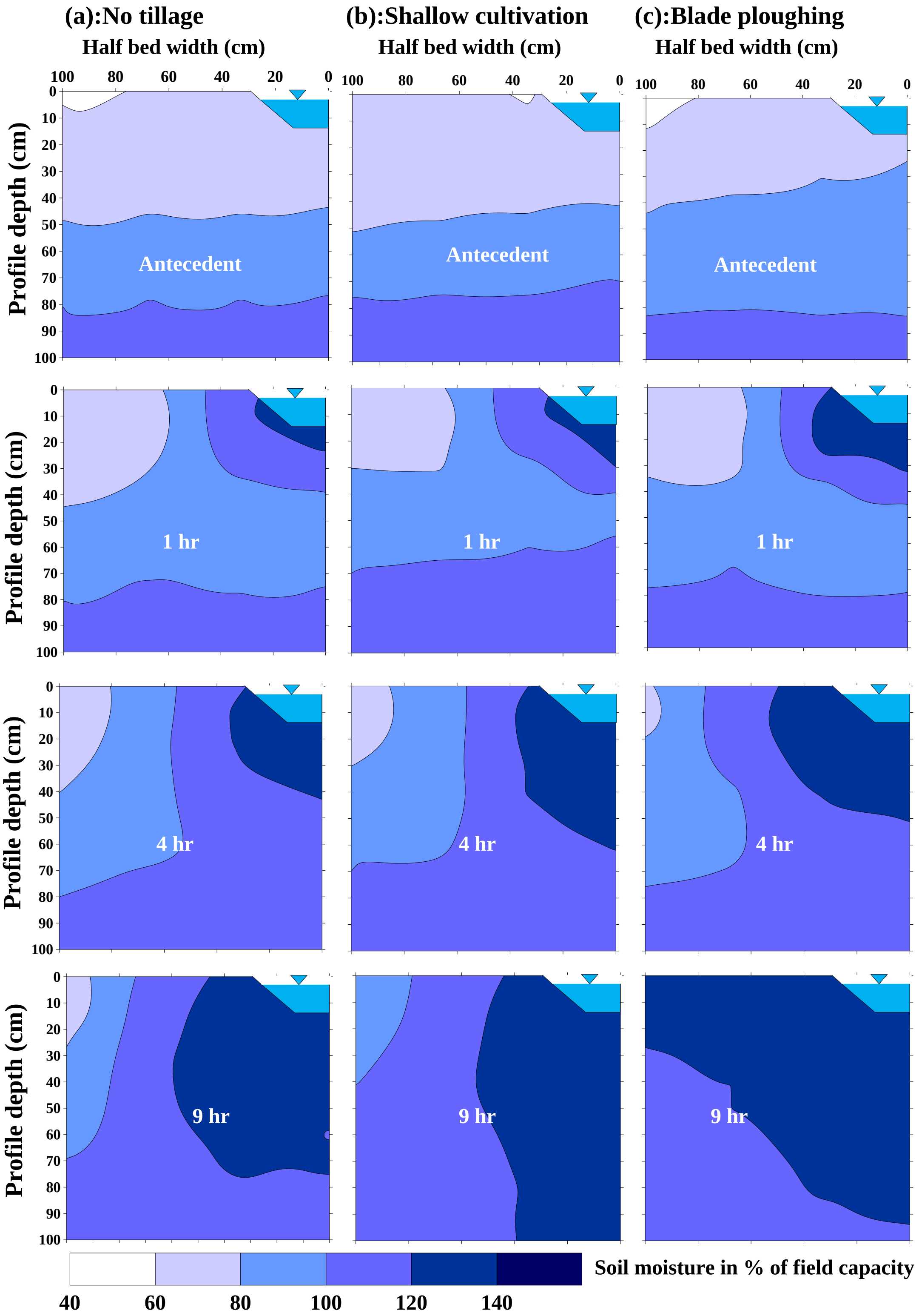


Figure 6.9: Soil moisture distribution for three PRB renovation treatments across a 200 cm wide bed during the first irrigation at site A1-Vertisol

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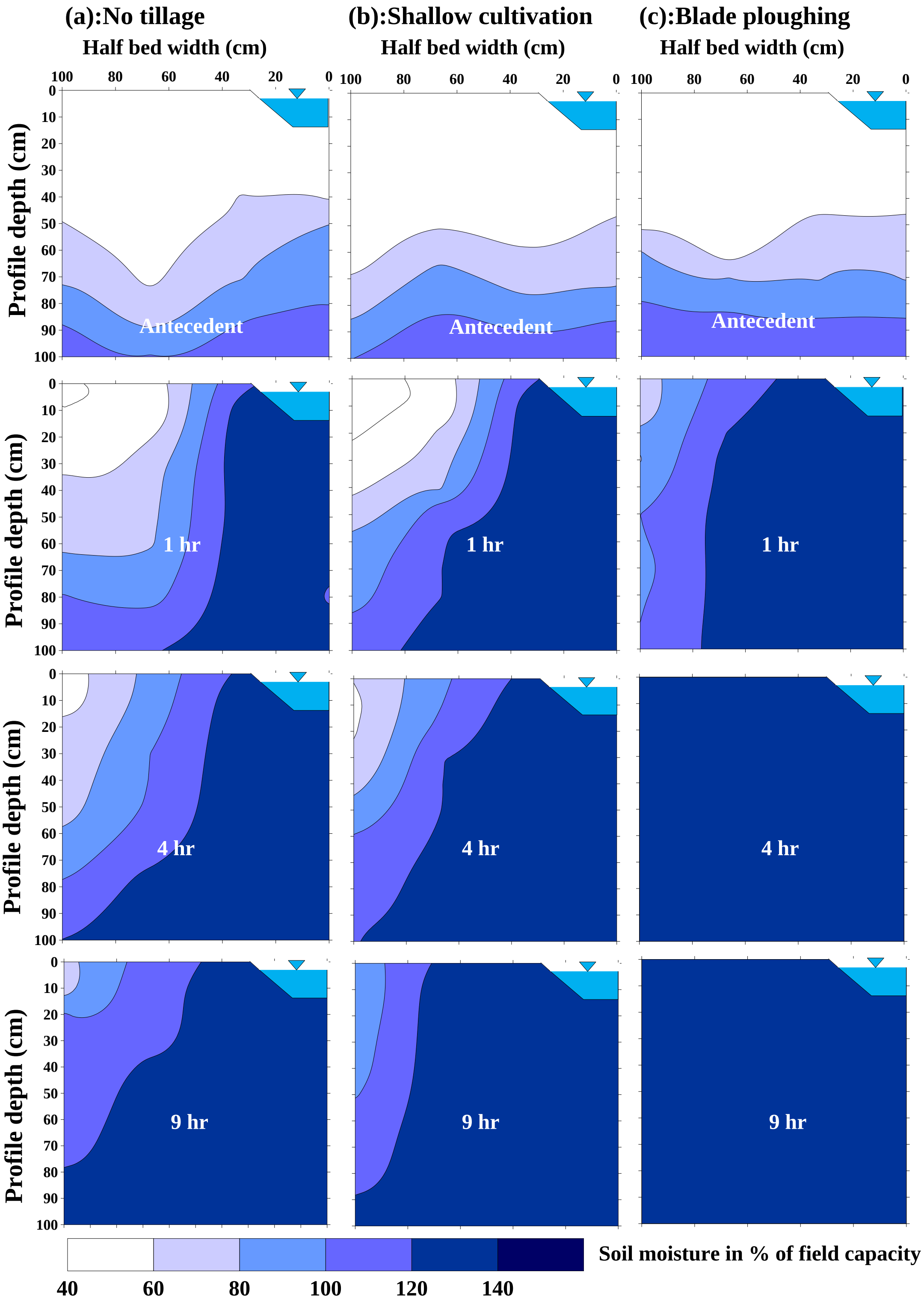


Figure 6.10: Soil moisture distribution for three PRB renovation treatments across a 200 cm wide bed during the second irrigation at site A1-Vertisol

6.3.2 Site P4-Sandy Clay Loam

The average bulk densities of the combined 0-30 cm layer were not significantly *(P=0.05)* different between irrigations for all treatments. However, the results showed significantly *(P=0.05)* lower bulk density for BP compared with NT (Figure 6.11) at all individual depths. The bulk density of the combined 0-20 cm layer on SC was significantly *(P=0.05)* lower than NT. However, the bulk density at 20-30 cm depth was similar between NT and SC. Overall results showed a similar average bulk density (0-30cm) between SC and the other two treatments, but the average bulk density of the combined (0-30cm) layer of BP was significantly *(P=0.05)* lower compared with NT.

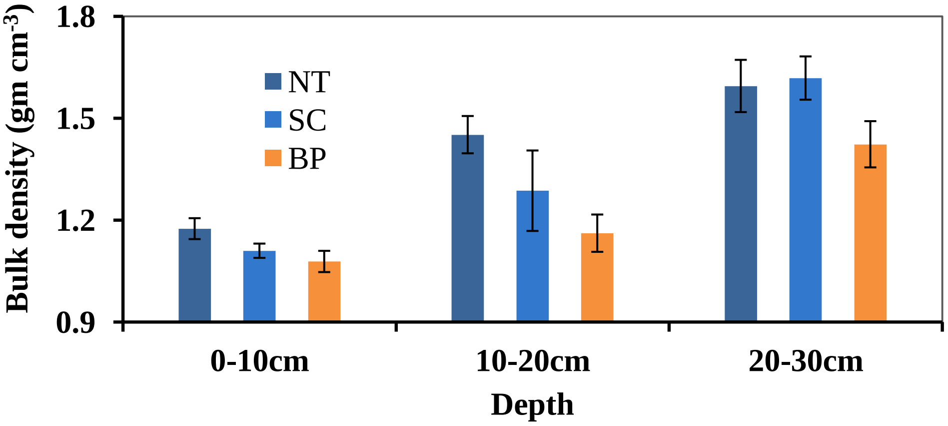


Figure 6.11: Average bulk density (BD) before two irrigations for three PRB renovation treatments at site P4-sandy clay loam (vertical bars show SD)

Average antecedent soil moisture was similar across 132 cm beds for all three treatments during both irrigations (Figure 6.12). The antecedent soil moisture was slightly higher near the furrow compared with the bed middle. However, the differences in antecedent soil moisture between experiments and between treatments were not significant *(P=0.05)*. Therefore, the data for both experiments were treated as a single population and analysed together.

The soil moisture at 22 cm after one hour and four hours of wetting was significantly *(P=0.05)* higher for SC and BP compared with NT (Figure 6.12). However, the difference in soil moisture between SC and BP was not significant *(P=0.05)* after one hour and four hours of wetting. All treatments soil moisture became significantly

(P=0.05) different after nine hours of wetting. BP had significantly *(P=0.05)* higher soil moisture at 44 cm compared with the other treatments after nine hours of wetting.

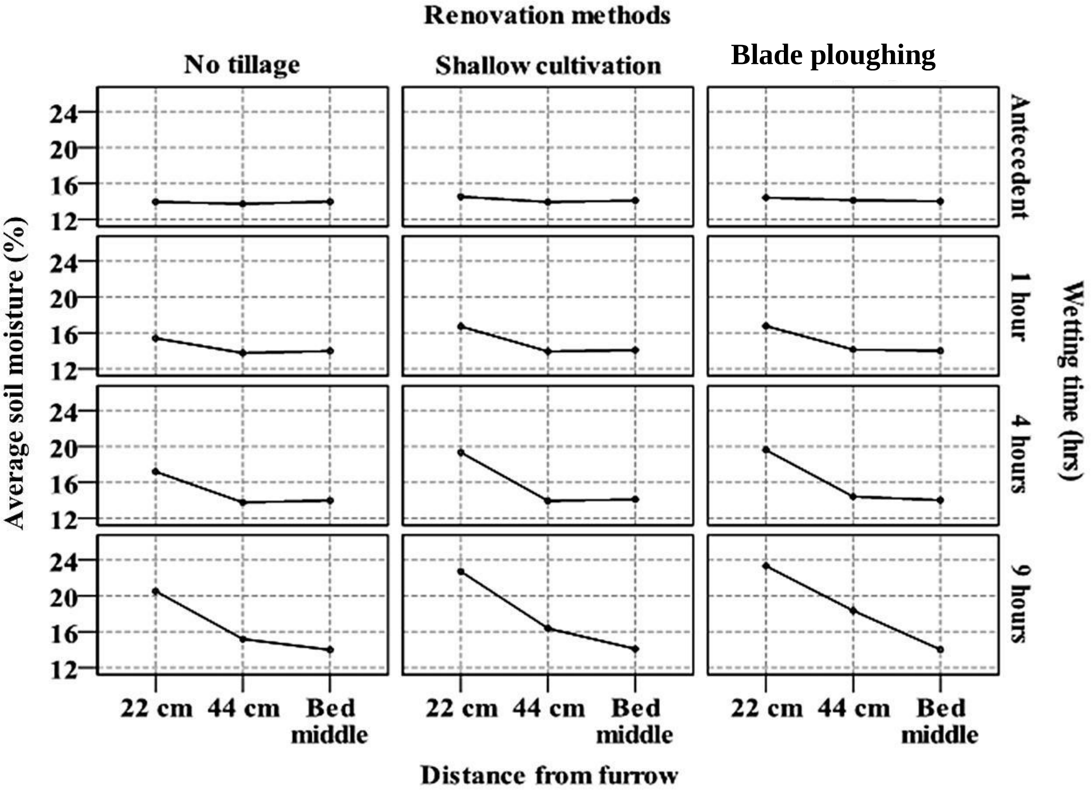


Figure 6.12: Impact of renovation method, wetting time, and distance from furrow centre on average soil moisture in 100 cm profile depth during two irrigations at site P4-sandy clay loam

There were considerable variations in infiltrated depth after nine hours of wetting, especially at 44 cm (Figure 6.13). The wetting front movement both vertically and laterally was considerably reduced for NT compared with SC and BP. The BP treatment considerably increased the soil moisture at 44 cm but none of the renovation treatments were successful in wetting the bed middle to field capacity during the nine hours of wetting.

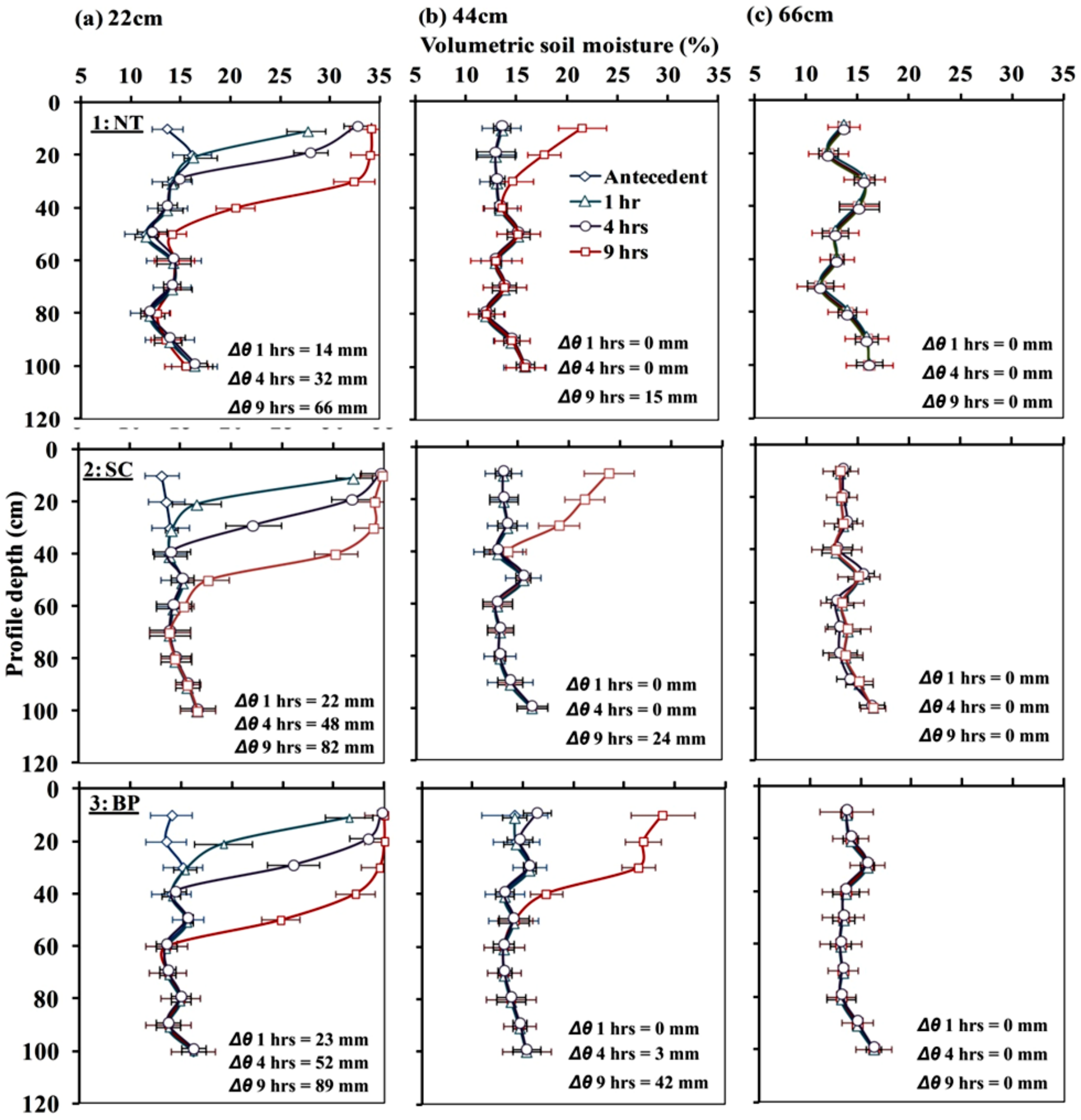


Figure 6.13: Change in soil moisture content *($\Delta\theta$)* across a 132 cm wide bed at given distances from furrow centre and given times with three renovation treatments during two irrigations at site P4-sandy clay loam

The comparison of cumulative infiltration after nine hours of wetting (Figure 6.14) shows most infiltration occurred at 22 cm for all treatments. The least cumulative infiltration at a 22 cm distance was on NT (66 mm) compared with SC (23% higher) and BP (68% higher). Similarly, at 44 cm the average cumulative infiltration after nine hours of wetting was 36% and 190% higher for SC and BP respectively compared with NT (15 mm). There was no infiltration into the bed middle for any treatment.

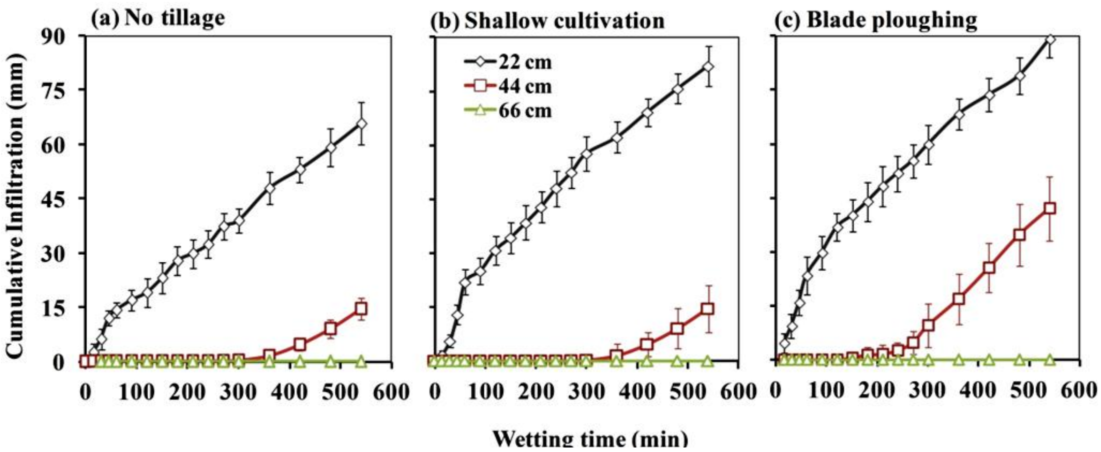


Figure 6.14: Cumulative infiltration across a 132 cm wide bed with three renovation treatments during two irrigations at site P4-sandy clay loam

The two dimensional soil moisture profiles were graphed at four time intervals (antecedent, one hour, four hours and nine hours) of wetting. The soil moisture distribution below the furrow bottom was estimated by extrapolation of the measured values and by the difference between the soil moisture volume measured in the profile, and total volume of water added to the furrow. The lateral movement of the wetting front penetration on the bed surface after nine hours of infiltration is summarised in Table 6.3. The average results of soil moisture profiles during both experiments for all three treatments are shown in Figure 6.15.

Table 6.3: Wetting front penetration (in cm from furrow centre) at the bed surface after 9 hrs of wetting for three renovation treatments during the two irrigation at site P4-sandy clay loam

Treatment	70% FC	90% FC	110 % FC
NT	60	50	38
SC	64	54	40
BP	> 66	57	48

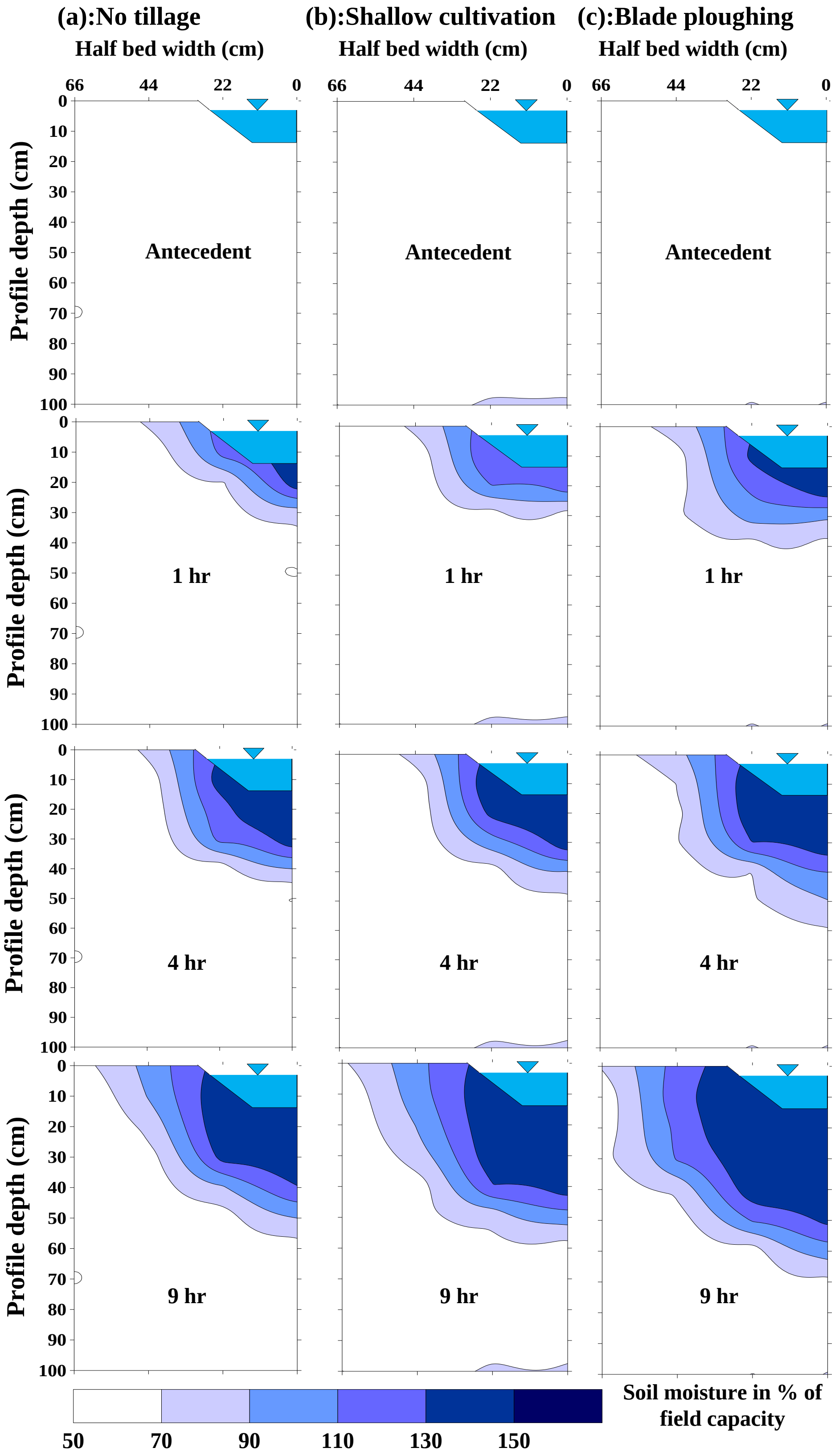


Figure 6.15: Soil moisture distribution for three PRB renovation treatments across a 132 cm wide bed during two irrigations at site P4-sandy clay loam

6.3.3 Field sorptivity

Field sorptivity (S) on Vertisol was variable between treatments and soil types (Table 6.4 and Figure 6.16). The S for the BP treatment was 19% and 15% higher than the NT and SC treatments respectively, in Vertisol. For sandy clay loam the S for BP treatment was 71% and 16% higher than the NT and SC treatments respectively. Comparison of both soils showed 4 to 6 times higher field sorptivity in Vertisol compared with sandy clay loam.

Table 6.4: Field sorptivity (mm hr$^{-0.5}$) during 9 hrs wetting time for three PRB renovation treatments during the first irrigation at site A1-Vertisol and average of two irrigations at site P4-sandy clay loam (SD in brackets)

Site/Soil	NT	SC	BP
A1-Vertisol	107 *(3)*	110 *(9)*	126 *(4)*
P4-sandy clay loam	17 *(3)*	25 *(5)*	29 *(6)*

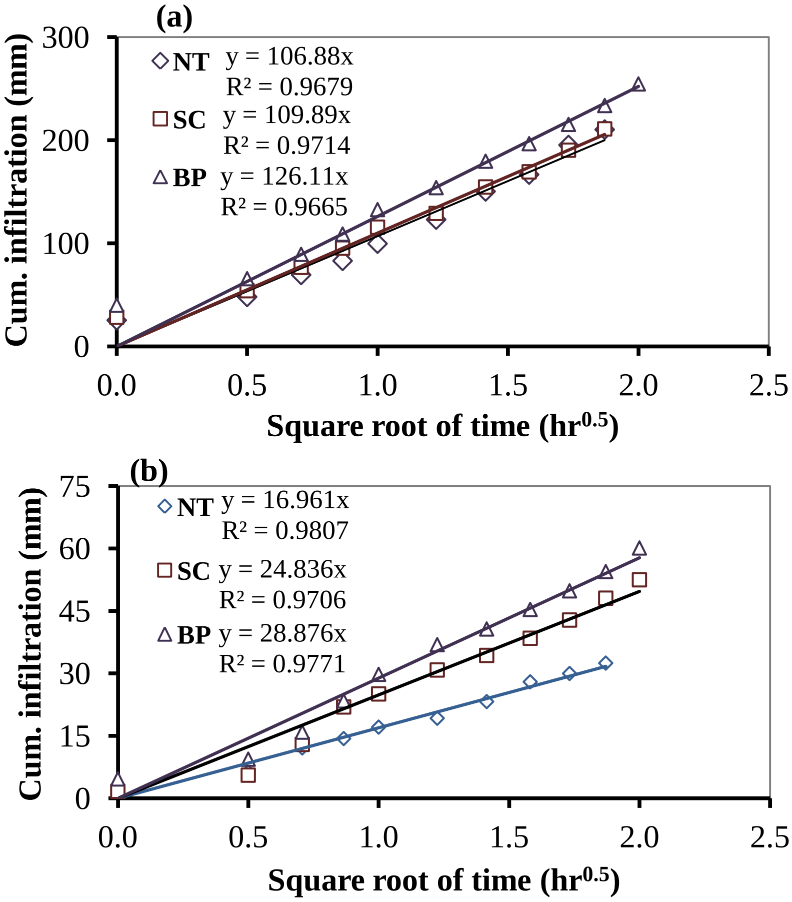


Figure 6.16: Effect of three PRB renovation methods on average field sorptivity for (a) site A1-Vertisol during first irrigation and (b) site P4-sandy clay loam during two irrigations

6.4 Discussion

6.4.1 Lateral infiltration on Vertisol

The significantly lower bulk density for BP compared with NT indicates that the renovation method has altered the soil structure in the bed. Thus, the differences in soil moisture distribution were most likely due to differences in soil hydraulic properties associated with the different renovation methods. As the antecedent soil moisture during each experiment was not significantly *(P=0.05)* different between treatments, this suggests that the results were not confounded by antecedent soil moisture effects even though the two irrigations had significantly *(P=0.05)* different antecedent soil moisture content.

This study found significantly lower soil moisture at the middle of the bed compared with the bed shoulder in the majority of cases. This confirms that the soil moisture distribution between the wetted furrow and the centre of a 200 cm wide PRB is not uniform. Thus, the assumption of uniform soil moisture distribution across the beds is not appropriate for irrigated wide PRB farming systems. Enhanced lateral infiltration appeared to be due to the presence of cracks (Lin et al. 1998) when the soil was dry during the second irrigation. This enhanced lateral infiltration may reduce the risk of water stress in the bed middle (Lucy 1993). However, deep drainage losses are also likely to be increased due to cracks.

The lower cumulative infiltration observed at the furrow centre of all treatments compared with the bed is consistent with the compacted permanent wheel tracks reducing vertical infiltration in the furrow area (Khalid & Smith 1976; Potter et al. 1995; Coutadeur et al. 2002). However, a lower vertical infiltration may also have been due to the relatively higher moisture content in the furrow (Turner & Sumner 1978) as occurred during the first irrigation.

Overall results showed greater lateral infiltration for BP followed by SC and then NT. The treatment effect was significantly different during both irrigations. This confirms that the renovation method of PRB can significantly alter the lateral infiltration on Vertisol. More interestingly, it has also confirmed that impacts of renovation methods on lateral infiltration still existed under very dry soil conditions on a Vertisol in the presence of cracks. One of the reasons may have been the loose and porous soil conditions of the BP treatment. In any case, BP can be used as a tool to enhance lateral infiltration in wide PRBs on Vertisol soils.

BP had higher lateral infiltration but lower vertical infiltration compared with SC. One of the reasons was the soil tilth associated with SC that enhanced vertical infiltration by gravity due to the presence of temporary macro pores (Lipiec et al. 2006). However, the enhanced lateral infiltration for BP was likely due to higher lateral hydraulic conductivity, sorptivity and water storage capacity (Thomas et al. 1990; Eldridge & Robson 1997; Hamilton et al. 2005; Jin et al. 2007; Akbar et al. 2010). The objective of gentle, non-inverting, controlled mechanical loosening with BP was to retain roots and bio-pores, which seems likely to have increased the organic matter, stability of aggregates and retained a stable porous environment with enhanced sorptivity (Collis-George & Laryea 1972), thus lateral infiltration was improved. The uniform distribution of soil moisture across the bed for BP treatment indicates no smearing that could constrain water movement below the mechanically loosened 30 cm profile depth.

Variations in infiltration between irrigations were largely affected by the antecedent soil moisture levels, being drier prior to the second irrigation than the first. However, the drier profiles for the second irrigation do not account for all of the differences. If this was the sole reason, one would expect the magnitude of increase to be about the same for all treatments. It seems that the active growth of the corn crop and its roots along with the associated biological activity around the roots may have enhanced the soil aggregation and the stability of aggregates to wetting, as evidenced by the greater sorptivity. The larger horizontal infiltration under BP is consistent with a larger, stable porosity in this treatment. Greater root development has been documented for PRBs with 30 cm deep blade ploughing practices (Hamilton, D. pers. comm.). The resulting larger soil moisture storage under BP may also be helpful in extending the period between irrigations, making better use of in-season rainfall, and controlling deleterious effects on crops due to in-season water stress if the crop is not fully irrigated.

6.4.2 Lateral infiltration on sandy clay loam

The similar bulk densities for both irrigations indicated that there was no further degradation or subsidence over this time frame on the sandy clay loam at this site. However, the significantly lower bulk density (0-30cm) for BP indicated greater porosity compared with NT. Similarly, SC also showed significantly lower bulk density in the cultivated zone (10 cm) compared with NT. Thus, the three treatments significantly altered the soil structure and the resulting differences in lateral infiltration would be expected to be due to changes in hydraulic properties caused by the different soil management techniques.

The sandy clay loam had an extremely poor lateral and vertical infiltration. Although lateral infiltration in the three renovation treatments was significantly different, none of the treatments successfully wet the bed middle to field capacity during the nine hours of wetting. This is most likely due to the general poor soil structure at the site associated with a history of intensive cultivation with top soil inversion (Gill 1994; Kahlown et al. 1998; Akbar et al. 2007) and high soil salinity (Qureshi et al. 2008), which has made the soil susceptible to dispersion and sealing due to rapid wetting.

NT is not a common practice in north west Pakistan (Akbar et al. 2007) as it is normally associated with higher weed infestation, poor lateral infiltration and hard seed beds, which are difficult to manage manually. The current results showed NT resulted in lowest lateral infiltration. Therefore, NT could be expected to increase the risk of poor crop performance in the bed middle due to water stress under degraded soil conditions. Poor lateral infiltration was also reported by Jin et al. (2007) and Akbar et al. (2007), while Wang et al. (2012) did not recommend continuous NT on sandy clay loam.

SC is the most commonly used method of tillage in north west Pakistan due to the common perception that it helps in cleaning the weeds from the previous crop, improve soil infiltration capacity and also helps in making a soft seed bed for the convenient manual sowing of row crops (Akbar et al. 2007). However, this study found poor lateral infiltration under this treatment. It also seems likely that the continued use of SC may negatively affect soil structure and destroy the soil's natural ability to ameliorate. Initially high vertical infiltration for SC may be due to the existence of temporary macro pores (Coquet et al. 2005; Bormann & Klaassen 2008). However, the macro pores would be expected to rapidly collapse or to clog due to soil dispersion (Smith et al. 1983). The resultant poor lateral infiltration has been found (Hassan et al. 2005) to negatively affect crop performance on the bed middle and crop yield.

The higher lateral infiltration observed for BP treatment was consistent with the findings of Jin et al. (2007) and Akbar et al. (2009). The higher lateral infiltration associated with BP was found in both irrigations. Although BP was also not successful in wetting the middle of the bed in the nine hours of wetting, the higher infiltration rates over the NT and SC raise the prospect of further improvement in combination with other irrigation and agronomic (CA) measures.

Increasing the infiltration opportunity time and/or furrow water head through optimised irrigation management practices may assist in wetting the middle of a 132 cm wide bed on sandy clay loam, which needs to be investigated and the following Chapter 7 explores this possibility. Alternatively, decreasing the bed width or leaving a larger gap in plant rows on the bed middle may also address poor lateral infiltration issues. However, the long term measures for such a soil with non-expansive mineralogy and degraded structure could involve structural improvement and stabilisation by organic matter and soil biology.

6.5 Conclusions

Lateral infiltration was increased by BP relative to both NT and SC on both the Vertisol and sandy clay loam. The higher lateral infiltration capacity and longer irrigation times used on Australian Vertisol (due to long fields) mean that wide beds (200 cm furrow spacing) are less susceptible to poor crop performance in the middle of the beds. In contrast, the poor lateral infiltration and short irrigation times used on smaller Pakistani farms make wide beds (132 cm furrow spacing) on sandy clay loams more susceptible to poor crop performance. The main conclusions from this study are:

- The soil moisture distribution across the beds was not uniform and varied under all three PRB renovation methods. Thus, the assumption of uniform soil moisture distribution across the beds is not appropriate for the irrigated wide bed farming systems.
- The three PRB renovation treatments significantly altered the lateral infiltration capacity on both soils. Thus, bed renovation can be used as a management tool to minimise yield loss of densely grown crops in the middle of wide beds.
- BP was more efficient than SC and NT in reducing the bulk density and increasing the sorptivity, lateral infiltration capacity and soil water storage on both soils.
- The increased sorptivity with BP treatment enhanced the legitimacy and validity of most surface irrigation simulation models that assume uniform distribution of soil moisture across the beds.

CHAPTER 7: Strategies to improve lateral infiltration in permanent raised beds using Hydrus 2D

7.1 Introduction

The previous field trials (Chapter 6) revealed large differences in infiltration between three PRB renovation methods due to soil structural and antecedent soil moisture differences. These differences in lateral infiltration on the Vertisol and sandy clay loam raised concerns about the appropriateness of current PRB irrigation management and field design. The common assumption of uniform sub-surface distribution of soil moisture across the beds was shown to be inappropriate for wide PRBs. In fact, without management aimed specifically at improving lateral infiltration, PRB farming will not reach its potential levels of irrigation efficiency and productivity. This lack of adequate wetting of the centre of PRB has already been shown to affect crop germination on Vertisol (Lucy 1993) and crop yield on sandy clay loam (Hassan et al. 2005) leading to low *WP*. Therefore, this study used a calibrated soil water simulation model to evaluate renovation and furrow water head (flow rate) strategies for improving lateral infiltration in wide PRBs.

The PRB renovation methods (described in Chapter 5) were simulated using Hydrus 2D (Šimunek et al. 1999). The lateral and vertical movement of the wetting front, cumulative infiltration, deep drainage losses (water penetrated beyond arbitrary root zone depths), and soil water storage were determined at a range of furrow water heads (flow rates). The outcomes were used to develop relationship between furrow inflow rate and bed width to improve irrigation management on both sites.

7.2 Material and methods

The Hydrus 2D model was calibrated on both soils (Appendix E) using the pre-processing procedures as outlined by Rassam et al. (2004) and Simunek et al. (2007). For the Vertisol, the field data measured during the first experiment (Chapter 6: 9 cm furrow water head) and during the first 2011 corn crop irrigation (Chapter 5: 6 cm furrow water head) were used. For the sandy clay loam, the average field data of both experiments (Chapter 6: 9 cm furrow water head) were used.

The flow domain was designed to simulate the 200 cm wide PRB on Vertisol and 132 cm wide PRB on sandy clay loam. The depth of the flow domain was set at 100 cm below the bed surface to match the root zone depth for mass balance, deep drainage and soil water storage evaluations (Figure 7.1) on both soils. The calibrated model was run for 20 hrs on the Vertisol and for 40 hrs on the sandy clay loam. Six lateral observation nodes (L1 to L6) were located on the bed surface at 40, 60, 70, 80, 90 and 100 cm on the Vertisol (Figure 7.1) and at 36, 46, 51, 56, 61 and 66 cm distance from the furrow centre on the sandy clay loam (layout not shown). Ten observation nodes were fixed on the vertical boundary in the middle of bed (M1 to M10) and nine on the vertical boundary below the furrow centre (F1 to F9) at 10 cm depth intervals (Figure 7.1) for both soils. These observation nodes were used to evaluate temporal variations in soil moisture for the three renovation treatments with 9 cm furrow water head (as 9 cm represented large range of flow rates). Further analysis of lateral and vertical infiltration was undertaken using furrow water heads of 4 cm, 6 cm, 9 cm and full furrow depth (D in Table 6.1) to represent a range of furrow flow rates (*Q*). The *Q* versus furrow water head relationship was identified from field measured experimental data on both soils. Cumulative infiltration, deep drainage and volume stored were identified from the Hydrus output.

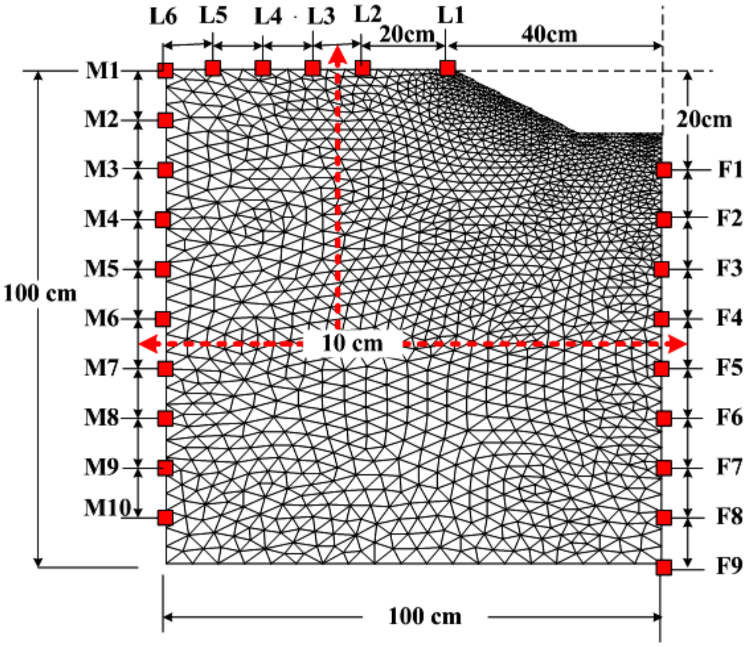


Figure 7.1: Locations of observation nodes on surface and vertical boundaries of flow domain for Vertisol

7.3 Results

7.3.1 Hydrus calibration

There was a strong correlation between measured and predicted soil moisture values on both soils and all bed renovation treatments as shown in Figure 7.2 and presented in detail in Appendix E. The errors identified were mainly due to a slight over-prediction near the furrow and slight under-prediction in the bed middle. However, the overall results showed a good estimation of temporal variation in soil moisture distribution under three different PRB renovation methods on both soils confirming that the calibration of the model was appropriate.

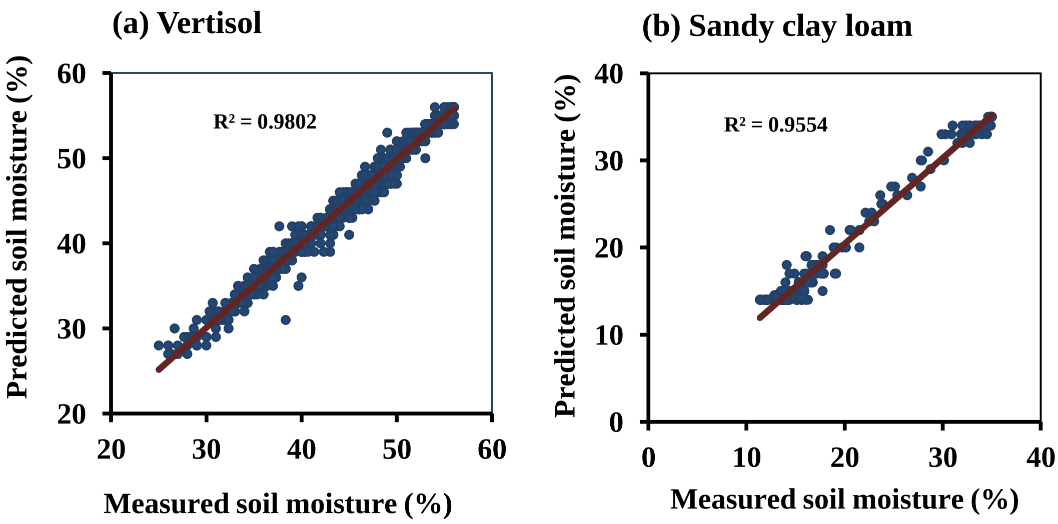


Figure 7.2: Correlation between measured vs. predicted soil moisture during 9 hrs wetting for three renovation treatments with 9 cm furrow water head

7.3.2 Effect of renovation on infiltration with 9 cm furrow water head

7.3.2.1 *Lateral infiltration*

For Vertisol, there were substantial temporal and spatial differences in soil moisture on the top surface of the bed between treatments (Figure 7.3) identified from six observation nodes (location given in Figure 7.1). The field capacity front took ~17 hrs on NT, ~11 hrs on SC and ~6 hrs on BP treatments to reach the bed middle (node L6 in Figure 7.3) when 9 cm of furrow water head was applied.

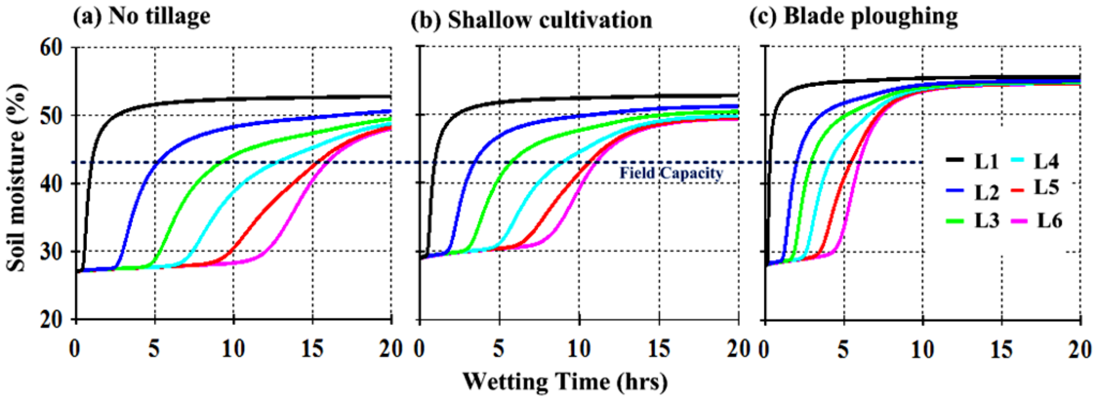


Figure 7.3: Simulated soil moisture variation on the bed surface (shown by observation node number: Figure 7.1) for three PRB renovation treatments with 9 cm furrow water head applied on a Vertisol

For sandy clay loam there were substantial differences in lateral wetting between the renovation treatments (Figure 7.4). More than 40, ~32 and 20 hrs wetting time was required for the bed middle (node L6) to reach field capacity for the NT, SC and BP treatments respectively when 9 cm furrow water head was applied.

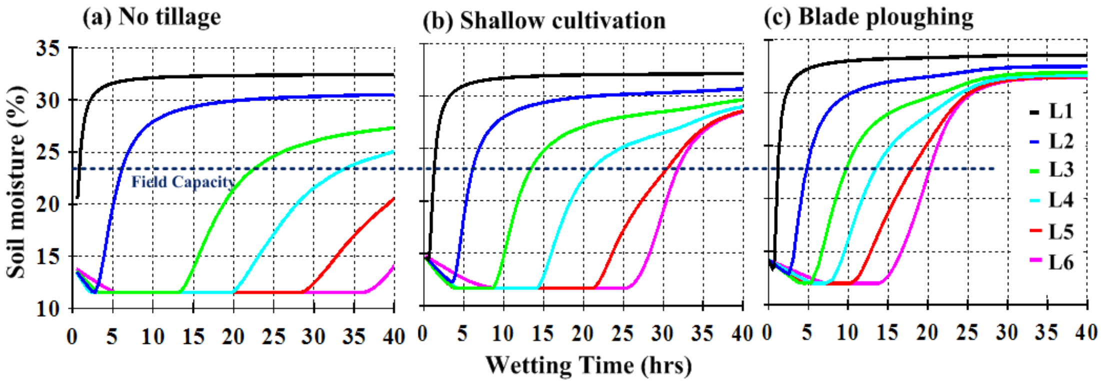


Figure 7.4: Simulated soil moisture variation on the bed surface at (L1 = 36, L2 =46, L3 = 51, L4 = 56, L5 = 61 and L6 = 66 cm distance from furrow centre) for three PRB renovation treatments with 9 cm furrow water head applied on a sandy clay loam

7.3.2.2 Vertical infiltration

For Vertisol, vertical infiltration below the furrow base was quickest for SC and slowest for NT (Figure 7.5). It took ~8, ~5 and ~7 hrs for the wetting front to reach 100 cm depth below datum in the furrow centre (node F9) for NT, SC, and BP treatments respectively, with 9 cm furrow water head applied.

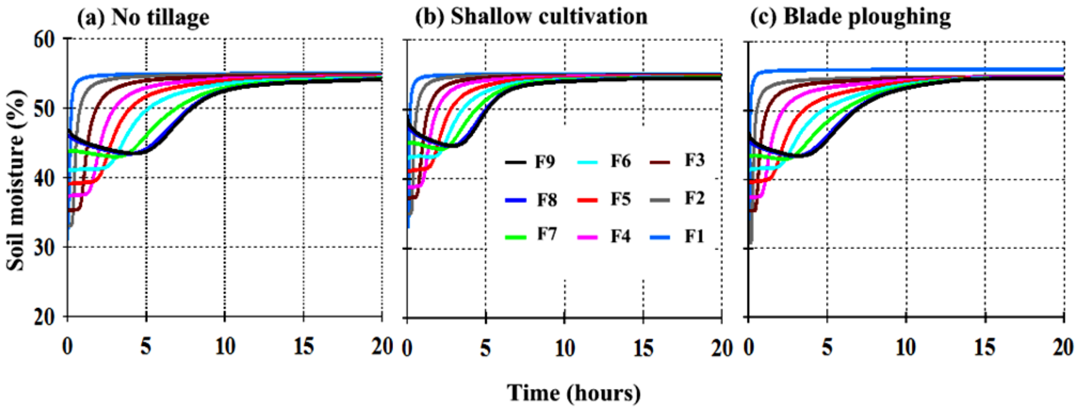


Figure 7.5: Simulated soil moisture variations below furrow (shown by observation node number: Figure 7.1) for three PRB renovation treatments with 9 cm furrow water head applied on a Vertisol

For Vertisol, infiltration to depths below the bed was slower than under the furrow (Figure 7.6). The lateral wetting front movement to the bed middle occurred faster on the bed surface than at deeper depths for BP (Figure 7.6c). It took ~17, ~13 and ~12 hrs for the wetting front to reach the 90 cm depth (M10) in the bed middle for NT, SC and BP treatments, respectively. The 0-30 cm depth filled much sooner with BP, while field capacity front took longer (8 to 16 hrs) on the other two treatments.

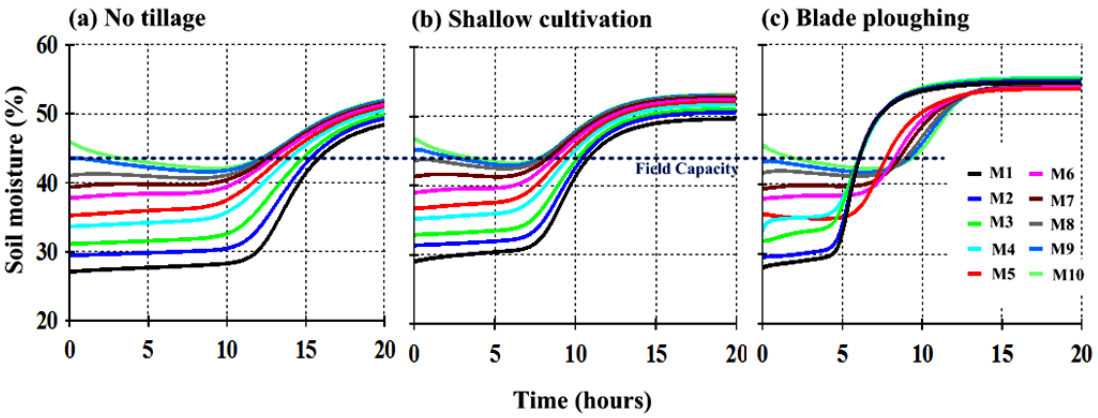


Figure 7.6: Simulated soil moisture variations on the vertical boundary under the bed middle (shown by observation node number: Figure 7.1) for three PRB renovation treatments with 9 cm furrow water head applied on a Vertisol

For sandy clay loam, vertical infiltration below the furrow centre also varied between treatments with infiltration occurring fastest on the BP treatment (Figure 7.7). The wetting front took ~35 hrs, ~30 hrs and ~27 hrs to reach 100 cm depth (node F9) on the NT, SC, and BP treatments, respectively.

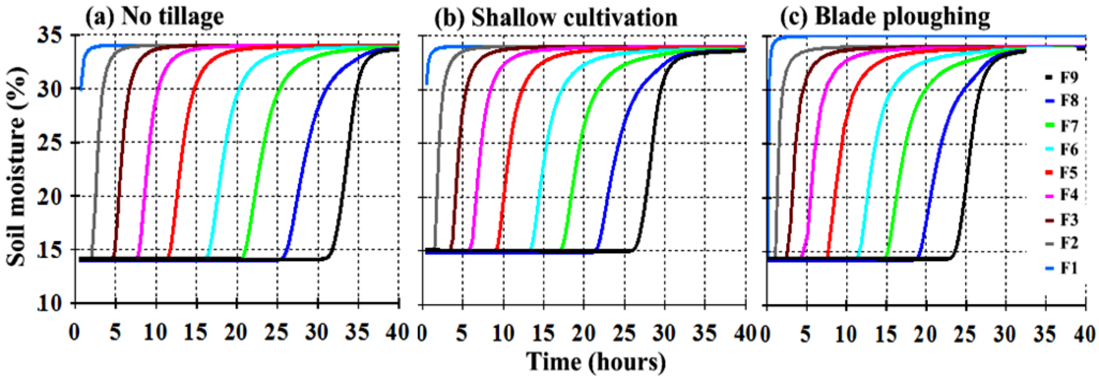


Figure 7.7: Simulated soil moisture variations below furrow (shown by observation node number: Figure 7.1) for three PRB renovation treatments with 9 cm furrow water head applied on a sandy clay loam

Soil moisture on the vertical boundary beneath the bed middle was unchanged until ~35 hrs for NT, 26 hrs for SC and 17 hrs for BP, when a 9 cm furrow water head was applied (Figure 7.8). Water reached the 30 cm depth (node M3) before the bed surface (node M1) and 90 cm depth (node M10) in all treatments (Figure 7.8). Evaporation during the simulation period reduced soil moisture in the 10 cm depth (node M1). The wetting times of extreme boundary positions are given in Table 7.1.

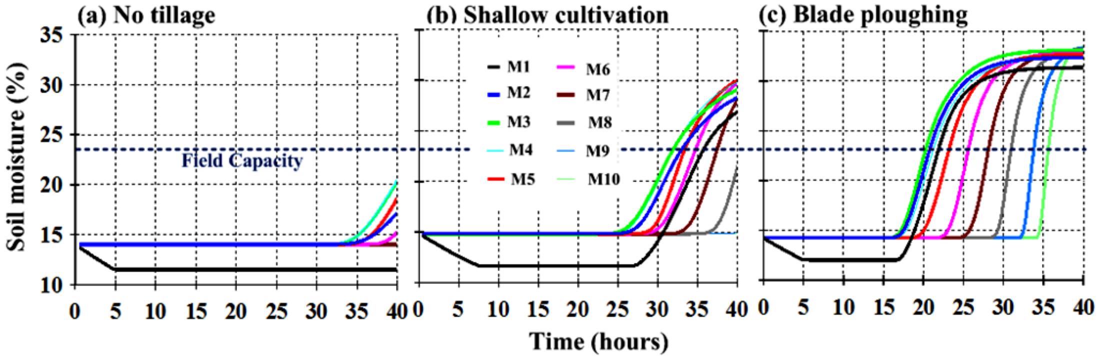


Figure 7.8: Simulated soil moisture variations on the vertical boundary under the bed middle (shown by observation node number: Figure 7.1) for three PRB renovations with 9 cm furrow water head applied on a sandy clay loam

Table 7.1: Time required for the wetting front to reach the given positions on the two soils with three PRB renovation methods at 9 cm furrow water head applied

Position	Wetting time (hrs)					
	Vertisol			Sandy clay loam		
	NT	SC	BP	NT	SC	BP
Bed middle at surface	17	11	6	> 40	32	20
Bed middle at 90 cm depth	17	13	12	[a]35	[a]26	[a]17
Furrow centre at 100 cm depth	8	5	7	35	30	27

[a]Wetting front arrival time to 90 cm depth in bed middle

7.3.3 Effect of furrow water head on soil moisture distribution

7.3.3.1 Lateral wetting on bed surface

For Vertisol, increasing the furrow water head decreased the time taken to wet the beds (Figure 7.9). For instance, to wet the bed middle to field capacity when the furrow was at full depth it required ~14, ~10 and ~5.5 hrs for NT, SC and BP, respectively. However, reducing the furrow water head to 4 cm increased the wetting time by 43% on NT, 35% on SC and on BP. Thus, the 200 cm wide beds would experience water stress in the bed middle at wetting times less than: ~20 hrs for NT, ~13.5 hrs for SC and ~7.5 hrs for BP if 4 cm furrow water head is applied.

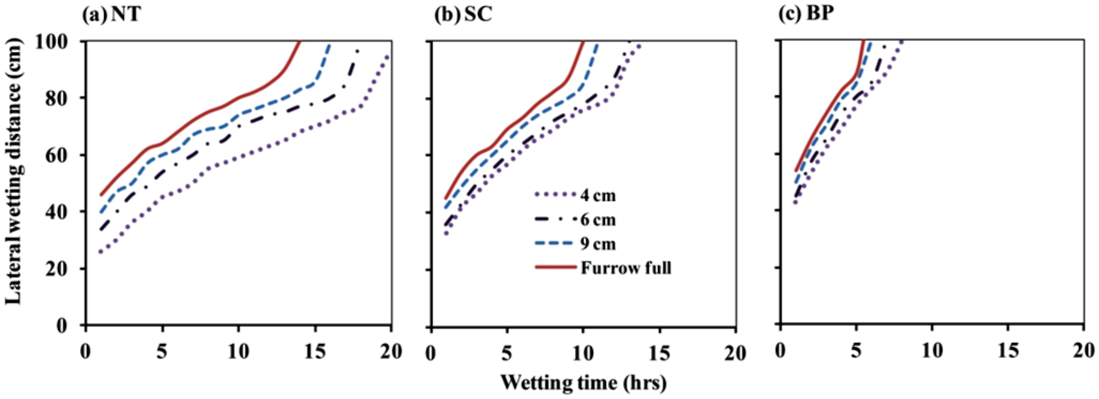


Figure 7.9: Effect of furrow water head on the wetting time required to reach field capacity at different lateral distances from furrow centre on a Vertisol

For sandy clay loam, increasing the furrow water head decreased the time required to wet the bed middle (Figure 7.10). For instance, it took the field capacity front ~37 hrs, 24 hrs, and 15 hrs for NT, SC and BP respectively, to reach the bed middle when the furrow was full of water. However, decreasing the furrow water head to 4 cm resulted in the bed middle not being wet during 40 hrs for NT and SC. For BP, decreasing the furrow water head to 4 cm increased the wetting time to ~31 hours. This data suggests that during the maximum 7 hrs wetting time, normal local irrigation period, the maximum bed width should be < 90 cm for NT and SC and < 105 cm for BP. However, if the furrow water head is reduced to 4 cm, the maximum bed width should be < 55 cm for NT and SC and < 66 cm for BP to ensure soil moisture in the bed middle reaches field capacity in the available 7 hrs wetting time.

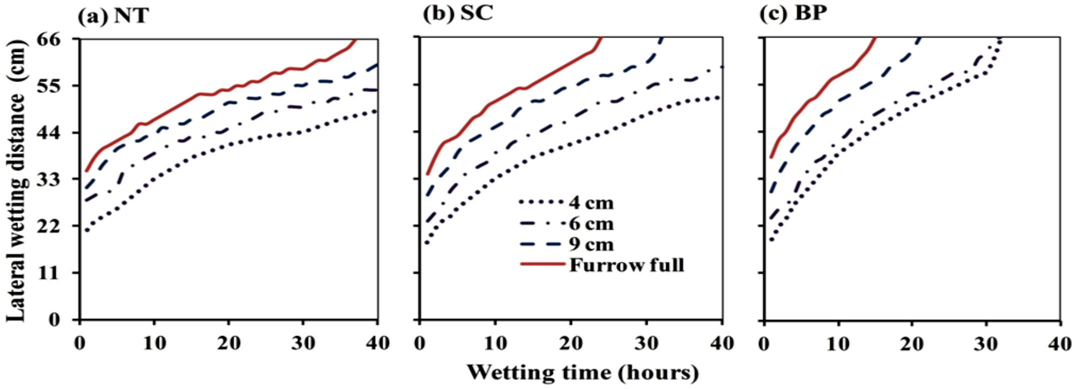


Figure 7.10: Effect of furrow water head on the wetting time required to reach field capacity at different lateral distances from furrow on a sandy clay loam

7.3.3.2 *Vertical wetting below furrow centre*

For Vertisol, vertical infiltration was fastest for SC and slowest for NT (Figure 7.11). When the furrow was full of water (Figure 7.11), it took ~8, ~6 and ~7 hrs in wetting the 100 cm profile depth for NT, SC, and BP, respectively. However, the wetting time increased by 65% for NT, 53% for SC and 40% for BP when the furrow water head was reduced to 4 cm.

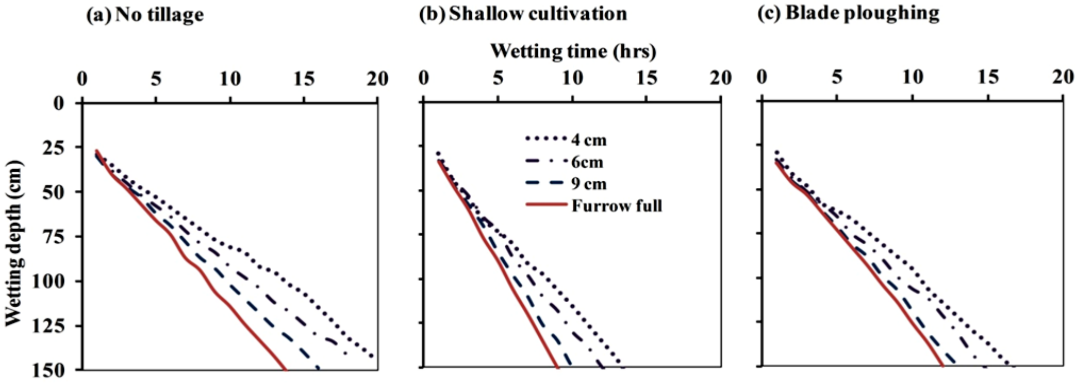


Figure 7.11: Effect of furrow water head and wetting time on the depth of wetting beneath the furrow on a Vertisol

For sandy clay loam, the soil moisture movement below the furrow centre was faster for BP than for SC and NT. The wetting front took ~33 hrs, 26 hrs and 23 hrs to reach 100 cm depth for NT, SC and BP, respectively (Figure 7.12) when the furrow was full of water. Decreasing the furrow water head to 4 cm increased the wetting time by 21% on NT, 46% on SC and 62% on BP.

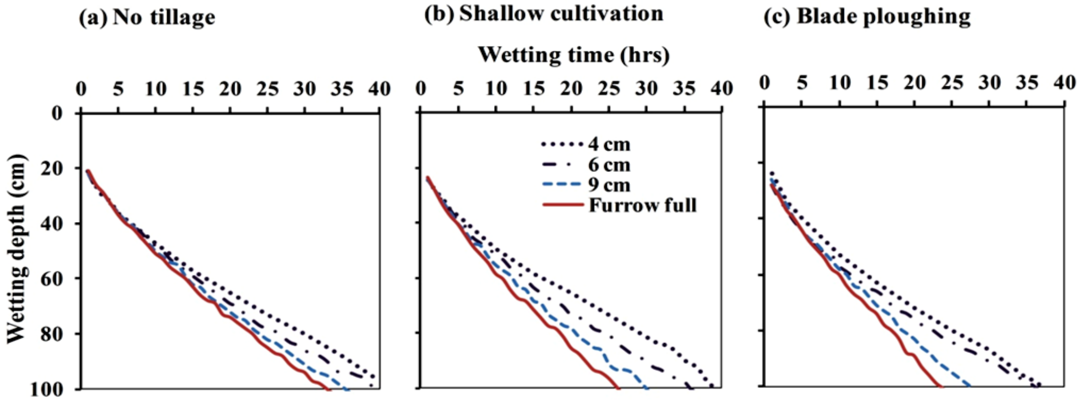


Figure 7.12: Effect of furrow water head and wetting time on the depth of wetting beneath the furrow on a sandy clay loam

7.3.3.3 *Cumulative infiltration*

BP had the highest cumulative infiltration at a short period (< 10 hrs) but SC had slightly higher cumulative infiltration after 12 hours (Figure 7.13). However, cumulative infiltration was lower for NT at all times. A comparison of cumulative infiltration after 17 hrs of wetting (wetting front arrival time to bed middle for NT) showed 33% and 25% higher infiltration for SC and BP, respectively, compared with NT (177 mm) at 9 cm furrow water head. Increasing furrow water head generally increased cumulative infiltration. For instance, cumulative infiltration after 20 hrs of wetting was increased by 58% for NT, 26% for SC and 22% for BP, when the furrow water head was increased from 4 cm to furrow full depth. Change in furrow water head had a larger effect on cumulative infiltration for NT than the other treatments. The difference between 9 cm and furrow full head was negligible for SC and BP.

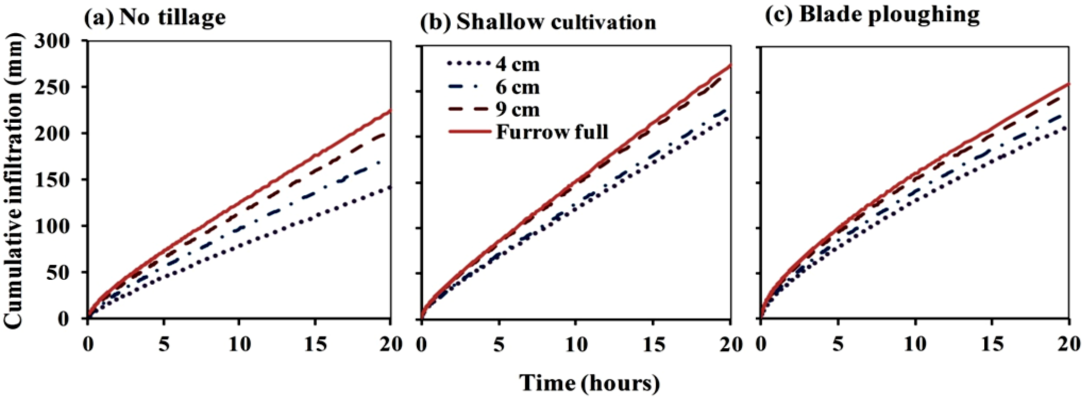


Figure 7.13: Effect of furrow water head on simulated cumulative infiltration for three PRB renovation methods on a Vertisol

For sandy clay loam, cumulative infiltration on NT was lower than SC and BP (Figure 7.14). After 20 hrs of wetting the cumulative infiltration was up to 24% greater for SC and 52% greater for BP compared with NT at all furrow water heads. Increasing furrow water head from 4 cm to furrow full water head increased cumulative infiltration by 85% for NT, 79% for SC and 49% for BP respectively, after 20 hrs of wetting.

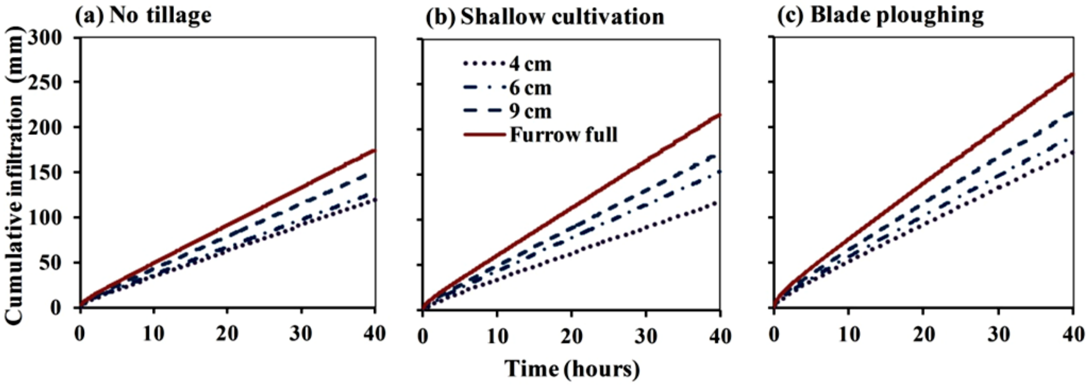


Figure 7.14: Effect of furrow water head on simulated cumulative infiltration for three PRB renovation methods on a sandy clay loam

7.3.3.4 *Soil water storage*

For Vertisol, the volume of water stored in the flow domain was generally lower for NT than for SC and BP (Figure 7.15). For instance, the volume stored after 10 hrs of wetting was 40%, 18%, 13% and 6% higher for SC and 70%, 46%, 27% and 29% higher for BP compared with NT (73, 91, 106 and 116 mm), when the furrow water head was 4 cm, 6 cm, 9 cm and furrow full respectively. However, the difference between the treatments was smaller at longer wetting periods when deep drainage losses occurred in the SC and BP treatments. Increasing the furrow water head increased the rate at which the water was stored in the profile. For instance, increasing the furrow water head from 4 cm to 6 cm, 9 cm, furrow full head increased the volume of water stored after 10 hrs of wetting by: 25, 45, 59% for NT, 5, 18, 21% for SC and 7, 17, 21% for BP respectively. Comparison of soil water storage as to when the wetting front reaches the centre of the bed for the flow depths used ranged 100-150 mm for NT, 110-130 mm for SC and 80-100 mm for BP treatments. The uniformly distributed soil moisture in BP across the bed shows greater potential for more efficient irrigation performance.

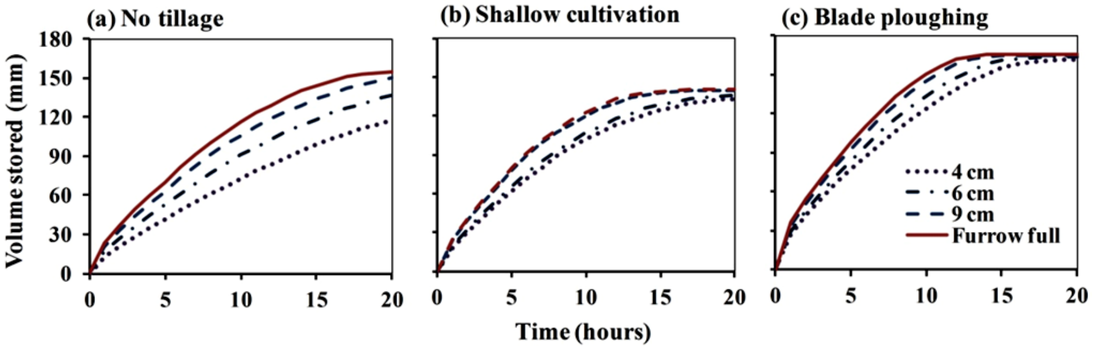


Figure 7.15: Effect of wetting time and furrow head on the water stored in 100 cm deep root zone across half bed width for three renovation treatments on a Vertisol

For sandy clay loam, the volume of water stored in the flow domain was generally lower for NT than for SC and BP (Figure 7.16). The volume stored after 20 hrs of wetting was up to 24% higher for SC and 49-52% higher for BP compared with NT at all furrow water heads. However, the difference between treatments was smaller at longer wetting periods when deep drainage losses occurred. For instance, after 40 hrs of wetting the water stored was 2-16% higher for SC and 17-42% higher for BP compared with NT. Increasing the furrow water head from 4 cm to full furrow depth increased the volume of water stored in the root zone by 45% for NT, 81% for SC and 47% for BP after 20 hrs of wetting.

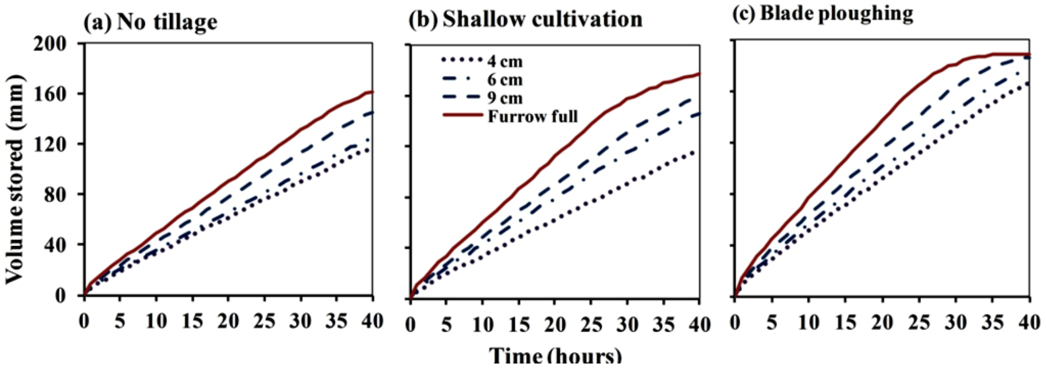


Figure 7.16: Effect of wetting time and furrow head on the water stored in 100 cm deep root zone across half bed for three renovation treatments on a sandy clay loam

7.3.3.5 Deep drainage losses

For Vertisol, after 20 hrs of wetting, deep drainage losses were 263%, 155%, 143% and 100% higher for SC and 113%, 68%, 54% and 35% higher for BP compared with NT (24, 38, 54 and 69 mm) at 4 cm, 6 cm, 9 cm and full furrow depth (Figure 7.17)., respectively. Similarly, increasing the water head from 4 cm to the full furrow condition increased deep drainage losses by 188% for NT, 59% for SC and 82% for BP after 20 hrs of wetting. By the time the wetting front reached the bed middle the deep drainage losses ranged from 10-40 mm for NT, 22-40 mm for SC and < 2 mm for BP treatment.

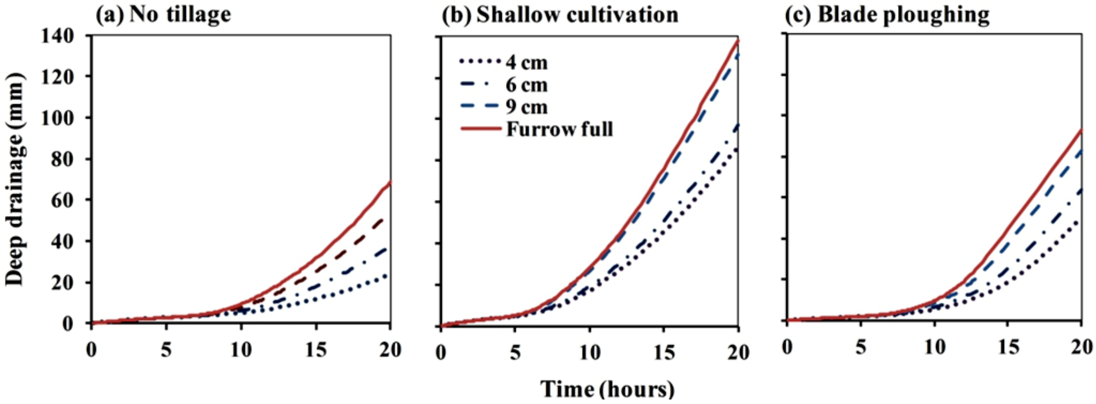


Figure 7.17: Effect of wetting time and furrow head on deep drainage losses below 100 cm root zone depth (across half bed x-section) for three PRB renovation methods on a Vertisol

For sandy clay loam, deep drainage losses were incurred after 33 hrs wetting on NT, 26 hrs on SC and 25 hrs on BP when a full furrow water head was applied (Figure 7.18). Deep drainage losses after 40 hrs of full furrow head wetting were ~3 times and ~6 times higher for SC and BP, respectively compared with NT (10 mm).

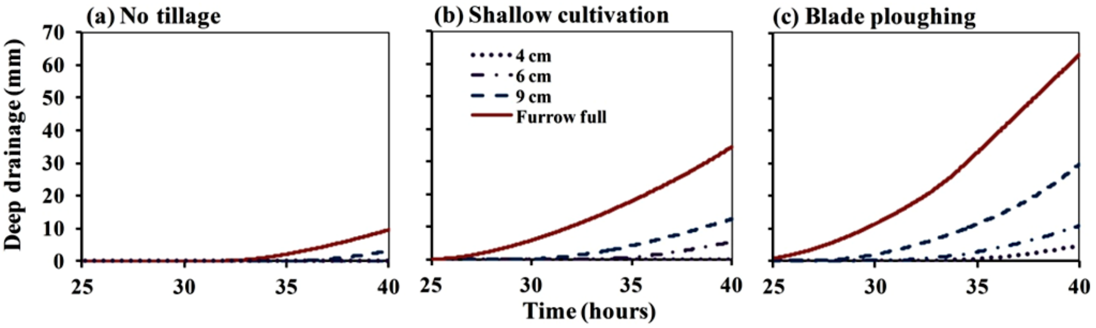


Figure 7.18: Effect of wetting time and furrow head on deep drainage losses below 100 cm root zone depth (across half bed x-section) for three PRB renovation methods on a sandy clay loam

7.3.3.6 Soil moisture distribution for normal irrigation applications

For Vertisol, to apply 100 mm (a common irrigation application depth in Australia) with a 9 cm furrow water head took ~9 hrs, ~7 hrs and ~5 hrs for NT, SC, and BP treatments respectively. The soil moisture distribution at the time of 100 mm water application (Figure 7.19) shows lateral penetration of the field capacity wetting front has reached 70, 74 and 85 cm distance from furrow centre for the NT, SC, and BP treatments, respectively. The vertical penetration of the wetting front was at 93, 110, and 71 cm below the datum line in the furrow centre for NT, SC and BP treatments, respectively.

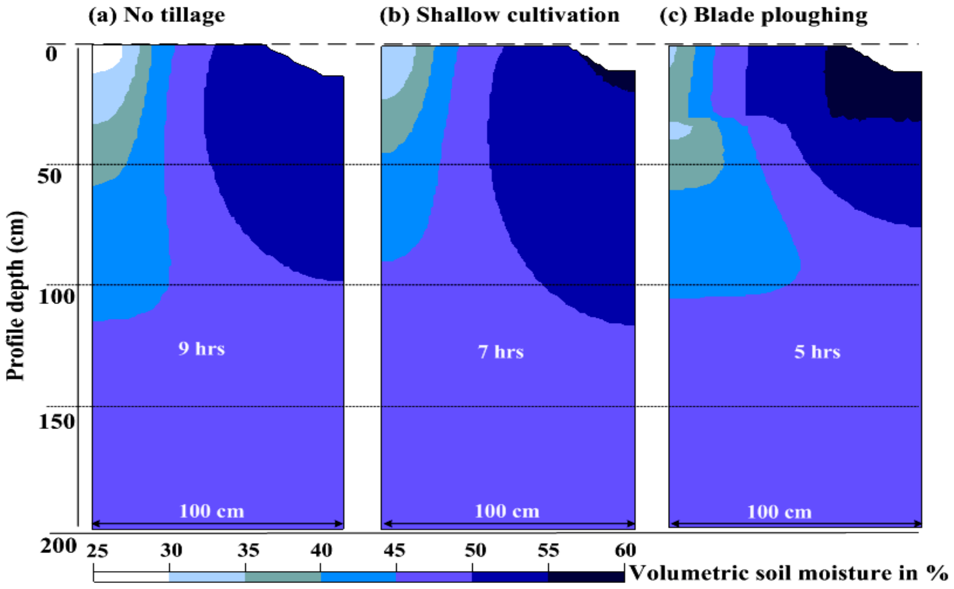


Figure 7.19: Simulated soil moisture distribution across the flow domain after 100 mm water application for three PRB renovation treatments with 9 cm furrow water head on a Vertisol

For sandy clay loam, to apply 60 mm (a common irrigation application in north west Pakistan) it took ~14 hrs, ~11 hrs and ~9 hrs for NT, SC and BP, respectively with full furrow water head (Figure 7.20). The wetting front reached 50 cm, 51 cm and 56 cm lateral distance on bed surface and ~61 cm, 62 cm, and 58 cm vertical distance below furrow centre with NT, SC and BP, respectively.

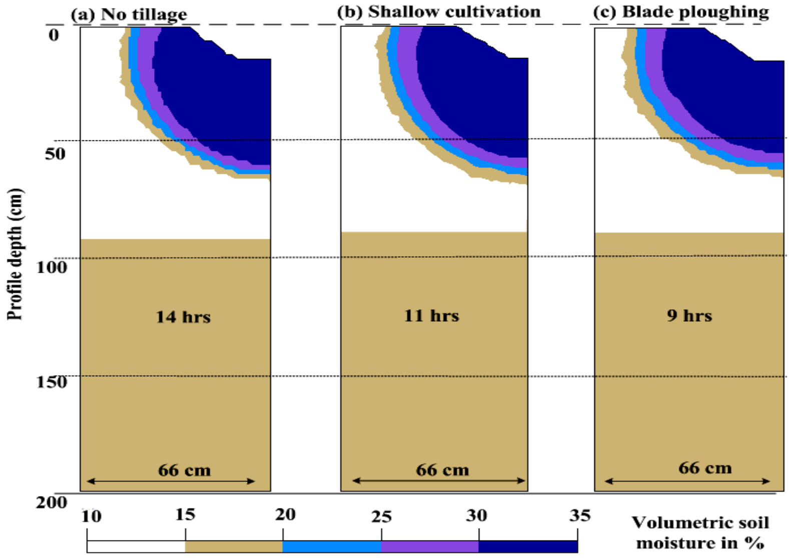


Figure 7.20: Simulated soil moisture distribution across the flow domain after 60 mm water application for three PRB renovation treatments with full furrow water head on a sandy clay loam

7.3.4 Implications of lateral infiltration for irrigation management

Inflow rate and furrow water heads were measured under field conditions as reported in Chapters 4 and 5. The data also revealed that beside inflow rate, the field measured water head varied along the furrow length presumably due to differences in furrow dimensions, furrow slope and antecedent soil moisture (Oyonarte et al. 2002). Water head in the furrow decreased up to 50% in the field tail section compared with the field head section (465 m long furrows in Vertisol) at low inflow rate (1 L s^{-1}) and up to 23% at high inflow rates (3 L s^{-1}). There was insufficient data to establish treatment specific relationships. Hence, the data was pooled to identify a single relationship (Figure 7.21). The furrow water head was found to vary from 4 cm to 10 cm when the inflow rate was changed from ~1 L s^{-1} to ~5 L s^{-1}. This relationship indicated that flow rate can be increased with comparatively little increase in velocity and erosivity of flow, which reinforces the practical application of the aforementioned relationships. The inflow rate and the furrow head was subsequently used to develop charts to highlight the relationship between inflow rate and target wetting time for each soil.

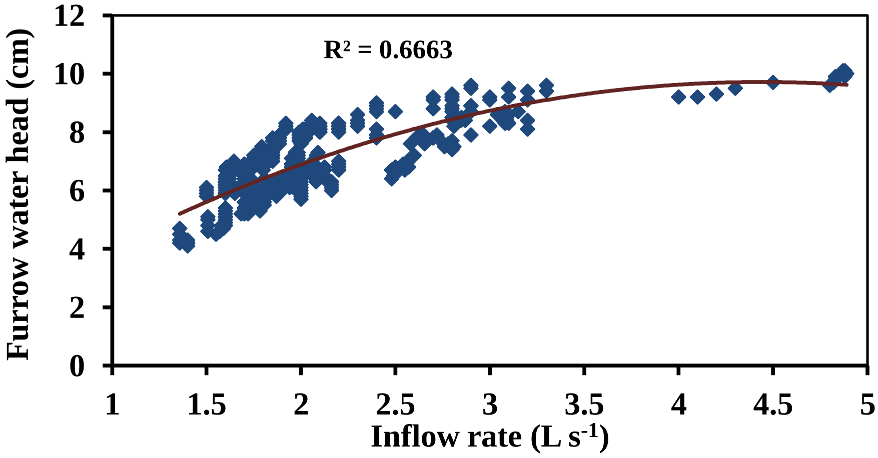


Figure 7.21: **Effect of inflow rate on furrow water head measured in the field head section during experiments on a Vertisol and a sandy clay loam**

Using the above relationship with the earlier simulation results (Figure 7.9) revealed that the inflow rate affected the lateral infiltration on all renovation treatments. For instance, increasing the inflow rate from 1 to 5 L s^{-1} reduced the time required to wet the bed middle (200 cm wide PRB) on a Vertisol by 30%, 26% and 27% for NT, SC and BP treatments, respectively (Figure 7.22). However, for a 66 cm wide PRB on the sandy clay loam the renovation treatment differences were negligible at high inflow rates (Figure 7.23). At low inflow rates (1 L s^{-1}) the wetting time was ~7 and 9 hrs on BP and SC treatments, respectively but 10 hrs for NT (Figure 7.23).

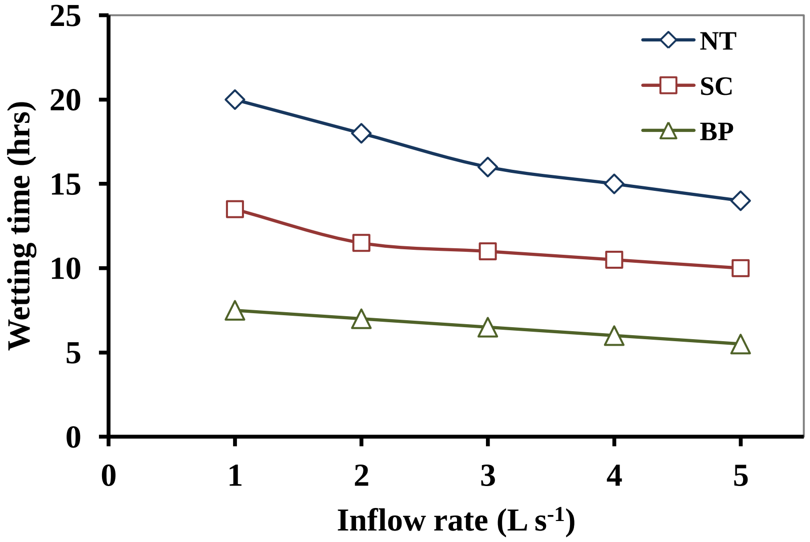


Figure 7.22: **Effect of inflow rate on wetting time of bed middle (200 cm wide bed) to field capacity for three PRB renovation methods on a Vertisol**

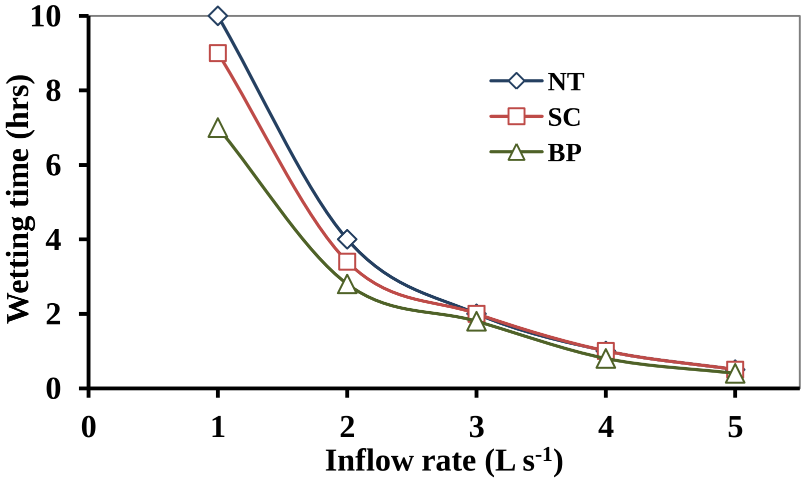


Figure 7.23: Effect of inflow rate on wetting time of bed middle (66 cm furrow spacing-NB) to reach field capacity for three PRB renovation treatments on a sandy clay loam

The maximum bed width was calculated based on lateral penetration of the wetting front for a seven hour wetting period (Figure 7.24). The maximum bed width whose middle could be wetted to field capacity when 5 L s^{-1} is applied is 98 cm for BP compared with 83 cm for NT. However, the maximum bed width was ~55 cm for NT and ~67 cm for BP when 1 L s^{-1} was applied. Similarly, the nominal bed width increased by 51%, 55% and 48% for NT, SC and BP treatments respectively, when inflow rate was increased from 1 L s^{-1} to 5 L s^{-1} (Figure 7.24). This figure may be useful to optimise irrigation management and bed width for a sandy clay loam soil under similar field conditions.

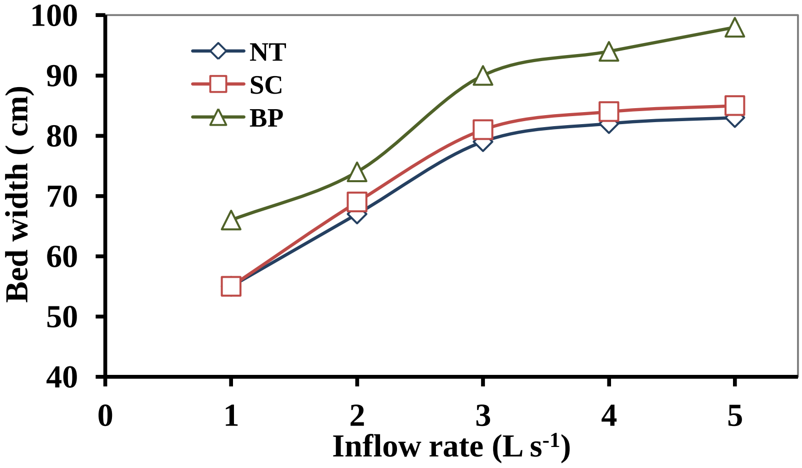


Figure 7.24: Effect of inflow rate on maximum bed width required to ensure wetting of bed middle to field capacity within 7 hrs of wetting time on a sandy clay loam

7.4 Discussion

7.4.1 Effect of renovation methods and furrow head on infiltration

The simulations confirmed the large impact of renovation methods on lateral infiltration into PRBs on both soils. The fast lateral infiltration shown for BP on both soils (Vertisol and sandy clay loam) suggests that this treatment should be beneficial at mitigating the negative impacts on crops in the bed middle caused by poor lateral infiltration (Jin et al. 2007). However, the maximum wetting time of 20 hrs identified for NT when a 4 cm furrow water head is applied may create difficulties on Vertisols with long furrows under Australian farm conditions. On sandy clay loam soils the wetting time required to wet the bed middle (> 40, > 40 and 32 hrs on NT, SC and BP, respectively) at low flow rates will be difficult to achieve if the furrows are short (as is common in Pakistan conditions). However, the fast lateral infiltration in BP treatment offers greater potential for improved irrigation performance within shorter irrigation application time.

There was more vertical infiltration in the SC and NT treatment on the Vertisol compared with the BP treatment (Figure 7.19). This resulted in larger deep drainage losses on both the NT and SC treatments. In contrast, the faster lateral infiltration in the surface layer of the BP treatment on both soils reduced the vertical infiltration beneath the furrow reducing deep drainage losses. Thus BP treatment may be used to improve irrigation efficiency by reducing excessive deep drainage losses.

While renovation methods did affect infiltration on the sandy clay loam soil the speed of wetting front movement in both directions (lateral & vertical) was up to 50% less than in the Vertisol. BP on the sandy clay loam was not successful in improving lateral infiltration to the extent that the bed middle could be wetted in less than 7 hrs. Therefore, alternative strategies, including increasing the furrow water head or decreasing the bed width, should be considered to ensure wetting to the middle of the bed.

Cumulative infiltration was indicative of soil infiltration capacity and was variable between treatments on both soils. The higher cumulative infiltration for BP on the

Vertisol, at short periods, and for longer periods on the sandy clay loam, reflected the higher lateral infiltration capacity compared with other two treatments.

The volume of water stored in the root zone was indicative of soil porosity and water holding capacity, which was improved by BP treatment (Thomas et al. 1990; Eldridge & Robson 1997). The increased soil water storage on BP treatment suggested that this treatment may be helpful in reducing the frequency of irrigation application, improving effective use of in-season rainfall and avoiding economic crop damage from water stress in water limited/drought conditions.

Irrigation is generally aimed at applying approximately 100 mm on the Vertisol in Australia and ~60 mm on the sandy clay loam in Pakistan. An analysis of applying the required irrigation depth showed that the wetting front would still be short of reaching the middle of the bed in all treatments on both soils. Thus, wetting of the bed middle could only be achieved with deep drainage losses, which seems to be larger on SC and NT compared with BP on the Vertisol.

Furrow water head considerably affected lateral and vertical infiltration on all treatments. However, wetting front movement for NT on the Vertisol and for SC on the sandy clay loam was more sensitive to furrow water head changes. For instance, increasing furrow water head from 4 cm to full furrow reduced wetting time by up to 43% on the Vertisol and up to 113% on the sandy clay loam. Greater lateral infiltration with increased furrow water head was also demonstrated by Tabuada et al. (1995). Thus, increasing furrow water head can be used to improve lateral infiltration. However, this will also enhance the vertical infiltration, and can promote excessive deep drainage losses as evidenced by up to 188% increased deep drainage losses with increased furrow water head from 4 cm to full furrow on NT after 20 hrs of wetting on the Vertisol. However, increasing the furrow water head to full furrow on BP did not reduce the wetting time to below 7 hrs on the sandy clay loam. The relationships identified between inflow rate and furrow water head may be helpful in optimise irrigation management for improved lateral infiltration in both soils.

7.4.2 Implications for irrigation management

The shrink-swell nature of Vertisol and long Australian furrows make these systems less susceptible to poor lateral infiltration due to both soil crack development under dry soil conditions and often long irrigation cut-off times. However, at the furrow tail section due to less wetting time than at the head section or when dry soil overlies wet soil at planting time, absence of cracks (Dexter 1991) can negatively affect crop germination due to poor lateral infiltration (Lucy 1993). Poor lateral infiltration is a significant problem in the sandy clay loam soil and has been shown to affect crop performance (Hassan et al. 2005; Akbar et al. 2007; Jin et al. 2007). Therefore, alternative irrigation practices could be suggested. The most common alternative practice could be to fill the furrow and just overtop the wide beds at planting stage and as the season progresses the roots will enhance the infiltration. The second practice could be to use narrow beds with wider furrows in short fields so that a larger volume of water is held in the furrows for a longer period to ensure the wetting of the bed middle. The third option is to increase the space between the centre rows.

The hydrus simulation demonstrated large differences in infiltration with renovation methods and inflow rates on both soils. These figures may be helpful to optimise irrigation management and bed width design on similar site and field conditions. Although these guidelines are applicable to the specific field conditions encountered during the experiments, the general findings also have broader applications. The simulations demonstrated that increasing water head in the furrow and increasing wetting time can improve the lateral infiltration on wider beds. However, the longer term benefits of PRB and the renovation strategies could be expected to enhance soil structure and nutrients with reduced soil disturbance, crop residue retention, soil fauna, and biota (Smith et al. 1983; McHugh et al. 2009). These benefits seem vital for the sustainable improvement and crop production, especially for the degraded soil structure found on the sandy clay loam site. This suggests that the renovation methods need to be adopted judiciously, keeping in view their transient impacts on soil hydro-physical properties and production. However, the dominance of lateral infiltration in BP treatment can encourage farmers to combine CA practices for achieving improvement over time.

7.5 Conclusions

The variable renovation methods and furrow water head were shown to affect both lateral and vertical infiltration into PRBs on both the Vertisol and sandy clay loam. This suggests that both strategies can be used as management tools to improve the efficiency and effectiveness of irrigation. The specific conclusions are:

- Hydrus 2D, properly parameterised by and crossed checked against field measured data, adequately simulated the distribution of soil moisture in PRB systems and accounted for the variable soil management, thus was used to explore management options to improve irrigation practice and thereby provide insight to improve lateral infiltration.
- The BP treatment increased lateral infiltration and the SC treatment increased vertical infiltration compared with the NT treatment. Thus, different wetting times are required to replenish *SMD* depending on the renovation method.
- In the sandy clay loam, which was badly structurally degraded, the BP treatment showed sufficient improvement over the NT and SC treatments in the amount and dominance of lateral infiltration to encourage farmers to combine BP with CA practices to achieve further improvement over time.
- The wetting time of bed middle was 20, 14 and 8 hrs on the Vertisol and > 40, > 40 and ~32 hrs on the sandy clay loam when 4 cm furrow head (1 L s^{-1}) was applied to NT, SC and BP treatments, respectively. Hence, the required wetting time may be achievable under Australian conditions but is likely to be difficult to achieve on the sandy clay loam under Pakistani conditions.
- The minimum wetting time (15 hrs) required to wet the bed middle on the sandy clay loam with BP and full furrow water head is greater than the irrigation application period (~7 hrs) commonly available in Pakistan. This suggests that the bed width may need to be reduced. Another option could be to fill the furrow by just overtopping the bed at the crop early stage.

The figures developed in this work may be used as decision support tools to assist in improving irrigation management and for the selection of optimum bed width based on lateral infiltration.

CHAPTER 8: Managing irrigation and field design to improve performance

8.1 Introduction

The literature review outlined the significant gains in irrigation performance of furrow irrigation systems with optimised irrigation management and field design (Raine & Shannon 1996; Bakker et al. 1997; Dalton et al. 2001; Smith et al. 2005; Langat & Raine 2006; Smith et al. 2009). However, specific studies on this topic are rare for PRB farming systems. The benchmarking study (Chapter 4) revealed variable irrigation performance in existing PRB farming systems, which appeared to be largely inefficient in both Australian and Pakistani contexts. The main reasons for inefficiency seem to be the uninformed selection of *Q*, *Tco* and inappropriate furrow lengths in both countries. Field trials (Chapter 6) and simulation (Chapter 7) evaluating lateral infiltration showed non-uniform soil moisture distribution in wide PRBs. Prevailing irrigation management techniques assume uniform soil moisture distribution across the beds and do not generally account for lateral infiltration, which may limit crop performance in the middle of the bed.

Irrigation applications during three cropping seasons (Chapter 5) under three PRB renovation treatments were difficult to optimise both within and between seasons. For instance, field application losses were significantly larger on freshly applied BP during the 2010 wheat and 2011 corn seasons (Chapter 5) due to a larger infiltration capacity compared with NT. The high infiltration produced a slower water advance rate in the furrow, which may be managed with increased inflow rate (*Q)*. Similarly, *SMD* was not fully met during the 2011 hemp crop due to insufficient water application. This was because the fast water advance in the compacted furrows at applied *Q* resulted in switching off the irrigation much sooner than other furrows to prevent bed overtopping at the furrow tail end. In this case, inadequate lateral infiltration reduced crop performance in the bed middle. Hence, there is a need to optimise irrigation management in response to the specific effects of bed renovation on infiltration.

It was therefore hypothesised that the existing irrigation performance of PRB farming systems in both countries (Chapter 4) was not optimal and optimised irrigation management and field design can improve the existing irrigation performance in both countries. It was also hypothesised that optimal irrigation management and field design can further improve the irrigation performance by reducing the irrigation application losses, replenishing *SMD* and improving lateral infiltration on the three PRB renovation treatments evaluated on a Vertisol (Chapter 5), with permissible trade-offs. Therefore, this chapter aimed to test these hypotheses and to develop guidelines for improving irrigation performance according to the specific field conditions of both countries as discussed in Chapter 3.

8.2 Material and methods

To achieve these objectives a desktop study was undertaken, where the derived infiltration and irrigation performance data, which were experimentally obtained in Chapters 4, 5, 6 & 7, were used to explore the scope of irrigation performance improvement and replenishment of *SMD* using optimised irrigation management and field design strategies. The strategies were selected on the basis of observed field conditions, relevance to prevailing practices and convenience of implementation.

Four strategies were evaluated that involved optimising: (1) *Tco* alone; (2) *Q* and *Tco* together; (3) furrow length; and (4) *Tco* relative to *Ta*. Each strategy has practical significance under actual field conditions. For instance, it may not always be possible to control *Q* and *Tco* together, but controlling *Tco* alone may still be beneficial. Similarly, optimising furrow length may not be feasible on most farms, especially the long Australian fields, due to cost, but could be feasible under some farm conditions, where infrastructure is currently under development or redevelopment. Additionally, exploring the optimum relationship between *Tco* and *Ta* under variable field conditions should be beneficial. Except for change to field length, the majority of the proposed strategies can be implemented with minimal cost to infrastructure, machinery or labour. Simulation of irrigation performance and calculation of performance indices and deep drainage losses were determined according to the procedure described by Smith et al. (2005). The statistical analysis was conducted using the procedure described in section 3.7.

8.2.1 Irrigation management and field design optimisation protocol

The SIRMOD III model, which was calibrated for the benchmarking of existing PRB systems in Chapter 4 and for evaluation of three PRB renovation methods in Chapter 5, was used to optimise the irrigation management of the benchmarked Australian and Pakistani irrigation events and those of the renovation treatments. The input parameters of *Q*, *Tco* and furrow length were adjusted in the model until the best simulated irrigation performance in terms of efficiency, uniformity and lateral infiltration was achieved for each measured furrow during irrigation events recorded. The lateral infiltration condition was fulfilled by matching simulated infiltration opportunity time (recession - advance time) along the furrow length with the field measured and simulated wetting time (Chapter 7) of the bed middle.

The irrigation efficiency outputs were based on certain criteria i.e. ensuring water arrived at the tail end of each furrow, $Er \geq 85\%$, maximising $Ea \geq 90\%$ and confirming lateral infiltration into the bed centre, especially for densely grown crops. In other words, the selected parameterisation and criteria ensured avoidance of dry field sections, fulfilment of *SMD*, minimised irrigation water losses, and maximised lateral infiltration. The efficiency settings were successfully achieved in the majority of the simulations. However, on a few occasions when $Er \geq 85\%$ was not possible under settled bed-furrows (e.g. 2011 hemp crop), then $Ea \geq 90\%$ was used to avoid losses and overtopping of the beds at the tail end of the field. Similarly, the lateral wetting to the bed centre was largely met at $Er = \sim 85\%$ in the majority of cases on Vertisol, but in a few cases when this condition was not met then *Tco* was increased to ensure wetting to the middle of the bed. The lateral wetting times and distance recorded with the Sentek EnviroSCAN® during each cropping period (Chapters 4, 5 & 7) were used for identifying lateral infiltration. However, the lateral wetting to the bed middle condition was not met for a 132 cm wide bed on sandy clay loam due to prolonged wetting time and close cotton and corn crop rows to wetted furrow.

Optimisation of current PRB farming systems (Chapter 4) were analysed separately for Australia and Pakistan due to differences in soil properties, field designs and irrigation management. Similarly, the analyses of the three PRB treatments on the Vertisol (Chapter 5) are presented separately.

8.3 Results

8.3.1 Optimising irrigation management of PRB systems in Australia

The majority of the measured furrow irrigation events (Chapter 4) were over-irrigated, thus irrigations were able to be successfully optimised by changes in management. The field measured and best simulated results with improved irrigation efficiencies and irrigation water saving were summarised in Table 8.1.

Table 8.1: Average irrigation performance parameters for strategies of optimising (i) time to cut-off (*Tco*) and (ii) inflow rate (*Q*) plus *Tco* compared with field measured farmer practice (FP) for two sites (site A1 = 465 m long furrows with blocked tail ends and site A2 = 455 m long furrows with open end furrows at tail end) evaluated during two irrigation events on a Vertisol (SD in brackets)

Irrigation Performance parameter	Site A1-Soybean			Site A2-Cotton		
	FP	Optimised		FP	Optimised	
		Tco	*Q & Tco*		*Tco*	*Q & Tco*
Q	1.94a	1.94a	2.75b	2.54a	2.54a	3.13b
(L s^{-1})	*(0.1)*	*(0.1)*	*(0.1)*	*(0.1)*	*(0.1)*	*(0.2)*
Tco	1100a	981b	503c	635a	473b	370c
(min)	*(61)*	*(72)*	*(38)*	*(64)*	*(78)*	*(40)*
Inflow	138a	127b	89c	107a	80b	77b
(mm/irrigation)	*(11)*	*(10)*	*(7)*	*(9)*	*(12)*	*(12)*
^{a}DD	37a	25b	2c	13a	2b	1b
(mm/irrigation)	*(3)*	*(2)*	*(0)*	*(0)*	*(0)*	*(0)*
Ea	73a	80b	98c	79a	97b	97b
(%)	*(6)*	*(6)*	*(3)*	*(5)*	*(2)*	*(3)*
Er	98a	95a	88b	97a	88b	85b
(%)	*(2)*	*(3)*	*(4)*	*(2)*	*(3)*	*(0)*
DU	90a	85b	90a	87a	77b	82c
(%)	*(3)*	*(3)*	*(3)*	*(2)*	*(2)*	*(4)*

^{a}DD= Deep drainage losses per irrigation
**Figures followed by the different letters in rows for each site are significantly (P=0.05) different between strategies*

In the majority of cases, setting *Er* at ~85% was successful in avoiding dry field sections and in fulfilling lateral infiltration into the bed centre. However, in a few cases under densely grown crops (e.g. soybean and wheat) the simulated wetting time (difference of recession and advance time) was closely evaluated to ensure wetting of the bed middle in tail sections of the field. For instance, the lateral wetting time to the bed middle of ~300 minutes during soybean crop was not met in ~65 m length from the end of the furrow (Figure 8.1: dotted box) at *Er* =~85%, which was rectified by increased *Tco* to avoid water stress in centre rows.

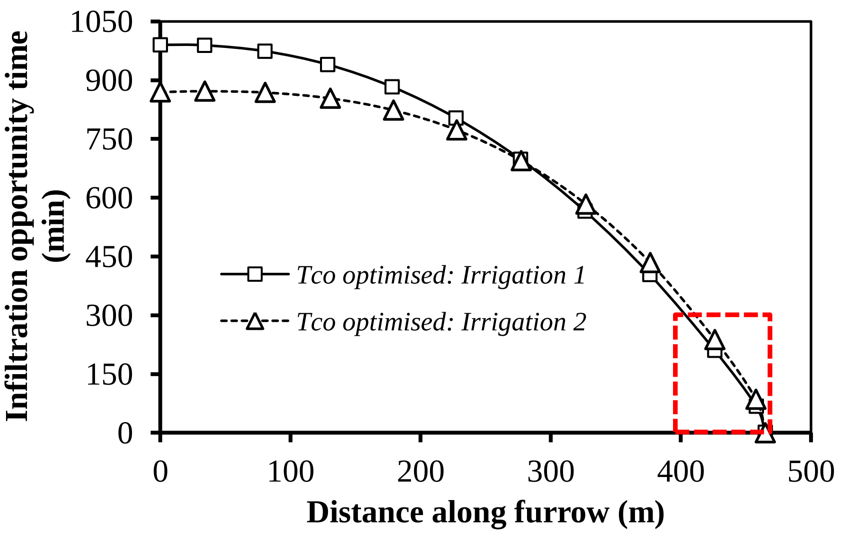


Figure 8.1: **Impact of optimizing *Tco* at *Er* = 85% on the distribution of infiltration opportunity time along the furrow length during two irrigations of 2009 soybean. The dotted box highlights the tail end area susceptible to poor lateral infiltration.**

8.3.1.1 Optimising time to cut-off

Strategy 1 (*Tco* optimisation alone) suggested a significant reduction in *Tco* to improve performance (Table 8.1). At site A1, *Tco* optimisation produced an improvement (7%) in *Ea* with significant 8% irrigation water saving (32% reduction in deep drainage losses), however a reduction of ~3% in *Er* and ~5% in *DU* was observed for both irrigations compared with existing practice. At site A2, *Tco* optimisation resulted improved (~18%) *Ea* and ~25% irrigation water saving (85% reduced *DD*) with a reduction of 9% in *Er* and 10% in *DU* from existing practice.

8.3.1.2 Optimising inflow rate and time to cut-off

Strategy 2 (optimising *Q* and *Tco* together) produced a large improvement in irrigation performance (Table 8.1). At site A1, optimisation identified a significant (~25%) improvement in *Ea* and 36% irrigation water saving (95% reduction in deep drainage losses) with a reduction of ~10% in *Er* from farmer values. Similarly, at site A2, optimisation achieved a significant (~18%) improvement in *Ea* and 28% irrigation water saving (92% reduction in deep drainage losses) with a reduction of ~12% in *Er* and 5% in *DU* from farmer values. Optimised *Tco* over a range of *Q* was plotted on both sites (Figure 8.2), which may be used to support decision making under similar field conditions. For instance, comparisons of both sites indicated increased optimised *Tco* and *Er* on site A1 when compared with site A2 at given *Q*, while increased Q negatively impacted on DU at site A1 when compared with site A2.

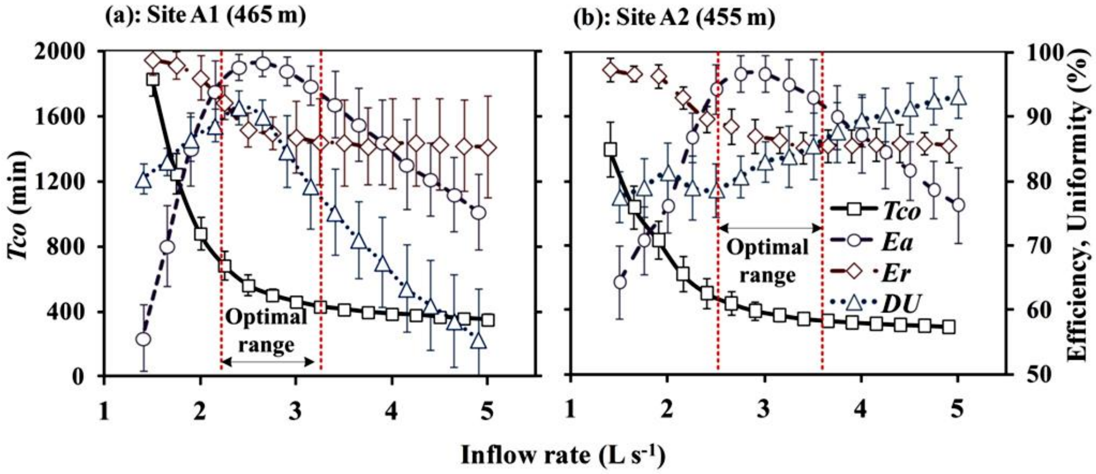


Figure 8.2: Example irrigation management tool for illustrating the optimised *Tco* vs. *Q* and resulting *Ea, Er* and *DU* evaluated for two irrigations at two sites

8.3.1.3 Optimising furrow length

Irrigation performance was greatly affected by furrow length (Figure 8.3). As furrow length increases, there is a need to increase Q to achieve the same Ea and DU. For instance on site A1, applying 2 L s^{-1} to a blocked end furrow, achieved Ea ~99% for a 100 m furrow length but only ~60% for a 600 m furrow length (Figure 8.3a). In contrast on site A2, applying 5 L s^{-1} to an open ended furrow achieved Ea =~90% when the furrow length was 600 m but only ~45% for a 200 m furrow (Figure 8.3b). The impact of furrow length on DU was greater on site A1 than at site A2. For instance, DU dropped to ~45% at 300 m furrow length with Q = 5L s^{-1}, while DU was above 80% for all tested furrow lengths and Q on site A2. In contrast, the impact of furrow length on inflow volume was smaller on site A1 than on site A2. For instance, a maximum inflow volume of ~160 mm was applied to 600 m furrow length at Q = 2 L s^{-1}on site A1. In contrast, a maximum inflow volume of ~190 mm was required for 200 m furrow length at Q = 5 L s^{-1}on site A2. Figure 8.3 provides a simple chart to assist understanding of irrigation management and field design inputs under different field conditions on a Vertisol where there is a requirement to fully wet the middle of the beds according to site A1 with blocked furrows at tail ends and site A2 with open ends at tail ends.

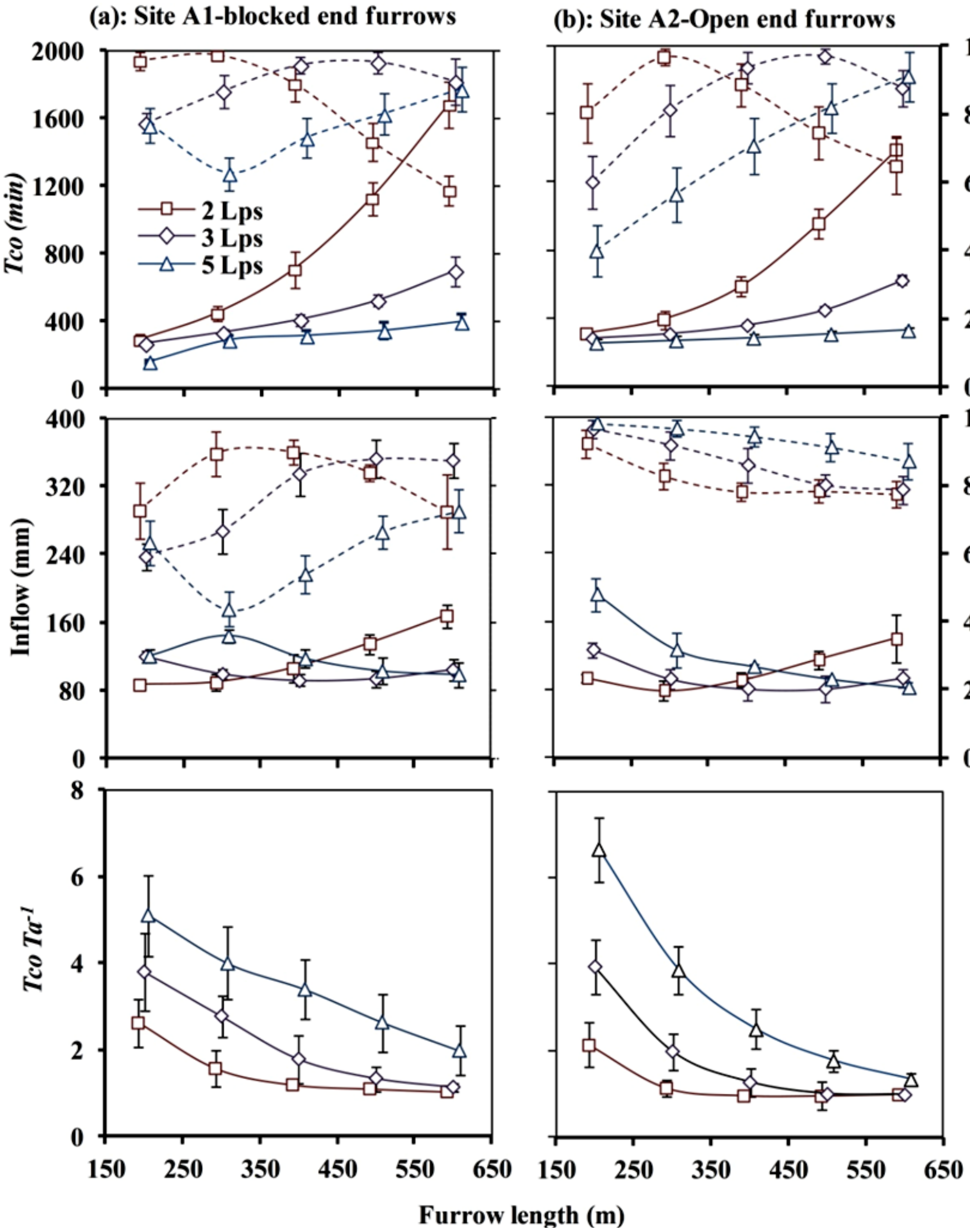


Figure 8.3: Example irrigation management and field design tool illustrating the effect of furrow length and *Q* on *Tco,* inflow volume and *Tco Ta*$^{-1}$(solid lines) and *Ea and DU* (dotted line) for achieving *Er* ≥ 85%, water reaching furrow tail end on (a) site A1 with blocked end furrows and (b) site A2 with open ended furrows requiring wetting to bed middle on site A1 on Vertisol (vertical bars show SD)

8.3.1.4 Optimising time to cut-off relative to water advance time

The optimised *Tco* was evaluated relative to *Ta* at different furrow lengths. If optimisation suggests *Tco Ta*$^{-1}$ = 2, then the irrigation needs to be switched off at twice the time that the water reached the furrow tail end. A comparison of *Tco Ta*$^{-1}$

showed larger values with shorter furrow length and larger Q as shown in Figure 8.3. The ratio converged to unity at longer furrow lengths, while the effect of Q on the ratio ($Tco\ Ta^{-1}$) was negligible on longer furrow lengths. Comparing the sites showed a larger $Tco\ Ta^{-1}$ with higher Q and short furrow lengths on site A2 with open ended furrows than on site A1 with blocked end furrows.

8.3.2 Optimising irrigation management of PRB farming systems in Pakistan

Optimisation of Q, Tco and L were carried out to evaluate the irrigation performance on three sites in Pakistan. The bed middle wetting condition was not met due to the long wetting time requirement for sandy clay loam on 132 cm wide PRBs. However, the maize crop was less susceptible to water stress in the bed middle, as the crop rows were close to the wetted furrows. Thus, the optimisation was based on $Er \geq 85\%$, water reaching to the tail end, minimising water losses and avoiding excessive tail end water overtopping the bed, as the furrow ends were blocked at tail ends.

The results showed that the irrigation performance of existing PRBs in Pakistan (Chapter 4) can be improved with optimised irrigation management. However, the results were highly site specific. For instance, at site P1 the infiltration capacity of soil was high, thus increasing Q and reducing Tco (Figure 8.4) improved irrigation performance. In contrast, at site P2 the infiltration capacity of soil was low, thus using a lower Q and a longer Tco (Figure 8.5) improved the irrigation performance.

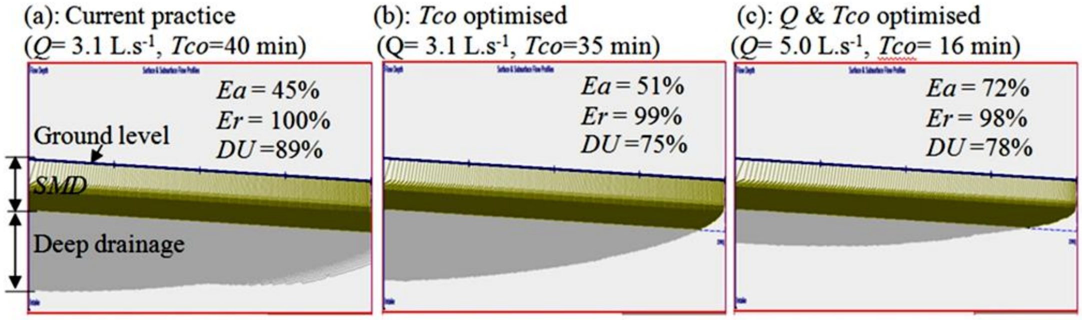
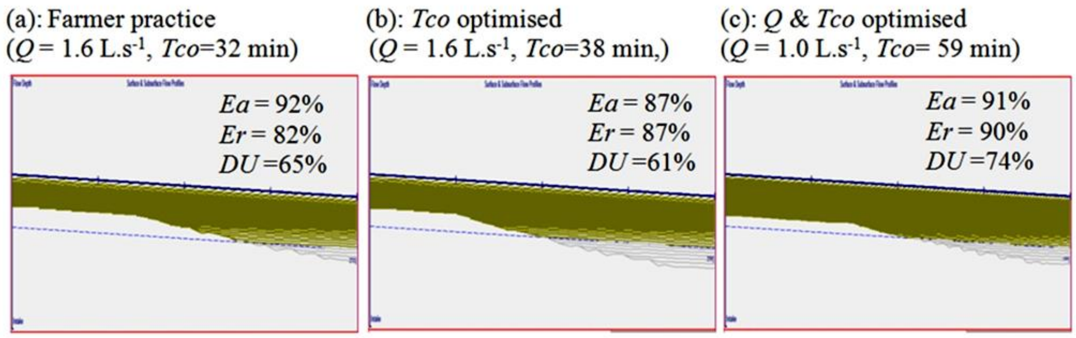


Figure 8.4: SIRMOD screen shots for showing the impact of irrigation management strategies on infiltration along a blocked end furrow (86 m) for a high infiltration (site P1-NB during first irrigation) sandy clay loam soil



(a): Farmer practice (Q = 1.6 L.s^{-1}, Tco=32 min)

(b): Tco optimised (Q = 1.6 L.s^{-1}, Tco=38 min,)

(c): Q & Tco optimised (Q = 1.0 L.s^{-1}, Tco= 59 min)

Figure 8.5: SIRMOD screen shots for showing the impact of irrigation management strategies on infiltration along a blocked end furrow (90 m) for a low infiltration (site P2- NB during first irrigation) sandy clay loam soil

8.3.2.1 Optimising time to cut-off

Optimising the *Tco* at the existing inflow rate (Strategy 1) provided an average improvement of 11% in *Ea*, 3% in *DU*, 14% in irrigation water saving and a 44% reduction in deep drainage losses on the NB systems compared with farmer practice (Table 8.2). Optimising *Tco* for WB did not produce any significant benefits because optimisation suggested increased *Tco*, which was not possible due to tail end overtopping in majority of cases. However, the effect was highly variable between sites (Table D5: Appendix D). For instance, optimising *Tco* on NB systems at site P1 provided an average improvement of 9% in *Ea* and ~15% irrigation water saving, 31% reduction in deep drainage losses at the cost of 10% reduction in *DU*. For WB systems, *Tco* optimisation improved *Ea* by 27%, *DU* by 15% and irrigation water saving by 35% with up to 96% reduction in deep drainage losses. However, *Er* decreased by 10%. At site P2, the challenge was to replenish the *SMD* and to avoid tail end over topping. Hence, increasing *Tco* on NB increased *Er* by up to 5% but *Ea* was reduced by 5%. Similarly on WB, increasing *Tco* resulted in a 10% increase in *Er* but required a 13% increase in volume applied. For site P3, optimisation involved reducing *Tco* on NB which improved *Ea* by 30%, *DU* by 21% and irrigation water saving by 36% with up to 96% reduction in deep drainage losses but a 7% reduction in *Er*. In contrast, increasing *Tco* on WB increased *Er* by 4% and the applied volume by 8% reducing *Ea* by 2%. The average best achievable results for optimised *Tco* on individual sites are summarised in Table D5 (Appendix D).

Table 8.2: Average irrigation performance parameters for strategies of optimising (i) time to cut-off (*Tco*) and (ii) inflow rate (*Q*) plus *Tco* compared with field measured farmer practice (FP) for two bed sizes evaluated during two irrigation events (~90 m furrow length) on a sandy clay loam (SD in brackets)

Irrigation Performance parameter	**Narrow bed**			**Wide Bed**		
	FP	**Optimised**		**FP**	**Optimised**	
		Tco	***Q & Tco***		***Tco***	***Q & Tco***
Q	2.3a	2.3a	3.0a	3.5b	3.5b	1.5b
(L s^{-1})	*(0.6)*	*(0.6)*	*(0)*	*(1.0)*	*(1.0)*	*(0)*
Tco	37a	31a	24a	34b	34b	72b
(min)	*(3)*	*(7)*	*(7)*	*(2)*	*(2)*	*(8)*
Inflow	88a	74a	73a	60b	60b	55b
(mm/irrigation)	*(27)*	*(22)*	*(10)*	*(17)*	*(17)*	*(7)*
DD	32a	18a	13a	8b	8b	2b
(mm/irrigation)	*(14)*	*(12)*	*(5)*	*(6)*	*(6)*	*(1)*
Ea	70a	81a	82a	90b	90b	97b
(%)	*(18)*	*(17)*	*(11)*	*(9)*	*(9)*	*(2)*
Er	94a	93a	93a	86b	86b	89b
(%)	*(5)*	*(6)*	*(5)*	*(10)*	*(10)*	*(5)*
DU	76a	79a	80a	79a	79a	86b
(%)	*(13)*	*(14)*	*(12)*	*(10)*	*(10)*	*(9)*

** Figures followed by same letters in rows for a strategy are not significantly different (P=0.05) between the bed sizes*

8.3.2.2 Optimising inflow rate and time to cut-off

Optimising the *Q* and *Tco* (strategy 2) achieved further improved irrigation performance and irrigation water saving for both NB and WB compared with farmer managed practices (Table 8.2). Comparisons for all three sites are summarised in Table D5 (Appendix D). The optimum *Tco* for a range of *Q* (1-5 L s^{-1}) is shown for both NB (Figure 8.6a) and WB (Figure 8.6b) and all three sites (Figure D1: Appendix D). These figures illustrate the impact of bed widths, site conditions, and management parameters (*Q* and *Tco*) on irrigation performance, which supported decision making under existing field conditions. For instance, at *Q* = 2 L s^{-1} the NB would require ~40 minutes (Figure 8.6a) and WB ~55 minutes (8.6b) for achieving *Ea* = 80%, *Er* = 90% and *DU* = 80% on NB and *Ea* = 90%, *Er* = 85% and *DU* = 80% on WB.

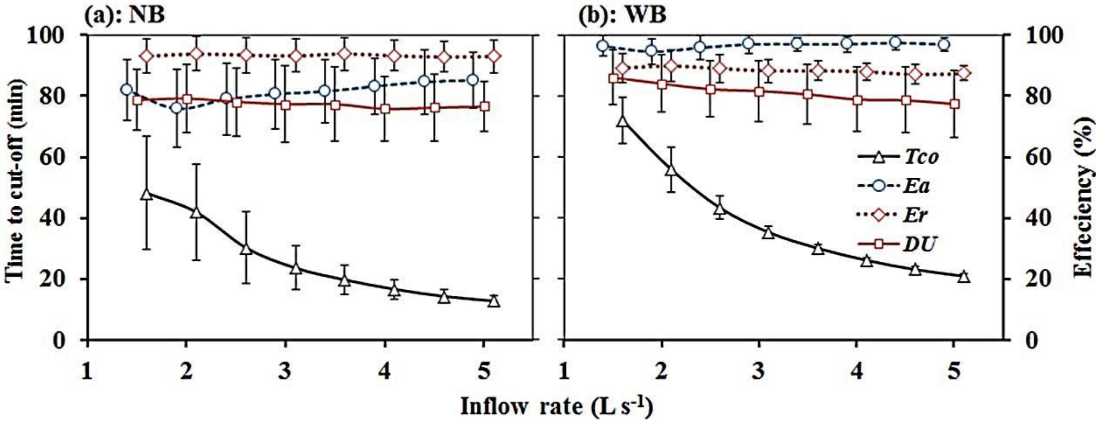


Figure 8.6: Example irrigation management tool showing the effect of inflow rate on optimum time to cut-off for (a) narrow and (b) wide beds with ~90 m furrow length at three sites on a sandy clay loam (vertical bars show SD)

Optimising *Q* and *Tco* together were more beneficial than optimising *Tco* alone using the farmer managed inflow rate. For instance, optimising both *Q* and *Tco* improved *Ea* by 12% and 7%, *DU* by 4% and 7%, irrigation water saving by 17% and 8% and *DD* reduced by 60% and 75% on NB and WB systems, respectively (Table 8.2). However improvements in *Ea* (up to 30%), *DU* (up to 21%), and irrigation water saving (up to 38%) compared with farmer practice were achieved on individual sites (Table D5: Appendix D). Optimising both *Q* and *Tco* was beneficial for the over-irrigated events in saving water (Figure 8.7a) and under-irrigated events by fulfilling *SMD* with less additional water (Figure 8.7b) compared with *Tco* optimisation alone. For the over-irrigated events (*Er* > 85%, i.e. Site P1 both beds and site P3 NB only), applying the optimum *Q* and switching off the irrigation at the appropriate time, saved up to 32% on average and reduced deep drainage by up to 96% (Figure 8.7a). Half of the measured irrigation events were under-irrigated (*Er* < 85%), with 75% of the under-irrigated events identified in WB systems. These systems required a longer *Tco* at the existing *Q*. Thus, the irrigation efficiency was reduced when the *Tco* was increased (Figure 8.7b). However, by optimising both *Q* and *Tco* the *Er* was increased and irrigation performance improved with a negligible reduction in *Ea* (Figure 8.7b).

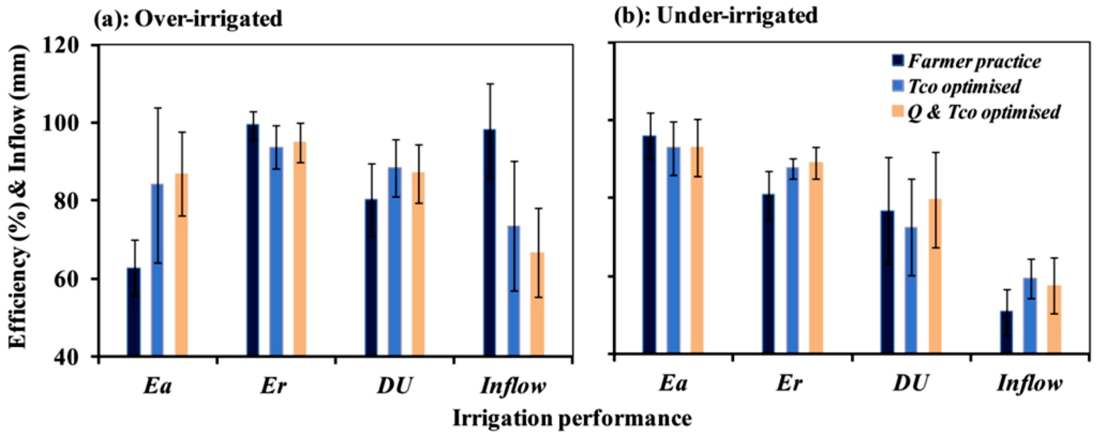


Figure 8.7: Impact of irrigation management strategies on performance of (a) over-irrigated events (NB & WB at site P1 and NB at site P3) and (b) under-irrigated events (NB & WB at site P2 and WB at site P3) in a sandy clay loam (vertical bars show SD)

8.3.2.3 Optimising furrow length

The interaction of furrow length (*L*), *Q* and *Tco* on irrigation performance is illustrated in Figure 8.8(a) for NB and Figure 8.8(b) for WB. A comparable irrigation performance (*Ea and DU*) is possible with different furrow length by optimising *Q* and *Tco* on both bed sizes. However, the optimisation is highly site specific (Figures D2 & D3: Appendix D).

Increasing furrow length generally reduces irrigation performance irrespective of bed size (Figure 8.8). However, site to site comparisons indicated that sub-optimal *Q* exacerbated the reduction on irrigation performance with longer furrow lengths. For instance, at site P3, *Ea* reduced to ~45% when *Q* was 1 L s^{-1} and *L* was 300 m (Figure D2c: Appendix D), but when *Q* = 5 L s^{-1}, *Ea* was ~90% for the same furrow length. Similarly, *DU* and *Er* of under-irrigated site P2 (both bed sizes) was improved with a lower *Q* and longer furrow length (Figure D2b & D3b: Appendix D) which was contrary to results observed for sites P1 and P3.

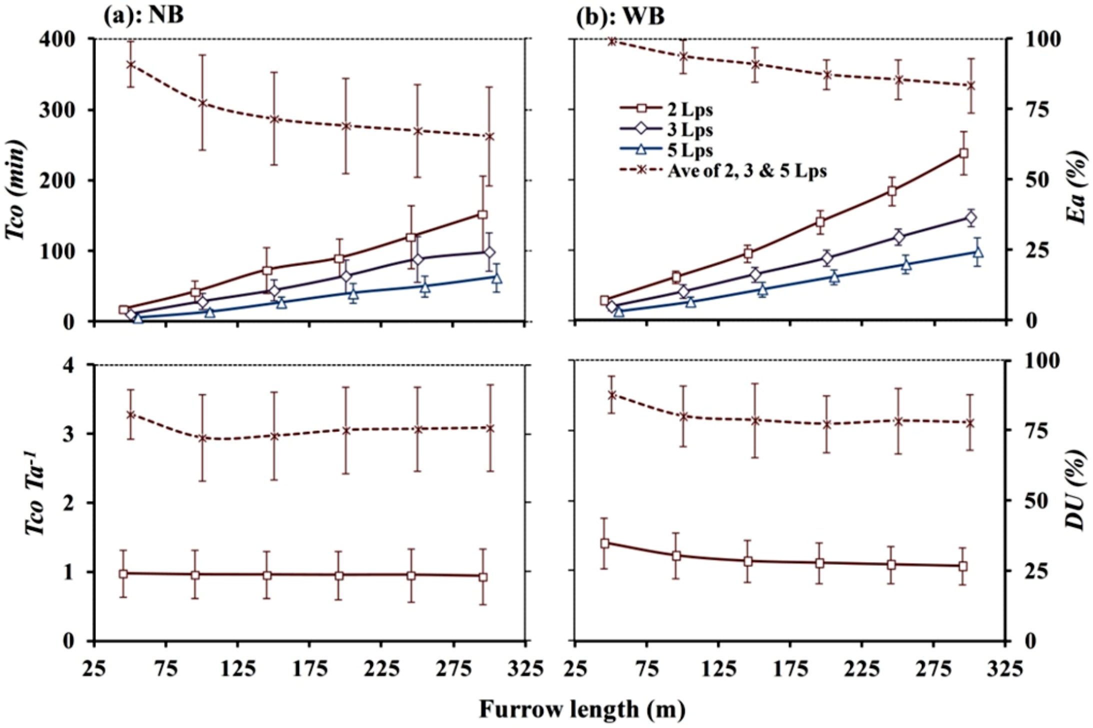


Figure 8.8: Example field design and irrigation management tool illustrating the effect of furrow length and inflow rate on optimised *Tco* and *Tco Ta*$^{-1}$ (solid lines) and *Ea* and *DU* (dotted lines) for (a) narrow beds (66 cm furrow spacing) and (b) wide beds (132 cm furrow spacing) in a sandy clay loam. Optimisation required *Er* ≥ 85% and water reaching to the tail end)

8.3.2.4 Optimising time to cut-off relative to water advance time

The optimum *Tco Ta*$^{-1}$ was affected by *Q*, *L*, bed sizes, and soil infiltration properties. The optimum ratio was below unity on NB (Figure 8.8a) and above unity on WB (Figure 8.8b) for all furrow lengths and inflow rates evaluated. Similarly, individual site comparisons indicated that the optimum ratio (*Tco Ta*$^{-1}$) was below unity for the over-irrigated sites (i.e. sites P1 NB & WB, site P3 NB) with high infiltrative soils and above unity for the under-irrigated sites (e.g. sites P2 NB & WB, site P3 WB) with low infiltrative soil (Figure D2 & D3: Appendix D). The optimum ratio tended to increase on short furrows and decrease on longer furrows. Thus, switching off irrigation at the time of flow arrival at the tail end of the field will cause over-irrigation on NB and under-irrigation on WB.

8.3.3 Optimising irrigation management in response to PRB renovation methods on the Vertisol in Australia

The irrigation management observed during the trials over three cropping seasons (2010 wheat, 2011 hemp and 2011 corn) and PRB renovation methods (NT, SC and BP) were not optimal (Chapter 5). Thus, simulations were conducted to identify improved irrigation management practice for each renovation method. These practices are reported to be helpful in controlling over or under-irrigation and to avoid dry bed middles under densely grown crops (e.g. wheat).

8.3.3.1 Optimising time to cut-off

Optimised *Tco* alone (strategy 1) showed variable results for the three renovation methods over the three cropping seasons (Table D6: Appendix D). For instance, the existing irrigation management during the first irrigation to 2010 wheat under freshly renovated PRB caused poor lateral infiltration at the tail end of the field in all treatments. Thus, *Tco* optimisation suggested increasing *Tco*, which significantly ($P=0.05$) reduced *Ea* and increased irrigation applications in the majority of treatments.

Fast water advance in settled bed furrows of un-renovated PRB during the 2011 hemp season caused under-irrigation (*Er* ranged 65-71%; Table D6: Appendix D). Thus *Tco* optimisation was aimed to replenish the *SMD*. However, evaluations showed no benefit from increasing *Tco* as the water overtopped the bed at the tail end of the field on all treatments.

The freshly renovated PRB during the 2011 corn season resulted in low *Ea* and high *Er*. Thus, *Tco* optimisation aimed to improve *Ea*, which suggested a reduction in *Tco*. However, this resulted in no significant ($P=0.05$) improvement in *Ea*.

8.3.3.2 Optimising inflow rate and time to cut-off

Optimising *Q* and *Tco* together (strategy 2) significantly ($P=0.05$) improved irrigation performance for the most sub-optimally managed and freshly applied BP treatment during the first (2010 wheat) and last (2011 corn) seasons (Table 8.3). Results indicated improved *Ea* (20%), *DU* (8%), irrigation water saving (24%) and reduced (71%) deep drainage losses on freshly applied BP with optimised *Q* and *Tco*. Optimising *Q* and *Tco* also significantly *(P=0.05)* improved *Ea* (7%), irrigation water saving (8%) and reduced deep drainage losses (44%) on freshly applied SC. However, there was no significant improvement in irrigation performance on the NT treatment (Table 8.3) as the *Q* and Tco applied in the field were similar to the optimised values.

Irrigation management optimisation required significantly *(P=0.05)* higher *Q* and significantly shorter *Tco* for freshly applied SC and BP during the wheat and corn crop seasons (Table 8.3). Optimisation also suggested increasing *Q* on NT but the resultant impact on *Tco*, *Ea*, *Er*, *DU*, inflow volume and *DD* were negligible.

Table 8.3: Impact of three fresh PRB renovation methods and optimised (*Q* and *Tco*) on irrigation performance during two cropping seasons on Vertisol (SD in brackets)

Irrigation Parameter	**Wheat 2010 and corn 2011**					
	Field measured			***Q* & *Tco* optimised**		
	NT	**SC**	**BP**	**NT**	**SC**	**BP**
Q	1.87a	1.97a	2.21a	2.00b	3.25b	4.00b
(L s^{-1})	*(0.1)*	*(0.1)*	*(0.2)*	*(0.1)*	*(0.4)*	*(0.1)*
Tco	904a	942a	963a	901a	540b	401b
(min)	*(90)*	*(99)*	*(135)*	*(104)*	*(110)*	*(59)*
Inflow	109a	120a	137a	109a	110b	104b
(mm/irrigation)	*(12)*	*(13)*	*(18)*	*(15)*	*(16)*	*(8)*
DD	13a	25a	49a	12a	14b	14c
(mm/irrigation)	*(4)*	*(9)*	*(11)*	*(5)*	*(4)*	*(5)*
Ea	87a	78a	66a	88a	85b	86b
(%)	*(10)*	*(15)*	*(16)*	*(10)*	*(9)*	*(15)*
Er	94a	97a	98a	95a	98a	97a
(%)	*(4)*	*(3)*	*(2)*	*(4)*	*(2)*	*(2)*
DU	83a	82a	80a	85a	83a	88b
(%)	*(7)*	*(8)*	*(7)*	*(6)*	*(5)*	*(5)*

**Figures followed by different letters for the same treatment in rows are significantly (P=0.05) different between strategies*

Irrigation management optimisation was highly season and event specific. For instance, the treatment difference in irrigation performance was not significant *(P=0.05)* during the 2011 hemp season when all the treatments were under effective NT. However, the irrigation performance during the 2011 hemp season could have been improved with significantly *(P=0.05)* lower *Q* and increased *Tco* compared with field measured values (Table 8.4). This is contrary to the freshly applied treatments (Table 8.3). In this case inflow volume and *Er* were significantly improved, while *Ea*, *DU* and deep drainage losses were unaffected. However, *SMD* was still not fully met due to bed over topping at the furrow tail end.

Table 8.4: Impact of one season old renovation methods and the optimised (*Q* and *Tco*) on irrigation performance across all experimental plots during the 2011 hemp season (SD in brackets)

Irrigation parameter	**Field measured**				***Q* & *Tco* optimised**			
	NT	**[a]SC/NT**	**[a]BP/NT**	**Mean**	**NT**	**[a]SC/NT**	**[a]BP/NT**	**Mean**
Q	1.79a	1.79a	2.01a	1.86a	1.17b	1.18b	1.59b	1.32b
(L s^{-1})	*(0.2)*	*(0.2)*	*(0.1)*	*(0.2)*	*(0.4)*	*(0.2)*	*(0.6)*	*(0.5)*
Tco	406a	438a	406a	417a	882b	834b	598b	764b
(min)	*(124)*	*(126)*	*(145)*	*(133)*	*(177)*	*(218)*	*(202)*	*(192)*
Inflow	47a	51a	53a	51a	66b	63b	61a	61b
(mm/irrigation)	*(17)*	*(18)*	*(17)*	*(19)*	*(26)*	*(29)*	*(28)*	*(22)*
DD	2a	3a	3a	4a	6b	5a	4a	7b
(mm/irrigation)	*(1)*	*(1)*	*(1)*	*(2)*	*(2)*	*(3)*	*(3)*	*(3)*
Ea	94a	92a	93a	93a	91a	92a	94a	92a
(%)	*(11)*	*(11)*	*(10)*	*(11)*	*(9)*	*(8)*	*(4)*	*(7)*
Er	65a	70a	71a	69a	78b	79b	80b	79b
(%)	*(6)*	*(11)*	*(8)*	*(11)*	*(10)*	*(10)*	*(7)*	*(9)*
DU	75a	73a	75a	74a	72a	75a	80a	76a
(%)	*(20)*	*(18)*	*(15)*	*(18)*	*(16)*	*(16)*	*(10)*	*(15)*

[a] The SC and BP were only furrow cleaned thus all treatments were effectively NT
**Figures followed by different letters in rows on same treatment show significant (P=0.05) difference between field measured and optimised results*

The optimised *Tco* for a range of *Q* (2 to 5 L s^{-1}) are shown (Figure 8.9) for the three freshly renovated PRBs during the wheat and corn crop seasons. The optimisation was based on confirming wetting of the bed middle throughout the furrow length, while accounting for variable furrow water head due to infiltration along the furrow (Chapter 7). This figure illustrates the impact of wetting time to the bed middle in irrigation management. The results show adverse effects on *Ea* and *DU* of increasing *Q* for NT and SC during the first wheat season (Figure 8.9a). In contrast, *Ea* and *DU* of BP were reduced when *Q* was reduced. During the 2011 corn season (Figure 8.9b) the BP treatment generally had a better irrigation performance than the other two treatments. However, the optimised irrigation performance was very low (e.g. *Ea* = 25-40% and *DU* = 30-80%) in all treatments during the 2011 corn season due to the long lateral wetting time. These figures highlight the interactions between renovation methods (i.e. lateral infiltration) on the irrigation performance for a Vertisol.

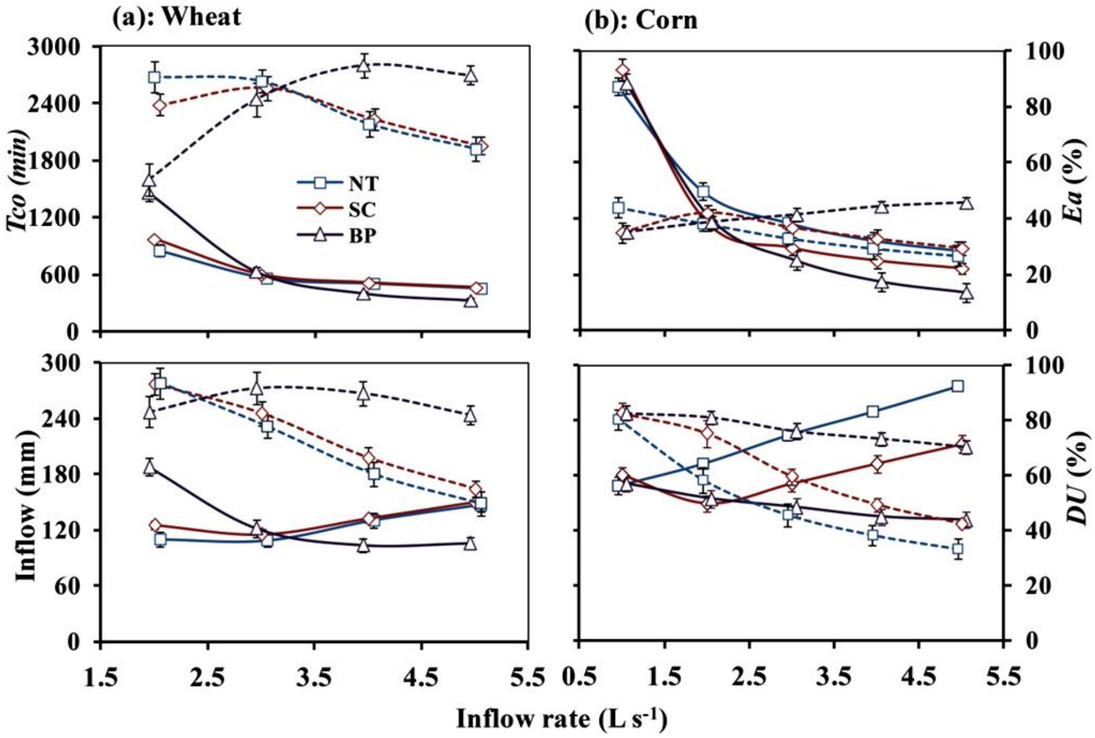


Figure 8.9: Impact of renovation methods and *Q* on optimal *Tco* and inflow volume (solid lines) and *Ea* and *DU* (dotted line) on (a) one season old PRBs (2010 wheat) (b) three season old PRBs (2011 corn) at site A1, Australia. Optimisation requires wetting of bed middle and accounts for furrow water head effect on lateral infiltration

8.3.3.3 Optimising furrow length

Furrow length greatly affects *Tco*, irrigation applications and efficiencies (Figure 8.10). For instance, *Ea* and *DU* was low in the 200 to 400 m furrow length range on all treatments, where wetting of the bed middle, especially in the head section of the field, was achieved only with large deep drainage losses. However, the optimal field length was a function of the flow rate applied. For instance, maximum *Ea* and *DU* was achieved at ~400, ~300 and ~200 m furrow length for NT, SC and BP, respectively at *Q* = 2 L s^{-1} (Figure 8.10). However, at *Q* = 5 L s^{-1}, the maximum *Ea* and *DU* was identified at 1000, 800 and 600 m furrow lengths for NT, SC and BP, respectively.

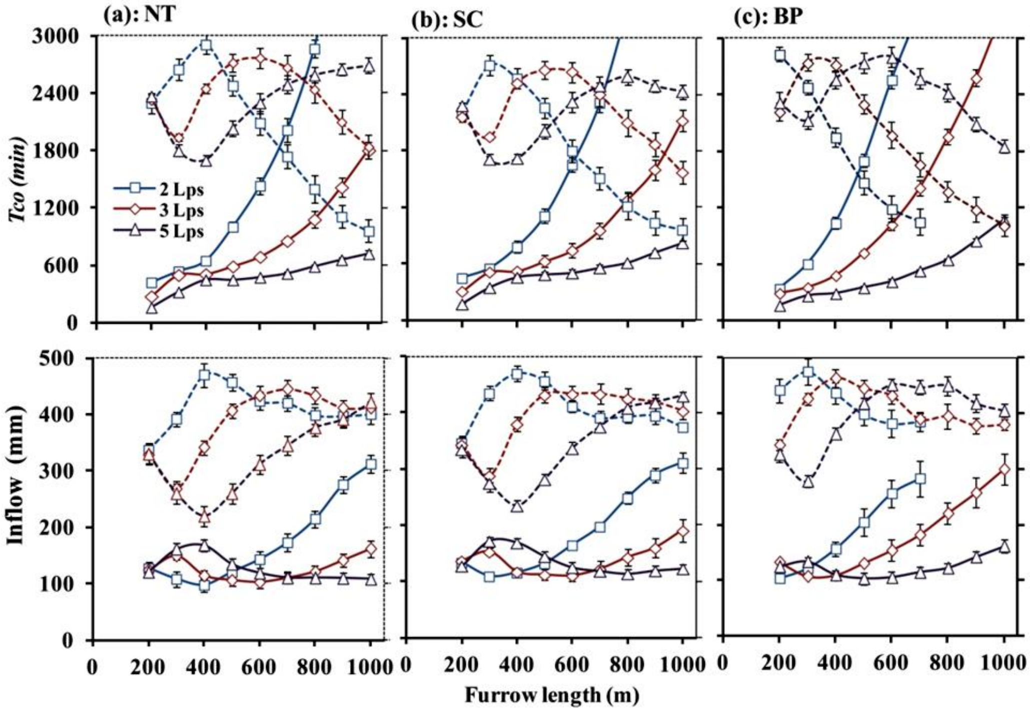


Figure 8.10: Example field design and irrigation management tool for showing the effect of furrow length and *Q* on optimum *Tco* & Inflow volume (solid lines) and *Ea* & *DU* (dotted lines). Optimisation data for a single irrigation to 2010 wheat requiring lateral wetting of bed middle on a Vertisol at site A1, Australia

Improved irrigation performance during the hemp crop season could be achieved with increased furrow length, reduced *Q* and increased *Tco* (data not given). For instance, increasing furrow length to 600 m would increase *Ea* up to 4% in all treatments, *Er* would be increased by up to 23%, 13%, and 14%, while *DU* increased by 4%, 4% and 10% on NT, SC and BP, respectively.

The 2011 crop was grown on the bed shoulders. Thus, for the 2011 corn season simulations, the furrow length optimisation was conducted by requiring $Er \geq 85\%$, but without requiring field wetting to the bed middle. In this season, irrigation performance improved with lower *Q* applied to short furrows and higher *Q* applied to long furrows (Figure 8.11). Similarly, improved irrigation performance (*Ea* and *DU*) was achieved with higher *Q* on SC and BP treatments, while reduced *Q* in longer furrows adversely affected their irrigation performance. In contrast, irrigation performance was not affected at low *Q* (i.e. $Q = 2$ L s^{-1}) on NT for furrow lengths.

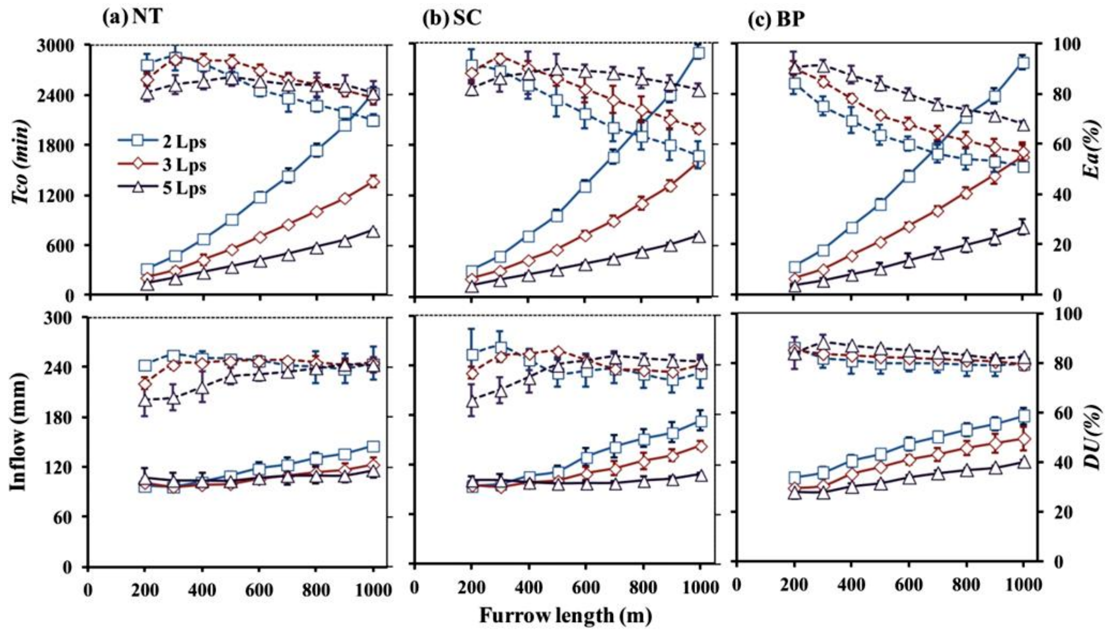


Figure 8.11: Example field design and irrigation management tool for showing the effect of furrow length and *Q* on optimum *Tco* & Inflow volume (solid lines) and *Ea* & *DU* (dotted lines). Optimisation data for two irrigations on a 2011 corn crop requiring *Er* ≥ 85% and water reaching to furrow tail ends at site A1, Australia

8.3.3.4 Optimising time to cut-off relative to water advance time

The $Tco\ Ta^{-1}$ (Figure 8.12) showed higher values (4 to 5) on short furrows and smaller values (~1) on longer furrows. The ratio tended to be higher with NT compared with SC and BP. For instance $Tco\ Ta^{-1}$ were ~4.5, ~4 and ~3.5 for NT, SC and BP treatments at Q = 2 L s^{-1} and L = 100 m, respectively. However, the ratio was unity at ~500 m on BP compared with ~600 m for SC and ~700 m for NT.

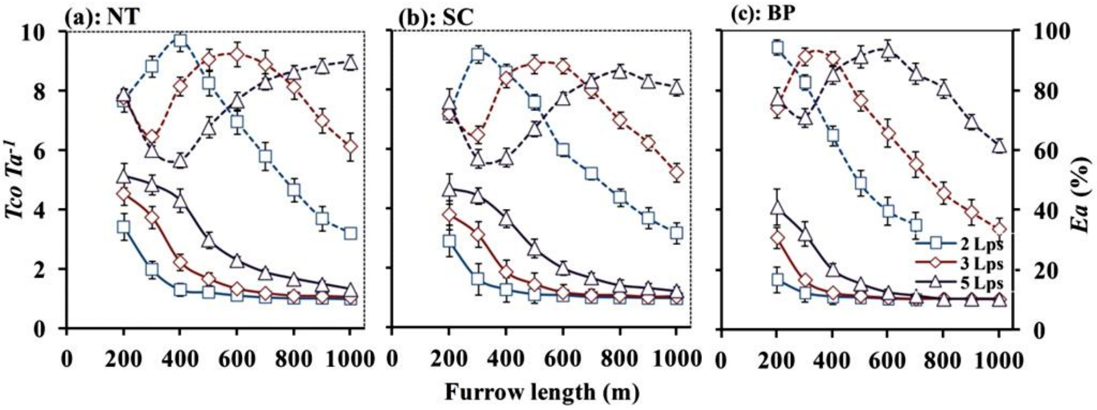


Figure 8.12: Effect of furrow length on optimum $Tco\ Ta^{-1}$(solid line) and *Ea* (dotted line) for freshly renovated PRBs (2010 wheat season) for different *Q* and requiring wetting of bed middle at site A1, Australia

8.4 Discussion

8.4.1 Irrigation management practices of PRB systems in Australia

The current irrigation management of Australian farms was not optimal, evidenced from current excessive deep drainage and tail drain runoff losses as discussed in Chapter 4. Therefore, the four irrigation management strategies were successful in improving the existing irrigation performance. The results of all four optimisation strategies have shown significant improvement in current irrigation performance, which conformed with the views of Playán and Mateos (2006) and also consistent with this study hypotheses.

The *Q* and *Tco* were identified as the key irrigation management parameters which significantly influenced the irrigation performance on both Australian farms. This study showed that up to 25% irrigation water savings could be achieved by adjusting *Tco* and that up to 36% irrigation water saving could be achieved by adjusting both *Q* and *Tco*. This agrees closely with the findings of Smith et al. (2005) despite the fact that the requirement to fulfil lateral infiltration to the bed middle reduced the irrigation water savings. The optimisation of *Q* and *Tco* together was more beneficial than *Tco* optimisation alone as demonstrated by reducing the applied water volume by up to 28% on site A1 and 3% on site A2 and by reducing deep drainage losses up to 85%. These improvements were achieved with an acceptable small trade-off in *Er* and *DU*.

Consistent with the findings of Sanchez et al. (2009) furrow length was found to greatly affect irrigation performance on both sites. The current study findings at both sites revealed that appropriate furrow length is one of the most important considerations and will determine the maximum achievable irrigation performance.

The relationship between *Tco* and *Ta* is often used as a convenient field tool for irrigation management. However, the current study has shown that $Tco\ Ta^{-1}$ was greatly affected by *Q*, furrow length, blocked end condition and field infiltration. For instance, the optimal ratio increased up to 5 times for short furrows (200 m) on site A1 (blocked ended furrows) and up to 7 times on site A2 (open ended furrows) with larger *Q* (5 L s^{-1}). In longer furrows (L > 500 m) the ratio was found to converge to unity irrespective of *Q* at both sites. Thus, switching off irrigation at the time of water arrival to the furrow tail end largely resulted in under-irrigation on short furrows, while for long furrows it resulted in either over or under-irrigation depending on *Q* and soil infiltration properties. However, the relationships developed in graphical form may be helpful as decision support to identify optimised irrigation management.

8.4.2 Irrigation management practices of PRB systems in Pakistan

Irrigated raised beds are considered a relatively efficient irrigation system in Pakistan (Kahlown et al. 1998). These systems have the potential to save up to 60% irrigation water losses (Gill et al. 2005) compared with existing flat basin or bay irrigation systems if managed properly. However, this study has revealed that the irrigation management of existing irrigated raised bed farming systems in north west Pakistan is sub-optimal with low irrigation performance. The evaluations demonstrated the 50% *Ea* and up to 61 mm/irrigation deep drainage losses, which agree with results reported by World Bank (1997). Thus, there is potential to optimise irrigation management of PRB farming systems in Pakistan.

The small Pakistani fields have short *Tco* and the farmers are generally keen to apply the limited available canal water by personally monitoring the irrigation events. The current experiments were monitored carefully under farmer supervision, apparently leaving little scope for further optimisation. However, the SIRMOD evaluations indicated that the existing irrigation practices are not optimal due to a lack of decision support guidelines. In particular, further improvements are possible by selecting suitable field lengths, appropriate *Q* and irrigation switching off time.

Half of the measured irrigation events were over-irrigated with excessive tail end over topping and half were under-irrigated. The furrows are characterised by a quick recession time at the head section of the field leading to poor lateral infiltration (Akbar et al. 2007). All the four irrigation management strategies were shown to produce irrigation water saving in over-irrigated events and to adequately replenish *SMD* in under-irrigated events. Optimisation of *Q* and *Tco* together was effective at meeting the *SMD* and in improving *DU* along the furrow length, especially for WB. Hence, this strategy may be particularly beneficial for improving *DU* without dividing the field into smaller segments, a common practice in the locality, and thus may save the additional labour costs and time associated with shorter furrows. Furrow length optimisation showed a further improved irrigation performance.

Seasonal changes and field conditions played a key role in the irrigation performance (Gates & Clyma 1984) and effectiveness of irrigation management strategies. Similarly, irrigation performance was shown to be sensitive to management on short furrow lengths (Eldeiry et al. 2005). This may have made the current irrigation management optimisation highly sensitive to a range of contributing factors. The current results indicate that irrigation performance improvement strategies are highly site and event specific, subject to variations caused by infiltration capacity of the soil, weeds, cultural practices, and bed settlement during a cropping season. For instance, site P1 showed improved irrigation performance (irrigation water saving, *Ea* and *DU*) with increased *Q* due to higher infiltration capacity, which agree with the findings of Gillies et al. (2010). However, site P2 and P3 showed improved irrigation performance with reduced *Q* due to a lower surface roughness and low infiltration. Thus, the irrigation management optimisation strategies evaluated were able to account for seasonal and spatial (site to site) variations. This suggests that these processes used in this study may be used to develop guidelines for other field conditions.

According to Sanchez et al. (2009) optimum furrow length (strategy 3) is an important factor for achieving improved irrigation performance. This study showed that optimising furrow length improved irrigation performance with reduced furrow length, increased *Q* and reduced *Tco* at all sites. The relationships identified and plotted graphically provided guidelines for the optimum irrigation management and field design under the existing field conditions. Maximised irrigation water saving and irrigation performance with optimised *Q*, *Tco* and *L* strategies were identified as very beneficial, which can be very important for the water deficient Indus Basin in improving the existing poor *WP*.

Relating *Tco* to *Ta* for improved performance required better understanding of the irrigation and field conditions. For instance, optimisation required increased *Tco* up to two fold of *Ta*, on low infiltration soils, when furrow lengths were shorter (50 m) and *Q* were larger (3 L s^{-1}). In contrast, irrigation performance improved for high infiltration soil when *Tco* was equal to *Ta* at longer furrows and low *Q*. Similarly, NB required switching off irrigation before the water reached the furrow tail end. In contrast switching off irrigation at the time of water arrival to the furrow tail end was identified as not adequate to replenish *SMD* on WB.

8.4.3 Irrigation management practices in response to renovation methods

Irrigation applications of three PRB renovation treatments during three cropping seasons (Chapter 6) were strictly monitored during the experiments. The *Tco* was based on fulfilling *SMD* by applying the required volume of irrigation water, without overtopping the beds at the tail ends of furrows. The *Q* per furrow selection was restricted by the available *Q* from the source, water head in distribution channel, farmers’ commitments for fulfilment of water demand in nearby vegetable farms, lack of decision support tools and high cost involved with prolonged irrigation times. Thus, optimum irrigation management was difficult to implement under existing field conditions. Therefore, impacts of four irrigation management strategies were explored for improved performance and mitigating management issues experienced during field trials that negatively affected irrigation performance.

During the 2010 wheat season, optimised *Tco* alone (strategy 1) significantly reduced *Ea* with significant increases in inflow volume and deep drainage losses to ensure wetting of the bed middle. In contrast, optimised *Q* and *Tco* together significantly improved *Ea*, *DU*, irrigation water saving and reduced deep drainage losses while wetting of the bed middle was confirmed. Moreover, strategy 2 was more effective improving the existing poor irrigation performance of freshly applied BP treatment with increased *Q* and reduced *Tco* compared with the other two treatments.

During the 2011 hemp season, the early two irrigations were applied under low *SMD* to avoid poor crop germination in the bed middle, when the top soil was dry and the deep soil below 10 cm depth was moist. Due to quicker water advance in relatively wet and compacted furrows the irrigation was switched off earlier to avoid excessive tail end overtopping, as the furrows were blocked at the tail end. Thus, the wetting front did not penetrate to the bed middle. Evaluations suggested no further increase in *Tco* at existing *Q* due to fast water advance. Therefore, overall results of *Tco* optimisation did not produce any benefit during the 2011 hemp season. However, strategy 2 improved *Er* and increased lateral infiltration with reduced *Q* and increased *Tco.*

During the 2011 corn season, the three seasons’ old PRB had compacted furrows, which increased water advance rate in furrows but renovations were freshly applied and cracks were developed due to dry antecedent soil moisture, especially before the second irrigation, which improved soil infiltration properties in the bed area. Therefore, *Tco* optimisation did not produce any benefits in improving irrigation performance, except inflow volume was significantly reduced for BP treatment. However, strategy 2 significantly improved irrigation performance on SC and BP with up to 17% irrigation water saving and up to ~48% reduced deep drainage losses.

Furrow length optimisation suggested further improved performance during all three cropping seasons. However, optimum furrow lengths varied for the different seasons and treatments. For instance, the results suggested decreased furrow length during the 2010 wheat season when the beds and furrows were relatively loose and porous due to fresh renovation and recent realignment. Similarly, the results indicated the largest improvement on BP treatment with reduced furrow length during the 2010 wheat crop season. However, due to seasonal bed settlement and furrow compaction with machinery traffic, sealing, and sedimentation, the furrow length optimisation suggested increased furrow length in the subsequent 2011 hemp and 2011 corn seasons for achieving improved irrigation performance.

The current study revealed significant variation in water advance rate in furrows among irrigations and seasons caused by variable furrow compaction, bed settlement, antecedent soil moisture, furrow length, *Q* and miscellaneous field conditions. Thus, deciding *Tco* on the basis of *Ta* may be affected by *L*, *Q* and PRB renovation methods. The graphical illustrations may supported decision making.

8.5 Conclusions

This study showed that optimised irrigation management and field design can significantly improve the irrigation performance of existing farmer managed irrigated PRB systems and that comparable irrigation performance among the three freshly applied renovation methods is possible. The main conclusions are:

- Irrigation performance of existing PRB farming systems in Australia and Pakistan were poor leading to over or under-irrigation. However, significant improvements in irrigation performance are achievable through irrigation management.
- Optimising *Q* and *Tco* together was more beneficial than optimisation of *Tco* alone. Optimisation of *Q* and *Tco* saved up to 38% water and reduced deep drainage losses by up to 96%.
- Shorter furrow lengths generally had high irrigation performance on high infiltration soils while longer furrows were beneficial on compacted furrows. However, the irrigation performance of short furrows was sensitive to *Q* and Tco, thus requiring more refined and intensive irrigation management to achieve improved performance.
- Relating *Tco* to *Ta* required an understanding of field infiltration characteristics, *Q* and furrow length. Using a $Tco\ Ta^{-1}$ ratio of 1 caused under-irrigation, especially in short furrows and wide beds. The graphical illustration may be helpful in improving understanding for the identification of improved irrigation management practices.
- Renovation methods involving tillage affected irrigation performance due to changed soil infiltration properties. Renovated PRB, especially BP, require monitoring and evaluation to identify the appropriate irrigation management practices to improve irrigation performance.
- The optimised irrigation management practices (e.g. *Q* and Tco) can improve irrigation performance, which can normally be implemented without incurring significant costs to infrastructure, machinery, or labour.
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CHAPTER 9: General discussion and recommendations

9.1 Introduction

The permanent raised bed (PRB) farming system has evolved over multiple attempts to implement various aspects of CA. Control traffic farming (CTF) has been shown to successfully improve soil hydro-physical properties (Tullberg et al. 2007; McHugh et al. 2009). The transformed farming system in the form of PRB has been adopted in some developed countries (e.g. Australia and USA) but is still in its infancy in many developing countries (e.g. China, India and Pakistan). Lack of adequate guidelines and decision support aids for agronomic and irrigation management, poor lateral infiltration in wide spaced furrows and resulting poor *WP* are some of the main impediments to the successful implementation of PRBs in many parts of the world.

The majority of previous studies evaluating PRB have focussed on comparison with traditional flat basin, border irrigation, or random traffic systems. Measurements are often taken using point evaluation methods over small areas, which are subject to large variations. Similarly, the majority of previous work evaluating the impact of PRB farming systems on soil hydro-physical properties has been conducted under rain-fed conditions. Therefore, the effects of different agronomic and irrigation management factors on the *WP* of irrigated PRBs are largely unknown.

This research evaluated the potential to improve the *WP* of irrigated PRBs by focussing on four key areas:

- Benchmarking the irrigation performance of PRB farming systems;
- Evaluating the effect of PRB renovation methods on irrigation performance and productivity;
- Evaluating the effect of PRB renovation methods on lateral infiltration into the beds; and
- Identifying strategies to improve lateral infiltration and irrigation performance of PRBs with optimised irrigation management and field design.

9.2 Major outcomes and key findings

9.2.1 Benchmarking irrigation performance of PRB farming systems

This study showed that the interaction of agronomic, soil and irrigation variables make it difficult for farmers to identify optimal irrigation management practices. The uninformed selection of *Q* and *Tco* resulted in application losses (*Ea* down to 68% in Australia and 50% in Pakistan) and low *DU,* which conforms with the findings of Schwankl et al. (2000) and Mailhol et al. (2005). Soil infiltration, *Q, SMD* prior to irrigation, bed furrow configurations and furrow compaction affected the water advance rate along the furrow as mentioned by Raine and Bakker (1996) and Bakker et al. (1997). Thus, farmer decision making was affected by multiple field factors and irrigation performance was negatively affected.

Different renovation and tillage techniques were identified as being used in commercial practice on both soils. Practices ranged from no tillage to either annual or occasional deep ripping with the aim of loosening the compacted soil and to control pests and diseases in Australia. Differences in PRB renovation methods in Australia were also reported by Bell et al. (2003), Hulugalle and Daniells (2005), and Garside (2005). In Pakistan, seasonal shallow cultivation or rotary hoeing is the common practice (Akbar et al. 2007). However, the majority of these renovation methods cause excessive soil disturbance, which reduces soil infiltration, soil resistance to wetting and increase soil erosion. Degraded soil structure and accelerated erosion, which was attributed to current intensive cultivation methods, was observed on both soils and is consistent with reports in past studies (Smith et al. 1983; Dexter 1991; Cook et al. 1992; Ishaq et al. 2001; Akbar et al. 2007).

The water advance in the furrows showed a linear response with the square root of time in both soils. This indicates that capillary forces were dominant in the soil infiltration (Philip 1969). Hence it can be inferred that the soil properties of pore size distribution, clay type, and soil structural stability to wetting are influencing irrigation performance. Certainly the practices that deliver the water to the soil will also impact on irrigation performance. So, any particular irrigation event will be primarily affected by the soil properties, and secondarily by the irrigation practices of rate and duration of application and length of furrow over which free water must pass to wet the entire length of a field. Both Australian and Pakistani irrigation practices were shown to be sub-optimal and would probably respond favourably to both improved soil management and irrigation practices.

9.2.2 Impact of renovations on irrigation performance and productivity

This study highlighted the large impact of machinery design, operation control and renovation methods on PRB performance. Generally, PRBs renovated with excessive tillage required extra machinery operating time, created fatigue during sowing, had lower crop establishment rates, and soil disturbance. According to Canakci et al. (2005) and Hussain et al. (2010) land preparation and tillage consume large amounts of total energy, which can also affect farm income. All these factors favoured the NT treatment than SC and BP on Vertisol at this site under normal field conditions.

The tillage/renovation methods were shown to significantly impact on soil hydro-physical properties which is in close agreement with other studies (Lipiec et al. 2006; Verhulst et al. 2011). The significantly reduced (~6%) seasonal bulk density and increased cumulative infiltration (23%) of BP and the smaller seasonal increase (~5%) for NT and BP indicate greater soil structural stability compared with SC, which conform to the findings of Hussain et al. (1998), Jin et al. (2007) and Wang et al. (2012). However, the 3 fold reduction in lateral infiltration during the three cropping seasons for the NT indicate bed renovation may be helpful to avoid negative impacts of poor lateral infiltration. Thus different renovation techniques can alter soil hydro-physical properties and can improve *WP* of PRB farming system.

The different renovation methods altered profile water storage evidenced by increased (up to 4%) seasonal profile water content on BP compared with NT and SC. This was also demonstrated by the consistently dry bed middles on NT and SC treatments due to poor lateral infiltration, which effectively reduced the volume of soil storing water in the active root zone. Dry bed middles under NT and SC treatments were also reported by Jin et al. (2007) on a sandy clay loam and Lucy (1993) on a Vertisol. The lack of inversion of the bed surface by BP improved the soil structural stability during wetting and reduced evaporation losses. According to

(Hamilton et al. 2005) the undisturbed crop roots under BP work as reinforcing rods, which enhance soil strength and aggregation. The enhanced water storage in BP can be beneficial in reducing irrigation frequency and improving capture and use of in-season rainfall (Thomas et al. 1990; Eldridge & Robson 1997).

The furrow sizes and shapes have been shown to affect irrigation performance due to changes in wetted perimeter (Raine et al. 1998). The large furrow sizes (up to 17%) of BP than NT were due to greater porosity and deeper furrow excavation. However, the greater seasonal reduction (up to 47%) in furrow sizes for the cultivated treatments indicates the improvements in soil hydro-physical properties may be temporary due to adverse seasonal changes. This reflected increased soil resistance to deformation by wetting under NT compared with BP and SC treatment. Therefore, mechanical loosening need to be applied judiciously keeping in view their negative impacts on soil structure stability and adverse seasonal changes.

Impact of renovation methods on crop yield and *WP* was not significant. However, the significantly higher 2010 wheat yield and *WP* on NT during the first season was attributed to poor seeder performance on renovated beds evidenced the significantly lower tillers density for BP than NT and SC. The double disc planter performance on renovated beds was poor because it was designed and set up to operate normally in firm zero till soils as has been the case on the farm for 40 years. During the 2011 hemp season, the excessive pre-sowing rainfall caused bed subsidence, sealing and resulted in poor lateral infiltration as the beds were not freshly renovated. Thus, the 2011 hemp yield was reduced (~55%) in the middle of the beds compared with the bed shoulder. Decreased yield due to poor lateral infiltration was also reported by Lucy (1993), Jin et al. (2007) and Akbar et al. (2007). The comparable crop yield and *WP* of fresh BP compared with NT during the 2011 corn season was indicative of a good rooting environment, larger soil water storage and reduced soil disturbance resulting from newly designed equipment, with enhanced performance (Hamilton et al. 2005). As with structural stability, the similar yield and *WP* of mechanically loosened PRBs (SC and BP) and NT suggests that NT and BP may be preferable on a Vertisol but the benefits may take longer than three seasons to significantly emerge.

This study confirmed that BP reduced bulk density, improved lateral infiltration, improved profile water storage, and gradually increased *WP* on a Vertisol. One of the reasons for the gradual improvement on BP compared with other treatments was the fact that the BP treatment was not most appropriately imposed until the third season. Additionally, BP was shown to be sensitive to the selection of equipment, soil moisture (may be destructive to soil structure above or below plastic limit and can promote smearing) and operating expertise for its successful implementation. It can be concluded that due to the fragile and sensitive nature of Vertisol to soil disturbance (Coughlan 1981; Smith et al. 1983; Dexter 1991; Cook et al. 1992), the NT may be the preferred option at this site. However, keeping in view the aforementioned benefits in soil hydro-physical properties, the BP treatment can be more beneficial compared with SC. However, long term impacts of BP on soil structure needs to be further investigated.

9.2.3 Effect of renovation on lateral infiltration

Poor lateral infiltration is generally considered as one of the major limiting factors for achieving high *WP* on wide PRBs (Lucy 1993; Hassan et al. 2005; Jin et al. 2007). However, only few studies have investigated lateral infiltration in wide PRBs. This study revealed a significantly different lateral infiltration capacity among the three PRB renovation treatments on both soils. Other factors including *SMD* and soil type were also identified to have major contribution in lateral infiltration.

The study revealed increased lateral infiltration on BP, increased vertical infiltration on SC and the least cumulative infiltration (both lateral and vertical) on NT treatments. The freshly applied BP increased lateral infiltration and soil moisture storage capacity. Increased infiltration and soil moisture storage for BP were also reported by Thomas et al. (1990), Eldridge and Eldridge and Robson (1997), Hamilton et al. (2005) and Jin et al. (2007). Its impact was far greater on the Vertisol with its inherently greater level of aggregation and stability of structure than on the highly unstable soil structure on the sandy clay loam (Alfisol) soil, which produced the same patterns of responses but with a much smaller magnitude and significance. Thus, the BP did not wet the middle of 132 cm wide beds within (~7 hrs) irrigation time.

The significantly different soil moisture content identified between the shoulder and middle of the bed, on both soils, confirmed the non-uniform nature of soil moisture distribution on wide PRB farming systems (Tabuada et al. 1995) and raised concerns regarding the adequacy of field design and irrigation management practices that assume uniform soil moisture distribution across the beds. The shrink swell nature of Vertisol and the long irrigation times under Australian conditions, make the 200 cm wide PRBs less vulnerable to poor lateral infiltration compared with the 132 cm wide PRB on rigid and degraded sandy clay loam soil.

9.2.4 Strategies to improve lateral infiltration and irrigation performance

When the Hydrus 2D (Šimunek et al. 1999) model was appropriately parameterised by field measured data for both soil types, the lateral infiltration process of these soil types with the same treatments as imposed in the field experiments in Australia showed just how this BP treatment and the soil structure it produces is capable of very large improvements in the rate and distribution of water absorption two dimensionally, but dominantly laterally to the bed centre. The contrasting extent of these improvements between the two soils indicates the potential improvement in irrigation performance and productivity for Pakistan sandy clay loam would be likely to be proportionately greater once the soil structure had built up and become stable. The enhancement of lateral infiltration rate indicated that soils so treated could be watered faster (with larger Q), completely to the middle of the beds with less water and less deep drainage loss.

This study showed differences in lateral infiltration due to renovation methods and water head in furrows. The maximum wetting time of bed middle to reach field capacity (~17, ~11 and ~6 hours on NT, SC and BP, respectively) at 9 cm furrow water head seems manageable on the Vertisol under Australian field conditions. The increased lateral infiltration with increased furrow water head was consistent with the findings of Tabuada et al. (1995). Thus both strategies (renovation method and furrow water head) can affect lateral infiltration and may be helpful as management tools on a Vertisol.

Lateral infiltration was very poor in sandy clay loam evidenced by the 37, 24 and 15 hours predicted minimum wetting time of the bed middle on NT, SC and BP respectively, at full furrow water head, which seems difficult to manage under Pakistani field conditions. Poor lateral infiltration was also reported on sandy clay loam in many past studies (Hassan et al. 2005; Akbar et al. 2007; Jin et al. 2007). The minimum time (~15 hrs) required to wet the bed middle, identified with BP at full furrow water head, is likely to be difficult to achieve using the existing bed width (132 cm) and degraded soil conditions. However, this research has evaluated decision support tools, which may be helpful in selecting the optimum bed width, inflow rate and infiltration opportunity time for different bed renovation methods.

The SIRMOD III model, appropriately parameterised with the field data from Australia and Pakistan, showed how each of the soil type and management induced soil conditions would affect irrigation performance. The four optimisation strategies were: (1) Tco optimisation, (2) Q and Tco optimisation, (3) furrow length optimisation and (4) Relating optimum Tco to Ta. Evaluation of the strategies for PRBs on a Vertisol (Australia) highlighted the potential for significant improvement in irrigation water saving (36%), efficiency, and uniformity. Optimising furrow length further improved irrigation performance. Increasing field length generally reduced irrigation performance. These findings agreed with findings of Raine and Bakker (1996), Smith et al. (2005) and Gillies et al. (2010).

The sandy clay loam (Pakistan) with short furrows (< 100 m) generally showed improved irrigation performance with each of the four irrigation management and field design strategies, which conformed to the findings of Kalwij (1997). The Q and Tco optimisation produced greater (~38%) irrigation water saving and up to 93% reduction in deep drainage potential. Poor DU is a significant problem and the current local method of improving DU by putting bunds in the furrow is labour intensive. Thus improving DU by optimised Q and Tco can save labour. $Tco\ Ta^{-1}$ was sensitive to Q, soil infiltration properties and furrow configurations (Kalwij 1997). The analysis suggested the ($Tco\ Ta^{-1}$) ratio should be above unity for WB and below unity for NB and high infiltration soils.

Renovation of a long furrow Vertisol reduced irrigation performance unless *Q* was increased to match the increased soil infiltration. In all cases the BP treatment showed the greatest improvements (up to 33% *Ea* and up to 35% irrigation water saving) but also, because of its responsiveness was the most sensitive to changed conditions. Importantly, the BP treatment also showed itself to be more flexible in its furrow length, its capacity to absorb higher *Q* rates and maintain $Tco\ Ta^{-1} = 1$ over a longer length than the soils treated by SC or NT. Interestingly, the compacted furrows required reduced *Q* and increased *Tco* for improved performance. Hence, SC and BP treatments benefitted more from irrigation management optimisation than NT as the farmer managed irrigation matched the infiltration of the NT treatment.

Irrigation practice, especially on BP treated soil, would require awareness of the antecedent moisture content in particular. But offsetting this is the fact that the increased lateral infiltration behaviour allows the simply observed and applied management practice of equating *Tco* with time when water advance in the furrow reaches the tail end. Because of the rapidity of lateral infiltration this management guide is needed, otherwise too much water infiltrates and deep drainage increase.

The four strategies evaluated have practical significance and have the potential to reduce deep drainage losses, enhance infiltration opportunity time, and improve uniformity. Importantly, these strategies offer an opportunity of PRB performance improvement which can be implemented without incurring significant increases in infrastructure, machinery, or labour costs.

9.3 Summary

The water productivity of PRB farming systems may be constrained by sub-optimal irrigation management, excessively wide beds, and renovation methods involving intensive tillage. Consequently, excessive water losses, soil structural degradation, and poor lateral infiltration are frequently observed. This study has shown that improved agronomic management, specifically renovation of PRB consistent with the principles of conservation agriculture, combined with optimised irrigation management, has great potential to improve irrigation and crop performance that can lead to improved *WP* of existing PRB systems.

Renovating PRBs involving inversion can reduce soil structural stability and can make the bed vulnerable to slumping. If renovation is applied without modifying *Q* and *Tco* then irrigation performance will also be adversely affected. Hence, NT would be the preferred choice for managing beds on a Vertisol under normal field conditions. However, if poor lateral infiltration is observed and mechanical loosening is required then BP renovation is more beneficial compared with SC. This is because BP improves lateral infiltration, enhances profile water content, and maintains soil structural stability. However, BP requires better machinery operating control, specialised equipment, and the correct soil moisture during renovation to avoid soil smearing and clodiness. Similarly, BP requires improved irrigation management, optimised *Q* and *Tco* for the changed soil infiltration properties.

Optimised irrigation management and appropriate bed and field design has the potential to improve the *WP* of PRB farming systems. The procedures developed for understanding the soil, water and agronomic interactions may be beneficial in making the PRB farming system a more attractive option in both countries. This will be especially important in developing countries, where the adoption of PRB systems is still in its infancy and water and food security are pressing issues.

All these outcomes confirmed that the hypotheses and objectives of this study have been successfully satisfied to a greater or lesser extent. However, further extensive work is needed to assess the level of probable *WP* improvement.

9.4 Practical implications of this research

This research involved evaluation of irrigation performance, PRB renovation methods/cultivation methods, soil hydro-physical properties, lateral infiltration, and crop performance for existing and variably renovated PRB farming systems. Evaluations were conducted in the two contrasting environmental conditions of Australia and Pakistan. This research has elucidated the plausible consequences of prevailing irrigation management practices, which generally assume uniform soil moisture distribution across the beds. The following are the implications arising from the research:

- PRB have not been widely adopted yet in developing countries and is still in transition in many developed countries. This research identified inappropriate agronomic and irrigation management as the major areas, which can enhance the current *WP* and thus may assist in stimulating the adoption of PRB farming systems worldwide.
- The *WP* of PRBs under commercial practices has been shown to be generally poor and that improvement is possible at no significant cost. Thus well managed PRBs can be helpful for sustainable crop production to feed the growing population and to conserve the natural resource for the future.
- This work has identified temporal and spatial variations in soil hydro-physical properties of PRB, which may be helpful in improving understanding and refining decision making for improved irrigation and soil management of PRB under a wide range of environmental conditions.
- The soil management involve intensive tillage in both Australia and Pakistan, which have deleterious consequences on soil hydro-physical characteristics. This research showed that loosening of compacted soil is possible with controlled mechanical loosening without excessive soil disturbance, which may lead to increased soil porosity, lateral infiltration and profile water storage. Thus the general practice of diseases, pests, weeds control and soil loosening with excessive tillage in both countries can be replaced with improved soil management practices.
- Poor lateral infiltration is perceived to be a barrier in PRB adoption in developing countries. The outcomes of this study are of particular benefit in supporting decision making about the selection of the renovation methods, irrigation management, and bed furrow sizes for improved lateral infiltration.
- The measurement and modelling procedures demonstrated for the development of management guidelines are robust and have broad implications.
- This research compared PRB performance under contrasting environmental and socio economic conditions. This has made the scope of these outcomes comparable, representative, beneficial, and applicable for PRB systems under wide ranging farming conditions.

9.5 Recommendations for further research

The outcomes of this study have confirmed that the water productivity of PRB farming systems can be increased if managed properly. The irrigation performance of PRBs may be improved using appropriate irrigation management, field design optimisation, and renovation methods matched to specific soil and field conditions. However, opportunities for further research include:

- Development of a simplified routine irrigation performance evaluation and management optimisation protocol that can account for lateral infiltration into the bed with different furrow spacing.
- Field evaluation of the optimisation techniques on different PRB farming systems and raised beds across a broad range of environmental conditions (e.g. throughout the Indus Basin).
- Testing the proposed strategies of improving lateral infiltration under variable soil salinity levels of PRB systems on both soils.
- Evaluating the renovation methods on a wider range of soils (including soil affected by salinity and sodicity).
- Investigating the longer term impacts and optimal frequency of applying the different PRB renovation techniques, especially the blade ploughing method, under different environmental conditions.
- Evaluating the energy requirement and practicalities of the different PRB renovation techniques under a wider range of field, environmental and socio-economic conditions (including comparison with traditional cultivation).
- Evaluating the long term impact of renovation methods on the *WP* of both soils, but particularly the sandy clay loam in Pakistan. This will need the consistent application of conservation agriculture and blade ploughing practices for 4 to 5 years before the improvement in soil structure is sufficient to demonstrate the limit to potential improvements achievable to both *WP* and irrigation performance

CHAPTER 10: Conclusions

The literature review identified two key areas of research (i.e. agronomic and irrigation management) for improving the *WP* of PRB farming systems. The benchmarking study successfully quantified the performance of existing PRB farming systems on a Vertisol (Australia) and a sandy clay loam (Pakistan) under usual farmer management. The results of this benchmarking study guided the research to focus on bed renovation, the effect on lateral infiltration, and the potential to improve irrigation management.

This study assessed three PRB renovation methods (no tillage, shallow cultivation, and blade ploughing) for changes in: soil hydro-physical properties (bulk density, lateral infiltration, and profile water content), bed furrow configurations, crop yield, and *WP* over three cropping seasons on the Vertisol. The effects of (1) renovation method and (2) furrow water head on lateral infiltration into both soils were evaluated using the Hydrus 2D model. Four strategies for improving irrigation performance including optimising (1) *Tco* alone (2) *Q* and *Tco* together (3) furrow length and (4) optimum *Tco* relative to *Ta*, were assessed using SIRMOD. The four strategies were also used to explore the potential irrigation performance benefits for the three PRB renovation methods. The outcomes of these studies have shown that:

1. The irrigation and soil management of existing PRB farming systems in Australia and Pakistan is sub-optimal leading to poor irrigation performance. This was demonstrated by:
    - The uninformed selection of sub-optimal inflow rate and time to cut-off.
    - Application efficiencies as low as 68% in Australia and 50% in Pakistan.
    - Excessive irrigation application in both countries with deep drainage potential up to 61 mm/irrigation, while wide beds in Pakistan were under-irrigated.
    - Renovation methods involving intensive tillage are destructive to soil structural stability and reduced irrigation performance if the irrigation management was not altered to match the changed infiltration characteristics.

2. PRB renovation methods (e.g. no tillage with furrow cleaning, shallow cultivation and blade ploughing) significantly altered soil hydro-physical properties, irrigation performance, crop yield and thereby has the potential to improve the water productivity on a Vertisol. The three seasons results demonstrated that:

- No tillage enhanced *Ea* and productivity, thus for this site, soil and operating conditions are the preferred option for sustainable production.
- Shallow cultivation was destructive to soil structure, accelerated furrow filling, and enhanced deep drainage losses, thus is not preferable.
- Seasonal bed subsidence reduced irrigation performance and lateral infiltration, thereby reduced crop performance in the bed middle (e.g. ~55% in 2011 hemp crop with no tillage) when compared with bed shoulder.
- Blade ploughing reduced soil bulk density (~6%), and enhanced profile water storage, lateral infiltration and productivity, compared with shallow cultivation but was sensitive to *Q* & *Tco* for high irrigation performance.

3. Lateral infiltration was significantly affected by renovation methods and furrow water head. Thus, these may be used to avoid yield loss due to dry bed middle caused by low infiltration soils or bed subsidence. The outcomes demonstrated that:

- Blade ploughing enhanced lateral infiltration compared with shallow cultivation and no tillage treatment on both sandy clay loam and Vertisol.
- Increased furrow water head increased lateral infiltration on both soils.
- Bed middle of 200 cm wide PRB on Vertisol under normal Australian field condition is less susceptible to poor crop performance due to fast lateral infiltration, cracking and prolonged irrigation times on long furrows.
- The 132 cm wide PRB on sandy clay loam required a minimum of 15 hours to wet the bed middle under blade ploughing treatment at full furrow head. Where the beds are renovated with blade ploughing the bed width would need to be reduced to 105 cm to permit full wetting in the 7 hrs evaluated with normal irrigation. However, if no tillage or shallow cultivation were used then the beds would need to be < 90 cm because of the reduced lateral infiltration.

4. Irrigation management and field design strategies improved irrigation performance of PRB systems on both soils. These strategies may be used to improve water productivity. This was evidenced by:

- Optimising *Q* and *Tco* together saved up to 38% of water, which was up to 23% more than optimising *Tco* alone for the farmer managed PRB systems.
- Furrow length optimisation further improved irrigation performance.
- Optimising *Tco* relative to *Ta* improved understanding of the complex interaction between variable field conditions.

5. Several examples of decision support tools were illustrated in this research for the specific soils and sites evaluated. While the applicability of these decision support tools is not universal, they do demonstrate the principles of performance variations and their interactions with changed soil and field conditions, which are applicable to a wider range of environmental conditions.

This study demonstrated the effectiveness of improved soil management and optimised irrigation management in improving irrigation performance and *WP* of PRB farming systems. This work has shown no tillage with furrow cleaning as the most efficient and productive PRB renovation method on a Vertisol, which is also consistent with the principles of conservation agriculture. However, seasonal subsidence, compaction, and low infiltration soils can reduce crop performance, in the middle of a no tillage bed. In these conditions, controlled mechanical loosening with blade ploughing can be beneficial for enhancing lateral infiltration, profile water storage and soil stability compared with shallow cultivation. However, the long term impacts on soil properties and optimal frequency of blade ploughing application needs to be investigated. Improving irrigation management and field design has the potential to significantly improve irrigation performance of PRB farming systems. Importantly, these strategies may be implemented with little infrastructure, labour, or machinery costs and offer an opportunity of improved *WP* on a sustainable basis.

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Appendix A: Specific field measured data

Table A 1: Soil properties at given depths at site A1, Australia (Soil analysis conducted by Topoclimate services Pty Ltd)

Soil Element	0-20cm	21-100cm
pH	6.7-7.4	7.3-8.5
Na (meq/100gm)	0.48-4.38	1.13-16.6
Ca (meq/100gm)	13.7-26.0	12.4-21.8
Mg (meq/100gm)	16.8-22.3	15.4-26.6
K (meq/100gm)	0.71-1.86	025-0.40
Organic Carbon (%)	1.0-1.8-	0.6-1.4
Phosphorus (mg/kg)	6.4-17.6	5.7-.16.6
Sulphur (mg/kg)	5.3-21.2	8.5-17.0
Soil type	Irving-Black Vertisol	Irving Black Vertisol

Table A 2: Soil properties at given depths on two bed sizes measured at the harvest of wheat 2008-09 crop at site P1, Pakistan.

Soil Elements	Bed size and profile depth (cm)								
	Wide bed (132 cm) middle			Wide bed (132 cm) Edge			Narrow Bed (66 cm)		
	0--10	11--20	21--30	0--10	11--20	21--30	0--10	11--20	21--30
EC(µS)	413.7	331.3	322.9	349.8	326.9	307.1	372.4	331.1	324.1
pH	8.1	8.1	8.0	8.0	8.1	7.9	8.1	8.1	7.9
Na(mg/l)	10.6	11.3	13.5	10.2	10.9	11.0	10.1	10.5	11.6
Ca(mg/l)	55.0	50.9	48.6	51.4	48.0	51.6	50.6	48.4	50.2
Mg(mg/l)	12.2	11.7	10.8	12.2	11.1	10.9	12.3	11.4	11.1
SAR	2.7	2.1	2.5	1.8	2.1	2.0	1.8	1.9	2.1
FeSO4(mg/l)	17.2	17.3	17.1	17.3	17.1	17.3	17.3	17.0	17.1
Meq of FeSO4	8.6	8.7	8.5	8.6	8.6	8.7	8.6	8.5	8.6
Meq of K2Cr2O7	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Difference	1.4	1.4	1.5	1.4	1.4	1.3	1.4	1.5	1.4
O.M (%)	1.0	0.9	1.0	0.9	1.0	0.9	0.9	1.0	1.0
N2(mg/l)	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0
Saturation	46	44	44	45	43	42	44	42	41

Table A3: Average monthly weather data at site A1 during four cropping seasons (SD in brackets)

Month	Ave. Temperature (°c)		Ave. Humidity (%)	Ave. Wind Speed (m/s)	Total Rainfall (mm)
	Min.	Max.			
Dec. 2009	18 (2)	30 (2)	67 (8)	4 (1)	27
Jan. 2010	17 (3)	32 (3)	60 (10)	4 (1)	29
Feb. 2010	18 (2)	29 (3)	68 (6)	4 (1)	35
Mar. 2010	16 (3)	27 (2)	71 (7)	4 (1)	81
Apr. 2010	12 (3)	26 (2)	68 (6)	3 (1)	14
May 2010	5 (5)	22 (3)	66 (12)	3 (1)	9
June 2010	3 (4)	18 (2)	71 (7)	3(1)	3
July 2010	4 (5)	18(3)	72 (7)	3(1)	26
Aug. 2010	3 (5)	17 (3)	70 (8)	3(1)	59
Sept. 2010	9 (5)	21 (3)	75 (7)	2(1)	47
Oct. 2010	10 (4)	23 (4)	74 (6)	2(1)	63
Nov. 2010	14 (4)	25 (4)	69 (6)	2(1)	48
Dec. 2010	16 (3)	26 (2)	75 (9)	3(1)	260
Jan. 2011	17 (2)	29 (4)	70 (8)	3(1)	94
Feb. 201	17 (3)	30 (3)	68 (5)	3(1)	23
Mar. 2011	15 (4)	27 (3)	71 (8)	3(1)	86
Apr. 2011	10 (2)	25 (3)	73 (5)	3(1)	87
May 2011	3 (2)	21 (3)	75 (7)	2(1)	48
June 2011	1 (4)	19 (2)	72 (11)	2 (2)	0
July 2011	1 (5)	17 (2)	60 (6)	3 (1)	4
Aug. 2011	2 (3)	20 (2)	63 (7)	3 (1)	20
Sep. 2011	5 (3)	23 (4)	65 (7)	3 (1)	15
Oct. 2011	8 (7)	24 (3)	70 (7)	3 (1)	82
Nov. 2011	10 (4)	29 (3)	64 (8)	3 (1)	37
Dec. 2011	12 (3)	27 (3)	66 (7)	3 (1)	83
Jan. 2012	14 (6)	29 (4)	66 (12)	3 (1)	49
Feb. 2012	15 (7)	30 (3)	72 (6)	3 (1)	52

Table A4: Average bed furrow dimensions measured before irrigations during the benchmarking study in both soils and three renovation experiments in Australia (TW = top width, MW = middle width, BW = Bottom width and D = furrow depth)

Site/Crop/Treatment	Irrig. No	Furrow dimensions (cm)				
		Spacing	TW	MW	BW	D
Site A1/Soybean/Existing	1	200 cm	41.7	23.7	11.0	8.3
Site A1/Soybean/Existing	2	200 cm	53.3	30.3	14.3	10.0
Site A2/Cotton/Existing	1	100 cm	62	42	20.5	8.75
Site A2/Cotton/Existing	2	100 cm	60.0	43.7	27.3	10.2
Site P1/Cotton/NB-Existing	1	66 cm	36.7	24.6	18.2	10
Site P1/Cotton/NB-Existing	2	66 cm	37	25.7	18.8	9.74
Site P1/Cotton/WB-Existing	1	132cm	62.1	52.3	39.4	11.9
Site P1/Cotton/WB-Existing	2	132cm	62	50.8	37.4	11.3
Site P2/Maize/NB-Existing	1	66 cm	50.1	35.7	22.4	12.4
Site P2/Maize/NB-Existing	2	66 cm	50.6	33.8	18.0	11.8
Site P2/Maize/WB-Existing	1	132cm	42.8	34.8	15.8	11.5
Site P2/Maize/WB-Existing	2	132cm	42.4	32.8	15.1	11.1
Site P3/Maize/NB-Existing	1	66 cm	47.4	30.6	14.8	9.2
Site P3/Maize/NB-Existing	2	66 cm	48.1	31.2	14.1	9.3
Site P3/Maize/WB-Existing	1	132 cm	51.5	33.4	17.9	9.7
Site P3/Maize/WB-Existing	2	132 cm	51.6	32.9	17.6	9.5
Site A1/Wheat/No till	1	200 cm	53.4	35.1	15.3	12.4
Site A1/Wheat/Shallow cultivation	1	200 cm	48.8	32.0	15.6	10.6
Site A1/Wheat/Blade ploughing	1	200 cm	60.6	38.6	18.6	14.3
Site A1/Hemp/No till	1	200 cm	44.8	33.0	21.3	12.6
Site A1/Hemp/Shallow cultivation	1	200 cm	45.7	34.7	23.2	13.3
Site A1/Hemp/Blade ploughing	1	200 cm	45.7	34.8	22.7	12.8
Site A1/Hemp/No till	2	200 cm	44.8	33.0	21.3	12.6
Site A1/Hemp/Shallow cultivation	2	200 cm	45.7	34.7	23.2	13.3
Site A1/Hemp/Blade ploughing	2	200 cm	45.7	34.8	22.7	12.8
Site A1/Hemp/No till	3	200 cm	52.5	30.5	14.5	13.3
Site A1/Hemp/Shallow cultivation	3	200 cm	51.7	32.7	18.3	12.5
Site A1/Hemp/Blade ploughing	3	200 cm	57.0	35.0	16.5	14.8
Site A1/Hemp/No till	4	200 cm	53	31	14.5	13.0
Site A1/Hemp/Shallow cultivation	4	200 cm	52	33	18.0	12.0
Site A1/Hemp/Blade ploughing	4	200 cm	57.0	35.0	16.5	14.5
Site A1/Corn/No till	1	200 cm	57.0	43.5	17.5	13.0
Site A1/Corn/Shallow cultivation	1	200 cm	54.5	39.3	23.5	11.8
Site A1/Corn/Blade ploughing	1	200 cm	59.8	46.8	26.8	11.8
Site A1/Corn/No till	2	200 cm	52.7	39.5	21.3	12.4
Site A1/Corn/Shallow cultivation	2	200 cm	48.3	35.0	26.5	11.1
Site A1/Corn/Blade ploughing	2	200 cm	56.3	41.5	30.5	11.2

Table A5: Average water advance and variability during the benchmarking study

Country, Site no. & bed width	Irrigation No.	Statistical parameters	Average advance time (min)				
			Distance along furrow				
			100m	**200m**	**300m**	**400m**	**465m**
Australia							
Site A1 200cm	**1st Irrigation**	***Mean***	54.7	160.7	415.0	696.7	993.3
		n	21	21	21	21	21
		SD	*5.0*	*23.7*	*31.2*	*50.3*	*51.3*
	2nd irrigation	***Mean***	32.4	119.3	248.6	423.1	861.8
		n	24	24	24	24	24
		SD	*4.3*	*9.6*	*15.2*	*14.2*	*17.4*
Site A2 100cm			**90m**	**180m**	**270m**	**360m**	**450m**
	1st Irrigation	***Mean***	11.3	64.2	131.7	234.7	386.7
		n	22	22	22	22	22
		SD	*2.3*	*5.5*	*9.9*	*9.5*	*13.6*
	2nd irrigation	***Mean***	69.9	168.6	299.6	454.9	584
		n	20	20	20	20	20
		SD	*10.0*	*16.0*	*8.4*	*7.1*	*6.7*
Pakistan			Distance along furrow				
			21m	**42m**	**64m**	**86m**	
Site P1 NB	**1st Irrigation**	***Mean***	4.0	11.8	23.2	38.2	
		n	10	10	10	10	
		SD	*0.7*	*0.8*	*1.5*	*1.5*	
	2nd irrigation	***Mean***	5.0	12.0	21.4	33.8	
		n	10	10	10	10	
		SD	*0.7*	*2.4*	*2.4*	*2.9*	
Site P1 WB	**1st Irrigation**	***Mean***	3.8	10.5	17.8	23.5	
		n	8	8	8	8	
		SD	*0.5*	*1.7*	*2.1*	*2.1*	
	2nd irrigation	***Mean***	4.5	10.8	17.5	24.5	
		n	8	8	8	8	
		SD	*1.0*	*2.1*	*2.4*	*2.4*	
Pakistan			Distance along furrow				
			18m	**36m**	**54m**	**72m**	**90m**
Site P2 NB	**1st Irrigation**	***Mean***	4.2	9.2	14.2	20.2	24.8
		n	10	10	10	10	10
		SD	*1.1*	*1.8*	*2.2*	*3.0*	*1.7*
	2nd irrigation	***Mean***	4.4	9.6	15.6	21.8	26.0
		n	10	10	10	10	10
		SD	*0.9*	*1.3*	*3.0*	*4.1*	*0.8*
Site P2 WB	**1st Irrigation**	***Mean***	3.5	7.8	12.5	18.0	23.8
		n	8	8	8	8	8
		SD	*0.6*	*1.7*	*3.1*	*4.8*	*6.2*
	2nd irrigation	***Mean***	3.8	9.0	14.5	22.0	29.5
		n	8	8	8	8	8
		SD	*0.5*	*0.8*	*1.0*	*1.4*	*1.3*
Site P3 NB	**1st Irrigation**	***Mean***	5.2	11.0	17.4	24.0	31.2
		n	10	10	10	10	10
		SD	*1.1*	*1.9*	*2.7*	*3.5*	*3.9*
	2nd irrigation	***Mean***	4.6	9.6	15.4	21.4	27.8
		n	10	10	10	10	10
		SD	*0.5*	*0.5*	*0.9*	*0.9*	*1.1*
Site P3 WB	**1st Irrigation**	***Mean***	3.8	8.8	14.3	20.8	27.8
		n	8	8	8	8	8
		SD	*0.5*	*1.3*	*1.7*	*2.2*	*3.8*
	2nd irrigation	***Mean***	3.5	8.0	13.3	18.8	24.5
		n	8	8	8	8	8
		SD	*0.6*	*1.2*	*1.5*	*1.5*	*1.3*

Table A6: Temporal variation in average bulk density (BD in gm cm^{-3}) and soil moisture (SM in %) of 0-30 cm profile at 10 cm interval for three PRB renovation treatments during three cropping seasons in a Vertisol, Australia (SD in brackets)

Crop	Date	Depth (cm)	No tillage		Shallow cultivation		Blade ploughing	
			BD	SM	BD	SM	BD	SM
Wheat 2010	13/06/2010	0--10	1.01 (0.02)	40(2)	0.95 (0.06)	41 (3)	0.96 (0.04)	42 (2)
		10--20	1.05 (0.03)	44 (3)	1.06 (0.04)	46 (3)	1.03 (0.03)	48 (1)
		20--30	1.10 (0.02)	47 (2)	1.11 (0.02)	52 (2)	1.06 (0.03)	51 (2)
	30/06/2010	0--10	1.00 (0.01)	47 (4)	0.96 (0.04)	50 (2)	0.96 (0.05)	44 (3)
		10--20	1.05 (0.02)	52 (2)	1.03 (0.05)	54 (1)	1.02 (0.03)	53 (5)
		20--30	1.09 (0.03)	56 (1)	1.09 (0.02)	54 (2)	1.05 (0.04)	57 (2)
	4/10/2011	0--10	1.06 (0.03)	45 (4)	0.98 (0.03)	44 (2)	0.96 (0.03)	47 (5)
		10--20	1.09 (0.02)	53 (4)	1.07 (0.06)	48 (3)	1.03 (0.02)	54 (4)
		20--30	1.11 (0.04)	55 (4)	1.14 (0.02)	53 (3)	1.08 (0.01)	57 (4)
	15/11/2011	0--10	1.03 (0.05)	46 (3)	0.97 (0.06)	39 (7)	0.96 (0.05)	51 (2)
		10--20	1.10 (0.05)	49 (4)	1.03 (0.05)	47 (5)	1.04 (0.06)	54 (2)
		20--30	1.11 (0.08)	55 (3)	1.09 (0.07)	50 (8)	1.10 (0.02)	57 (3)
Hemp 2011	26/01/2011	0--10	1.04 (0.03)	46 (3)	1.03 (0.05)	45 (3)	0.97 (0.04)	46 (3)
		10--20	1.08 (0.04)	52 (2)	1.06 (0.03)	51 (4)	1.06 (0.04)	52 (3)
		20--30	1.12 (0.01)	55 (3)	1.12 (0.02)	54 (4)	1.10 (0.01)	53 (3)
	4/02/2011	0--10	1.05 (0.04)	42 (4)	1.05 (0.05)	47 (5)	0.99 (0.01)	46 (2)
		10--20	1.09 (0.05)	54 (4)	1.09 (0.02)	56 (2)	1.07 (0.05)	53 (1)
		20--30	1.12 (0.03)	56 (4)	1.11 (0.01)	57 (2)	1.10 (0.03)	56 (2)
	16/02/2011	0--10	1.05 (0.06)	49 (2)	1.07 (0.04)	52 (2)	0.99 (0.09)	50 (1)
		10--20	1.09 (0.05)	55 (3)	1.10 (0.03)	57 (2)	1.08 (0.03)	56 (2)
		20--30	1.12 (0.04)	59 (3)	1.13 (0.03)	59 (2)	1.11 (0.02)	57 (1)
	25/03/2011	0--10	1.07 (0.05)	40 (2)	1.07 (0.04)	42 (1)	1.01 (0.05)	45 (1)
		10--20	1.12 (0.05)	45 (3)	1.10 (0.03)	45 (2)	1.09 (0.03)	46 (2)
		20--30	1.13 (0.03)	46 (3)	1.14 (0.03)	50 (2)	1.13 (0.02)	50 (1)
	2/04/2011	0--10	1.09 (0.01)	49 (2)	1.08 (0.04)	49 (5)	1.01 (0.03)	49 (2)
		10--20	1.11 (0.01)	52 (3)	1.11 (0.05)	50 (3)	1.10 (0.03)	52 (3)

		20--30	1.15 (0.05)	54 (2)	1.14 (0.04)	51 (3)	1.12 (0.01)	56 (2)
	22/04/2011	0--10	1.10 (0.04)	38 (3)	1.09 (0.04)	39 (4)	1.01 (0.02)	43 (1)
		10--20	1.12 (0.03)	44 (1)	1.12 (0.03)	43 (2)	1.10 (0.04)	47 (3)
		20--30	1.16 (0.03)	48 (2)	1.14 (0.03)	46 (2)	1.12 (0.01)	52 (3)
	14/05/2011	0--10	1.11 (0.02)	48 (3)	1.10 (0.01)	53 (2)	0.98 (0.02)	51 (1)
		10--20	1.11 (0.04)	52 (2)	1.13 (0.02)	54 (1)	1.11 (0.04)	56 (3)
		20--30	1.16 (0.03)	54 (3)	1.16 (0.02)	56 (1)	1.13 (0.05)	59 (3)
Corn 2011	10/10/2011	0--10	1.05 (0.10)	36 (2)	0.97 (0.04)	36 (3))	0.94 (0.04)	40 (2)
		10--20	1.07 (0.04)	39 (1)	1.02 (0.02)	40 (3)	1.00 (0.04)	43 (2)
		20--30	1.11 (0.10)	42 (1)	1.09 (0.04)	44 (2)	1.08 (0.02)	45 (2)
	13/11/2011	0--10	1.08 (0.04)	33 (2)	1.01 (0.02)	36 (2)	0.96 (0.05)	37 (2)
		10--20	1.11 (0.01)	35 (4)	1.09 (0.03)	38 (2)	1.05 (0.03)	42 (2)
		20--30	1.17 (0.02)	39 (5)	1.12 (0.01)	41 (3)	1.11 (0.01)	45 (1)
	11/12/2011	0--10	1.06 (0.04)	33 (3)	1.01 (0.02)	36 (3)	0.94 (0.03)	38 (2)
		10--20	1.14 (0.02)	36 (2)	1.10 (0.02)	39 (4)	1.07 (0.02)	43 (4)
		20--30	1.16 (0.02)	39 (2)	1.17 (0.02)	42 (4)	1.14 (0.02)	46 (3)
	5/01/2012	0--10	1.07 (0.02)	14 (1)	1.08 (0.05)	15 (2)	1.03 (0.03)	17 (3)
		10--20	1.12 (0.01)	17 (1)	1.13 (0.02)	17 (3)	1.07 (0.05)	20 (3)
		20--30	1.17 (0.01)	19 (2)	1.19 (0.03)	20 (4)	1.13 (0.04)	21 (3)
	15/02/2011	0--10	1.08 (0.02)	48 (2)	1.06 (0.03)	51 (1)	1.02 (0.04)	51 (2)
		10--20	1.13 (0.02)	51 (1)	1.10 (0.01)	52 (1)	1.05 (0.01)	52 (2)
		20--30	1.18 (0.03)	53 (2)	1.16 (0.03)	54 (1)	1.10 (0.03)	55 (1)

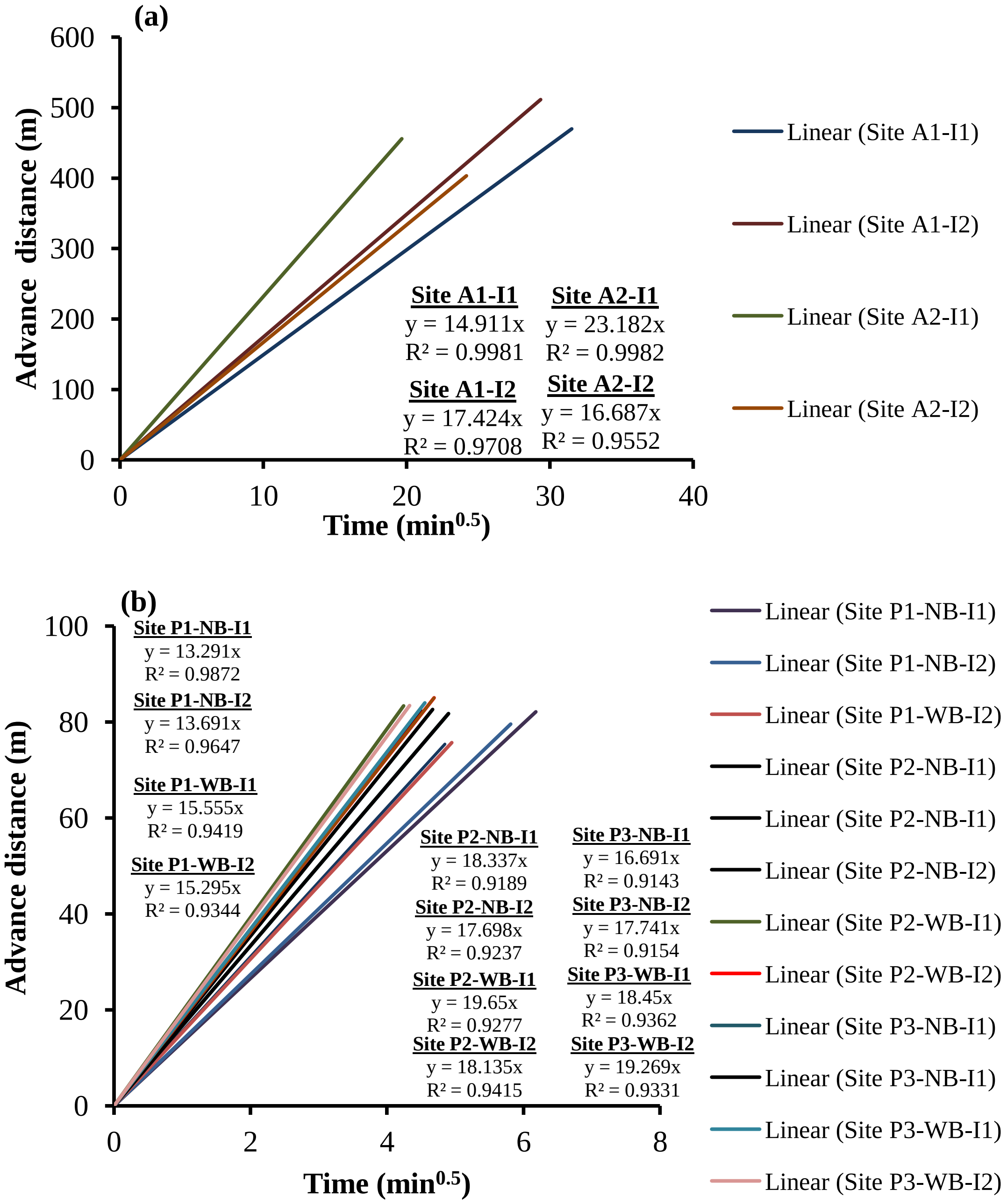
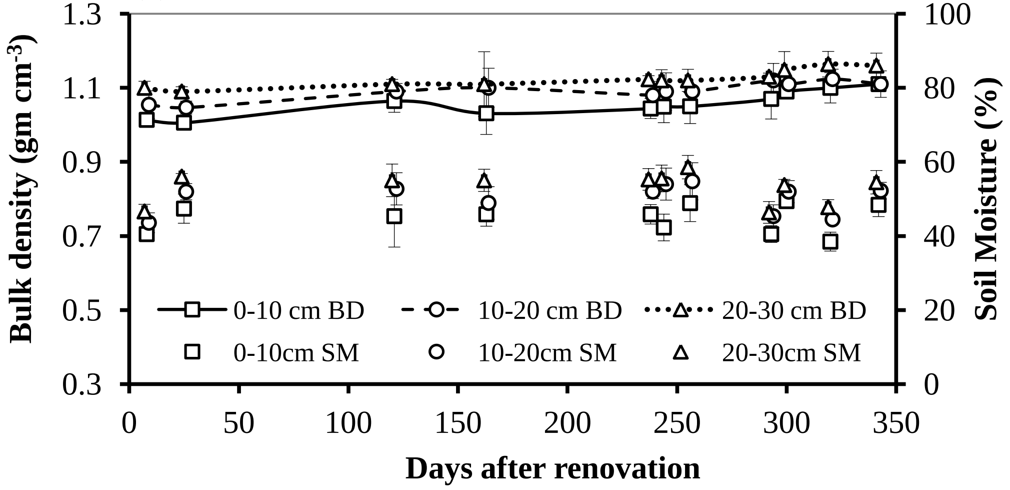
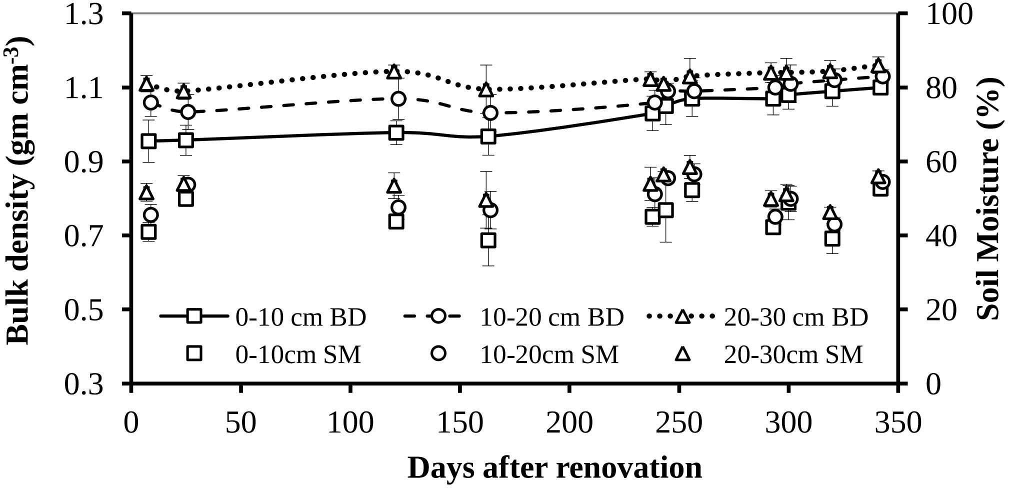


Figure A1: Average water advance distance along furrow vs. square root of time during two irrigations (I1 = irrigation 1 and I2 = irrigation 2) for (a) site A1 and A2 on a Vertisol, Australia and (b) site P1, P2 and P3 on a sandy clay loam, Pakistan

(a): NT



(b): SC



(c): BP

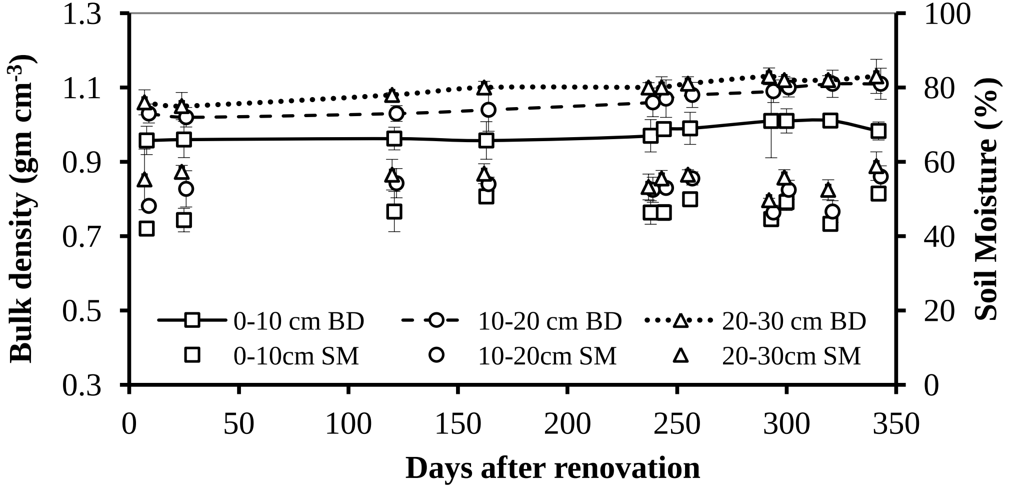
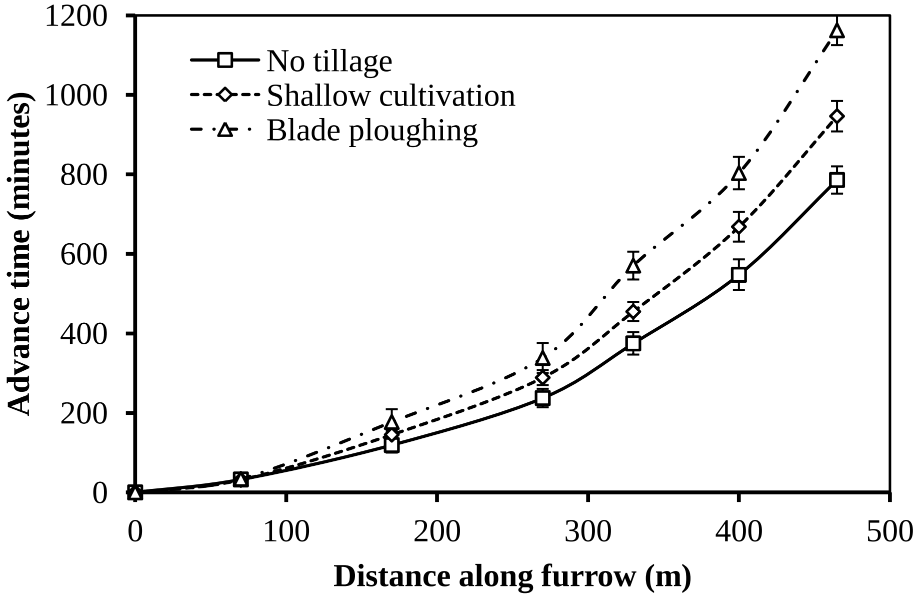


Figure A2: Temporal variations in bulk density and soil moisture for 0-30 cm profile of three PRB renovation treatments during two cropping seasons (2010 wheat and 2011 hemp) seasons at site A1, Australia (vertical bars show SD)

(a): Wheat



(b): Corn

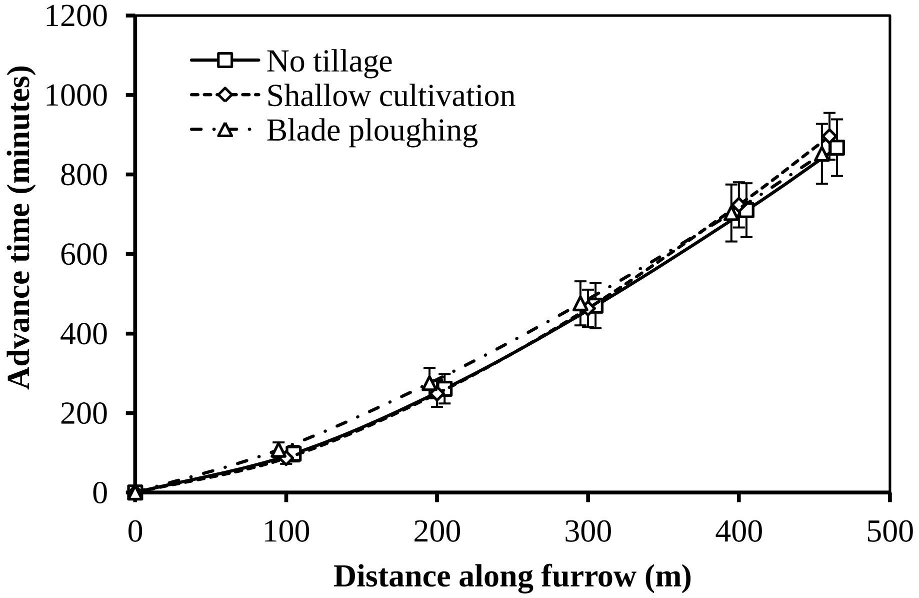
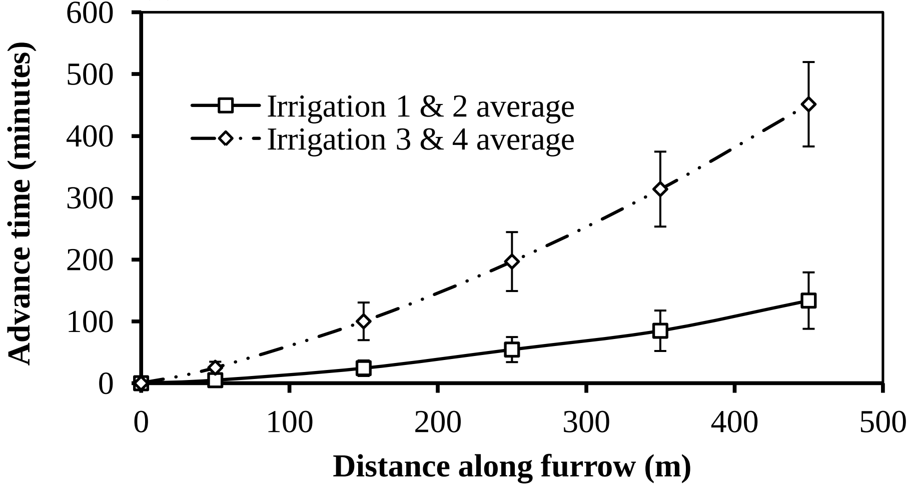
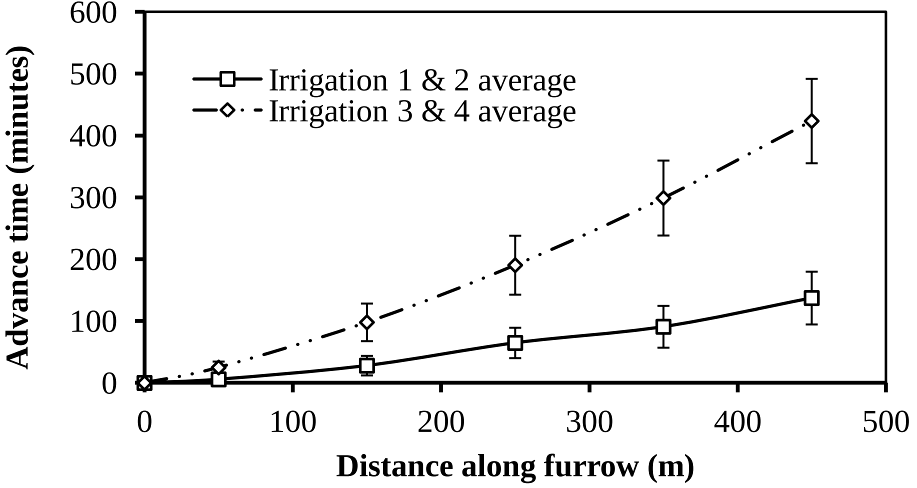


Figure A3: Impact of three fresh renovation methods and irrigation management on water advance rate along furrow during single irrigation to wheat crop (a) and two irrigations to corn crop (b) at site A1, Australia

(a): NT



(b): SC



(c): BP

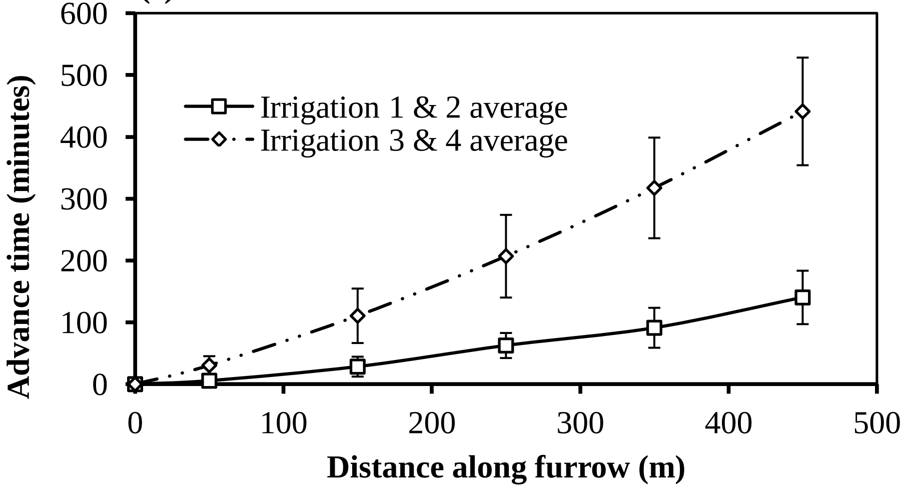


Figure A4: Impact of *SMD* (low during irrigation 1 & 2 and high during irrigation 3 & 4) on water advance rate along furrow during four irrigations to 2011 hemp crop under three PRB renovation treatments (one season old) at site A1, Australia

Appendix B: IPARM and SIRMOD calibration

Comparison of field measured advance time during benchmarking study (Chapter 4) with IPARM and SIRMOD simulated advance times to tail end was analysed using trend line analysis. The results showed a strong correlation (R2 > 0.99) between the two parameters at both sites (site A1 and site A2) in Australia (Figure B1). This confirmed the validity of the evaluations using IPARM and SIRMOD simulation techniques under the field conditions of both sites in Australia.

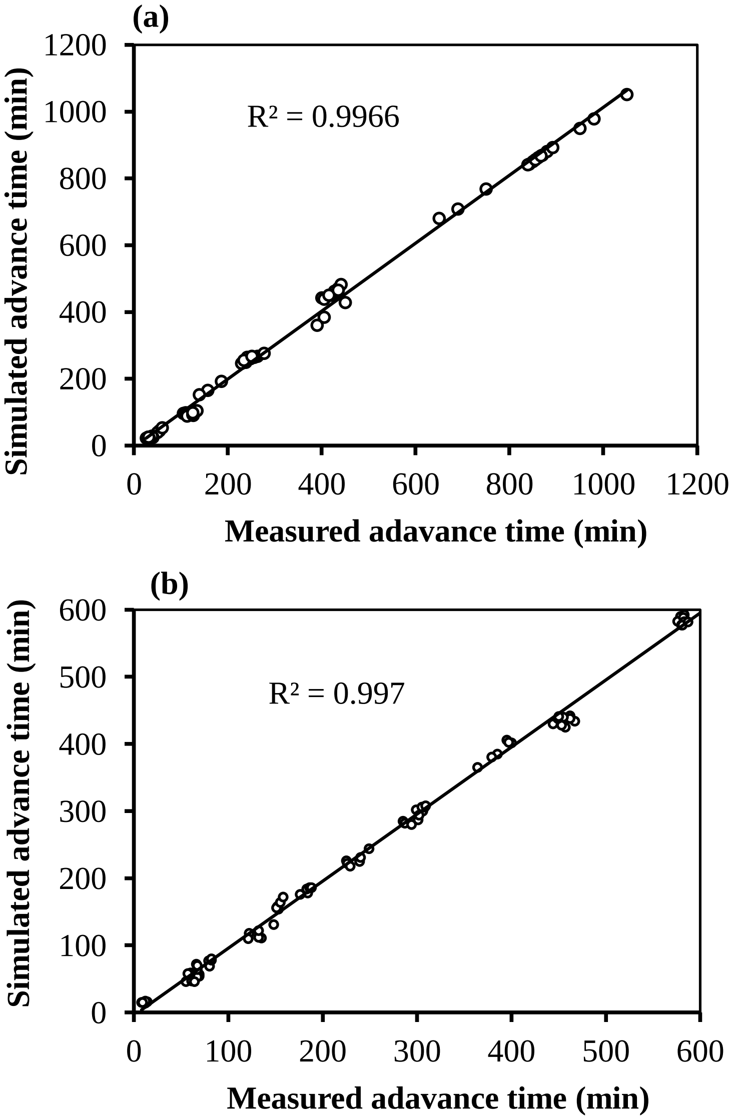


Figure B1: Measured vs. simulated water advance times along furrow length during two irrigations at (a) site A1 and (b) site A2 in Australia

The trend line analysis was also indicative of a very strong correlation ($R^2 > 0.98$) between the fields measured and SIRMOD simulated advance times (Figure B2) in Pakistan, which confirmed the validity of IRPARM and SIRMOD evaluation under the north west Pakistan field conditions.

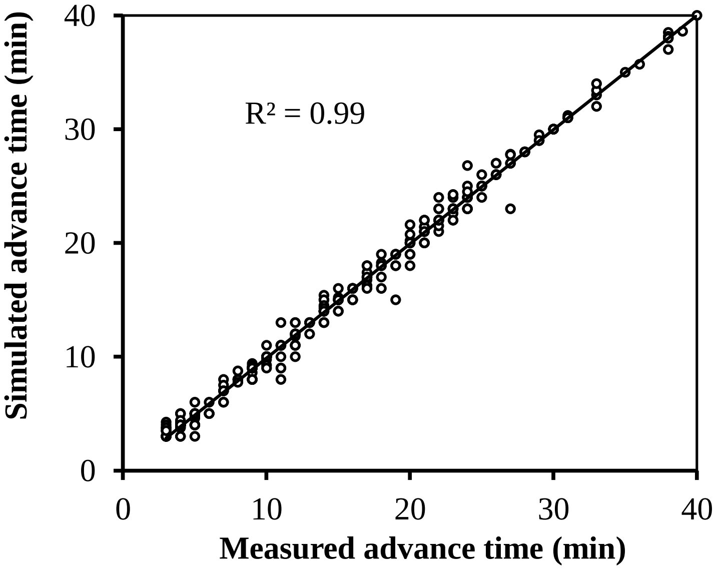
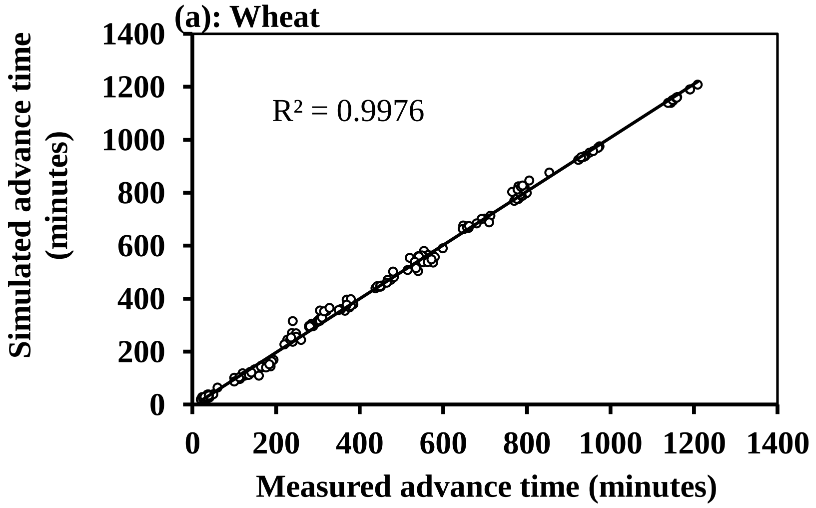
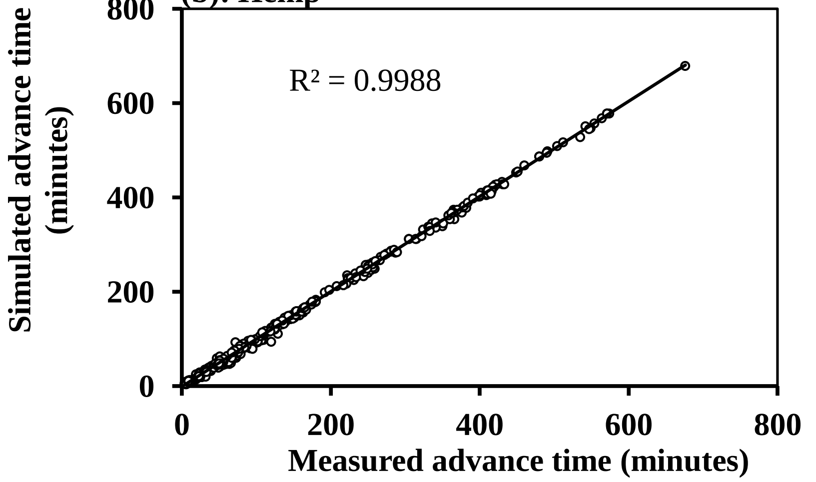


Figure B2: Measured vs. simulated water advance times along furrow length at three sites under both (NB and WB) bed sizes in Mardan, Pakistan

(a): Wheat



(b): Hemp



(c): Corn

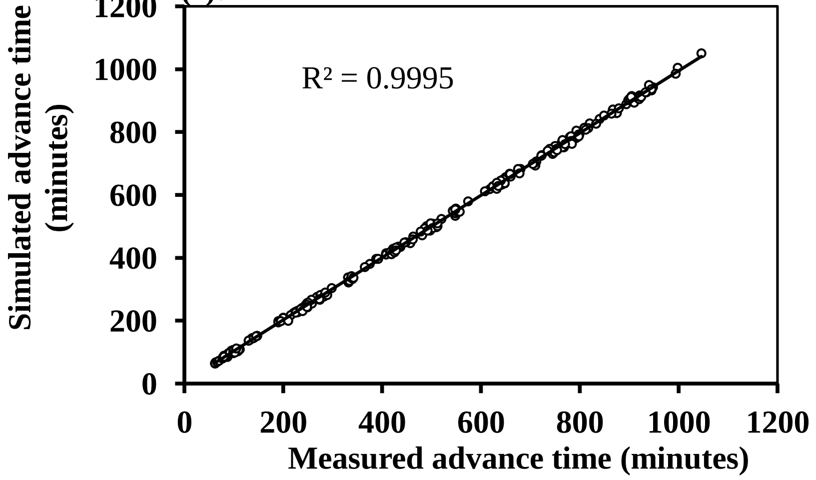


Figure B3: Measured vs. simulated water advance times along furrow length of thee fresh PRB renovation treatments during three cropping seasons at site A1, Australia

Appendix C: EnviroSCAN and Micro-Gopher calibration validation

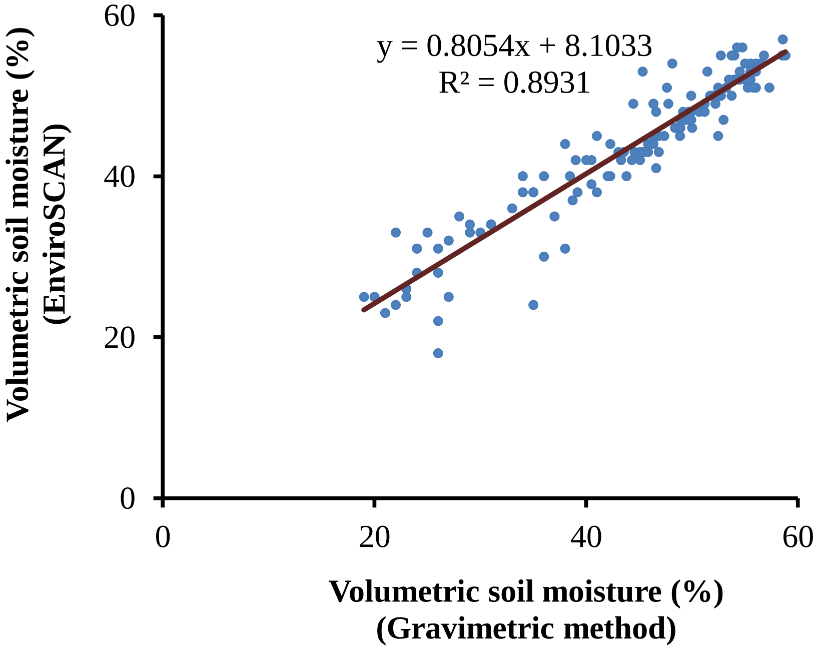


Figure C1: Volumetric soil moisture in 0-30 cm at 10 cm depth interval measured gravimetrically vs. volumetirc soil moisture measure with calibrated Sentek enviroSCAN across bed during three cropping seasons

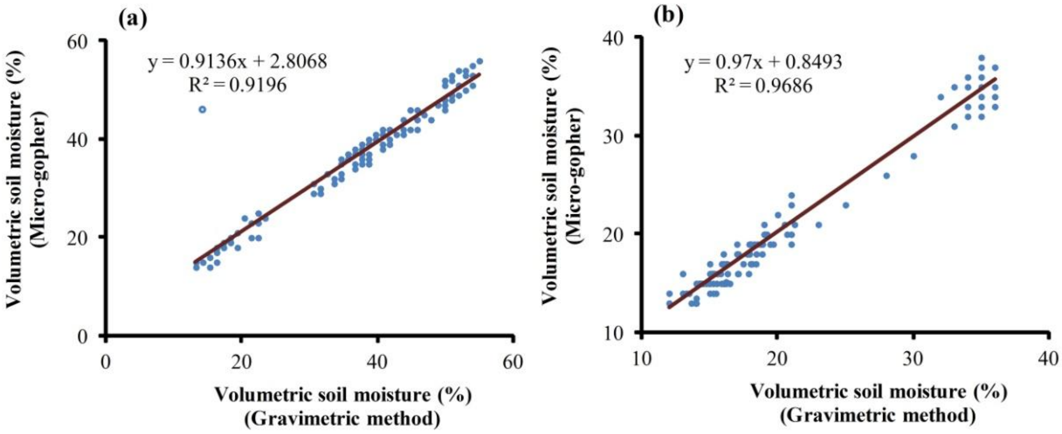


Figure C2: Volumetric soil moisture in 0-30 cm at 10 cm depth interval measured gravimetrically vs. volumetric soil moisture measured with calibrated Micro-Gopher (measured before and after irrigation during 2011 corn crop experiments) across bed under (a) Vertisol, Australia and (b) sandy clay loam, Pakistan.

Appendix D: Irrigation performance and optimisation for all sites and seasons

Table D1: Existing irrigation performance of raised beds and deep drainage losses (*DD*) during two irrigations on two sites in south east Queensland, Australia (SD in brackets)

Site	Event	*Q* *(L s^{-1})*	*Tco* *(min)*	SIRMOD simulation				DD *(mm)*
				Ea *(%)*	*Er* *(%)*	*DU* *(%)*	Inflow *(mm)*	
A1	Irrig.1	1.98	1143	68	100	88	146	47
		(0.11)	*(15)*	*(3)*	*(0)*	*(4)*	*(5)*	*(2)*
	Irrig.2	1.91	1057	77	99	92	130	30
		(0.03)	*(7)*	*(1)*	*(0)*	*(2)*	*(3)*	*(1)*
A2	Irrig.1	2.58	590	74	98	88	101	18
		(0.03)	*(0)*	*(1)*	*(0)*	*(1)*	*(2)*	*(0)*
	Irrig.2	2.50	680	85	96	86	113	7
		(0.02)	*(42)*	*(3)*	*(1)*	*(4)*	*(4)*	*(0)*

Table D2: Existing irrigation performance of raised beds and deep drainage losses (DD) during two irrigations on three sites with two bed sizes in north west Pakistan (SD in brackets)

Site/ Bed	Crop	Event	*Q* *(L.s^{-1})*	*Tco* *(min)*	SIRMOD simulated results				*DD* *(mm)*
					Ea *(%)*	*Er* *(%)*	*DU* *(%)*	Inflow *(mm)*	
P1/ NB	**Cotton**	Irrig.1	3.09	40	45 *(1)*	99 *(1)*	88 *(2)*	132	73
		Irrig.2	2.81	37	55 *(1)*	99 *(1)*	94 *(5)*	110	50
P1/ WB	**Cotton**	Irrig.1	4.88	31	75 *(2)*	99 *(1)*	75 *(7)*	79	20
		Irrig.2	4.83	34	69 *(1)*	99 *(1)*	77 *(2)*	87	27
P2/ NB	**Maize**	Irrig.1	1.55	32	97 *(3)*	78 *(4)*	71 *(4)*	52	2
		Irrig.2	1.68	36	86 *(2)*	88 *(1)*	61 *(4)*	62	9
P2/ WB	**Maize**	Irrig.1	2.76	34	99 *(1)*	77 *(1)*	79 *(5)*	46	0
		Irrig.2	2.66	35	99 *(1)*	77 *(1)*	90 *(6)*	46	0
P3/ NB	**Maize**	Irrig.1	2.09	38	74 *(2)*	99 *(1)*	74 *(7)*	80	21
		Irrig.2	2.63	36	62 *(1)*	100 *(0)*	72 *(5)*	96	36
P3/ WB	**Maize**	Irrig.1	3.08	35	98 *(2)*	88 *(2)*	80 *(6)*	54	1
		Irrig.2	2.85	33	100 *(0)*	78 *(2)*	70 *(5)*	47	0

Table D3: Average irrigation performance for all irrigation events applied on three PRB renovation methods during three cropping seasons on a Vertisol at site A1, Australia (SD in brackets)

Treatment	Crop	Irri. No.	*Q* *(L s^{-1})*	*Tco* *(min)*	SIRMOD simulation				*DD* *(mm)*
					Ea *(%)*	*Er* *(%)*	*DU* *(%)*	Inflow *(mm)*	
No Tillage	**Wheat 2010**	1	1.90 *(0.1)*	843 *(70)*	90 *(2)*	93 *(4)*	82 *(8)*	103 *(6)*	10 *(2)*
	Hemp 2011	1	1.95 *(0.1)*	243 *(40)*	99 *(1)*	76 *(18)*	88 *(8)*	31 *(7)*	0 *(0)*
		2	1.49 *(0.1)*	338 *(13)*	77 *(11)*	62 *(7)*	46 *(17)*	32 *(3)*	7 *(2)*
		3	1.97 *(0.1)*	508 *(7)*	99 *(1)*	64 *(5)*	87 *(4)*	65 *(5)*	1 *(0)*
		4	1.75 *(0.0)*	534 *(18)*	100 *(0)*	60 *(3)*	81 *(5)*	61 *(4)*	0 *(0)*
	Corn 2011	1	1.8 *(0.1)*	857 *(17)*	74 *(2)*	98 *(1)*	79 *(3)*	99 *(3)*	26 *(2)*
		2	1.90 *(0.1)*	1013 *(26)*	98 *(2)*	91 *(3)*	89 *(2)*	124 *(7)*	2 *(0)*
Shallow Cultivation	**Wheat 2010**	1	1.9 *(0.03)*	957 *(32)*	81 *(2)*	94 *(2)*	76 *(4)*	116 *(5)*	22 *(3)*
	Hemp 2011	1	1.66 *(0.1)*	288 *(62)*	94 *(5)*	72 *(17)*	75 *(11)*	31 *(7)*	6 *(1)*
		2	1.65 *(0.02)*	353 *(24)*	77 *(14)*	72 *(13)*	52 *(23)*	37 *(2)*	9 *(2)*
		3	2.01 *(0.03)*	538 *(13)*	98 *(2)*	68 *(1)*	79 *(5)*	70 *(1)*	1 *(0)*
		4	1.83 *(0.2)*	573 *(10)*	99 *(1)*	67 *(5)*	85 *(5)*	67 *(5)*	1 *(0)*
	Corn 2011	1	2.00 *(0.1)*	828 *(16)*	59 *(2)*	99 *(1)*	78 *(4)*	107 *(5)*	44 *(3)*
		2	2.03 *(0.1)*	1040 *(73)*	95 *(2)*	97 *(1)*	91 *(1)*	137 *(3)*	7 *(1)*
Blade Ploughing	**Wheat 2010**	1	2.12 *(0.1)*	1167 *(25)*	61 *(3)*	97 *(1)*	73 *(5)*	160 *(9)*	62 *(4)*
	Hemp 2011	1	2.04 *(0.05)*	200 *(4)*	95 *(3)*	63 *(3)*	74 *(7)*	26 *(1)*	1 *(0)*
		2	1.85 *(0.08)*	337 *(28)*	79 *(12)*	79 *(7)*	58 *(16)*	40 *(3)*	8 *(3)*
		3	2.03 *(0.07)*	543 *(7)*	97 *(4)*	69 *(4)*	77 *(13)*	71 *(2)*	2 *(1)*
		4	2.13 *(0.11)*	543 *(36)*	99 *(1)*	74 *(7)*	89 *(4)*	75 *(7)*	1 *(0)*
	Corn 2011	1	2.3 *(0.23)*	857 *(69)*	47 *(2)*	99 *(1)*	80 *(3)*	126 *(3)*	67 *(5)*
		2	2.20 *(0.2)*	867 *(65)*	85 *(4)*	98 *(1)*	85 *(7)*	122 *(4)*	18 *(1)*

Table D4: Average seasonal irrigation performance for three PRB renovation methods during three cropping seasons on a Vertisol at site A1, Australia (SD in brackets)

Crop	**Treatment**	***Q*** *($L\ s^{-1}$)*	***Tco*** *(min)*	**SIRMOD simulation**				**DD** *(mm)*
				Ea *(%)*	***Er*** *(%)*	***DU*** *(%)*	**Inflow** *(mm)*	
Wheat 2010	**NT**	1.90a	843a	90a	93a	82a	103a	10a
		(0.1)	*(55)*	*(2)*	*(4)*	*(8)*	*(6)*	*(1)*
	SC	1.9a	957b	81b	94a	76b	116b	22b
		(0.03)	*(32)*	*(2)*	*(2)*	*(4)*	*(5)*	*(1)*
	BP	2.12b	1167c	61c	97b	73b	160c	62c
		(0.1)	*(25)*	*(3)*	*(1)*	*(5)*	*(9)*	*(4)*
Hemp 2011	**NT**	1.79a	406a	94a	65a	75a	47a	2a
		(0.2)	*(62)*	*(5)*	*(11)*	*(20)*	*(16)*	*(1)*
	SC	1.79a	438a	92a	70ab	73a	51a	3a
		(0.2)	*(47)*	*(6)*	*(9)*	*(11)*	*(18)*	*(1)*
	BP	2.01b	406a	93a	71b	75a	53a	3a
		(0.1)	*(58)*	*(7)*	*(8)*	*(15)*	*(21)*	*(1)*
Corn 2011	**NT**	1.85a	935a	86a	94a	84a	112a	15a
		(0.1)	*(83)*	*(12)*	*(5)*	*(6)*	*(14)*	*(6)*
	SC	2.02b	934a	77ab	98b	85a	122b	26a
		(0.1)	*(95)*	*(19)*	*(1)*	*(7)*	*(16)*	*(9)*
	BP	2.25c	862b	66b	99b	83a	124b	42b
		(0.2)	*(65)*	*(8)*	*(1)*	*(6)*	*(13)*	*(10)*

**Figures followed by same letters in columns for each cropping season are not significantly (P=0.05) between treatments*

Table D5: Effect of two irrigation management optimisation strategies on current irrigation performance of three sites with two bed sizes during two irrigations under sandy clay loam during benchmarking study in Mardan, Pakistan (SD in brackets)

Site	**Bed Size**	**Strategy**[a]	***Q*** (L.s^{-1})	***Tco*** (min)	***Ea*** (%)	***Er*** (%)	***DU*** (%)	**Inflow** (mm)	***DD*** (mm)
P1	**NB**	0	3.0 *(0.1)*	39a *(2)*	50a *(6)*	100a *(0)*	90a *(6)*	121a *(11)*	61a
		1	3.0 *(0.2)*	32b *(4)*	59b *(10)*	99ab *(1)*	80b *(5)*	103b *(17)*	42b
		2	5.0 *(0.0)*	14c *(2)*	80c *(10)*	98b *(2)*	85c *(4)*	75c *(10)*	15c
	WB	0	4.9 *(0.0)*	33a *(2)*	72a *(2)*	99a *(1)*	77a *(5)*	83a *(4)*	23a
		1	4.9 *(0.0)*	21b *(1)*	99b *(1)*	89b *(2)*	92b *(5)*	54b *(3)*	1b
		2	4.9 *(0.0)*	21b *(1)*	99b *(1)*	89b *(2)*	92b *(5)*	54b *(3)*	1b
P2	**NB**	0	1.6 *(0.1)*	34a *(2)*	90a *(7)*	83a *(8)*	66a *(11)*	56a *(6)*	6a
		1	1.6 *(0.1)*	38b *(3)*	85a *(4)*	88b *(4)*	63a *(10)*	62b *(3)*	9a
		2	1.0 *(0.0)*	58c *(9)*	90a *(5)*	89b *(4)*	72a *(14)*	58ab *(6)*	6a
	WB	0	2.7 *(0.1)*	35a *(1)*	99a *(1)*	77a *(1)*	84a *(13)*	47a *(4)*	0a
		1	2.7 *(0.1)*	38b *(1)*	98a *(2)*	87b *(1)*	82a *(9)*	53b *(3)*	1a
		2	1.5 *(0.0)*	68c *(1)*	99a *(1)*	87b *(1)*	86a *(10)*	52b *(4)*	1a
P3	**NB**	0	2.4 *(0.3)*	37a *(1)*	68a *(4)*	99a *(1)*	73a *(6)*	88a *(8)*	28a
		1	2.4 *(0.4)*	24b *(3)*	98b *(2)*	92b *(2)*	94b *(3)*	56b *(5)*	1b
		2	2.4 *(0.4)*	24b *(2)*	98b *(2)*	92b *(2)*	94b *(3)*	56b *(4)*	1b
	WB	0	3.0 *(0.1)*	34a *(1)*	99a *(1)*	83a *(4)*	75a *(10)*	50a *(4)*	1a
		1	3.0 *(0.2)*	36a *(2)*	97a *(2)*	87b *(2)*	75a *(10)*	54b *(2)*	2a
		2	2.5 *(0.0)*	42b *(1)*	98a *(2)*	86b *(2)*	78a *(11)*	53b *(2)*	1a

**Figures followed by different letters in columns for each bed size on each site show significantly (p=0.05) different values between strategies*

[a] *0: Farmer managed, 1: Tco optimised and 2: Q and Tco optimised*

Table D6: Effect of two irrigation management optimisation strategies on current irrigation performance of three PRB renovation treatments during three cropping seasons on Vertisol at site A1, Australia (SD in brackets)

Crop	Treatment	^{a}Strategy	*Q* $(L.s^{-1})$	*Tco* *(min)*	*Ea* *(%)*	*Er* *(%)*	*DU* *(%)*	Total Inflow *(mm)*	^{b}*DD* *(mm)*
Wheat 2010	**No tillage**	0	1.90*(0.1)*	843a*(55)*	90a*(2)*	93a*(2)*	82a*(7)*	103a*(6)*	10a
		1	1.90*(0.1)*	965b*(30)*	84b*(3)*	99b*(1)*	93b*(3)*	118b*(5)*	19b
		2	2.00*(0.0)*	853a*(60)*	89a*(5)*	98b*(1)*	93b*(5)*	110a*(8)*	12a
	Shallow Cultivation	0	1.90*(0.0)*	957a*(32)*	81a*(2)*	94a*(2)*	76a*(4)*	116a*(3)*	22a
		1	1.90*(0.0)*	1125b*(18)*	73b*(2)*	100b*(0)*	90b*(2)*	137b*(4)*	37b
		2	3.00*(0.0)*	598c*(16)*	86c*(1)*	99b*(1)*	82c*(4)*	116a*(2)*	16c
	Blade Ploughing	0	2.12*(0.1)*	1167a*(24)*	61a*(3)*	97a*(1)*	73a*(5)*	160a*(9)*	62a
		1	2.12*(0.1)*	1245b*(31)*	59a*(3)*	100b*(0)*	85b*(2)*	170b*(8)*	70b
		2	4.00*(0.0)*	403c*(28)*	94b*(5)*	97a*(2)*	89b*(3)*	104c*(7)*	6c
Hemp 2011	**No tillage**	0	1.81*(0.1)*	415a*(19)*	94a*(2)*	65a*(8)*	75a*(10)*	191a*(16)*	3a
		1	1.81*(0.1)*	415a*(19)*	94a*(2)*	65a*(8)*	75a*(10)*	189a*(16)*	3a
		2	1.00*(0.0)*	941b*(67)*	91a*(4)*	78b*(7)*	72a*(8)*	240b*(18)*	5a
	Shallow Cultivation	0	1.79*(0.1)*	438a*(47)*	92a*(6)*	70a*(9)*	73a*(11)*	204a*(18)*	4a
		1	1.79*(0.1)*	438a*(47)*	92a*(6)*	70a*(9)*	73a*(11)*	206a*(18)*	4a
		2	1.13*(0.1)*	810b*(60)*	91a*(5)*	79b*(8)*	75a*(10)*	246b*(29)*	6a
	Blade Ploughing	0	2.00*(0.1)*	406a*(58)*	93a*(6)*	71a*(8)*	72a*(9)*	212a*(21)*	4a
		1	2.00*(0.1)*	406a*(48)*	93a*(6)*	71a*(8)*	72a*(9)*	212a*(21)*	4a
		2	1.50*(0.1)*	797b*(85)*	94a*(4)*	80b*(7)*	80a*(8)*	243b*(27)*	4a
Corn 2011	**No tillage**	0	1.85*(0.1)*	935a*(55)*	86a*(12)*	94a*(5)*	84a*(6)*	224a*(14)*	16a
		1	1.85*(0.1)*	913a*(65)*	87a*(11)*	94a*(4)*	84a*(6)*	218a*(17)*	14a
		2	1.85*(0.1)*	913a*(65)*	87a*(11)*	94a*(4)*	84a*(6)*	218a*(17)*	14a
	Shallow Cultivation	0	2.02*(0.1)*	934a*(60)*	77a*(12)*	98a*(1)*	85a*(3)*	244a*(16)*	28a
		1	2.02*(0.1)*	898a*(65)*	79a*(11)*	97a*(1)*	84a*(3)*	33ab*(16)*	24a
		2	3.5*(0.0)*	483b*(70)*	84b*(8)*	95a*(1)*	83a*(3)*	208b*(22)*	17b
	Blade Ploughing	0	2.25*(0.2)*	862a*(47)*	66a*(8)*	98a*(2)*	83a*(6)*	248a*(7)*	42a
		1	2.25*(0.2)*	833a*(49)*	68a*(8)*	98a*(2)*	81a*(5)*	240b*(6)*	38b
		2	4.00*(0.0)*	399b*(33)*	79b*(5)*	99a*(1)*	86a*(6)*	206c*(10)*	22c

*Figures followed by different letters in columns for each treatment in each crop season are significantly *(P=0.05)* different between strategies

^{a}0: Existing management
1: *Tco* optimised
2: *Tco* and *Q* optimised

^{b}*DD* = Deep drainage losses in mm/irrigation

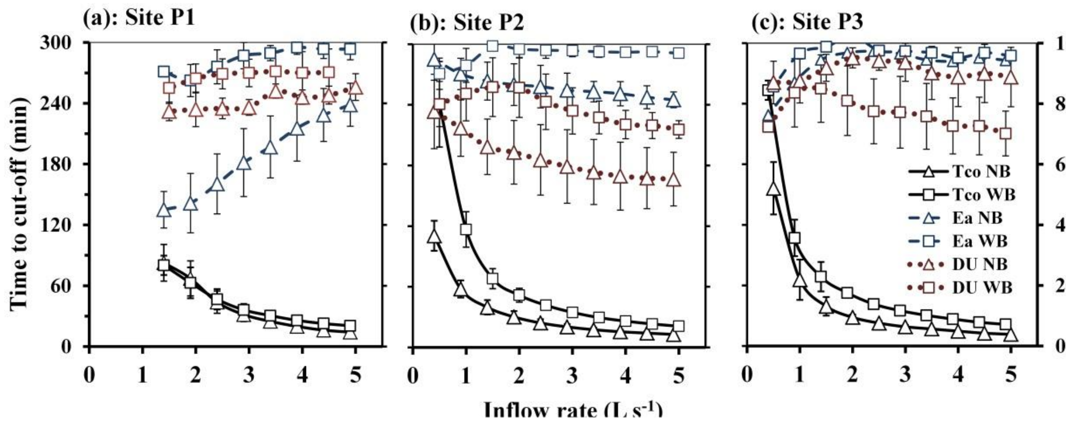


Figure D1: Example irrigation management tool showing the effect of inflow rate on optimum time to cut-off on irrigation performance (*Ea* and *DU*) by confirming *Er* ≥ 85% for two bed sizes (NB & WB) with 86-90 m furrow length at three sites on a sandy clay loam (vertical bars show SD)

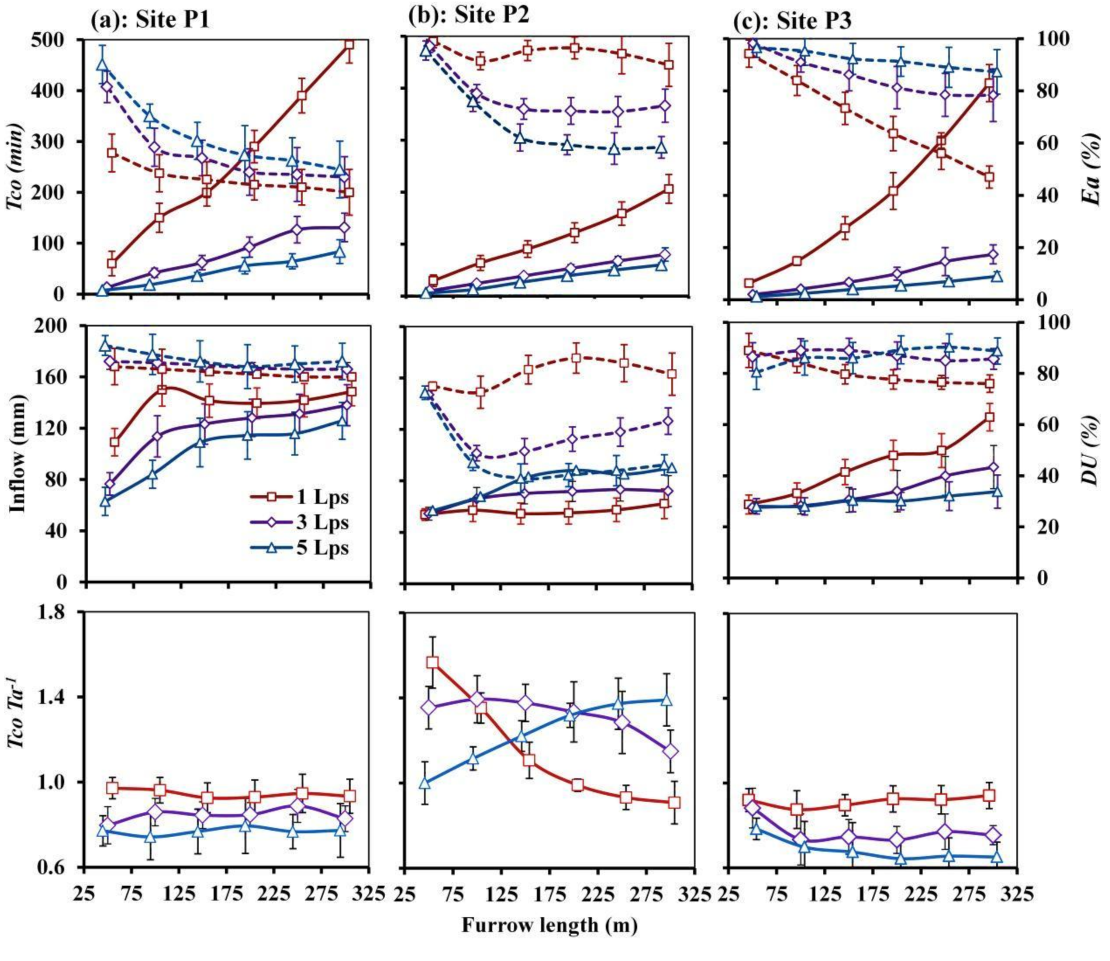


Figure D2: Example field design and irrigation management tool showing the effect of furrow length and inflow rate on optimum *Tco*, inflow volume and *Tco Ta*$^{-1}$ (solid lines) and; *Ea and DU* (dotted lines) for narrow beds (66 cm furrow spacing), by confirming *Er* ≥ 85% and water reaching tail end with 60 mm *SMD*, at given three sites in a sandy clay loam, at Mardan, Pakistan (Vertical bars show SD)

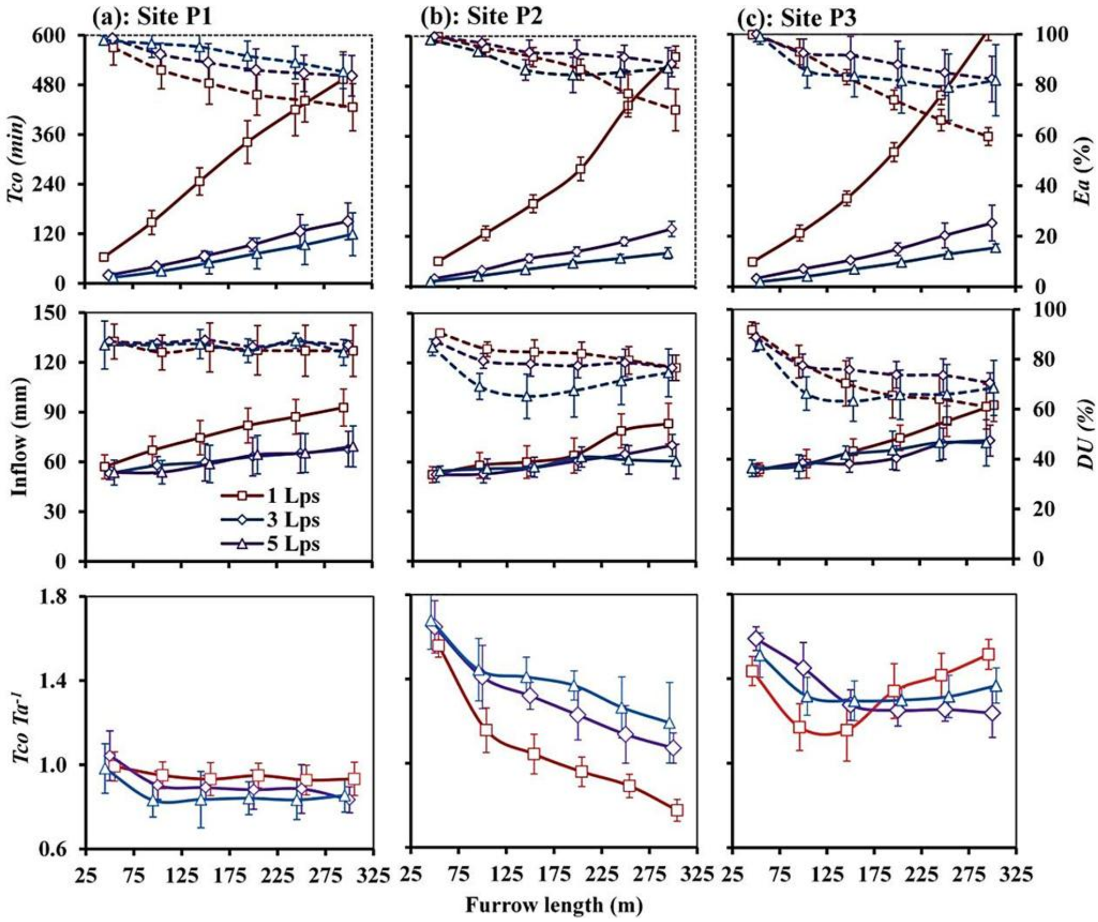


Figure D3: Example field design and irrigation management tool showing the effect of furrow length and inflow rate on optimum *Tco*, inflow volume and *Tco Ta*$^{-1}$ (solid lines) and *Ea* and *DU* (dotted lines) for <u>wide beds</u> (132 cm furrow spacing) by confirming *Er* ≥ 85% and water reaching to tail end with 60 mm *SMD*, at given three sites in a sandy clay loam, at Mardan, Pakistan (vertical bars show SD)

Appendix E: Hydrus 2D calibration

E1 Introduction

The Hydrus 2D (Šimunek et al. 1999) model was calibrated according to the field measured data of the first experiment (Chapter 6) and during the first irrigation to the 2011 corn crop on a Vertisol. For sandy clay loam the average field measured data of both experiments (Chapter 6) was used for calibrating the model. This study was aimed to calibrate the Hydrus 2D model for evaluating different strategies (Chapter 7) for improving the lateral infiltration on both soils.

E2 Material and methods

The Hydrus 2D model was calibrated according to the pre-processing procedure outlined in (Rassam et al. 2004). The model was set to simulate water flow only in the main processes. A general geometry type in vertical plane with cm as the length unit was selected. The soil profile was selected with single (layer) material for NT treatment and two materials (heterogeneity) for SC and BP treatments. Time units were set to hours with a final time of 9 hours. A single number of time variable boundary records was selected. All available print options were enabled and the number of print times was set to 9 in both soils for obtaining hourly details. The maximum number of iterations was selected at 30 and all other default values of iteration criteria were not changed. Initial conditions were set to water content instead of pressure head. The soil hydraulic model of van Genuchten Maulem with no hysteresis options, were selected. The air entry value of -2 cm was selected on Vertisol to account for the shrink swell characteristics. The soil hydraulic parameters for the analytical functions were initially selected from the Hydrus inbuilt database, which were subsequently moderately adjusted as given in Table E1 according to field measured values by taking guidance from previous studies (Carsel & Parrish 1988; Connolly et al. 2001; Connolly et al. 2002; Cook et al. 2008) and by attaining a good fit between the measured and simulated values. In the time variable boundary conditions precipitation was set to zero while evaporation and transpiration was set to 0.004 cm hr^{-1} and rGWL was set to zero.

Table E1: Soil hydraulic parameters for the analytical functions of Van Genuchten equation after calibrating the Hydrus 2D model according to the measured field conditions (Units for time (*t*) = hr and length (*l*) = cm)

Site/Soil	Treatment	Material	θr	θs	α	*n*	*Ks*	*I*
A1/ Vertisol	**NT**	1	0.1	0.55	0.0098	1.41	2.2	0.5
	SC	1	0.1	0.56	0.0103	1.41	3.0	0.5
		2	0.1	0.55	0.0104	1.41	2.9	0.5
	BP	1	0.1	0.56	0.005	1.41	2.7	0.5
		2	0.1	0.55	0.007	1.41	2.1	0.5
P4/ Sandy clay loam	**NT**	1	0.1	0.34	0.032	1.48	0.9	0.5
	SC	1	0.1	0.35	0.026	1.48	1.2	0.5
		2	0.1	0.34	0.028	1.48	1.18	0.5
	BP	1	0.1	0.35	0.019	1.48	1.25	0.5
		2	0.1	0.34	0.021	1.48	1.21	0.5

* *θr = residual moisture content ($l^3.l^{-3}$)*
θs = saturated moisture content ($l^3.l^{-3}$)
α = inverse of air entry value (or bubbling pressure) ($1.l^{-1}$)
n= pore size distribution index
Ks=saturated hydraulic conductivity ($l.t^{-1}$)
I= pore connectivity parameter

The soil profile geometry was set according to the layout of bed furrow configurations measured in the field on both soils as listed in Table E2 and drawn in Figure E1. The simulated soil profile was initially set to 200 cm deep x 100 cm wide on Vertisol and 200 m deep x 66 cm wide on sandy clay loam soils. The flow domain was capable of simulating one half bed cross sections at both sites. A fine mesh density in boundary of the wetted furrow (to enhance precision) and coarse density away from the furrow (to reduce simulation time) was introduced (Figure E1).

Table E2: Field measured furrow dimensions (TW = top width, BW = bottom width and D = depth of furrow) during experiments conducted on Vertisol and sandy clay loam

Site/soil	Treatment	*TW (cm)	BW (cm)	D (cm)
A1/Vertisol	**NT**	62	18	12
	SC	52	21	10
	BP	60	23	11
P4/Sandy clay loam	**NT**	56	22	13
	SC	51	14	13.5
	BP	55	20	14

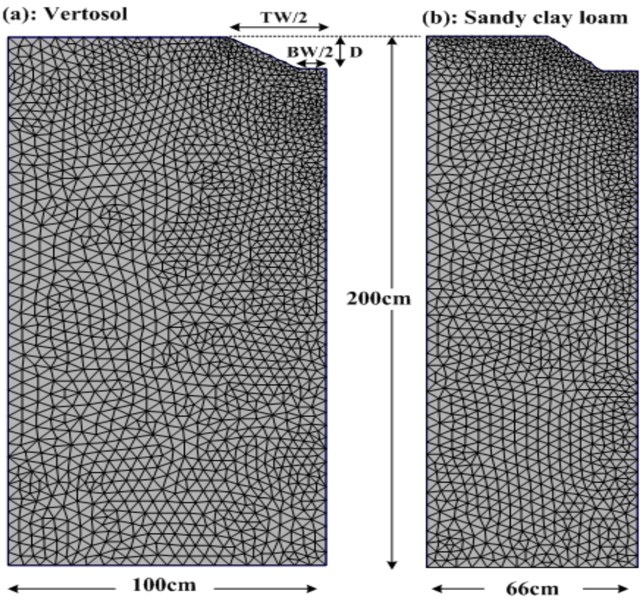


Figure E1: Flow domain x-sections for Hydrus 2D calibration on two soils. The notch at the top right side is a furrow with positions marked for measured furrow dimensions

The flow domain was divided into two layers (materials) in SC and BP treatments. The two layers represented the variable soil hydraulic parameters and soil structure caused by different renovation methods. The depth of material number 1 in the bed surface profile was 15 cm for SC treatment (Figure E2 (a)) and 30cm for blade plough renovation treatment (Figure E2 (b)). However, the NT treatment consisted of a single material (not shown).

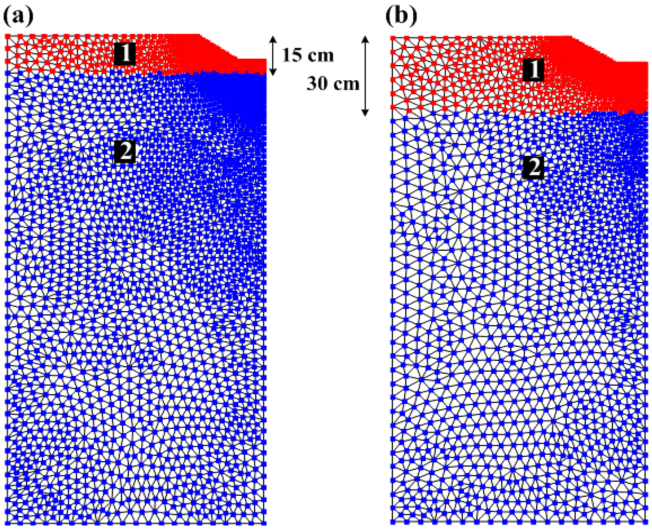


Figure E2: Material distribution in (a) shallow cultivation, and (b) blade plough renovation treatments in both soils

The flow domain was set according to the antecedent soil moisture levels measured in the field on both soils (Table E3) immediately prior to the experiments. Soil moisture of 100-200 cm depth range (not measured) was assumed to be equal to antecedent soil moisture of 100 depths on both soils. A no flux boundary was set on the vertical side boundaries of the flow domain to stop lateral water movement into and out of the soil profile, which was consistent with the assumption of soil-water potential symmetry across the boundaries. A constant pressure boundary was applied on the furrow surface to equalise a 9 cm water head on the furrow (to match the furrow water head during trials on both soils as given in Chapter 6) and 6 cm (to match irrigation 1 to corn on Vertisol only). An atmospheric boundary was placed along the remaining surface boundary exposed to atmosphere to enable interactions between the soil and the atmosphere. A free drainage boundary was set at the base of the flow domain (Figure E3). The evapo-transpiration was estimated according to local climatic conditions by getting guidance from David (2005), PARC (1982) and Ullah et al. (2001) according to both site conditions. The crop was in the establishment stage at both sites during the experiments thus root water extraction was negligible while evaporation and transpiration were each assumed to be equal to 0.004 cm hr^{-1} according to weather conditions during the experimental period.

Table E3: Antecedent soil moisture and soil moisture deficit (*SMD*) in 100 cm root zone depth in Vertisol and 60 cm depth in sandy clay loam

Soil and Treatment	**Volumetric soil moisture (%) at given depth (cm)**										***SMD (mm)***
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	
Vertisol											
NT	27	28	29	32	36	37	38	44	44	48	74
SC	27	31	32	33	35	39	41	45	46	48	63
BP	28	32	34	34	36	38	40	42	45	47	60
Sandy clay loam											
NT	14	14	14	14	13	13	13	13	15	16	59
SC	13	14	14	13	14	14	14	14	15	16	59
BP	14	14	14	14	14	13	14	14	16	17	58

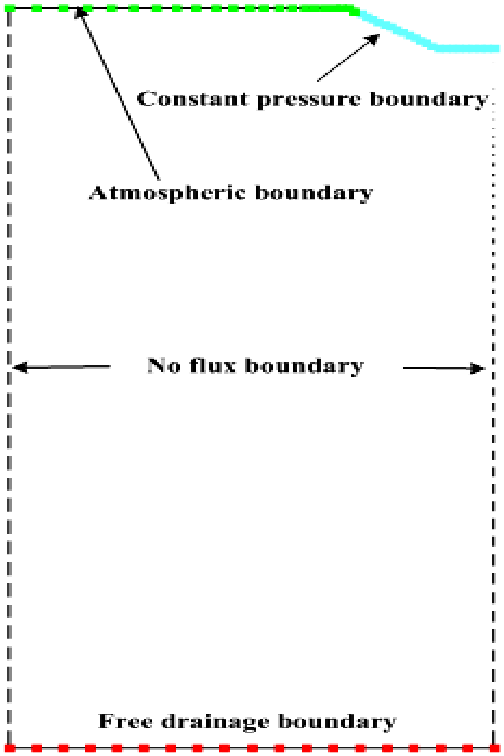


Figure E3: Outline of flow domain with applied boundary conditions

Calibration of the model was undertaken by first comparing the predicted and half of the total volume applied to the furrow during field trials on both soils (Chapter 6). At the same time the predicted and measured lateral wetting front infiltration were visually compared on the bed surface. The soil hydraulic parameters were moderately adjusted to get a good fit between the measured and predicted soil moisture profiles. After getting a good fit, the measured and simulated soil moisture at positions (where probes were located) and three time intervals (1 hr, 4 hrs and 9 hrs) were compared by utilising the Hydrus utility of values along cross sections. To calibrate the model at 6 cm water head in the furrow (recorded during first irrigation to the corn crop) on Vertisol, the constant pressure boundary was modified to 6 cm water head and the results were compared with the measured soil moisture data during the first irrigation to corn crop, following the same procedure as given for the 9 cm furrow water head. Coefficient of determination R^2 in percent was determined by plotting the measured and predicted values. The measured and predicted cumulative infiltration at all measured positions were also compared, to identify the model prediction capability with depth and lateral distance.

E3 Results

For Vertisol with 6 cm furrow water head, the coefficient of determination (R^2) between measured and predicted soil moisture values across the bed was higher at shallow depths (0-50 cm) compared with deeper depths (60-100 cm). The model slightly over-predicted the soil moisture on NT treatment and slightly under-predicted on SC and BP treatments (Table E4). However, the overall results were satisfactory.

Table E4: Relationship between measured and predicted soil moisture at given times and depths across the bed on a Vertisol at 6 cm furrow water head (R^2 values in %)

Treatment	Time	All depths at all distances	Distance from furrow (cm)			Depths at all distances (cm)	
			33	67	100	0-50	60-100
NT	1 hr	94	89	94	99	85	81
	4 hrs	92	82	97	98	97	70
	9 hrs	94	79	72	96	97	57
SC	1 hr	96	88	96	98	97	95
	4 hrs	97	93	97	98	99	75
	9 hrs	84	27	53	96	99	91
BP	1 hr	96	95	95	97	97	90
	4 hrs	97	93	88	98	98	83
	9 hrs	85	83	55	76	89	72

For Vertisol with 9 cm furrow water head, the coefficient of determination was initially higher when most of the bed profile was dry. The good match between initial conditions shows the model calibration was adequate. Overall results showed a good match between measured and predicted values. However, the coefficient of determination was identified to be very sensitive to individual values when the range between the minimum and maximum values was low, which was frequently noted on positions where the bed profile was saturated. For instance, the observed difference between measured and predicted values for NT at 9 hours was apparently not great but the poor match (Table E5) shown (i.e. R^2 = 51) was due to its sensitivity to the smaller range between the minimum and the maximum values.

Table E5: Relationship between measured and predicted soil moisture at given times and depths on Vertisol at 9 cm furrow water head (R^2 values in %)

Treatment	Time	All depths at all distances	Distance from furrow (cm)				Depths at all distances (cm)	
			0	33	67	100	0-50	60-100
NT	1 hr	95	96	94	98	97	97	82
	4 hrs	89	95	95	87	99	91	81
	9 hrs	95	85	97	51	95	98	80
SC	1 hr	97	93	94	99	98	99	78
	4 hrs	99	94	97	98	98	82	92
	9 hrs	97	70	75	79	96	99	95
BP	1 hr	98	97	98	99	97	98	94
	4 hrs	99	98	97	97	98	99	93
	9 hrs	95	89	98	96	88	96	92

For sandy clay loam soil with a 9 cm furrow water head, the coefficient of determination was poor when the range between the minimum and the maximum values was smaller, which was generally found in dry profile e.g. bed middle and in deeper depths. The coefficient of determination was stronger in the wetted profile near the furrow (i.e. 22 cm position) compared with dry profile in the bed middle. However, the measured and predicted values were well matched with an increase in wetting time as the wetting front moved towards the bed middle. For instance, the value of R^2 at 44 cm distance from furrow centre was 52%, 55% and 45% at 4 hours, which was increased to 86%, 91% and 99% after 9 hours of wetting on NT, SC and BP treatments respectively (Table E6).

Table E6: Relationship between measured and predicted soil moisture at given times and depths across bed on sandy clay loam soil at 9 cm furrow water head (R^2 in %)

Treatment	Time	All depths at all distances	Distance from furrow (cm)			Depths at all distances (cm)	
			22	44	66	0-50	60-100
NT	1 hr	76	89	52	38	89	67
	4 hrs	91	96	52	38	86	67
	9 hrs	96	99	86	38	98	61
SC	1 hr	90	97	55	57	97	66
	4 hrs	95	99	55	57	98	66
	9 hrs	97	99	91	57	98	64
BP	1 hr	89	97	22	53	94	66
	4 hrs	96	99	45	53	98	66
	9 hrs	98	99	99	53	99	68

Comparison of measured and predicted cumulative infiltration values on Vertisol across the bed (Figure E4) indicated a marginal over-prediction near the furrow to: 33 cm distance on NT, 67 cm distance on SC and 33 cm distance on BP treatment. The over prediction was higher in the furrow, which may be due to the models' inability to account for furrow compaction. However, the model slightly under-predicted the cumulative infiltration in the middle of the bed.

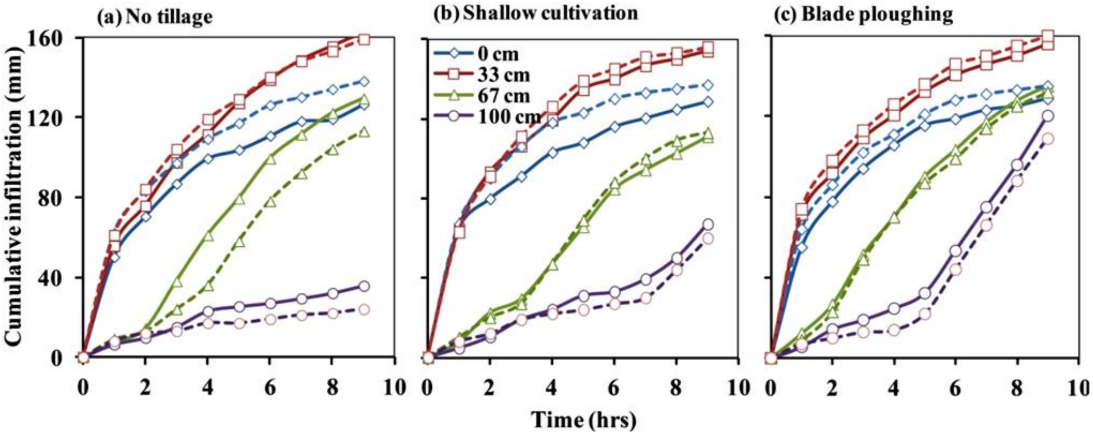


Figure E4: Comparison of measured (solid line) vs. predicted (dotted line) cumulative infiltration at four given distances from furrow centre for three PRB renovation methods at 9 cm furrow water head on a Vertisol

For sandy clay loam, the model slightly over-predicted the cumulative infiltration at 22 cm and under-predicted at 44 cm for NT and SC treatments. However, the overall match between the measured and predicted values was satisfactory (Figure E5).

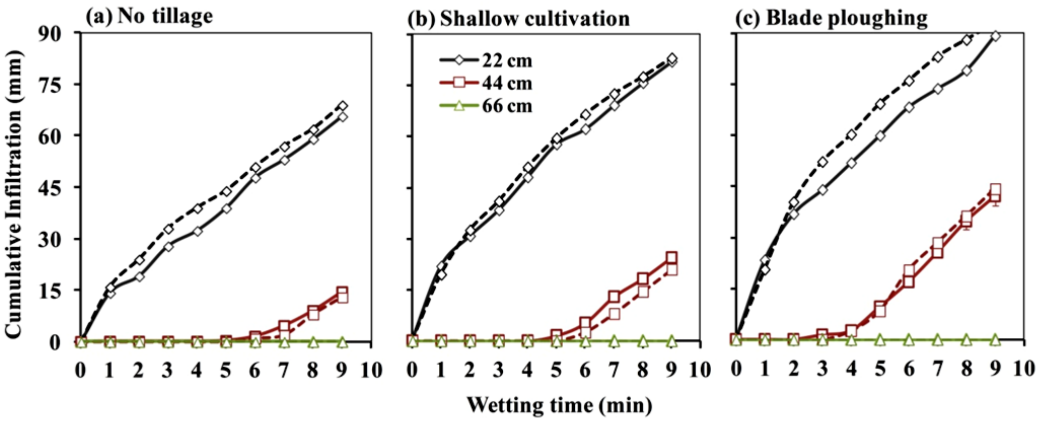


Figure E5: Comparison of measured (solid line) vs. predicted (dotted line) cumulative infiltration at three given distances from furrow centre for three PRB renovation methods at 9 cm furrow water head on a sandy clay loam

E4 Discussion

The Hydrus 2D model well predicted soil moisture movement for three PRB renovation methods on a Vertisol. Most errors in simulation were due to slight over-prediction in the top surface layers and slight under-prediction in the bottom layers of the profile when water head in the furrows was 9 cm. Similarly, the slight over-prediction on NT and under-prediction on the other two treatments, at 6 cm furrow water head, seems to be due to errors in fixing initial conditions. The slight over-prediction near the furrow and under-prediction in the bed middle seems to be due to the models' limitation to precisely predict the changed soil hydraulic properties.

For sandy clay loam, the stronger correlation between the measured and predicted soil moisture near the furrow compared with the bed middle was due to large differences in antecedent soil moisture below the furrow. However, the correlation gradually improved where the wetting front reached, which is good for this study.

The strong correlation between the measured and simulated results, especially with no tendency of increasing deviation at longer times and shallow depths, as indicated on both soils, suggests that the prediction capability of the model will not reduce with time and will tend to further improve. This assumption is particularly beneficial for this study, as most of the simulation times are intended to be longer than the times tested in this calibration study. The increased preciseness of simulation at shallow depths is also beneficial because the Hydrus simulation is intended to evaluate the lateral infiltration in the surface profile of beds.

E5 Conclusions

The Hydrus 2D appropriately parameterised by field measured data can adequately simulates the sub-surface distribution of soil moisture in PRB farming systems and can account for the variable soil management/renovation methods. Therefore, the calibrated model can be used to identify the lateral and vertical infiltration, irrigation applications, deep drainage losses, and soil water storage capacity for the three PRB renovation methods under the given environmental conditions.