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Options to improve irrigation efficiency and productivity under rotational delivery schedule, a bottom-up approach applied at canal irrigation scheme in Pakistan

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SUMMARY

In Punjab, Pakistan, the Warabandi principle guides the distribution of surface water over a network of canals providing farmers with limited water in proportion to land size in a fixed 7-days rotation. Cotton is the most important crop for textile industries in Punjab, but it is highly water-demanding. Current problems with the cotton irrigation performance include rigid rotation and limited supply of water by century-old infrastructure under the Warabandi principle causing substantial water losses and triggering huge abstractions of groundwater by farmers, resulting in low irrigation efficiency and productivity while endangering the aquifer in terms of quantity and quality.

This thesis suggests the introduction of more flexible and site-specific irrigation scheduling in a bottom-up approach starting from the farm level as an entry point for complementing the perspective of a top-down approach in managing the Warabandi large-scale water allocation. The domain of this thesis discusses four specific objectives. The first objective consists in assessing the performance of canal irrigation scheme and water availability, while the second aim was to evaluate cotton irrigation scheduling in the context of Warabandi under various cultivation methods. The competence of several irrigation scheduling scenarios for cotton was investigated under the third objective, and the fourth particular objective addressed a barriers assessment in a potential implementation of proposed water management interventions.

This thesis considered a data and model-driven approach. Between June 2019 to October 2020, water delivery in the canal network was monitored and six cotton fields were randomly selected in the Mungi Distributary canal command area in Punjab. Each field's cotton cropping season activities were monitored and measured. The AquaCrop model was parameterized and validated separately for each field, and then applied to quantify four irrigation scheduling scenarios for two fields. The scenarios were considered mainly to explore the yield response to water stress and the non-beneficial use of water balance parameters in crop's root zone under controlled deficit irrigation options in context of the Warabandi. Therefore, scenario 1 reflects the current irrigation practice in the canal and groundwater use, while for scenarios 2, 3, and 4, solely Warabandi canal water allowance was considered and irrigation followed a fixed rotation of 7-days, 14-days, and flexible intervals, respectively.

Moreover, for a barrier assessment in the adaptation of the proposed interventions and to explore on how to embed technical solutions into the socio-economic and institutional context, three groups of stakeholders were individually interviewed using a structured questionnaire during September-December 2020: (a) 72 farmers, (b) 15 officials, and (c) 14 academicians.

The analysis under the first objective revealed a conveyance efficiency of ~75% for the network of canals, while field application efficiency was estimated as ~64% that led to overall Mungi canal irrigation scheme efficiency of 48%. The deficits of canal water supply versus demand for six cotton fields ranged from 45% to 73%, whereas the Mungi Distributary canal water showed a 68.6% and 19.8% shortfall in the April–September (Kharif) and October–March (Rabi) seasons of 2018/2019, respectively. Considering the outcome of the second objective, a farmer using drip technique attained the highest gross water productivity (GWP) $1.13\ \mathrm{kg\ raw\ cotton\ yield/m^3}$gross water applied. In

contrast, the raised-bed furrow cultivator obtained the lowest GWP of $0.23 \mathrm{kg/m^3}$, respectively. While the GWP varied between 0.25 and 0.39 $\mathrm{kg/m^3}$ for flood basin, another field of raised-bed furrow, and two ridge-furrow cultivation methods. Moreover, the findings of the third objective unveiled that scenarios 2, 3, and 4 resulted in a substantial reduction of percolation water below the crop's root zone and lowered actual evaporation enabling similar yields and higher gross water productivity compared to the current practices in both fields using raised-bed furrow cultivation methods. The fourth objective's evaluation reflected that the most important barriers in the adaptation of the water management interventions (on-farm water storage, soil moisture sensor and drip) that were highly rated by the participants of the groups were low awareness, lack of training and financial resources. While the main problems in Warabandi water distribution provisions were expressed by the farmers as limited canal water allocation, academicians were concerned mostly with inflexibility and officials conveyed discussion among neighbors.

Under the framing conditions of Warabandi, the thesis considered the entry point for more flexible and demand-orientated irrigation at the farm level by (i) utilizing the AquaCrop for simulating pre- and within-season irrigation schedules, and (ii) advancing irrigation schedules by sensor-based soil moisture monitoring. These complementing interventions provide a strong package to improve on-farm water management, which can unfold its potential by (iii) combining the storage option of Warabandi allowance during the potential surplus time in a pond to create an enabling environment for demand-based irrigation. In addition, using the drip method could considerably reduce the undersupply situation in Warabandi-guided irrigation schemes.

This thesis builds a basis of a bottom-up approach for managing the Warabandi water allocation in a more flexible way on farm level. However, further research is necessary to advance the understanding and feasibility of deficit irrigation scheduling options under a rotational water distribution system for cotton at the farm level while aligning and boosting the farmers' capabilities in implementing these options. This thesis provided new on-farm water optimization options for cotton farming that will support key actors on interventions which can improve water productivity under increasingly variable water demand and supply conditions due to impacts by climate change.

Optionen zur Verbesserung von Bewässerungseffizienz und -produktivität unter den Rahmenbedingungen einer rotierenden Bewässerungsplanung: ein Bottom-up-Ansatz für ein Kanalbewässerungssystem in Pakistan

ZUSAMMENFASSUNG

Im pakistanischen Punjab wird das Oberflächenwasser nach dem Warabandi-Prinzip über ein Netz von Kanälen verteilt, welche den Landwirten in einem festen 7-Tage-Rhythmus eine begrenzte Wassermenge im Verhältnis zur Farmgröße zur Verfügung stellen. Baumwolle ist die wichtigste Anbaupflanze für die Textilindustrie im Punjab, hat aber einen sehr hohen Wasserbedarf. Zu den derzeitigen Problemen bei der Bewässerung von Baumwolle gehören die starre Rotation und die begrenzte Wasserversorgung durch die jahrhundertalte Infrastruktur nach dem Warabandi-Prinzip, was zu erheblichen Wasserverlusten führt und enorme Entnahmen aus dem Grundwasser als zusätzliches Wasserdargebot für die Landwirte zur Folge hat. Dies führt zu geringer Bewässerungseffizienz und produktivität und gefährdet die Grundwasserressourcen in Bezug auf Menge und Qualität.

In dieser Dissertation wird die Einführung einer flexiblen und Standort-angepassten Bewässerungssteuerung in einem Bottom-up-Ansatz vorgeschlagen, der auf der Ebene der landwirtschaftlichen Betriebe ansetzt. Dies ergänzt die als Top-down-Ansatz vorgenommene, großräumige Zuteilung des Kanalwassers nach dem Warabandi-Prinzip. Im Rahmen dieser Arbeit werden vier spezifische Ziele erörtert. Das erste Ziel besteht darin, die Durchführung der Kanalbewässerung zu bewerten und die Wasserverfügbarkeit einzuschätzen, während das zweite Ziel darin liegt, die Bewässerungsplanung für Baumwolle im Kontext von Warabandi unter verschiedenen Anbaumethoden zu evaluieren. Die Eignung verschiedener Szenarien für die Bewässerungsplanung von Baumwolle wird im Rahmen des dritten Ziels untersucht, und das vierte Ziel betrifft die Bewertung der Hindernisse bei einer möglichen Umsetzung der vorgeschlagenen innovativen wasserwirtschaftlichen Maßnahmen.

In dieser Arbeit wird ein daten und modellgestützter Ansatz verfolgt. Zwischen Juni 2019 und Oktober 2020 wurde die Wasserabgabe im Kanalnetz überwacht, und sechs Baumwollfelder wurden nach dem Zufallsprinzip im Versorgungsgebiet des Mungi Distributary-Kanals in Punjab zur detaillierten Untersuchung ausgewählt. Die land und wasserwirtschaftlichen Aktivitäten des Baumwollanbaus wurden auf jedem Feld überwacht und gemessen. Das AquaCrop-Modell wurde für jedes Feld separat kalibriert und validiert und dann angewandt, um vier Szenarien für die Bewässerungsplanung für zwei Felder zu erarbeiten. Die Szenarien stehen unter dem wesentlichen Zweck, die Reaktion der landwirtschaftlichen Erträge auf Wasserstress zu untersuchen und die Komponenten des Wasserhaushalts in der Wurzelzone der Pflanzen abzuschätzen, die keinen Beitrag zur Pflanzenwasserversorgung leisten. Diese Szenarien reflektieren kontrollierte Defizitbewässerungsoptionen unter den Rahmenbedingungen des Warabandi-Prinzips. Dabei spiegelt Szenario 1 die derzeitige Bewässerungspraxis der kombinierten Nutzung von Kanal- und Grundwasser, wohingegen für die Szenarien 2, 3 und 4 ausschließlich das nach dem Warabandi-Prinzip zugeteilte Kanalwasser

berücksichtigt und die Bewässerung in einem festen Turnus von 7 Tagen, 14 Tagen bzw. mit flexiblen Intervallen simuliert wurde.

Zur Untersuchung der Fragen, welche Hindernisse einer Einführung der entwickelten technischen Lösungen zur Flexibilisierung der Bewässerung im Weg stehen und wie die Lösungen in den sozioökonomischen und institutionellen Kontext eingebettet werden können, wurden von September bis Dezember 2020 drei Gruppen von relevanten Stakeholdern anhand eines strukturierten Fragebogens einzeln befragt: (a) 72 Landwirte, (b) 15 Vertreter der Bewässerungsverwaltung und (c) 14 Wissenschaftler. Die Untersuchungen im Rahmen des ersten Ziels ergeben einen technischen Wirkungsgrad von ~75% für das Kanalnetz, während die Effizienz der Feldaufleitung auf ~64% geschätzt wird, was zu einem Gesamtwirkungsgrad für das Versorgungsgebietes des Mungi-Kanals von ~48% führt. Die vom Kanalnetz bereitgestellten Wassermengen weisen gegenüber den Bedarfswerten für die sechs Baumwollfelder Defizite zwischen 45% bis 73% auf; die Unterversorgung auf der Ebene des Mungi-Kanals in den Zeiträumen April-September (Kharif) bzw. Oktober-März (Rabi) 2018/2019 liegen bei 68.6% bzw. 19.8%. Im Hinblick auf das zweite Ziel wurde die höchste Brutto-Wasserproduktivität (GWP) mit 1.13 kg Rohbaumwolle/m3 Bruttobewässerungswasser von einem Landwirt erreicht, Tropfbewässerungstechnik einsetzt. Im Gegensatz dazu wurde mit Furchenbewässerung (als raised-bed-Variante) die niedrigste GWP von 0.23 kg/m3 erzielt. Die GWP für die vier übrigen Felder (Beckenbewässerung, konventionelle Furchen (2 Felder) und Furchen mit raised-bed) lagen zwischen 0.25 und 0.39 kg/m3. Die Arbeiten zum dritten Ziel zeigen, dass die Szenarien 2, 3 und 4 (ausschließliche Verwendung von Kanalwasser) eine erhebliche Verringerung der Versickerung unter die Wurzelzone der Pflanzen ermöglichen und zu einer geringeren tatsächlichen Evaporation führen, so dass ähnliche Erträge und eine höhere Bruttowasserproduktivität im Vergleich zu der derzeitigen Praxis in Bezug auf zwei Feldern mit Verwendung von Kanal- und Grundwasser und der Aufleitung mit Furchenbewässerung als raised-bed-Variante erreicht werden. Die Evaluation des vierten Ziels führt zu dem Ergebnis, dass die gravierendsten Hindernisse bei einer Umsetzung innovativer Maßnahmen in der Bewässerung (Wasserspeicher auf der Farm, Sensoren zur Erfassung der Bodenfeuchte, Tropfbewässerung) in einem geringen Kenntnisstand über Innovationen und dem Mangel an Training sowie unzureichenden finanziellen Ressourcen bestehen. Die Einschätzung wurde von allen Gruppen der befragten Stakeholder geteilt. Darüber hinaus sahen die Landwirte die begrenzte Wasserverfügbarkeit im Kanalsystem als Hauptproblem derzeitiger Wasserverteilung nach dem Warabandi-Prinzip an, wohingegen die Wissenschaftler vor allem die mangelnde Flexibilität der Wasserverteilung als problematisch einschätzten und die Vertreter der Bewässerungsverwaltung auf die Diskussionen zwischen den Wassernutzern als Schwierigkeiten hinwiesen.

Unter den Rahmenbedingungen des Warabandi wird in dieser Arbeit der Einstieg in eine flexiblere und bedarfsgerechtere Bewässerung auf der Ebene der landwirtschaftlichen Betriebe berücksichtigt, und zwar unterstützt durch (i) die Nutzung von AquaCrop zur Simulation von Bewässerungsplänen vor und innerhalb der Saison und (ii) die Verfeinerung von Bewässerungsplänen durch sensorgestützte Bodenfeuchteüberwachung. Diese sich ergänzenden Maßnahmen stellen eine wirksame

Kombination von Interventionen zur Verbesserung des Bewässerungsmanagements im landwirtschaftlichen Betrieb dar, das ihr volles Potenzial entfalten kann, indem (iii) die Möglichkeit der Speicherung von Wasser in Überschusszeiten geschaffen wird (als ‚ermöglichende bzw. unterstützende infrastrukturelle Maßnahme' zur Einführung der bedarfsorientierten Bewässerung). Darüber hinaus kann der Einsatz der Tropfbewässerung die Unterversorgungssituation in Warabandi-gesteuerten Bewässerungssystemen erheblich reduzieren.

Diese Dissertation bildet die Grundlage für einen Bottom-up-Ansatz zur Flexibilisierung der Wasserverteilung innerhalb der Farm-Ebene unter den Bedingungen der großräumigen Wasserzuteilung nach dem Warabandi-Prinzip. Es sind jedoch weitere Forschungen erforderlich, um das Verständnis und die Durchführbarkeit von Optionen für die Defizitbewässerung im Rahmen eines rotierenden Wasserverteilungssystems für Baumwolle auf Betriebsebene zu verbessern, und gleichzeitig die Fähigkeiten der Landwirte bei der Umsetzung dieser Optionen zu fördern. Diese Arbeit liefert innovative Möglichkeiten für die Optimierung der Wassernutzung im Baumwollanbau auf der Farm-Ebene, die die Hauptakteure dabei unterstützen, Maßnahmen zur Verbesserung der Wasserproduktivität unter den aufgrund des Klimawandels zunehmend variablen Wasserbedarfs- und -dargebotsbedingungen zu konzipieren und umzusetzen.

DEDICATION

I want to express deepest gratitude to my mother, Anisa, for all of her sacrifices during my life in Afghanistan's turbulent situation. I am proud of her love and dignity. In addition, I extend appreciation to my father and, in particular, the Sajid family members for their continuous support.

I acknowledge and thank Dr. Bernhard Tischbein for his unwavering support during the PhD process. He not only helped me build research abilities, but his nice behavior also taught me about true research ethics. Moreover, I appreciate the supervision and guidance of Prof. Dr. Martina Flörke and Prof. Dr. Christian Borgemeister. I admire the administrative work and facilitating my stay in Bonn by Dr. Silke Tönsjost, Dr. Günther Manske, Max Voit and Maike Retat-Amin, while my colleagues and friends at ZEF will remain valuable people in my life.

I want to dedicate Mawlana's poem to my mother:

اشتیاقی که به دیدار تو دارد دل من
دل من داند و من دانم و دل داند ومن

The desire of meeting you in my heart
My heart knows and I know, the heart knows and I

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LIST OF ACRONYMS AND ABBREVIATIONS

CC_x	Maximum Canopy Cover
CC_0	Initial Canopy Cover
CCA	Canal Command Area
CSA	Climate Smart Agriculture
CV (RMSE)	Normalized Root Mean Square Error
D	Index of agreement
DAS	Days After Sowing
E_{ACT}	Actual Evaporation
ET	Evapotranspiration
EF	Model Efficiency Coefficient
FC	Field Capacity
GDD	Growing Degree Days
GIWR	Gross Irrigation Water Requirement
GWP	Gross Water Productivity
HI	Harvest Index
IBIS	Indus Basin Irrigation Scheme
LCC	Lower Chenab Canal
NIWR	Net Irrigation Water Requirement
PID	Punjab Irrigation Department
RMSE	Root Mean Square Error
SWC	Soil Water Content
T_{ACT}	Actual Transpiration
UAF	University of Agriculture Faisalabad
UNFAO	United Nation Food and Agriculture Organization
WP	Wilting Point

1 INTRODUCTION OF THE THESIS

1.1 Background information

In Pakistan, irrigated agriculture is the major consumer of surface and groundwater (Yongguang et al., 2018, Bhatti et al., 2009; Rizwan et al., 2018), with irrigation water withdrawals exceeding ~174 km^3 $year^{-1}$ out of total renewable freshwater resources of ~246 km^3 $year^{-1}$ (Frenken and Gillet, 2012). Pakistan's surface water originates mainly from precipitation during the Kharif season (April–September) and snowmelt from the Himalayas. The Indus basin is the country's primary provider of surface water through its tributaries, the Indus, Jhelum, Sutlej, Chenab, Ravi and Kabul rivers. Withdrawals from these rivers are fed into a complex and widespread network of canals and conveyed to farmers that established the main irrigation scheme of the country, called the Indus Basin Irrigation System (IBIS) (Bandaragoda et al., 1995; Sarwar, 2019).

The IBIS comprises large main and branch canals (the primary system) that provide water to major and minor distributaries (the secondary system). The major distributaries deliver water to minor channels that allow a fixed flow of water and are opened to smaller conduits as watercourses (the tertiary system) where farmers can divert water to their farmland (Figure 1.1). Moreover, the Irrigation Department in Pakistan is responsible for canal water supply and provision up to Mogha (outlets along the minor distributaries at different points to divert water to each watercourse), whereas the farmers manage the on-farm water outlets and distribution (Bhutta and Van der Velde, 1992).

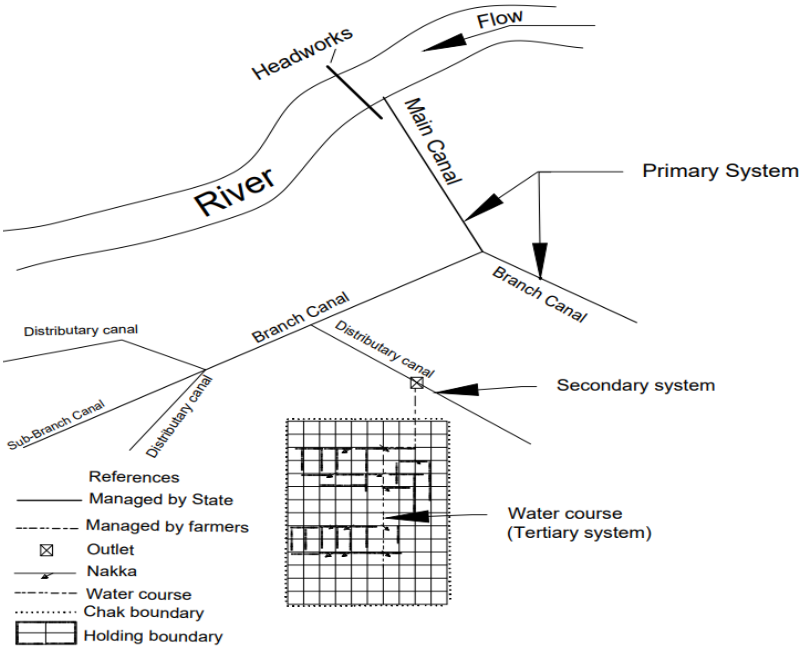


Figure 1.1: Irrigation canal hierarchy and structures layout adapted from the study of Malhotra (1982).

The Warabandi principle guides the flow of water in each watercourse to all farmers with fields along the watercourse. The term is taken from two words, "Wara" and "bandi". The meaning of wara is "turn" and bandi means "fixation". Together, it reflects rotation of water distribution according to a fixed timetable (Narain, 2008). Over a century ago, irrigation water delivery guided by the Warabandi principle was put in place within the IBIS. In the Warabandi system, surface water is distributed to farmers in fixed turns (after 7 days) in obedience to a predetermined timetable specifying the day, time and period of water supply proportional to the size of the land owned by each farmer. The main aim of Warabandi was to offer protective irrigation by maintaining an equitable distribution of the available water to farmers and to cope with water scarcity by efficiently irrigating as much land as possible with limited surface water (Bhutta and van der Velde, 1992; Jurriens et al., 1996). In order to preserve equitable water supply, the system was designed to divide the discharge into fixed ratio for distributing of canal water at the outlet structure of the tertiary units (Malhotra, 1982).

Therefore, in protective irrigation the main focus was on water productivity (maximum production per unit of water) but not land productivity that could build resilience against famine. Malhotra (1982) indicated that Warabandi schedules were produced in such a manner that each unit of agricultural land (cultivable command area) receives a specific flow rate known as a water allotment. The 0.2 $l(s*ha)^{-1}$water allowance was allocated for water courses in Punjab Pakistan, while the actual ratio varied between 0.2 and 0.3$l(s*ha)^{-1}$. Even though the maximum allocation of 0.3 $l(s*ha)^{-1}$ (equivalent to an irrigation amount of 2.6 mm per day) is not sufficient to fulfil the evapotranspiration demand of the coldest month which is 3 mm per day (Bandaragoda, 1995).

Pakistan's Punjab province, where 56% of the IBIS is located, accounts for around 80% of total cotton production (Pakistan Economic Survey, 2019). The province covers 69% of the total cropping area of the country and is known as the biggest consumer of water in the irrigation sector (FAO, 2016). Sugarcane (as an annual crop), rice, and cotton are highly water-demanding crops that are grown in April–September during the monsoon season (Kharif) in Punjab (Muzammil et al., 2020). Wheat and fodder crops are dominant in the second growing season of October–March (Rabi season), which is rather dry in Punjab, and during this period the major canals are closed for maintenance mostly for a month (Ahmad et al., 2019).

Cotton is known as "white gold" in Pakistan. Despite being a highly water-demanding crop, it is the main raw material used in the development of the country's textile industry; consequently, Pakistan is the fourth major producer of cotton in the world. It is cultivated on 2,527,000 hectares of land and contributes around 0.8% to GDP as well as 4.1% in total value addition in agriculture (Pakistan Economic Survey, 2019). The area of cotton cultivation expanded by 6.5% in 2020 compared to the recorded area in 2019; yet, production was 6.9% lower in 2020 than in 2019 due to adverse weather conditions, limited water for irrigation, and the spread of diseases (Pakistan Economic Survey, 2019).

Punjab has favorable growing conditions for cotton with enough heat (yet due to climate change, heat stress is increasingly occurring) and sunlight. Farmers in Punjab use traditional and often inefficient land and water management practices to produce cotton, resulting in low yields, high water losses, and hence, relatively low water productivity (Makhdum et al., 2011; Zulfiqar and Thapa, 2016).

1.2 Problem statement

The limited amount of water and fixed 7-day rotation under the current Warabandi principle frame the irrigation scheduling options of the farmers from the supply side. Therefore, farmers use the aquifer as further source of water supply in addition to canal water and as a buffer to raise flexibility at the supply side in order to match time-depending of crops' water demand. Yet, the magnitude of groundwater abstractions is reaching - and in some parts of the region even exceeding - recharge rates questioning the sustainability of water use by lowering the groundwater table (Jurriens et al., 1996; Kirby et al., 2017).

Although the Warabandi system is relatively easy to run, transparent, and managed by public authorities, it remains difficult to address the day-to-day challenges of water distribution. For example, it does not consider conveyance losses along canals to compensate for the lower water allowance of tail canal users. In addition, it is a rigid supply-based irrigation mode that does not match the time-depending demand of crops and does not consider soil features and increasingly variable environment (climate change) (Bhutta and van der Velde, 1992; Jurriens et al., 1996). Moreover, it was designed for a cropping intensity of 70%, whereas the intensity has been extended to 120% due to population growth, economic, and social factors (Ruigu, 2016). Some canals receive less than 75% of the design discharge for almost half of the year due to low flows in the main and branch canals, sedimentation, leakages, breaches, and faulty gates (Bhutta and van der Velde, 1992). The limited availability of surface water to farmers under Warabandi results in the uncontrolled pumping of groundwater (due to lack of regulation over access to groundwater) by farmers to overcome the limited canal water supply (Qureshi et al., 2010).

Social and technical challenges are associated with problems of water management in the irrigation sector in Punjab. Rapid population growth and an increase in cropping intensity to ~120% (Ruigu, 2016). Furthermore, it is projected that by 2025, Pakistan would experience a 30% deficit in surface water that is attributed to siltation in reservoirs and the country could be under further pressure due to sharpening competition for water (industry, drinking water provision ecology/environmental flow, agriculture) and the impact of climate change (increasing evapotranspiration by rising temperatures), which is expected to result in irrigation water scarcity in the country (Haddeland et al., 2014; Sarwar, 2019).

Additionally, substantial water losses during canal water delivery and conventional irrigation methods practiced by farmers result in low water productivity (Bakhsh et al, 2016). The combination of the shortfall of surface water and increased water demand has led to the uncontrolled abstraction of groundwater, which in turn has resulted in secondary salinization (Ahmad et al., 2019; Waqas et al., 2019). About 1.2 million private tube wells were built in Pakistan, with the majority (around 85%) located in Punjab. Substantial amounts of groundwater have been, and still are, abstracted with these wells and have lowered the groundwater table in the Lower Chenab canal area in Punjab (Qureshi, 2020; Usman et al., 2018). Moreover, this situation will very likely create potential sustainability challenges for the country's near and far future in terms of water quantity as well as quality by enhancing pollution, especially in water supply from drinking water provision (Cheema et al., 2014).

Although abstracted groundwater is widely used in Punjab, surface water is in high demand for its good quality. However, old irrigation infrastructure and poor operation and maintenance in Punjab result in low delivery efficiency (Hussain et al., 2011), leading to the inequitable and unreliable distribution of surface water, particularly to tail-end users. Moreover, the gap between supply and demand is further aggravated by poor on-farm water management techniques, such as insufficiently levelled fields and conventional and traditional surface irrigation methods that have a low application efficiency of ~35% (Asian Development Bank, 2006; Hussain et al., 2011; Mekonnen and Hoekstra, 2016; Young.W.J et al., 2019).

1.3 Scope of the thesis

In the present thesis, cotton farming is typically studied in the cotton-dominant cultivation area of Mungi in Punjab with consideration given to the conjunctive use of groundwater and canal water under the Warabandi principle (i.e., limited supply and a fixed 7-day rotation). The selection of the fields in the current work was based on three factors that were used to determine the effects on cotton water productivity: (i) various irrigation methods for cotton that covered (to the best of the knowledge) all relevant cultivation methods practiced in the study area, i.e., drip, flood basin, raised-bed furrow, and ridge-bed furrow; (ii) location of fields along the Mungi Distributary canal command area with different water supply situation (due to variation in Warabandi water allowance caused by conveyance losses in canals); and (iii) farm size holders (i.e., large and small farmers that indicated their farming experience and water optimization techniques).

The thesis assumed that large-scale water allocation in the future would remain under the Warabandi principle. Therefore, the within-farm water allocation (bottom-up approach) was considered as a promising entry-point for suggesting the introduction of more flexible irrigation practices (needed to cope with water scarcity and variability of the environment). The bottom-up approach in this thesis deliberated the introduction of irrigation scheduling as a tool to enable flexibility in the rigid rotational water allocation based on the Warabandi principle in farmers' fields. It is considered an entry point for complementing the perspective of a top-down approach, which reflects the change in water allowance or rotation in the current canal water distribution governed by institutions.

1.4 Specific objectives

The specific objectives of this thesis were defined as follows and each objective corresponds to a separate chapter:

1) To evaluate the irrigation performance (application and conveyance efficiencies) and water availability (supply-demand relationship) from the field to the Mungi Distributary canal level in Punjab, Pakistan. (Chapter 2)
2) To assess cotton irrigation scheduling in the context of Warabandi under various cultivation methods. (Chapter 3)
3) To generate cotton irrigation scheduling scenarios under rotational delivery schedule. (Chapter 4)

4) To explore the potential barriers in adaptation of the water management innovations in farmers' farms. (Chapter 5)

1.5 Study Area

The Mungi Distributary canal is one of the distributaries of the Lower Chenab Canal (LCC) that takes water from the lower Gogera branch and is located between 30°33' to 31°2' N and 72°08' to 72°48' E on an average altitude of 184 m above sea (m.a.s.l). It demonstrates a head design discharge of 4.6 m^3s^{-1} at full supply level and a tail design discharge of around 0.17 m^3s^{-1}. The gross and cultivable command areas are 20,290 and 17,683 hectares, respectively (PID, 2021). The Mungi Distributary canal command area (CCA) was selected to monitor farmers' cotton cultivation activities because cotton is highly water-demanding and the dominant crop in the Kharif season (April–September) in this area. Water flows in the Mungi Distributary canal from North to South as shown in Figure 1.2.

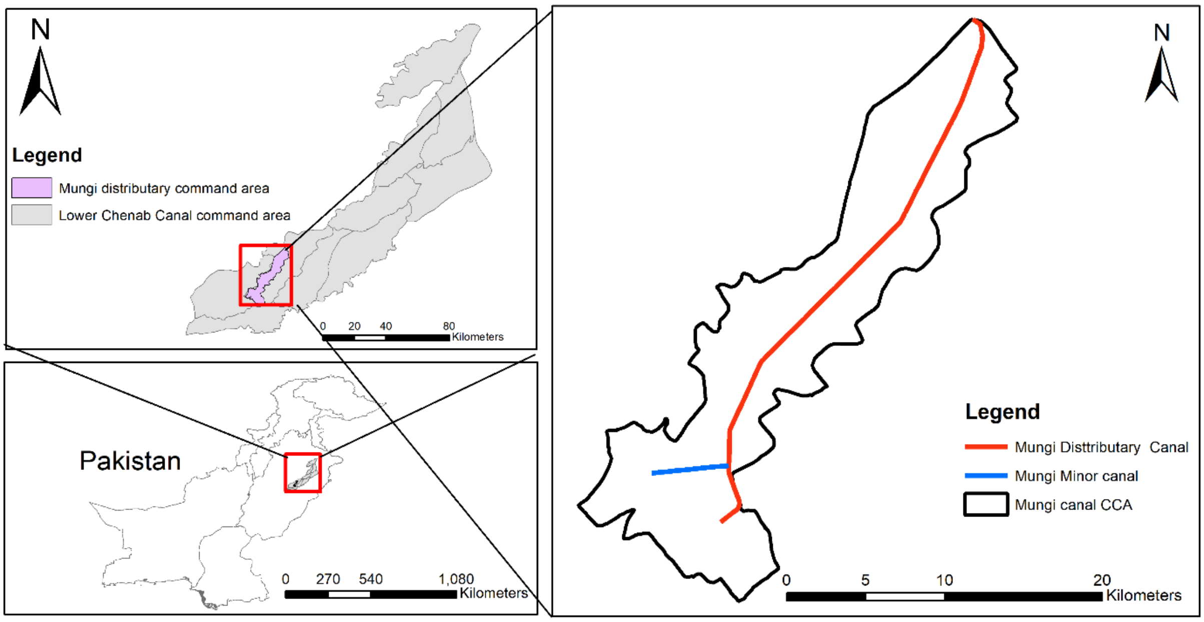


Figure 1.2: Geographical location of the study area.

1.6 Climate of the study area

The meteorological data were required to estimate crops' actual evapotranspiration in the Mungi CCA using AquaCrop model (Steduto et al, 2012). The data, including rainfall, solar radiation, wind speed, maximum and minimum air temperature, and relative humidity, were obtained from the meteorological station of the University of Agriculture Faisalabad (UAF), which is the nearest station located in a distance of 62 km from the Mungi area. The meteorological data were collected for the period 2008-2020 and the mean monthly rainfall, temperature and reference evapotranspiration are exemplarily depicted in Figure 1.3.

The Punjab province comprises mostly of plain areas with an elevation range of 11 to 258 m, whereas the altitude varies between 259 to 2,300 m.a.s.l. in the sub-mountain regions that include a small part in the southwest and the north of the province (Ahmad et al., 2019). The Punjab province has generally semi-arid to arid climate characteristics with primarily three seasons: (i) April to June as warm months with maximum daily temperature reaching up to 50 °C, (ii) July to September as monsoon or rainy months (Kharif season), and (iii) October to March having mild weather and the night temperature might drop to 0 °C as stated in the report of UNFAO on Agro-ecological zones of Punjab, Pakistan (Ahmad et al., 2019). The Mungi area locates in the flat plains of northeast Punjab on an average elevation of 184 m.a.s.l., and also features the climate characteristics of the province. During 2008-2020, mean monthly maximum temperature of UAF touches 40 °C in warm months of the year (May and June), whereas the minimum temperature drops to 4 °C in December and January. Average annual rainfall ranges from 508 to 630 mm on the plains of Punjab (Ahmad et al., 2019). Awan et al. (2016) stated an average annual rainfall of 250 mm considering the average of 20 years (1996-2015) for the southeast of the Punjab province. For the UAF station data, a mean annual rainfall of 411 mm was calculated for the 13 years period (2008-2020). Whereas an annual rainfall of 437 and 487 mm was recorded in 2019 and 2020, respectively, because this thesis focused on the agricultural water demand of the study area in these two years. Similarly, the average of 20 years of reference evapotranspiration (ET_0) was reported with 1,678 mm for the southeast of Punjab province (Awan et al., 2016), while at the UAF station the 13 years average was about 1,503 mm. For the years 2019 and 2020, the annual ET_0 was estimated with 1,472 and 1,492 mm, respectively. Measurements of the UAF station's meteorological parameters are in the range of data published by other authors (e.g. Awan et al., 2016) and characterize the typical three seasons of the study area (Fig. 1.3). The Meteorological data of the UAF station indicated slightly higher mean annual rainfall and lower ET_0 compared to that reported in the study by Awan et al. (2016). This variation might be attributed to the UAF station's geographical placement in the northeast of Punjab as opposed to the southeast area reflected by Awan et al (2016). Also, it could be associated with variation in other climatic parameters (temperature, humidity, wind speed, etc) and a consideration of different periods of meteorological data such as 13 and 20 years in the studies.

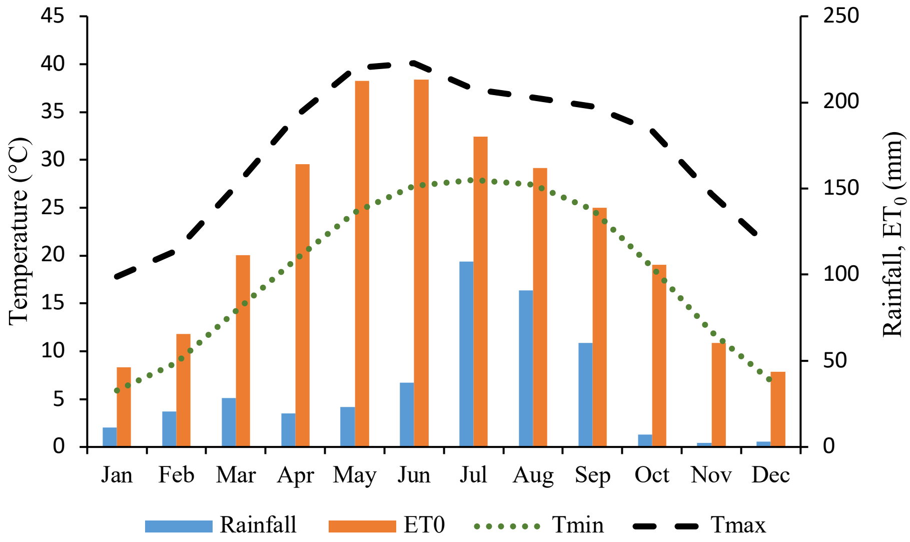


Figure 1.3: Climate of the study area (mean monthly values of rainfall, min and max air temperature, and potential evapotranspiration (ET_0) for the time period 2008-2020).

2 PERFORMANCE EVALUATION AND WATER AVAILABILITY OF CANAL IRRIGATION SCHEME IN PUNJAB PAKISTAN

This chapter has been published[1]: https://doi.org/10.3390/w14030405

2.1 Abstract

The supply of surface water by century-old infrastructure causes substantial water losses and triggers huge abstractions of groundwater, resulting in low irrigation efficiency and productivity. The study evaluated irrigation performance (application and conveyance efficiencies) and water availability (supply-demand) from the field to the Mungi Distributary canal level in Punjab, Pakistan. Between April–September 2019 and 2020, this study monitored water delivery in the canal network, soil moisture content in cotton fields, and the canal and groundwater quality. The crops' actual evapotranspiration was estimated using the AquaCrop model. The study revealed conveyance efficiencies >90% for minor distributaries, 70–89% for watercourses, and ~75% for field ditches per kilometer. Field application efficiency was >90% for drip and ~35% for flood basin, whereas for raised-bed furrow and ridge-furrow irrigation methods, it varied between 44% and 83%. The deficits of canal water supply versus demand for cotton fields ranged from 45% to 73%, whereas the Mungi Distributary canal water showed a 68.6% and 19.8% shortfall in the April–September and October–March seasons of 2018/2019, respectively. The study suggests prioritizing improvements to field water application rather than canals with better water quality; additionally, surplus water from the Mungi canal in November and December could be stored for later use.

Keywords: canal irrigation system; irrigation methods; crop demand; water losses

[1] Sajid, I.; Tischbein, B.; Borgemeister, C.; Flörke, M. Performance Evaluation and Water Availability of Canal Irrigation Scheme in Punjab Pakistan. *Water* **2022**, *14*, 405. https://doi.org/10.3390/w14030405

2.2 Introduction

This study is based on two years (2019 and 2020) of intensive fieldwork over a large command area of the Mungi Distributary canal irrigation scheme in Punjab, Pakistan. To add value to the quality of the results and represent the entire irrigation scheme, different types of irrigation canals were considered at the head, mid, and tail of the Mungi Distributary canal. Therefore, discharges in the minor distributary canals, watercourses, and field ditches were measured, while the most common irrigation methods for cotton cultivation were selected and evaluated based on the field water balance parameters using in-depth analysis of the soil moisture content in the root zone of the crop. Moreover, the estimated magnitude of pumped groundwater could be used as an entry-point for further studies on water-food-energy nexus including the issues of energy (fuel) demand and CO_2-emissions.

A number of studies have been conducted to address the irrigation water challenges in Punjab province. Some studies have used remote sensing data to estimate irrigation relevant indicators at a large scale (Ahmad et al., 2009; Ahmad et al., 2005; Ahmed et al., 2018; Finogenova et al., 2019; Iqbal and Mastorakis, 2015; Mikosch et al., 2020; Usman et al, 2020; Waqas et al., 2019), whereas other studies have examined the overall state of the canal irrigation scheme by carrying limited measurements in farmers' fields and canals in remote areas of Punjab (Ahmad et al., 2019; Bakhsh et al., 2018; Bakhsh et al, 2016; Rizwan et al., 2018; Ruigu, 2016; Shabbir et al., 2012; Shakir et al., 2011; Yongguang et al., 2018). However, the development of water supply–demand strategies necessitate tangible information on the actual field conditions. Therefore, in this study, repeated measurements from farmers' fields to the distributary canal level in distant areas of Punjab were used for an in-depth evaluation of the overall canal irrigation scheme performance.

The primary aim of this chapter was to evaluate the performance (conveyance and field application efficiencies) of the Mungi canal irrigation scheme and compare the actual canal water supply to crops' demand related to the field, farm, and the Mungi Distributary canal level. The chapter provides field-based information to inform decisions on water supply–demand strategies.

2.3 Materials and Methods

The study structure is depicted in Figure 2.1, and is based on primary and secondary data collection. Primary data were gathered during the Kharif season in 2019 and 2020, including soil moisture content, field/canal discharge measurements, and interviews of farmers on crops phenological stages, yield, and field management activities, while the secondary data comprises of land cover data of Mungi (2018–2019 cropping seasons), the daily discharge of major canals, and climatic parameters of the area. The obtained data were used as input to the AquaCrop model (Steduto et al, 2012) to estimate the crops' actual evapotranspiration, and empirical equations were applied to determine conveyance/application efficiencies and water supply–demand. Methods are described in more detail below.

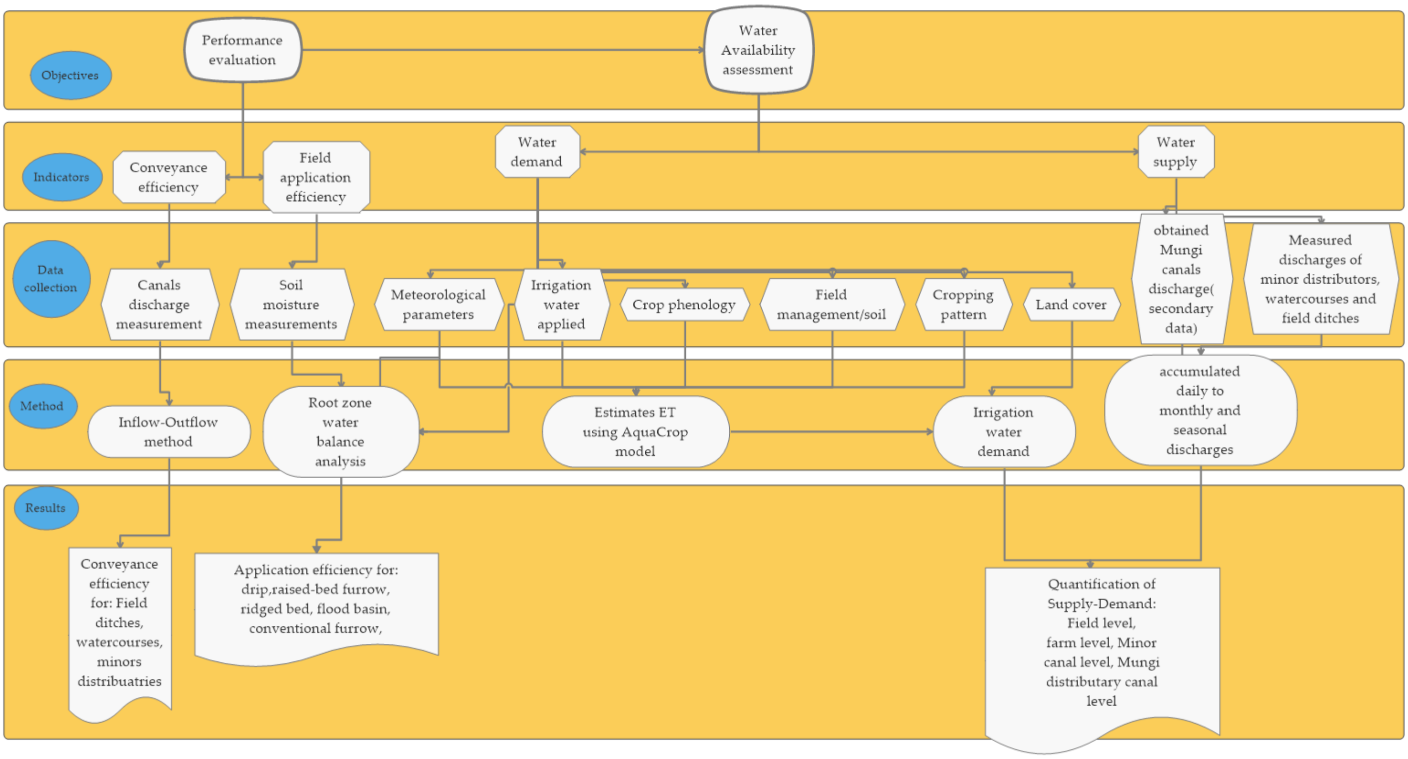


Figure 2.1: Study flow chart.

2.3.1 Description of the Study Area

The focus of this study was on cotton, which is dominating the cultivation in the Mungi area during Kharif season as a crop with high water demand. Table 2.1 presents the information on the selected fields. The fields were selected on the basis of their location along the Mungi canal (head, middle, and tail) and the application of different irrigation methods that are commonly used for cotton cultivation in Punjab. All fields are within the Mungi Distributary canal command area (CCA), except Field D (drip method), which is located at the Sumandry site next to Mungi Distributary CCA. Figure 2.2 shows the locations of fields and the canal discharge measurement points.

Table 2.1: Information regarding the fields that were selected in and near Mungi Distributary canal command area.

Field Name	Irrigation Method	Plot Size (Hectare)	Year of Observation
Field A	Raised Bed and Furrow	0.4	2019/2020
Field B	Raised Bed and Furrow	0.4 and 0.6	2019/2020
Field C	Flood basin	0.8	2019
Field D	Drip	0.3	2019
Field E	Ridge-furrow	0.6	2020
Field F	Ridge-furrow	0.48	2020
Cotton field In Farm G	Raised Bed and Furrow	0.4	2019

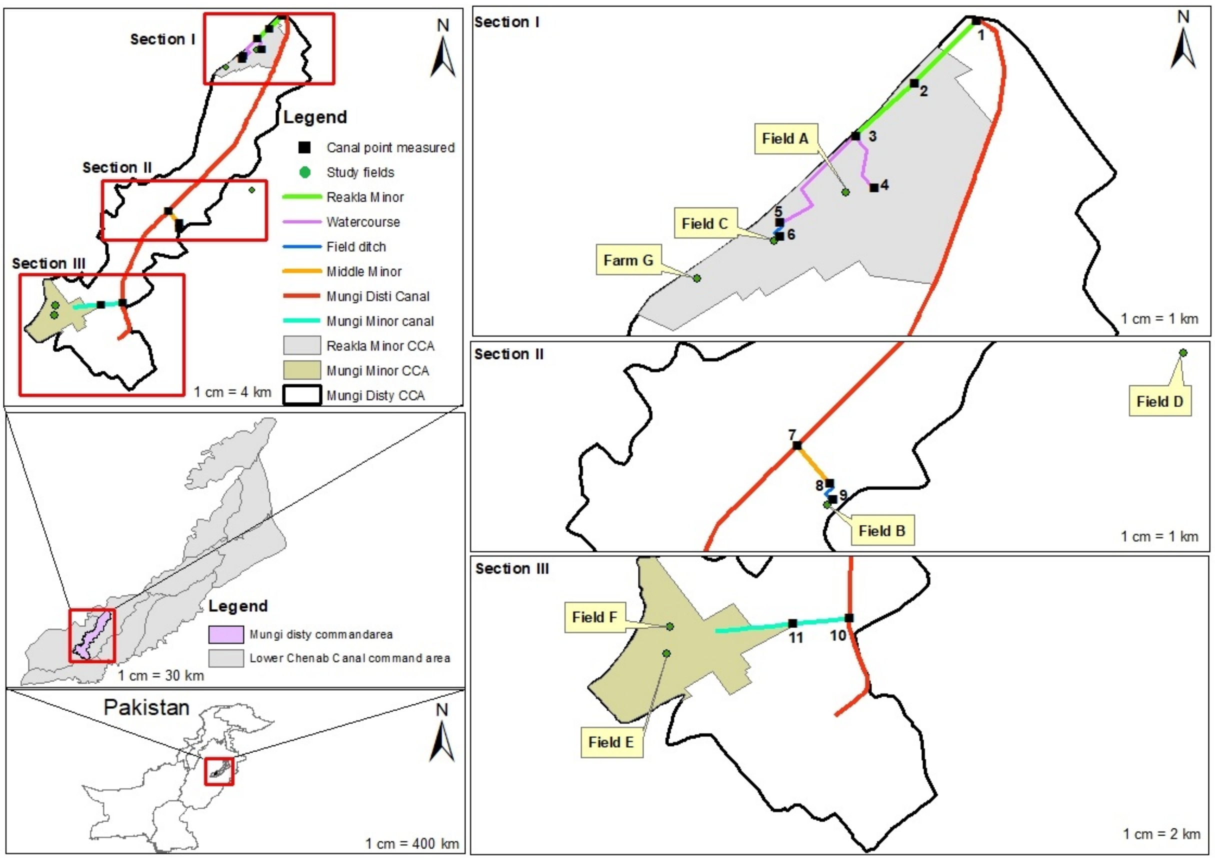


Figure 2.2: Location of the selected fields and canal measurement points in and near the Mungi Distributary canal command area.

Farm G was located at the tail of a watercourse that takes water from the Reakla minor distributary in the upper part of Mungi Distributary canal. It has 23.5 ha of land cultivating cropping patterns, as illustrated in Table 2.2. In Farm G, the monitoring of 0.4 ha (one acre) of cotton plot practicing the raised-bed and furrow method was considered for canal water supply and demand analysis.

Table 2.2: Farm G's Kharif and Rabi season cropping patterns for 2018/2019.

Season	Crops	Area of the crop (Hectare)
Kharif season	Maize	10.1
	Cotton	2.8
	Rice	5.3
	Vegetable (okra)	0.8
	Fodder (sorghum)	1.2
Annual crop	Sugarcane	3.2
Rabi season	Wheat	15.4
	Canola	2.8
	Maize	1.2
	Fodder (berseem)	0.8

2.3.2 Irrigation Scheme Performance Evaluation

Measurements for Conveyance Efficiency

The discharge in the network of canals in Mungi Distributary CCA was measured using an M1 mini current meter (SEBA, 2021), and the water losses in the canals were determined by the inflow-outflow method. During each measurement, an observation walk was conducted along each canal from the inflow to the outflow points to exclude that any outlet gets water before the outflow of the canal. Also, the discharge in the channels was measured repeatedly to minimize uncertainties. Figure 2.2 depicts the measurement points in the selected canals. A total of three important minor distributaries of the Mungi Distributary canal were considered: Reakla minor distributary (points 1–3) in the upper part, one minor distributary (points 7–8) in the middle, and Mungi minor distributary (points 10–11) in the lower section of Mungi Distributary canal. Additionally, two watercourses (points 3–4 and 3–5) and a field ditch (points 5–6) in the upper part and one field ditch (points 8–9) in the middle part of the

Mungi Distributary canal were selected for measurements representing canals of major categories in the area and lined and unlined reaches were included.

Determination of the Irrigation Application Efficiency

The application efficiency is the ratio of the amount of irrigation water that is stored in the crop's root zone to the water that is directed to the field. In this study, an in-depth analysis of the root zone water balance was considered following Equation (2.1) (Musa et al., 2016):

$$AP_{Ef} = \frac{W_A - W_B + nET}{W_i + W_r} \times 100 \qquad 2.1$$

where AP_{Ef} is the application efficiency, W_A is the depth of soil moisture content in mm (in the 1 m root depth of the crop) after an irrigation event, W_B is the depth of soil moisture content in mm (in the 1 m root depth) before an irrigation event, n is the number of days between sampling of the soil moisture before and after irrigation events, ET represents the actual evapotranspiration (mm) of the crop in the period of the two samplings, W_i is the depth of the irrigation water applied (mm), and W_r is the amount of rainfall during the two sampling periods (mm).

The application efficiency was solely estimated for cultivation methods of cotton crop considering the crop's one-meter root depth based on observation and to be comparable in all fields for soil moisture measurements. The applied water at each field by a canal, a tube well, or both was measured using a Cutthroat flume with a length of 1.2 m and width of 0.9 m. It was placed at the inlet of each field parallel to the direction of flow and leveled on all sides using a leveler. Once the flow was constant, the upstream and downstream readings were noted to determine the discharge.

Soil Moisture Measurements

The soil moisture content of each cotton field was measured periodically, yet always before and after irrigation events using an ML3 Theta Probe as a mobile soil moisture sensor (Theta probe, 2021). An auger was used to collect soil samples at intervals of 20 cm down to a depth of 100 cm at three random locations in each field: head, middle, and tail. The volumetric readings of each interval of soil samples were obtained using the soil moisture sensor in the field. Then, the samples were weighed in the field and brought to the laboratory. The samples were dried at 105 °C for 24 h in the oven to determine the gravimetric soil water content. The obtained gravimetric soil water content was multiplied by the bulk density of the referenced soil sample to attain the volumetric soil water content that was used for calibration of the soil moisture sensor's reading.

2.3.3 Water Availability Assessment

The study compared gross irrigation demand that was estimated from data that were collected in the fields, the Punjab Irrigation Department, and the output of the AquaCrop modelling versus canal water supplied.

Water Demand

Mungi Land Cover

The land cover of the Mungi Distributary CCA was obtained from the Punjab Irrigation Department and reveals the share of major crops that are cultivated in the Kharif and Rabi seasons of 2018/2019 (Figure 2.3). The dominant Kharif season crops were cotton, which covered >38% of the area and rice, whereas the dominant Rabi season crops were wheat, which was cultivated on 64% of the command area and fodder.

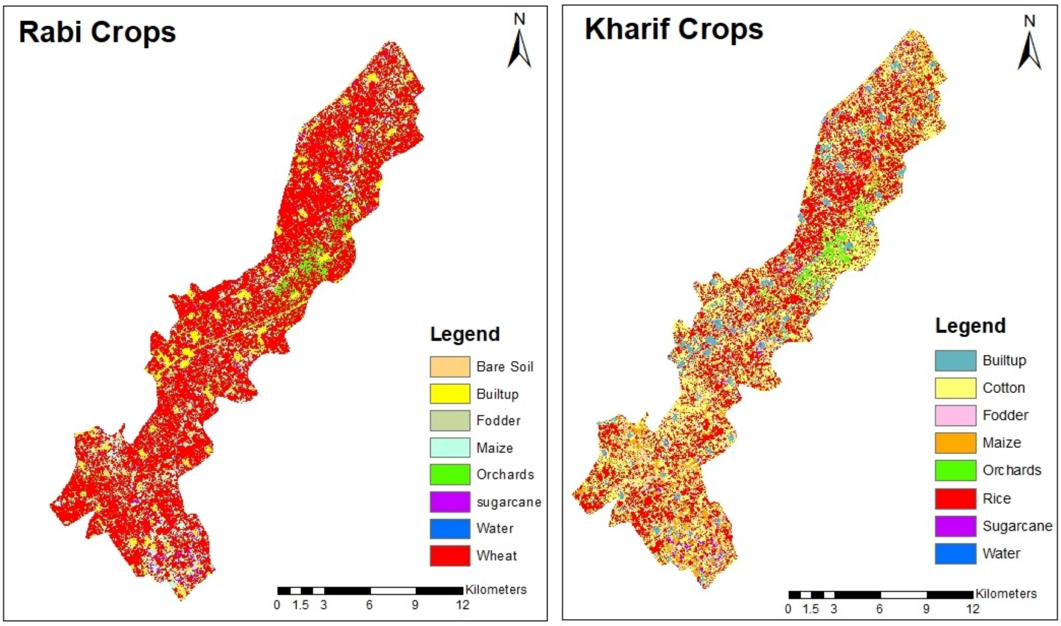


Figure 2.3: Land cover of Mungi Distributary canal command area for the Kharif and Rabi seasons of 2018/2019.

Application of AquaCrop Model

The AquaCrop (Steduto et al, 2012) as an atmosphere-soil-water-crop model can estimate the actual evapotranspiration of crops using Penman–Monteith equation. It was widely used based on its precision, simplicity, robustness and limited input data requirement, which can be attained through direct and relatively easy methods. Moreover, its realistic simulations can be assured through its holistic calculation processes impeded in the model (Foster et al., 2017). The model has been applied under various agro-ecological conditions around the world and has provided promising results in terms of estimating crop water requirement, field water balance components, and the crops' yield (Farahani et al., 2009; García-Vila et al., 2009; Hussein et al., 2011; Tan et al., 2018). Therefore, in this study it was used to determine the actual evapotranspiration of the common crops that were grown in the area that is depicted in Figure 2.3.

The Rabi crops in the Mungi area were wheat, fodder (berseem), tomato, potato, canola, and maize. While the Kharif crops that were cultivated as cotton, rice, fodder (sorghum), maize, and okra. Sugarcane and orchards (mainly citrus) were considered annual crops.

Most of the crops grown in the Mungi area were cultivated by the farmer in Farm G. Therefore, the crops information such as crop phenological stages, irrigation scheduling for each crop, and field management relevant information was obtained by interview questionnaires from the farmer of Farm G, and used as reference data representing the Mungi Distributary CCA. In addition, this information was cross-checked by other selected farmers in fields A, B, C, D, E, and F. The input data for the AquaCrop model, including climate, crop phenological stages, irrigation application, soil properties, and field management are described in more detail below.

Climatic data: parameters such as maximum and minimum air temperature, solar radiation, rainfall, relative humidity, and wind speed were collected from the meteorological station of the University of Agriculture Faisalabad (UAF) from January 2008 to December 2020.

Crop phenological stages: information on each of the crop development stages, such as the plant density, sowing and harvest time, duration of flowering, time to reach emergence, maximum canopy, flowering, senescence, crop maturity, and the estimated yield were obtained from the interview with farmers.

Irrigation water application: irrigation method, depth of water application (the discharge of canal water and tube well water of Farm G was measured), number of irrigation events, and the duration of irrigation for each crop was obtained by the farmer of Farm G. The groundwater contribution via capillary rise was negligible in the Mungi area, as groundwater is found at a depth of >10 m from the surface.

Field management: field management practices for each crop, such as weed management percentage estimation, surface runoff in field (closed-end field), and applicability of mulches were attained.

Soil: soil textures of the Mungi area are considered as loamy soils with relevant field capacity and wilting point of loamy soils as 31 and 15%, respectively (samples were taken from all cotton-selected fields in Figure 2.2 and tested in the lab that determined the soil texture in upper, middle, and lower part of Mungi as mostly loamy soil).

The Aquacrop model was parameterized for each crop grown in the Mungi using the model default referenced crop file and tuned based on the crop phenological stages and field management practices, while the obtained yield of the crops by the farmers were considered in the output of the model for the validation. The actual evapotranspiration of all crops was calculated using the Aquacrop model (considering the gross water that was applied to each field of the crop), except for citrus tree, which was designated as orchards, and its actual evapotranspiration was estimated by the CropWat model as not possible by the AquaCrop model.

Irrigation Water Requirement

The irrigation water demand from the field to the Mungi Distributary canal level was evaluated by calculating the actual evapotranspiration of crops that were cultivated in the Mungi area, crop water requirements, net, and gross irrigation water requirements.

The water requirement of each crop in the Mungi command area was calculated using Equation (2.2).

$$CWR_i = ET_i - P_{eff} \qquad 2.2$$

where CWR_i is the crop water requirement for a given crop i, ET_i is the actual evapotranspiration of crop i, and P_{eff} is the effective rainfall considering the same period of growth for crop i.

The net irrigation water requirement (NIWR) is “the quantity of water necessary for crop growth” (FAO, 1997). It depends on the effective rainfall and cropping pattern of the site, and it is described in Equation (2.3):

$$NIWR = \frac{\sum_{i=1}^{n} CWR_i S_i}{S} \qquad 2.3$$

where S_i is the cultivated area under crop i and n is the number of crops that are grown in the area. S is the total cultivable command area.

The gross irrigation water requirement (GIWR) is “the quantity of water to be applied in reality, taking into account water losses” (FAO, 1997). It is essential to have information on the irrigation efficiency of the scheme to calculate the GIWR from the NIWR (see Equation (2.4)). The total water requirement of the study area is obtained when the GIWR is multiplied by the area under cultivation.

$$GIWR = \frac{1}{E} NIWR \qquad 2.4$$

In Equation (4), E is the overall irrigation efficiency of a system that considers conveyance and application efficiencies.

Water Supply of Irrigation Canals

The daily water allocations at the head of the Mungi minor distributary and Mungi Distributary canal for the Kharif and Rabi seasons of 2018/2019 were obtained from the Punjab Irrigation Department (PID) (PID, 2021), while, for the same period, the daily allowance of Reakla minor distributary was attained from the office of PID. Furthermore, Reakla and Mungi minor distributaries’ head discharges were measured using the current meter in the field, while their command areas are provided in Figure 2.2 and the share of crops on these command areas were masked out from land cover in Figure 2.3.

Reakla is the first minor distributary that takes water from the Mungi Distributary canal (as depicted in Figure 2.2) and is lined. The area supplied by the

Reakla minor was ~919 ha of land in the Kharif season and ~827 ha of land in the Rabi season of 2018/2019. As shown in Figure 2.4.a, the gross irrigation amount that was provided as inflow to Reakla minor distributary in 2018/2019 was ~267 mm for the Kharif season, whereas it was reduced to ~210 mm for the Rabi season because of the closure of the Mungi canal for maintenance.

The Mungi minor distributary is the last large minor distributary that is located at the tail part of the Mungi Distributary canal, as shown in Figure 2.2. The head discharge of this minor distributary was 0.28 $m^3 s^{-1}$ when Mungi Distributary canal was at the full supply level. It provided canal water to ~1,341 ha of irrigated land in the Kharif season and ~1,218 ha in the Rabi season of 2018/2019. The gross irrigation water inflow at the head of Mungi minor distributary was ~231 mm in the Kharif season and ~195 mm in the Rabi season of 2018/2019 (Figure 2.4.b).

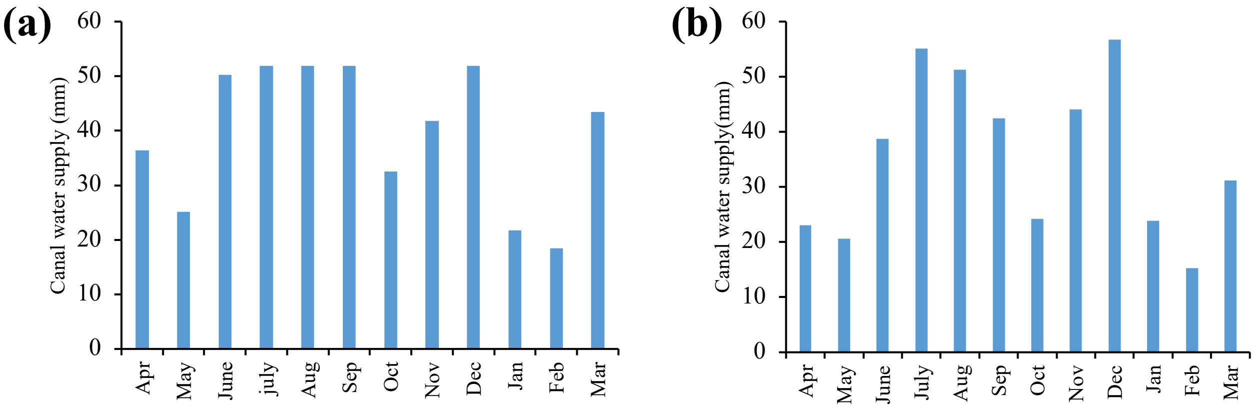


Figure 2.4: Monthly water supply of (a) the Reakla minor distributary and (b) the Mungi minor distributary in 2018/2019.

The Mungi Distributary canal conveyed water to ~21,194 ha of irrigated land in the Kharif season, whereas it reduced to ~19,416 ha in the Rabi season of 2018/2019 based on the land cover of the canal command area that is presented in Figure 2.3. The gross water inflow at the head of the Mungi Distributary canal during the Kharif season was ~259 mm, whereas during the Rabi season, it was ~227 mm in 2018/2019 (Figure 2.5). The Mungi Distributary canal is closed for more than a month (mostly mid-January to mid-February) of the year for the maintenance of canals, according to farmers and records on the Punjab Irrigation Department website.

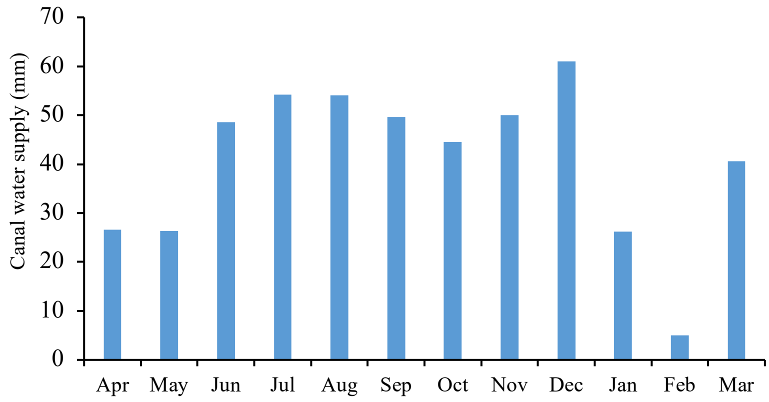


Figure 2.5: Monthly water supply of the Mungi Distributary canal 2018/2019.

2.4 Results

2.4.1 Irrigation Scheme Performance Evaluation

Conveyance Efficiency of Canals

Table 2.3 shows the results as losses per unit of wetted area per unit time and the conveyance efficiency per kilometer reach. Figure 2.2 depicts the measurement points at each canal.

Table 2.3: Evaluation conveyance efficiency in canals of typical hierarchy levels in the Mungi area.

Canal Description	Condition	Length (m)	Discharge Capacity ($L*s^{-1}$)	Percolation and Seepage Losses ($L*m^{-2}$ Wetted Area) × h	Conveyance Efficiency per Kilometer
(1–2) Reakla minor	Lined	2603	200	9.8	97.4
(10–11) Mungi minor	Lined	1728	71	7.1	95.1
(7–8) middle minor	Lined	1480	51	15.4	90.7
(3–5) Watercourse	Partially lined	2800	70	20.2	89.7
(3–4) Watercourse	unlined	1135	63	45.6	70.6
(8–9) Field ditch	unlined	620	44	36.6	74.3
(5–6) Field ditch	unlined	303	56	35.2	76.4

According to Table 2.3, the conveyance efficiency per kilometer in the lined canals of the minor distributaries was above 90% due to the prevention or at least strong reduction of seepage and percolation. However, the major component of water losses in lined canals, such as in the middle minor distributary (points 7–8 in Figure 2.2) was from water leakage through Mogas (outlets along the minor distributaries at different points to divert water to each watercourse). Most of the outlets (Mogas) are made from round concrete plates, and sometimes there are cracks and damaged parts, resulting in further leakages. Additionally, water losses that were perceived in the Mungi minor distributary (points 10–11) were due to sedimentation and vegetation growth, which is caused by poor maintenance. Also, a minor part of the losses in the canals was due to evaporation which was negligible in this study since it is not very high in relation to the seepage/percolation.

In the case of the watercourse (points 3–4) that was unlined and had a large amount of vegetation growing alongside, there was also considerable leakage of water that was observed from field outlets (Nakkas) that were located along this watercourse. Thus, the conveyance efficiency per kilometer was as low as 70%, whereas the watercourse (points 3–5) that was partially lined and had the smallest amount of leakage through outlets and had limited vegetation alongside, it had 89% efficiency per kilometer.

Most field ditches that convey canal or tube well water to irrigated fields are covered with substantial amounts of vegetation and, in general, the hydraulic capacity is lower than the capacity of the watercourses. The range of conveyance efficiency per kilometer for the two field ditches (points 8–9 and 5–6) were 74% and 76%, respectively (Table 2.3). Moreover, the information that is provided in Table 2.3 enables the estimation of the magnitude of potential water-saving by lining as a function of the wetted area and considering the time (e.g., 1 h).

Lining canals can save large amounts of water losses in the canals by preventing the percolation and seepage that would contribute to a more equitable distribution of water along the canals. Particularly, farmers that are located at the lower canal reaches can receive more water, which results in less pumping of groundwater. However, it hinders the recharge of groundwater, which currently acts as a storage facility for farmers. In the Mungi area, the farmers pump groundwater to compensate for the limited amount of surface water that they get from canals based on the Warabandi principle. The loss of water in canals that recharge groundwater is considered key in terms of this water being of better quality than the percolated water from crop fields to groundwater, which is polluted by fertilizer and plant substances. Therefore, the electrical conductivity (EC) of the canal water at fields A, B, C, E, and F was measured as ~0.2 dS m^{-1}, while groundwater EC was as 1.1, 1, 1.8, 2.09, and 2.42 dS m^{-1} for Fields C, G, B, F, and E, respectively. The groundwater EC indicated an increasing tendency from upstream to downstream of the Mungi Distributary CCA.

Field Application Efficiency

Table 2.4 provides the estimated application efficiencies based on analysis of the water balance parameters at the crop's root zone under various irrigation methods.

Table 2.4: Application efficiency of cotton cultivation methods in the Mungi area.

Field Description	Field Capacity (mm)	Date of Irrigation	Gross Water Applied(mm)	Date of Soil Sampling (Before–After) Irrigation	Application Efficiency (%)
Field A 2020	250	-	0	June 21–July 3	68.1
		July 9	50	July 9–12	74.6
		-	0	August 9–13	75
Field A 2019		-	0	June 21–26	68.7
		June 26	63	June 26 to July 3	61.6
		10 July	57	July 7–14	50.6
Field B 2020	240	June 28	38	June 28 to July 3	81.6
		July 12	29	July 12–19	76.9
		August 16	37	August 13–20	47.2
Field B 2019		June 23	42	June 19 to July 3	79.2
		July 3	35	July 3–14	84.4
		July 14	25	July 14–20	71.5
Field C 2019	210	June 23	93	June 21 to July 7	35
		July 17	102	July 17–20	39.3
Field D 2019	290	Irrigating everyday by 1 or 2 mm	12	June 25 to July 3	91.4
			5	July 3–7	93.02
			9	July 7–20	98.4
Field E 2020	270	June 30	15	June 28 to July 3	79.6
		July 12	32	July 12–16	44
Field F 2020	310	June 30	30	June 28 to July 3	83.9
		-	0	July 9–19	51.3
		August 17	34	August 9–20	77.7

The farmer of Field A cultivated cotton in both years (2019 and 2020) using raised-bed furrow. The application efficiency for Field A in 2020 for three events was estimated as 68.1%, 74.6%, and 75% (Table 2.4). Variation in the application efficiency was depending on the amount of irrigation, contribution of rainfall, climatic conditions for evapotranspiration, and the availability of moisture content in the root zone. In 2019, the technical efficiency for the same field was 68.7%, 61.1%, and 50.6% for three different measurement periods. The lowest efficiency in 2019 was 50.6% for the period of 7–14 July, which corresponded to an over-irrigation of 57 mm. Besides over-irrigation, 23 mm of rainfall was recorded during this time. Although the soil moisture was in field capacity level (261 mm) in one meter depth of root zone, the farmer still irrigated the field due to habit of seven day rotation using the allocated canal water on its turn due to lacking storage facilities to save surplus water. Similarly, the low application efficiency of 61.6% (26 June to 3 July) was caused by refilling (63 mm) the soil moisture to more than the field capacity level by over-irrigation. However, the application efficiency reading of 74.6% (on 9–12 July 2020) showed a better water application timing and amount via the farmer where most of the applied water was beneficially used by the crop.

Field B with a raised bed and furrow irrigation method showed better efficiencies in both 2019 and 2020 than Field A except the lowest irrigation efficiency for Field B, which was assessed as 47.2% in the period of 13–20 August 2020 (Table 2.4). The lowest efficiency was due to a recorded 53 mm of rainfall following an irrigation depth of 37 mm that was applied even though 262 mm of moisture content in the root zone was already available. The farmer irrigated after each seven day period, despite having moisture in the soil because of Warabandi turn to be used (no storage facility was available). The head farmer of Field B was skillful and tried to optimize the amount of irrigation water. Thus, the farmer achieved slightly better application efficiencies in 2019 of 79.2%, 84.4%, and 71.5% than in 2020 with 81.6%, 76.9% and 47.2%, respectively (Table 2.4).

The technical efficiency values for the two irrigation events in Field C, which was practicing the flood irrigation method, were 35% and 39.3%. This was due to low plant density (more space between plants) and over-irrigation of 93 and 102 mm at each event, respectively.

However, Field D, which used drip irrigation, showed the highest efficiency of over 90%. The farmer of Field D was very experienced and regularly optimized the irrigation quantity and timing by considering the soil properties of the field and used soil moisture sensor to consider availability of the moisture. Moreover, the farmer constructed a pond in the farm for frequent irrigating events by the drip and it enabled to store the surplus water of the canal when it was available in excess. Therefore, due to an increase in temperature during the months of May and June, the farmer irrigated the cotton field two times a day (in the morning and evening), applying 1 mm per event. Thus, Field D achieved the highest efficiency. Moreover, the farmer flooded the drip field due to availability of canal water in two events (20 days before sowing as pre-irrigation and on June 20; each event involved irrigation with 132 mm).

Similarly, Fields E and F cultivated cotton on the basis of a ridge-furrow method, and their application efficiency ranged from 44% to 83.9%. They showed similar efficiency in terms of water-saving compared to raised-bed irrigation method. Farmers downstream of the Mungi Distributary canal applied the ridged bed method to account for the limited availability of canal water and to consume less groundwater.

The application efficiencies in June were higher in irrigated fields when compared with those in July or August (Table 2.4). This finding was attributed to fulfilling two-thirds of the cotton water requirement through monsoon rainfall in July and August, and farmers did not appropriately utilize the obtained moisture content from rainfall, whereas in June, almost all cotton demand was achieved through irrigation water.

All the selected farmers, except the farmer of Field D, were not using soil moisture sensors or other tools to realize the availability of moisture content of the fields to refill the soil to field capacity and keep the moisture within the allowable depletion range. Therefore, they irrigated the fields based on observation of soil or plants, weather condition, or just simply allocating more water for cotton based on irrigation habit of seven day rotation, according to the farmers' descriptions.

2.4.2 Water Availability (Supply-Demand) Analysis

The obtained conveyance efficiency for the network of canals in the Mungi irrigation scheme (Table 2.3) was estimated to be 75%, assuming higher numbers of unlined watercourses and field ditches in the Mungi command area that their conveyance efficiencies ranged around 75% in Table 2.3. The technical application efficiency for the Mungi irrigation scheme was estimated as being 64% based on the mean of the cotton field efficiencies in Table 2.4, except for Field D (drip), as it is not located in the Mungi

CCA and drip is installed in a very small share of the area. Thus, the overall irrigation efficiency of the Mungi Distributary irrigation scheme was estimated as 48% (Equation. (2.5)). This coincides with a study that considered the overall irrigation efficiency 45% for Lower Chenab Canal command area that includes the Mungi area in Punjab (Waqas et al., 2019). Similarly, the overall irrigation efficiency of 42% was used for Kasur minor distributary canal command area in Punjab (Ahmad et al., 2019).

$$\text{Irrigation efficiency} = \text{field application efficiency} \times \text{conveyance efficiency} = 0.75 \times 0.64 = 0.48 \quad (2.5)$$

Field Level Supply and Demand

The canal water allocation of the cotton fields based on the Warabandi principle in Table 2.5 was measured at the inlet of the field when the Mungi Distributary canal was in full supply level and 19 weeks was considered as the growth period for cotton.

Table 2.5: Canal water supply and demand of cotton fields in the Mungi Distributary canal command area.

Field Name	Weekly Canal Water Allowance (mm)	Canal Water Applied Over Cotton Growth Period (mm)	Groundwater Applied Over Cotton Growth Period (mm)	Gross Water Applied Over Cotton Growth Period (mm)	Canal Water Percentage deficit (−)
Field A	17	324.5	756.5	1081	−69.98
Field B	10	187.6	486.4	674	−72.12
Field C	13.8	263.7	216.3	480	−45.07
Cotton field in Farm G	9	172.4	477.6	650	−73.48

The factors influencing the Warabandi canal water allowance depend on the location of the farmers' fields along the watercourse, conveyance efficiency of the minor distributors or watercourses, uptake of the water by referenced minor distributaries from the Mungi Distributary canal, and the allowance of head discharge to the Mungi Distributary canal. Hence, Farm G, which was located at the tail of the watercourse, received the least amount of canal water (9 mm) per seven day rotation, whereas Field C, which was in the middle of the same watercourse, received 13.8 mm of water per cycle. This is highlighted as a drawback of the Warabandi principle, which does not consider conveyance losses for the allocation of water to tail farmers, which results in the inequitable distribution of water between upstream and downstream farmers (Bandaragoda et al., 1995; Jurriens et al., 1996).

Additionally, there is a clear dependency on groundwater withdrawals in Punjab between upstream and downstream farmers (Kazmi et al., 2012). Downstream farmers, such as in the case of Field E and F (the study could not measure their canal water discharge due to irregular and unreliable flow of canal and they were mainly irrigating by tube well), were much more dependent on groundwater than upstream farmers. However, the middle minor distributary (points 7–8 in Figure 2.2) canal, which provides water to Field B received less canal water because of the construction of a bridge over the Mungi Distributary canal and interfered with the minor intake that resulted in a 10 mm canal water allowance per turn.

The Warabandi canal water deficit for cotton fields ranged from −45% to −73% comparing to the gross water that was applied (conjunctive use of canal and groundwater) over 19 weeks (cotton growth period) for the fields (Table 2.5).

It is evident from Figure 2.6 that despite having different locations in Mungi Distributary CCA, the farmers of fields A, B, and Farm G applied more than 60% groundwater using fuel energy over the crop growth period besides canal water contribution as ~25% and rainfall. However, the farmer of Field C, irrigated the field with limited gross water and the canal water input was ~45% of the total cotton requirement, as the farmer could not afford the fuel to extract groundwater for cotton, according to information provided by the farmer.

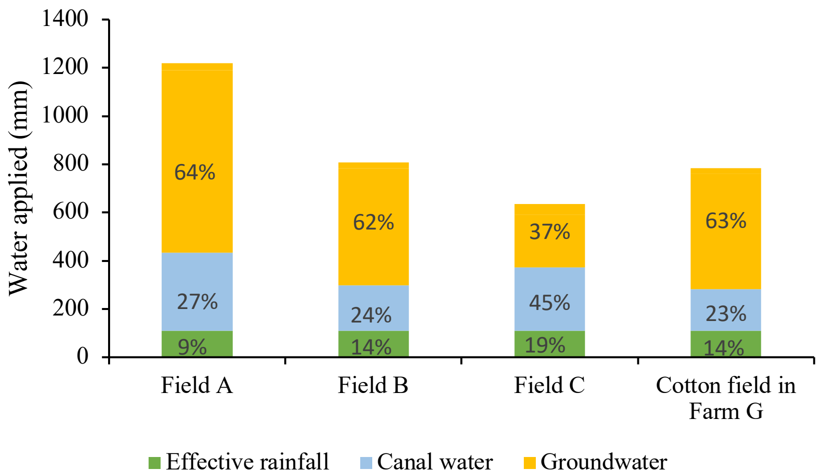


Figure 2.6: Water supply contribution to the cotton fields in the Mungi area.

Farm Level Supply and Demand

In Farm G, canal water deficit for the Kharif season reached 50.2%, whereas Rabi crops were lower-water consumers, which resulted in a 17.1% shortage in canal water in 2018/2019 (Figure 2.7). The deficit part in both seasons was fulfilled by groundwater contribution.

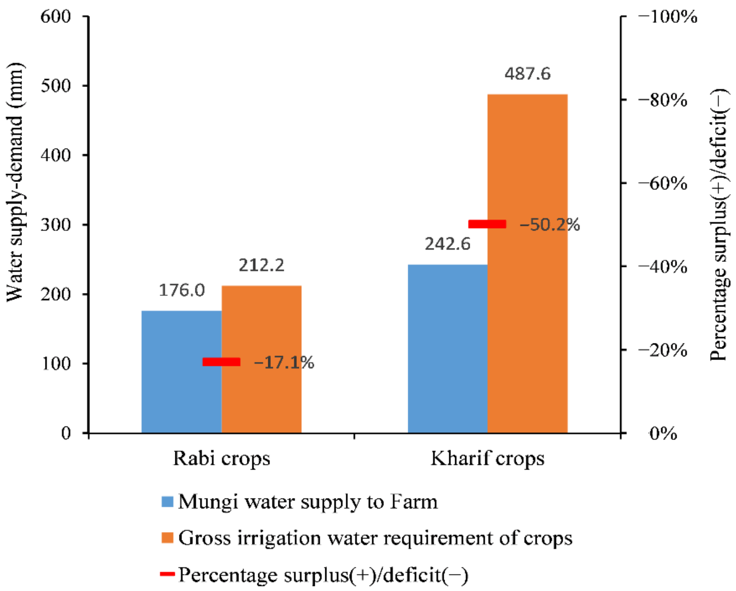


Figure 2.7: Farm G canal water supply and demand comparison.

Supply and demand of the Reakla and Mungi minor distributaries

Figure 2.8 presents the demand and supply of the Reakla and the Mungi minor distributaries. Considering a 48% overall irrigation efficiency of the Mungi scheme, the Reakla canal water in the Kharif season faced a 64% deficit to fulfill the requirement of crops in the Reakla command area, whereas for the Rabi crops, because of the climatic conditions and crops that consume less water, it was marked with a shortage of 25.1%.

In case of the Mungi minor distributary at tail of the Mungi Distributary canal, the Kharif season corresponds to a huge demand for water due to cultivated water-intensive crops, such as cotton, rice, and sugarcane. As shown in Figure 2.8, the Kharif season is marked as a 69.7% deficit, whereas the Rabi season accounted for a 29.3% shortfall in terms of fulfilling a demand by canal water.

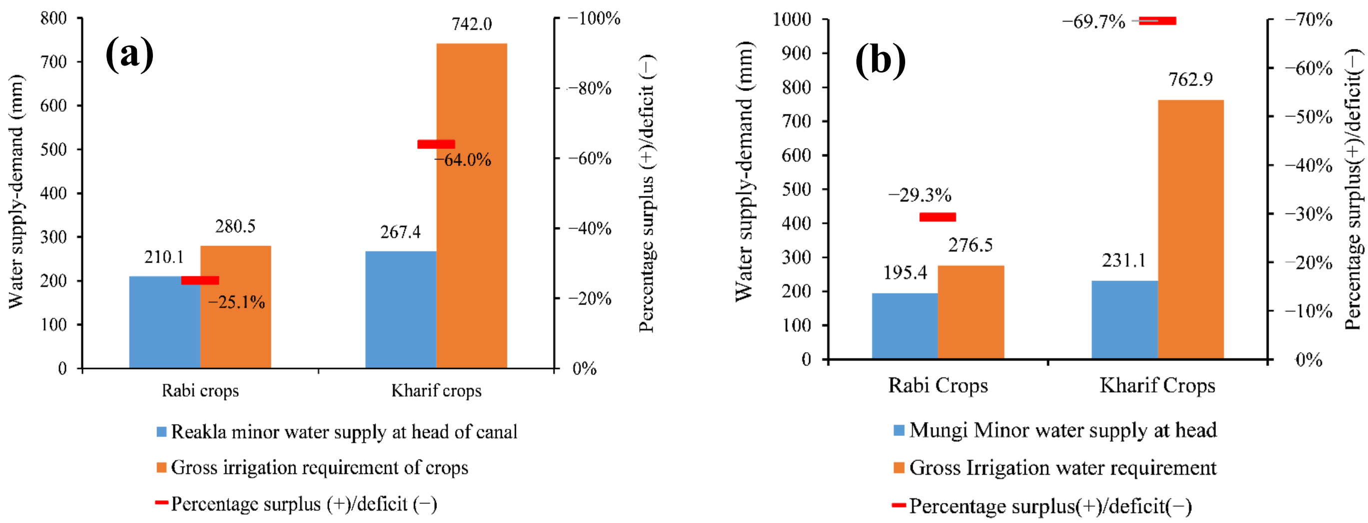


Figure 2.8: Water demand and supply of (a) the Reakla minor distributary and (b) Mungi minor distributary.

The slight difference of canal water deficit in the Kharif and Rabi season at both Reakla and Mungi minor distributaries was driven from a variation in the share of water-intensive crops in these command areas such as more lands that were under cultivation of cotton, rice, and orchards in the Mungi minor command area.

Mungi Distributary Canal Supply and Demand

The estimated actual evapotranspiration (ET) and monthly gross irrigation water requirements of the crops that were cultivated in the Mungi area are presented in Table 2.6. The estimated actual ET values in the Table 2.6 for each crop are in range of ET that was predicted in a study by UNFAO on agro-ecological zones of Punjab for the common crops that were cultivated in the Punjab province (Ahmad. et al, 2019).

Table 2.6: Monthly water supply of the Mungi Distributary Canal and the gross irrigation water requirement of the Mungi canal irrigation scheme.

	Rabi Crops						Kharif Crops					Annual Crop			Monthly
	Wheat	Fodder (Berseem)	Tomato	Potato	Canola	Maize	Cotton	Rice	Fodder (Surghum)	Maize	Okra	Sugarcane	Orchard as Citrus	Monthly [1] GIWR (mm)	Mungi Canal Water Supply (mm)
	Actual ET (mm)														
April	15.2	63.7	138.6			109.7	25.3		81.7		54.3	159.7	51.2	61.7	26.6
May			31				88.4	120	190		128.4	191.2	119.7	143.3	26.3
June							129.3	360	169	3.6	180.4	175.4	159.9	224.7	48.6
July							188.6	240		128.2	174.3	171.8	182.5	89.8	54.2
August							174.9	180		164.7	36.6	161.2	173.1	208.0	54.1
September							127.2	60		138.1		128.1	96.5	98.0	49.6
October				13.4	25.9		63.3			31.4		89.9	58.6	47.5	44.6
November	13.2	17.3		37.3	14.8		2					48.2	23.8	21.2	50.1
December	26.7	20.4		46.2	10.9							13.2	4.4	31.7	61.0
January	47.4	13.6	8.6	47.1	11.6	16						9.4	7.6	51.4	26.2
February	61.1	25.4	57.4		24.8	53.7						27.5	31.3	41.8	5.0
March	92.4	100.6	111.4		16	129.6			14.3			89.4	44.4	90.1	40.6
Sowing date	22 Nov	19 Nov	24 Jan	15 Oct	6 Oct	30 Jun	28 Apr	27 May	29 Mar	8 Jan	8 Apr	15 Feb	1 Apr		
Harvest date	16 Apr	24 Jan	13 May	30 Jan	14 Mar	17 Oct	31 Oct	10 Oct	30 Jun	28 Apr	21 Aug	14 Feb	30 Mar		

[1] GIWR: gross irrigation water requirement.

The Mungi Distributary canal water supply in the Kharif season showed a 68.6% deficit, whereas in the Rabi season, there was a shortage of 19.8% because of the cultivation of low water-consuming crops, which were mainly wheat in 2018/2019 (Figure 2.9).

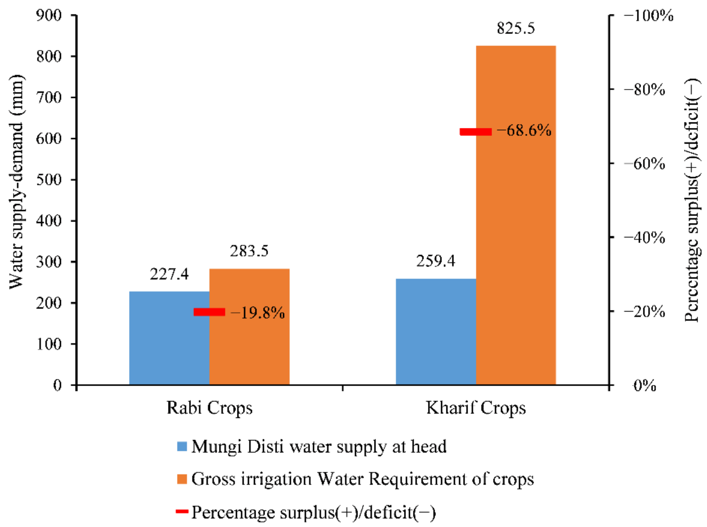


Figure 2.9: Mungi Distributary canal water supply and demand.

Figure 2.10 illustrates the monthly canal water supply and demand in the cropping season of 2018/2019 at the Mungi Distributary canal level. June was the most water-stressed month where no effective rainfall that contributed to match the demand for crops. This demand was mainly satisfied by pumping groundwater using fuel energy. However, in July, the monsoon season started with 131.6 mm of effective rainfall, which drastically lowered the net and gross irrigation demand. In August 2018, no effective rainfall was recorded, but 15 mm of effective rainfall contributed to plant growth in September. Additionally, in September, most crops required less water due to reaching maturity. Thus, the gross demand increased in August and lowered again in September.

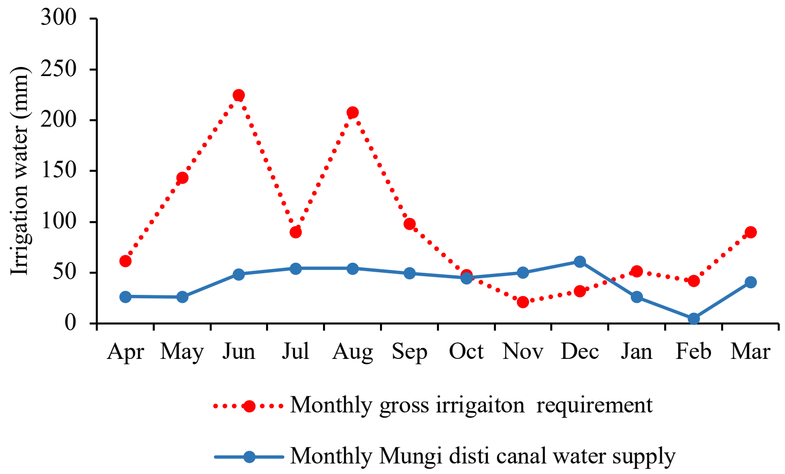


Figure 2.10: Monthly water supply of Mungi Distributary canal and gross irrigation water requirement.

Moreover, major crops of the Kharif season, such as cotton, rice, maize, okra, and fodder, were harvested in October and did not need water for irrigation, so the demand side dropped to the level of supply line in October. Furthermore, in the transition point that starts from October, the canal water supply of the Mungi canal remained above demand until the end of December. In these months, there was a shift from the Kharif to the Rabi season because of a short pause to prepare land for Rabi crops and climatic conditions that correspond to low potential evapotranspiration.

For this reason, most Rabi crops were sowed either in November or December, and after December, Rabi crops started to consume water, so demand exceeded supply again from January onwards. Thus, there is a potential option for canal water-saving at farmers' farms in a storage pond in October, November, and December so that the canal water can be used later on in January or February. The storage of water in ponds at farms of the farmers can enable some flexibility within the frame of the rigid Warabandi system. This would provide support to (i) better match the time –depending crop water demand, (ii) enhance utilizing rainfall, and (iii) lower the pressure on groundwater use in terms of conservation of this resource, save energy for fuel-based pumping, as well as reduce CO_2-emission.

2.5 Discussion and conclusions

The application efficiency that is improved by advancing surface irrigation techniques going from flood basin (~35% technical efficiency) towards raised bed-furrow, and ridge-bed furrow (the efficiency varied from 44% to 83%), while substituting irrigation technology could further boost the efficiency, for example, in case of drip method by over 90%. It was revealed that cultivating cotton under bed planting in Punjab could save up to 38% more irrigation water than conventional irrigation methods (Bakhsh et al, 2016), while another study in the Lower Chenab CCA in Punjab showed that the drip method saved 60–80% of applied water in comparison to the bed planting of maize fields (Rizwan et al., 2018). Therefore, the highly inadequate canal water supply under the Warabandi principle and the high cost of groundwater in Mungi area affected farmers' decisions on their choice of crop cultivation (Razzaq et al., 2019).

Losses in the canal network and during field water application were recharging the aquifer, which provides a supplementary storage facility for farmers by pumping groundwater using fuel energy to fulfill their crop demands under the Warabandi principle. On the other side, seepage and percolation drive matter flow, potentially polluting the aquifer. Thus, rising conveyance efficiency is interlinked with groundwater quantity and quality and the amount of CO_2 emissions that are caused by pumping. In general, canal water is of better quality than water that is percolating through the root zone of irrigated fields (loaded with fertilizers and plant protective agents) in Punjab (Murray-Rust and Vander Velde, 1994). Therefore, high priority should be given to improvements of field water application as these will lower potential groundwater pollution.

The major sources of recharging groundwater in Punjab are rainfall, field percolation, and water losses in irrigation canals (Usman et al., 2018). A study found that the adequacy and reliability deliveries of conjunctive use of surface and groundwater decrease towards the end of canals due to the combined effect of erratic supply of canal water and salinization of groundwater in the Rechna Doab irrigation scheme in Punjab (Ahmad et al., 2009). Deteriorating trends in groundwater quality have been observed in Punjab and more groundwater is expected to be used in the near and mid future that can enhance future sustainability challenges in terms of water quantity as well as quality, and severely impacting drinking water provision (Kirby et al., 2017; Shakir et al., 2011).

Focusing on technical interventions, this study considers two main entry points for optimizing irrigation application efficiency. First, irrigation scheduling that is considered in this study, which employs proper timing and efficient use of irrigation water based on crop production in the Mungi area. The moisture that is obtained from rainfall in the soil could be utilized by adapting irrigation events accordingly, or the soil moisture could be maintained within the optimal depletion zone by refilling it in each irrigation event slightly under the field capacity to reduce percolation and evaporation amounts. The soil moisture sensors as irrigation tools could be used to monitor the moisture contents in the soil and support irrigation scheduling. The second option involves advanced handling of the irrigation water application processes in the crops' root zone that could potentially reduce non-beneficial uses of water and have been investigated and addressed by several studies. Numerical simulations that are based on Richards's equation were used in a study to minimize the water percolation below the root level (Berardi et al., 2022), while another research applied a mathematical model for an optimal control zone of irrigation water optimization to preserve crop and prevent water non-beneficial usage (Lopes et al., 2016). Similarly, a study deliberated the analysis of irrigation water dynamics and soil moisture in crops' root zones considering a zone model predictive control (MPC) which keeps soil moisture at the optimal level with less water consumption (Mao et al., 2018).

The study also indicated a large gap in the Mungi Distributary canal water supply and demand of crops within its command area. The analysis revealed a canal water deficit of 68.6% in the Kharif season and 19.8% in the Rabi season of 2018/2019. In another study in Punjab, by using remote sensing data and considering an irrigation efficiency of 45%, the canal water deficit was estimated for the Mungi Distributary canal as 36% and 32% for the Rabi seasons of 2009/2010 and 2010/2011, respectively, which is slightly higher than the current study (Waqas et al., 2019). This difference could be due to the changes in the cropping pattern from year to year or could be also due to different meteorological conditions such as reference evapotranspiration (ET_0) that was estimated slightly lower as 421 mm in the Rabi season of 2018/2019 compared to that as 438 and 458 mm for 2009/10 and 2010/2011, respectively, or variation of inflow to the Mungi Distributary canal and also depends on the accuracy of the remote sensing data. Furthermore, the supply-demand of the Mungi Distributary canal was assessed during 2011–2012 using SWAT and CROPWAT models (Ahmed et al., 2018). The study showed an over 50% deficit of Mungi canal water in that year considering a 45% overall irrigation efficiency, whereas the most water-stressed months were highlighted as June, July, and August; although the study did not consider effective rainfall for the months of July and August.

Despite the fact that the Mungi Distributary canal is undersupplied in both the Kharif and Rabi seasons, there are periods with water availability that exceed the demand in the months of November and December. The potential of this surplus water is a source to be beneficially used in deficit periods and could be mobilized by constructing decentral storage facilities in the farmers' farms in the Mungi area. Comparable results were obtained by a study that found the supply of the Mungi Distributary canal exceeded the demand of crops during October, November, and December, but the demand increased from January in the Rabi seasons of both 2009/2010 and 2010/2011 (Waqas et al., 2019). Furthermore, the groundwater extraction significantly increased at the tail of Mungi Distributary, especially in peak water-stressed months (Yongguang et al., 2018b). This phenomenon could be confirmed in this study by observing zero discharge at the tail of the Mungi Distributary canal while crops were cultivated there, and, due to the unreliable supply of canal water, the farmers of Field E and F were more dependent on groundwater abstraction.

The study provided detailed information on the status of irrigation conditions in Mungi Distributary CCA that could be used as potential groundwork for policymakers to derive decisions that are based on actual field information for the development of water supply-demand strategies. Moreover, the quantification of groundwater that is extracted by farmers using fuel energy could further benefit scientific works on approaches to the water–food–energy nexus to reduce CO_2 emissions and conserve groundwater in terms of quantity and quality.

The behavior of over-irrigation can be changed or even avoided by training of farmers on the management of soil moisture content in crops' root zones and informing them by relevant institutions or by conducting joint field experiments on their plots together with scientists and extension service institutions (Chapter 5 discusses in detail the feasibility of adopting the interventions). These measures on improving knowledge and skills are especially promising in terms of the practical impact, when going hand-in-hand with creating incentives to implement the improvements; the willingness of farmers to avoid over-irrigation can be enhanced by establishing on-farm water storage facilities (e.g., small ponds) which enable them to store surplus water (instead of wasting by over-irrigation) for use at the farm in periods with insufficient water supply in the canal network (infrastructural re-design for creating an 'enabling environment' to avoid over-irrigation).

3 COTTON IRRIGATION SCHEDULING ASSESSED UNDER VARIOUS CULTIVATION METHODS IN CONTEXT OF WARABANDI PRINCIPLE

3.1 Abstract

This study assessed cotton irrigation scheduling in the context of Warabandi under various cultivation methods. Six cotton fields were randomly selected at the Mungi Distributary canal command area in Punjab and each field's one-cropping season activities were monitored during 2019 and 2020. The AquaCrop model was parameterized and validated separately for each field. The results revealed that the farmer using drip techniques attained the highest gross water productivity (GWP) of lint seed as 1.13 $\mathrm{kg\,m^{-3}}$ using gross water input of 396 mm over cotton growth period. In contrast, the raised-bed furrow cultivator obtained the lowest GWP of 0.23 by 1,086 mm applied water over the cultivation season, resulting in predicted non-productive water use as percolation and actual evaporation of 632 and 239 mm, respectively. While the GWP varied between 0.25 and 0.39 $\mathrm{kg\,m^{-3}}$ for basin, another field of raised-bed furrow and two ridge-furrow irrigation methods. Under the framing conditions of Warabandi, the practice of the farmer using the drip method was considered as an entry point for more flexible and demand-orientated irrigation at the farm level and the most promising approach to achieve higher water productivity by integrating interventions into a package for on-farm water management. It involved the (i) provision of demand-oriented irrigation schedules, (ii) advancing irrigation schedules by sensor-based soil moisture monitoring, which can unfold its potential by (iii) combining the storage option of Warabandi allowance during the potential surplus time in a pond to create enabling environment for demand-based irrigation. In addition, using the drip method could considerably reduce the undersupply situation in Warabandi guided irrigation schemes. The study highlights the potential on-farm water optimization options suitable for cotton farming in this water-scarce area.

Keywords: cotton irrigation planning; water use efficiency; on-farm water management; AquaCrop model

3.2 Introduction

In this chapter, cotton farming is typically studied in the Mungi area with consideration given to the conjunctive use of groundwater and canal water under the Warabandi principle (i.e., limited supply and a fixed 7-day rotation). The selection of the fields in the current work was based on three factors that were used to determine the effects on cotton water productivity: (i) various irrigation methods for cotton that covered (to the best of our knowledge) all cultivation methods practiced in the study area, i.e., flood basin, drip, ridge-bed furrow, and raised-bed furrow; (ii) location distribution of fields along the Mungi Distributary canal command area (due to variation in Warabandi water allowance caused by conveyance losses in canals); and (iii) farm size holders (i.e., large and small farmers that indicated their farming experience and water optimization techniques). The study assumed that large-scale water allocation in the future will remain under the Warabandi principle. Therefore, the within-farm water allocation (bottom-up approach) was considered as a promising entry-point for introducing more flexible irrigation (needed to cope with water scarcity and variability of the environment). In this context, the AquaCrop (Steduto et al., 2009) as a field-based model supports determining water balance components in the crop's root zone at a daily temporal resolution for advanced on-farm water management.

The current study aimed to assess cotton irrigation planning under different cultivation methods practiced in the context of Warabandi features (limited canal water distributed over a 7-day fixed rotation combined with groundwater) in the Mungi area of Punjab. The results highlight the potential on-farm water optimization options suitable for cotton farming in this water-scarce area.

3.3 Materials and methods

3.3.1 Description of study area

All selected fields fell under the canal command area of the Mungi except for Field D, which was situated near to the Mungi area at the Sumandry site. Figure 3.1 demonstrates the placements of the selected fields; Table 3.1 provides further information on the fields and figure 3.2 depicts geometry of the selected fields.

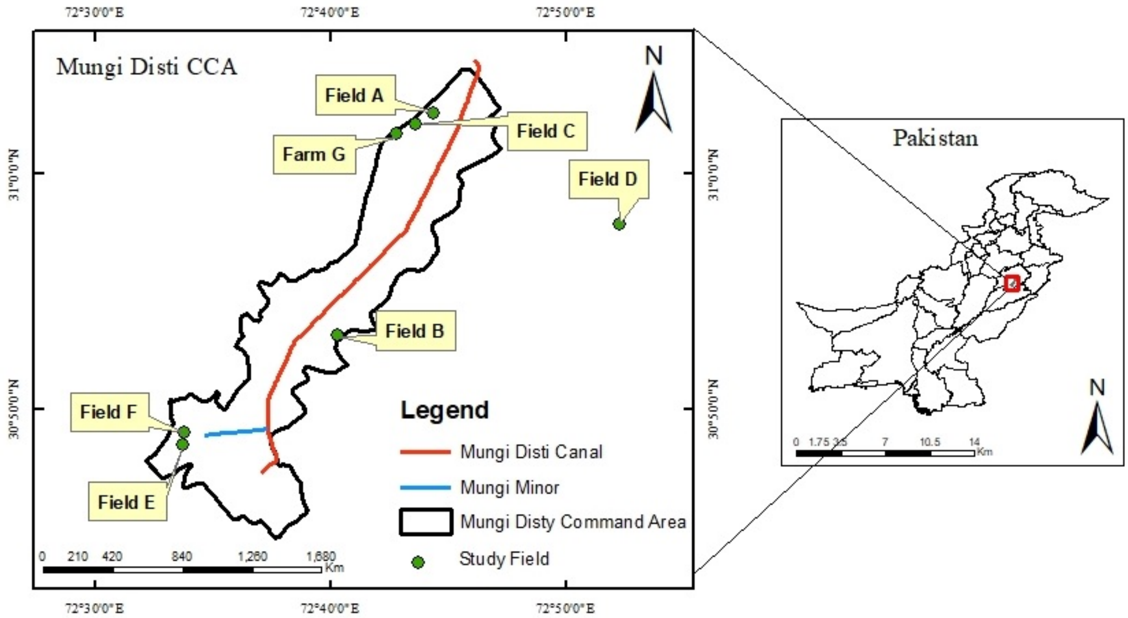


Figure 3.1: Geographical location of the study area.

Table 3.1: Information on the fields chosen for monitoring.

Field name	Cultivation method	Field size (Ha)	Year of monitoring	Sowing time of cotton	Land holding ownership
Field A	Raised bed and furrow	0.40	2019	1^{st} May	Small
Field B	Raised bed and furrow	0.40	2019	28^{th} April	Large
Field C	Flood basin	0.81	2019	1^{st} May	Small
Field D	Drip	0.30	2019	28^{th} March	Large
Field E	Ridged bed and furrow	0.61	2020	25^{th} April	Large
Field F	Ridged bed and furrow	0.48	2020	15^{th} March	Small

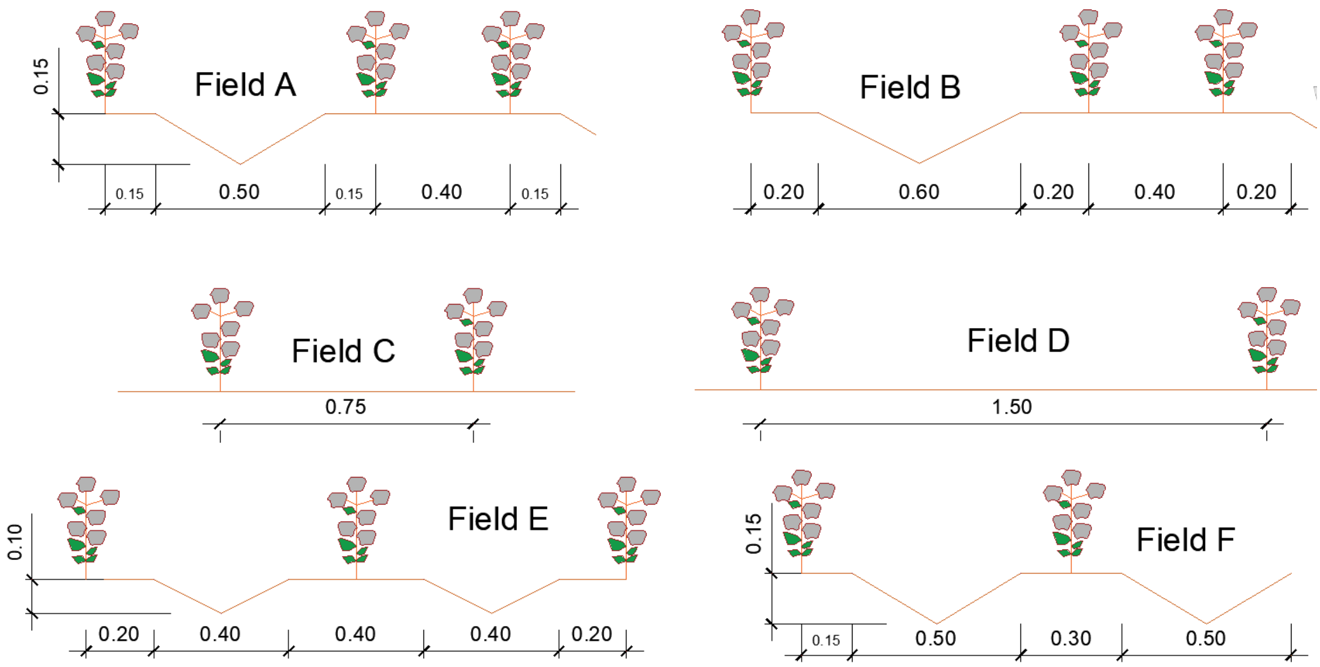


Figure 3.2: Geometry of the selected cultivation methods (units are in meter).

The farmers of selected fields sowed the cotton crop along a row and plant to plant distance in the rows were 0.30, 0.40 0.45, 0.30, 0.50, and 0.30 m for fields A, B, C, D, E, and F, respectively. The drip laterals were placed 5 cm below the topsoil, with a 1.5 m spacing between them and a 0.30 m distance between emitters.

3.3.2 AquaCrop Model

This study used the AquaCrop model to assess cotton irrigation under current practices by simulating field water balance components and estimating yield. Therefore, relevant field data were collected during the Kharif seasons of 2019 and 2020 and used to parameterize the model. The obtained data covered periodic soil moisture measurements, depth of applied irrigation water to selected fields, monitoring crop phenological stages, soil characteristics, harvest data such as raw yield, and field management activities of the farmers. The detailed information on data collection and usage of the model are provided in the following sub-sections. Moreover, at end of the cropping season, the perception of each farmer was obtained in a semi-structured interview on the field activities and estimated yield.

Climate data

Climatic data including rainfall, solar radiation, wind speed, maximum and minimum air temperature and relative humidity were obtained from the meteorological station of University of Agriculture Faisalabad (UAF) for the period (2008-2020).

Measurement of soil water content

The soil samples (before and after irrigation events) were collected during the Kharif season of 2019 and 2020 by an auger randomly from three locations (head, middle and tail) at each field, considering an interval of 20 cm up to 100 cm depth. Each sample was weighted at the field site, brought to the lab, dried out in an oven under 105 °C for 24 hours, and reweighted to find gravimetric soil water content (SWC).

In addition, soil samples from three random locations (head, middle and tail) of each field with an interval of 30 cm up to 100 cm depth were collected and tested in a private lab for soil characteristics such as soil texture, bulk density, field capacity, permanent wilting point, and electrical conductivity. The soil properties for all fields are depicted in Table 3.2.

Table 3.2: Soil characteristics of the fields.

Field	Soil depth (cm)	Texture	Sand %	Silt %	Clay %	Bulk density (gr cm^{-3})	Wilting point (% volume)	Field capacity (%volume)	Electrical conductivity (dsm^{-1})
Field A	0–30	Loam	40.1	42.7	17.2	1.6	10.9	23.5	1.9
	30–60		40.1	45.0	14.9	1.6	9.0	21.5	1.8
	60–100		40.1	33.6	26.3	1.6	16.1	28.3	1.9
Field B	0–30	Sandy Clay Loam	51.5	19.9	28.6	1.5	17.9	28.7	1.4
	30–60		51.5	26.8	21.7	1.5	14.2	24.5	1.3
	60–100		51.0	27.0	22.0	1.6	13.6	24.0	1.3
Field C	0–30	Loam	37.8	42.7	19.4	1.6	12.7	25.2	1.5
	30–60		43.4	42.7	14.9	1.6	9.0	22.3	1.2
	60–100		37.8	45.0	17.2	1.6	11.2	24.7	1.2
Field D	0–30	Silt Loam	28.7	63.3	8.0	1.6	14.5	26.7	1.5
	30–60	Clay Loam	28.7	40.4	30.9	1.5	18.4	32.4	1.4

	60–100	Loam	31.0	42.7	26.3	1.6	15.8	29.6	1.3
Field E	0–30	Loam	19.0	45.0	36.0	1.3	12.0	28.0	1.0
	30–60		29.0	37.5	33.5	1.4	10.0	26.0	1.8
	60–100		21.5	42.5	36.0	1.4	13.0	27.0	1.6
Field F	0–30	Loam	29.0	35.0	36.0	1.5	15.0	30.0	1.4
	30–60		24.0	37.5	38.5	1.3	17.0	33.0	1.2
	60–100		39.0	25.0	36.0	1.5	13.0	29.0	1.6

Measurement of water applied to fields

In the Mungi area, surface water distribution to farmers is based on Warabandi principle via canals. For 0.4 ha of land, approximately 20 minutes of canal water was allocated per week to each farmer. While the amount of canal water varied due to conveyance losses in canals and water availability at the head of the main distributary canal. Farmers accumulated the allowance of Warabandi of several plots (acres of land) to irrigate 0.4 hectare of cotton because they considered the current amount as insufficient to fulfill the crop demand. Therefore, farmers irrigated the cotton plot based on their understanding of the irrigation requirement and filled the furrow lines using conjunctive water use strategy either (i) by applying canal water or (ii) solely by pumping groundwater (depending on the irrigation planning of the farmers, because the rigid Warabandi rotation was not corresponding to the irrigation timing required for cotton) and (iii) mixed canal water with groundwater simultaneously at the outlet of the field to irrigate the crop.

Cutthroat flume (length of 1.2 m and width of 0.9 m) was used to measure the applied water (either by canal water, groundwater or mixed) at each field’s outlet. The flume was situated at the bed of the outlet for each field in the direction of flow and leveled by all edges. When the flow remained constant in the flume, the readings upstream and downstream of the flume were taken and timing was noted to calculate the discharge. In the case of Field D (drip), the discharge was estimated using the irrigation duration and emitters’ relevant information (emitter discharge was 1.3 liter $hour^{-1}$ and the distance between emitters was 30 cm and laterals’ spacing was 1.5 m).

Measurement of cotton phenological stages

BT cotton cultivar was widely used by farmers in southern Punjab, including the Mungi area (Shah et al., 2016). Crop parameters linked to BT cotton cultivar (considered as non-conservative) were observed and measured distinctly for each field throughout April-September of 2019 and 2020. Each cropping stage of cotton such as sowing time, days to reach germination, maximum canopy cover, flowering, duration of flowering, canopy senescence and crop maturity, was observed and monitored closely at both fields. Periodic photos (around twelve pictures after an interval of 7-15 days) of the cotton crop were taken at random locations of each field from two meters above the crop. GreenCrop Tracker software (Sandhu et al., 2019) was used to estimate the percentages of crop canopy cover based on these photos, which was then used for model validation. In addition, the plant density of the crop was estimated by measuring row to row and plant to plant distances and also by placing a 1 m^2 frame in the field to cover the number of the plants. Also, the seed lint yield was collected at different harvest intervals by farmers and weighed in the field. Several picking data at each field were recorded and accumulated for specific sizes of the study fields as the final seed lint yield. The harvest index (HI) was defined as the percentage ratio of seed cotton yield to total biomass.

Tuning AquaCrop model parameters

Modification of the parameters in the AquaCrop model depends on conservative and non-conservative crop parameters. Conservative parameters are linked to a group of factors considered not cultivar specific and have been widely used under different environmental conditions (Raes et al.,2009). The cotton conservative parameters which are adapted in this study can be found in the reference Manual of AquaCrop by Raes et al.,(2009) and are provided in Appendix in Table A. 1.

In contrast, non-conservative parameters are cultivar dependent and therefore must be synchronized to crop field management conditions and local agro-ecological circumstances. Non-conservative crop parameters linked to the BT cotton cultivar were observed and measured (discussed previously under the subtitle of measurement of cotton phenological stages), while, the model crop file was tuned based on the non-conservative parameters. The model ran as growing degree days (GDDs), an air temperature stress indicator in the model and was used to calculate thermal time for crop development (Steduto et al., 2012).

Model validation criteria

The study used five statistical indicators to evaluate the biases in the model output and the relationship between the observed and simulated data for canopy cover development and soil water content at the root zone of the crop. These indicators were normalized root mean square error (CV, RMSE), root mean square error (RMSE), coefficient of determination (R^2), the index of agreement (d), and the Nash–Sutcliffe model efficiency coefficient (EF).

Equation (3.1) defines R^2, whereas equation (3.2) presents d as an index of agreement that investigates the degree of relationship between measured and simulated data, while R^2 considers systematic errors in the model. Moreover, the model output is acceptable when d > 0.65 and R^2 > 0.5(Willmott et al., 1985).

The EF is presented in equation (3.3) that takes into account the process of extending the overall simulation period in the model. When EF is close to 1, the model achievement is counted to be excellent, whereas EF > 0.4 shows a satisfactory model performance (Toth, 1970).

For equation (3.4), when RMSE values are close to 0, this demonstrates a good agreement between the measured and model data. In comparison, the normalized RMSE in equation (3.5) demonstrates the deviation of measured data from model data. If the normalized RMSE has values of <10%, 10%–20%, 20%–30%, and >30%, this indicates excellent, good, fair, and poor model simulation results, respectively (Jamieson et al., 1998).

$$R^2 = \left(\frac{\sum_{i=1}^{n}(P_i - \bar{P})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2 \sum_{i=1}^{n}(O_i - \bar{O})^2}} \right)^2 \qquad 3.1$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(|\grave{P}|_i + |\grave{O}|_i\right)^2} \right] \qquad 3.2$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad 3.3$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad 3.4$$

$$CV\ RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} * 100/\bar{O} \qquad 3.5$$

In these equations, $P_i\ and\ O_i$ are the simulated and observed data, respectively. $\overline{O}$ is the average of the observed data and $\overline{P}$ is the average of simulated data, n presents the number of measurements, while $\grave{P} = P_i - C$ and $\grave{O} = O_i - C$ where C is the mean of the measured parameters.

Model application for quantifying field water balance components

Amounts of irrigation, rainfall and contribution by the capillary rise (which was considered negligible because the groundwater table was more than 10 m below surface in the Mungi area) were used as input into the water balance, whereas the output parameters were simulated by the model as percolation, transpiration, evaporation, and surface runoff (considered as zero because of the end-blocked edges of the fields). Moreover, gross water productivity is the ratio of attained seed lint yield to gross water applied and ET water productivity is the ratio of seed lint yield to amount of water evapotranspired.

3.4 Results

3.4.1 Parameterization and validation of the model

Parameterization of the model

The tuning of the non-conservative parameters relevant to each cultivar and field in the AquaCrop model is provided in Table 3.3. The differences in maximum and initial canopy covers were due to the different plant densities as depicted in Figure 2.

Table 3.3: Cotton non-conservative crop parameters.

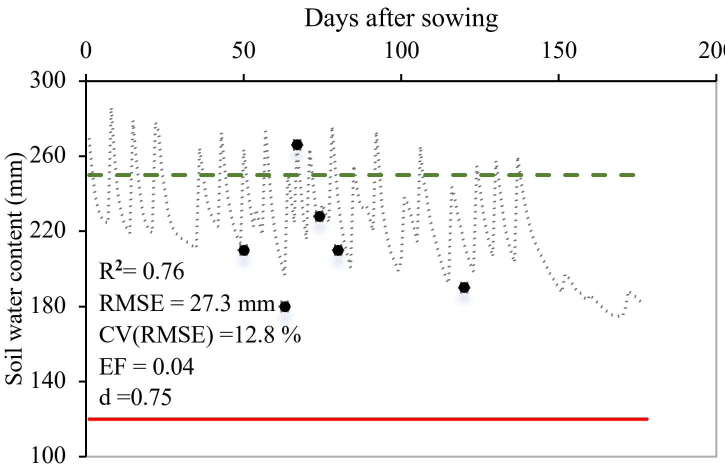
Parameter description	Unit	Field A	Field B	Field C	Field D	Field E	Field F
Sowing to emergence	GDD[1]	103	90	113	98	82	77
Sowing to maximum canopy cover	GDD	1611	1538	1683	1520	1303	1754

Sowing to flowering	GDD	1219	1203	1309	1204	951	1178
Length of flowering	GDD	676	998	777	887	996	977
Sowing to max rooting depth	GDD	1590	1517	1625	1520	1404	1441
Sowing to senescence	GDD	2434	2452	2705	2455	2150	2332
Sowing to maturity	GDD	3266	3402	3274	3526	3254	3076
Maximum canopy cover: CC_X	%	92	94	66	94	95	95
Initial canopy cover: CC_0	%	0.26	0.28	0.13	0.15	0.24	0.21
Maximum effective root depth	Meter	1	1	1	1	1	1

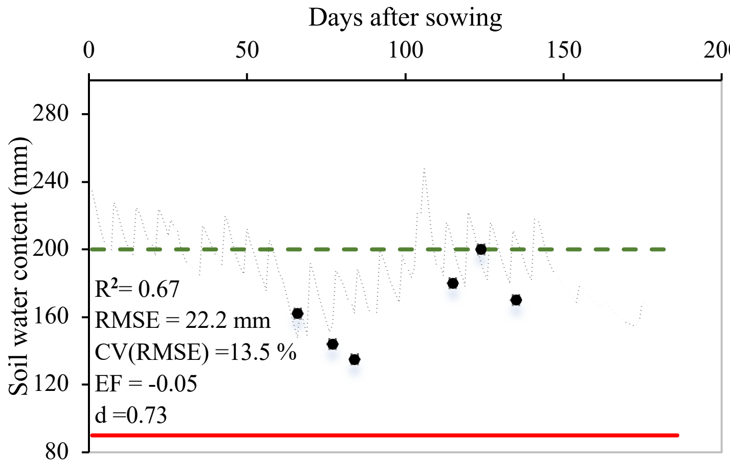
[1]*GDD: growing degree days.*

Validation of the model based on soil water content

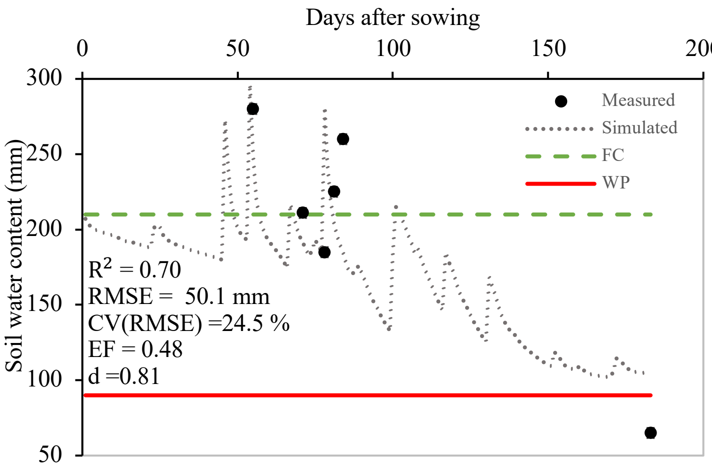
Overall, the model estimated well the soil water content (SWC) according to the statistical indicators outcomes for all selected fields considering comparison of simulated and observed SWC over the cotton growth period, as depicted in Figure 3.3. The model slightly overestimated the SWC for fields A, B, D and E, which could have been caused by a slight systematic deviation in determining of field capacity and/or permanent wilting point. For Field D, the overestimation likely arose because it was not possible to insert decimals or fractions in the irrigation tab of the model as water input; however, the drip farmer was irrigating Field D on some occasions at 1.3 or 2.1 mm. Generally, the slight deviation might have been due to differences in the rainfall pattern recorded in the UAF meteorological station and the Mungi area in the selected fields because they were 62 km apart. Notably, overestimation of SWC has been detected for cotton crops in previous studies (Farahani et al., 2009, Hsiao et al., 2009, Hussein et al., 2011; Tan et al., 2018).



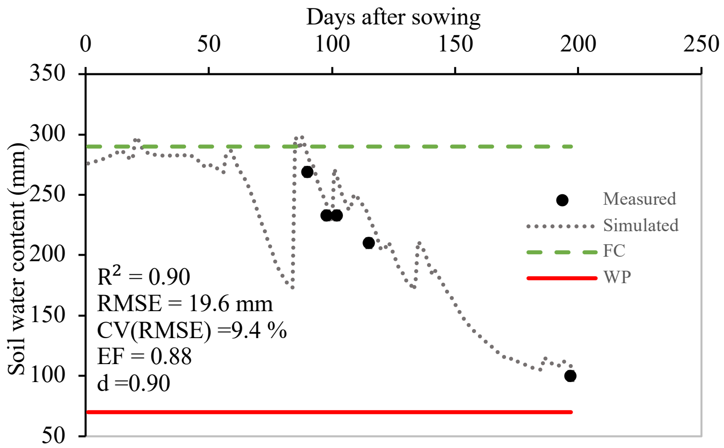
(a) Simulated versus measured soil water content of cotton for Field A.



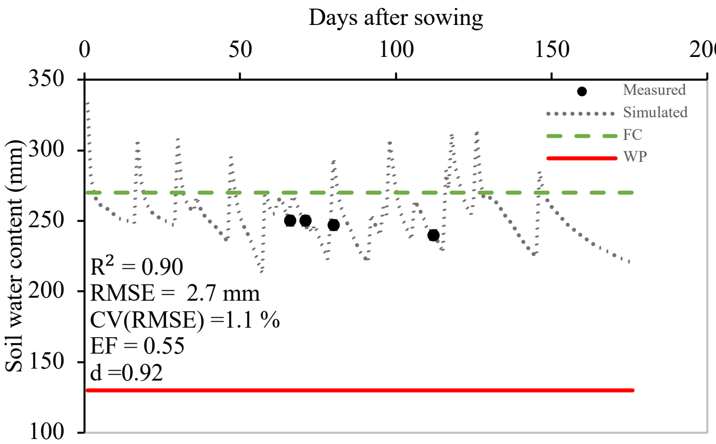
(b) Simulated versus measured soil water content of cotton for Field B.



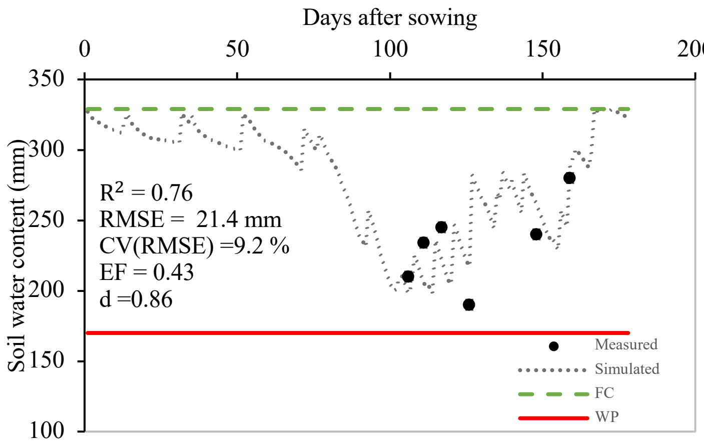
(c) Simulated versus measured soil water content of cotton for Field C.



(d) Simulated versus measured soil water content of cotton for Field D.



(e) Simulated versus measured soil water content of cotton for Field E.

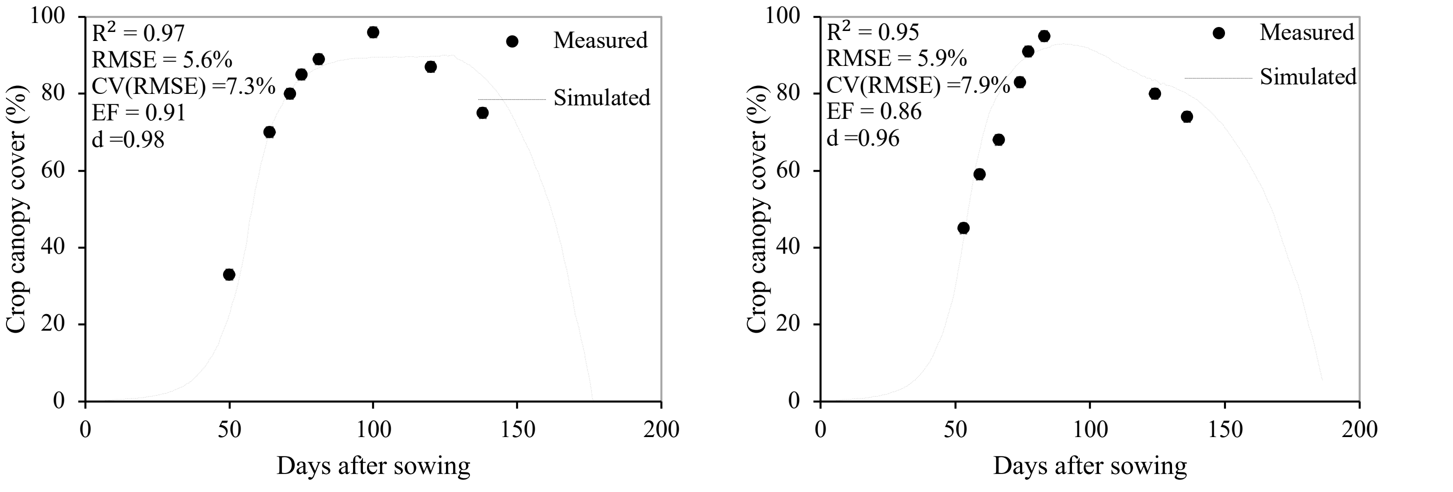


(f) Simulated versus measured soil water content of cotton for Field F.

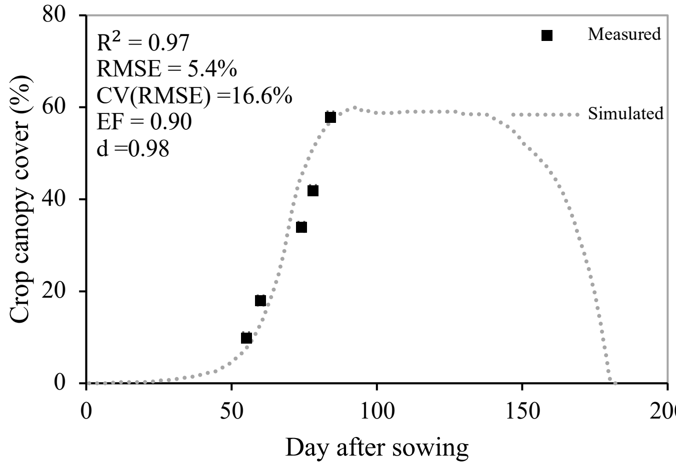
Figure 3.3: Temporal resolution of observed and simulated soil water content of cotton fields.

Validation of the model based on canopy cover development

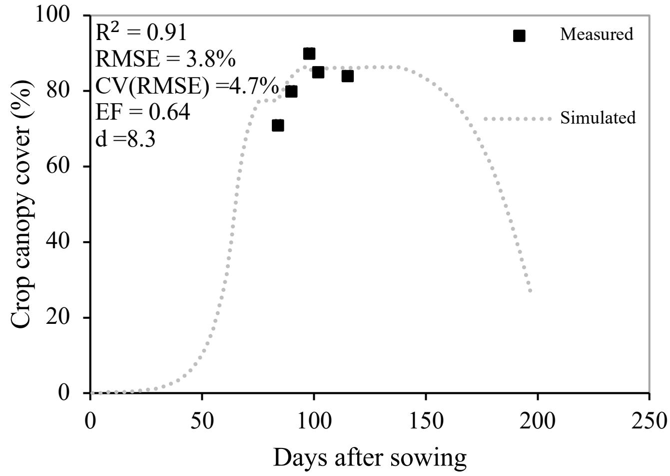
The model performed very well when estimating the canopy cover percentage of all fields, as indicated by the results for the statistical indicators in Figure 3.4. The observed and simulated canopy development stages for each field over the cotton growth period are shown in Figure 3.4 (a, b, c, d, e, and f). The model slightly over-predicted the canopy cover development at mid and senescence stages of the crop for fields A, B, E, and F, which could be associated to rapid increase of the temperature from anthesis onward that boosted the senescence stage and led to decline of canopy under the Mungi condition (Andarzian et al., 2011). The canopy cover of Field C developed to around 65% only because of poor field management and limited application of fertilizer, pesticide spray, water, and the low density of plants (two plants per m^2). Additionally, practicing different irrigation methods caused 6%–8% of the variation between measured and simulated maximum canopy cover in the AquaCrop model (García-Vila et al., 2009).



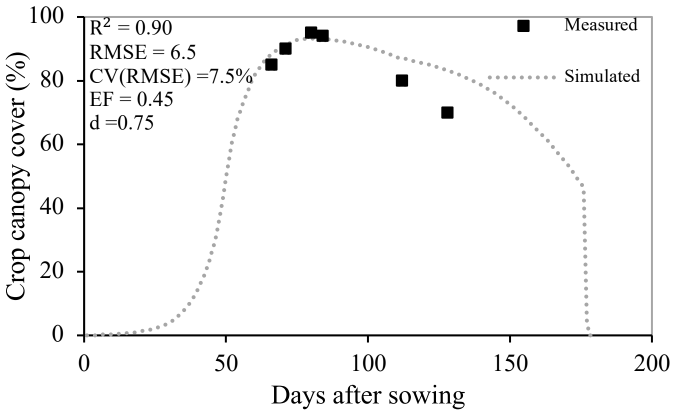
(a) Simulated versus measured canopy cover of cotton for Field A. **(b)** Simulated versus measured canopy cover of cotton for Field B.



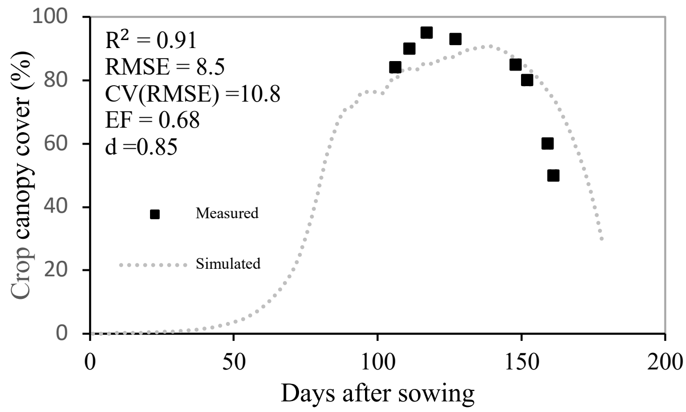
(c) Simulated versus measured canopy cover of cotton for Field C.



(d) Simulated versus measured canopy cover of cotton for Field D.



(e) Simulated versus measured canopy cover of cotton for Field E.



(f) Simulated versus measured canopy cover of cotton for Field F.

Figure 3.4: Temporal resolution of observed and simulated canopy cover development of cotton fields.

Validation based on seed lint yield of cotton

The model predicted well the seed lint yield of cotton for each field under the Mungi conditions considering R^2 as 0.99 (Fig. 3.5). Similarly, good fits for estimating cotton yield in the AquaCrop model were obtained in other studies (Akhtar et al., 2013; Hussein et al., 2011).

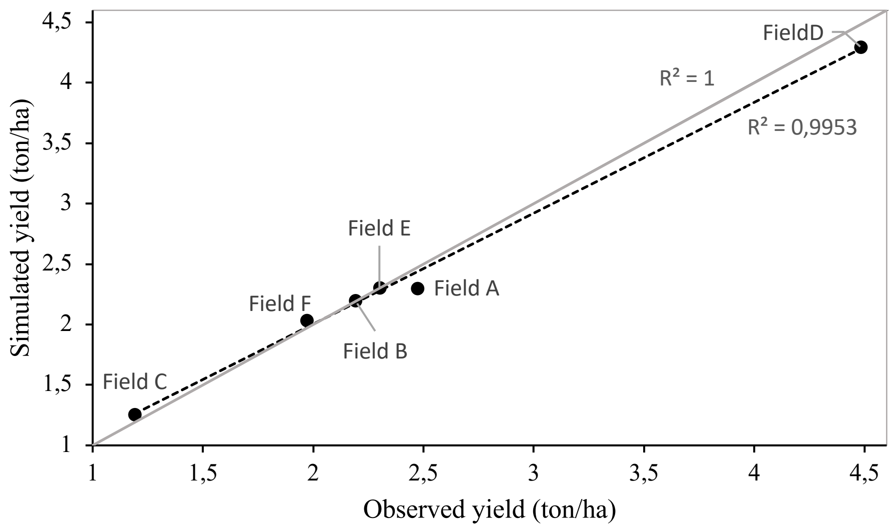


Figure 3.5: Observed versus simulated yield of cotton.

3.4.2 Cotton irrigation under various cultivation methods in the context of Warabandi

Table 3.4 presents the main water balance components, gross water applied and Warabandi water allocation over the cotton growth period for each field. Figures 3.6 and 3.7 depict the yield, gross water applied, ET and gross water productivity for all the fields.

Table 3.4: Main water balance parameters, gross water applied and Warabandi water allowance over cotton growth period for each field.

Field name	Rainfall over cotton growth period (mm)	Gross water applied (mm)	Warabandi allowance over the cotton growing period (mm)[1]	Percolation (mm)	Actual evaporation (mm)	Actual transpiration (mm)
Field A	296	1086	325	632	239	554
Field B	277	668	188	340	164	542
Field C	266	480	527	211	222	381
Field D	328	396	-	120	130	569
Field E	350	635	-	364	188	522
Field F	429	509	-	187	225	509

1Warabandi allowance over the cotton-growing period for Fields D, E and F for being located downstream of the canal was not determined due to irregular canal water supply.

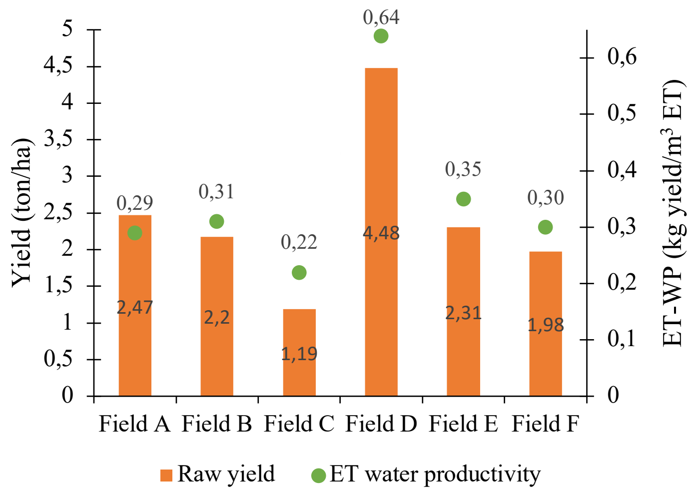


Figure 3.6: Yield and ET water productivity for the selected fields.

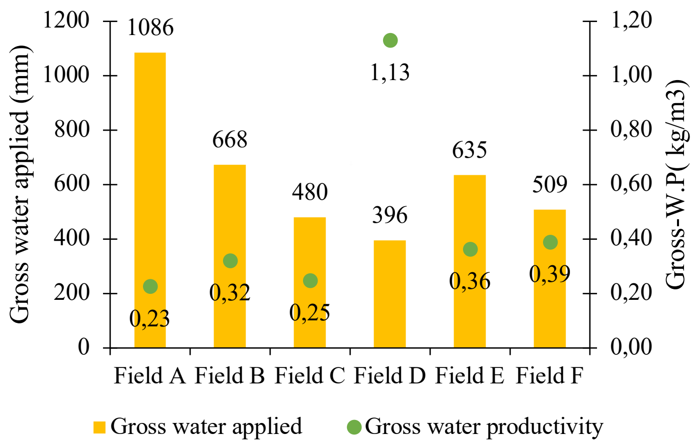


Figure 3.7: Gross irrigation water application and gross water productivity for the selected fields.

Cotton irrigation in Field A

The farmer in Field A used a raised-bed furrow method for cotton cultivation because this method enables the crop to reach maturity rapidly, improves yield, and is easy to irrigate after the 7-day rotation (according to the farmer's description). The farmer was a small landholder with a limited understanding of water demand, optimizing irrigation scheduling and water application; therefore, the field was over-irrigated (beyond the field capacity of the soil) by applying ~60 mm of water per event. Thus, the total gross water application for this field amounted to 1,086 mm (Table 3.4), while the total canal water allowance was 325 mm over crop growth (the field located at the head of the Mungi canal received a regular canal water supply of ~17 mm per week) and the remaining part of gross water applied was obtained by abstracting groundwater using fuel energy. The productive usage as estimated actual transpiration of the crop was 554 mm, whereas a substantial amount of non-beneficial water occurred and predicted as percolation below the root zone after each irrigation event (632 mm over the growth period) or some part of gross irrigation depth evaporated (239 mm) at the beginning of the season; during midseason, when the canopy cover reached its maximum level, evaporation from the soil surface decreased considerably (Figure 3.8).

Consequently, the farmer attained the lowest gross water productivity of 0.23 $\mathrm{kg\,m^{-3}}$, yet it was considered to be the second highest seed lint yield (2.4 $\mathrm{ton\,ha^{-1}}$) after drip method due to interventions such as fertilizer usage, pesticide spraying, practicing the raised-bed furrow irrigation method, and providing sufficient water for crops (Figures 3.6 and 3.7). The farmer's expectation of an even higher yield was not reached due to late sowing and attacks from whiteflies (according to the farmer's description).

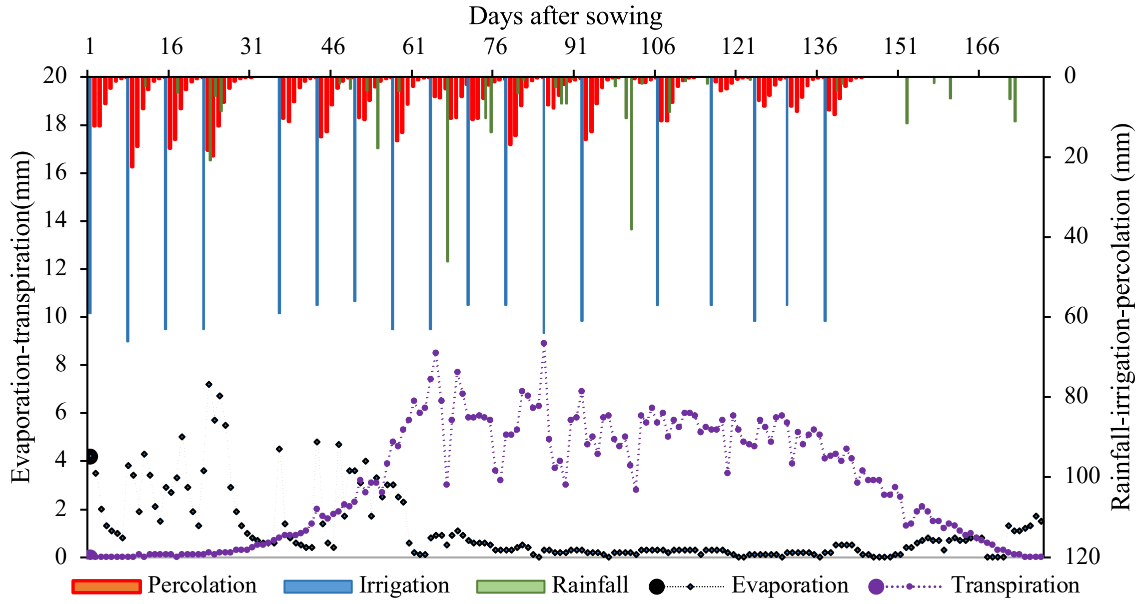


Figure 3.8: Field A temporal root zone water balance parameters over the cotton growth period.

Cotton irrigation in Field B

The farmer in Field B was a large landholder; thus, the owner attempted to optimize the usage of water and cultivated cotton using the raised-bed furrow method (mainly to improve yield). Although the farmer was irrigating around 37 mm per event, this refilled the soil beyond the field capacity due to the low water holding capacity of the soil, which was a sandy clay loam (Figure 3.3. b). The gross water application was 668 mm over the cotton cultivation period and the accumulated canal water allowance for this period was 188 mm (the field obtained a regular Warabandi allowance of ~10 mm per week for being located at the middle of the Mungi canal), while the remaining part of the applied water was pumped using groundwater. Beneficial use as actual transpiration of the crop was 542 mm (Table 3.4). In reference to Figure 3.9, a substantial amount of percolation as non-beneficial use was simulated during the early days of sowing and late season of the crop when the crop did not need more water; this was because the farmer continued to irrigate the same amount per event regularly over the growth period.

Furthermore, evaporation losses were higher at the beginning of the season, but reduced substantially in the mid and late periods of the season (Figure 3.9). Total percolation and evaporative non-beneficial uses were 340 mm and 164 mm, respectively (Table 3.4). Nevertheless, the farmer was able to optimize irrigation of cotton by providing less water across the non-uniform line of the raised-bed furrow method. The obtained gross water productivity was 0.32 $\mathrm{kg\ m^{-3}}$ and seed lint yield attained 2.2 ton $\mathrm{ha^{-1}}$ in this field (Figures 3.6 and 3.7). Rather a low yield was caused by pink worm-related disease, whiteflies, and heat stress, as stated by the farmer.

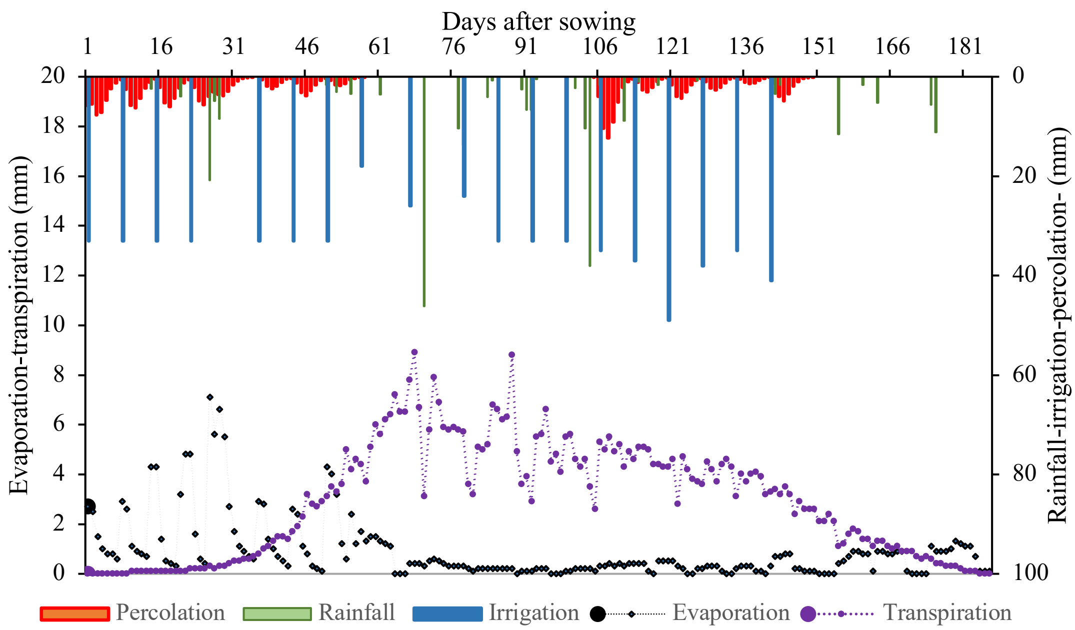


Figure 3.9: Field B temporal root zone water balance parameters over the cotton growth period.

Cotton irrigation in Field C

As shown in Table 3.4, the farmer in Field C was a small landholder and applied 480 mm of water over the cotton growth period; however, accumulated weekly canal water allowance over the crop season under the Warabandi system was 527 mm (due to the placement of the field at the head of the Mungi canal, a regular and reliable canal water supply of ~14 mm per week was possible). Since the Warabandi allowance was not demand-oriented and the cultivator also did not have storage facilities to store Warabandi's weekly allowance. Therefore, the farmer was supposed to abstract groundwater to irrigate cotton and exchange Warabandi allowance with neighbors or use it for any other crop in the farm despite not corresponding to the crop irrigation timing. The farmer irrigated in six events over the crop development period and decided on the irrigation of each event after 20 or 30 day intervals depending on the meteorological conditions and visual observation of the soil (Figure 3.10). Each water application event was 55–100 mm, which was usually beyond the field capacity; therefore, in the first three irrigation events, a considerable amount of the irrigation water was drained as deep percolation below the root zone.

Moreover, evaporation of water as non-beneficial use to the crop was substantially higher at the beginning of the season and some evaporation losses occurred during the middle and late crop seasons because of limited canopy cover and low plant density (Figure 3.10). Therefore, the farmer achieved the minimum yield of 1.19 $\mathrm{ton\ ha^{-1}}$, which led to the minimum irrigation and ET water productivity of 0.25 and seed lint 0.22 $\mathrm{kg\ m^{-3}}$, respectively (Figures 3.6 and 3.7). The minimum yield and water productivity were caused by the cultivation method (flood basin), irrigation behavior of the farmer (timing and amount), and limited use of fertilizer and pesticides. The farmer of Field C was not able to afford to pump groundwater due to the high cost of fuel; therefore, the cultivator used the flood irrigation method jointly with frequent plowing, to utilize soil moisture, apply less water, and irrigate less frequently (e.g., around 20-day intervals). Moreover, according to the farmer's description, the low yield was caused by the lack of drainage facilities to manage periods of waterlogging when heavy rainfall events followed by extensive flood irrigation.

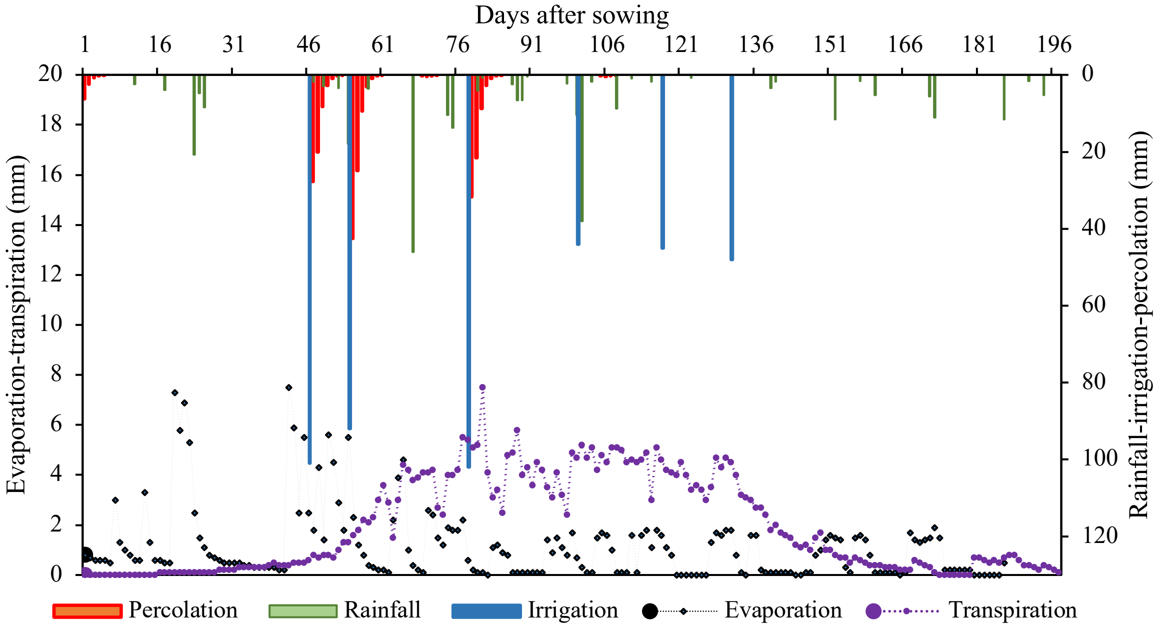


Figure 3.10: Field C temporal root zone water balance parameters over the cotton growth period.

Cotton irrigation in Field D

Field D was irrigated with a drip system operated by an experienced and skillful farmer; who had more than 15 years of experience in farming and held a large farm. The farmer experienced water scarcity conditions because the farm was located at the tail of the watercourse and dealt with the unreliability of canal water and brackish groundwater quality; thus, the drip technology was installed as a cultivation method for cotton to consume less water. The cultivator also constructed a water pond in the field to be used for demand-oriented and frequent application to store canal water when it was available; when canal water was unavailable, groundwater was pumped to the pond. The cultivator had undertaken experiments with irrigation water optimization techniques, e.g., assessing the amount of applied water and timing while considering soil holding capacity for several years. Moreover, a soil moisture sensor was used to control the allowable depletion of soil moisture in the root zone (this farmer had an appropriate understanding of the storage characteristics of the soil).

The farmer irrigated the cotton field with 1 or 2 mm of water per day; on hot days, such as those in June and irrigated the field twice per day (morning and evening), as shown in Figure 3.11. Gross water application was 396 mm over the cotton growth period, of which around 264 mm was used in two events (20 days before sowing as pre-irrigation and on June 20; each event involved irrigation with 132 mm) when flooding the entire drip field because canal water was obtained (Figure 3.11 and Table 3.4). The estimated actual transpiration amount was 569 mm, which revealed that a considerable part of the crop water requirement was fulfilled by rainfall. The farmer managed to maintain soil moisture close to field capacity level to avoid crop water stress and yield reduction (Fig 3.3.d). Drip technology lowered the portion of soil evaporation and percolation during the cultivation season to 130 mm and 120 mm, respectively (Table 3.4). Only a small amount of percolation was observed at the beginning of the season due to heavy rainfall and in mid-June due to flooding of the field (Figure 3.11).

The owner of Field D obtained under the actual field conditions realistically upper limit of the seed lint yield of 4.48 $\mathrm{ton\ ha^{-1}}$, which resulted in the highest gross and ET water productivity of 1.13 and 0.64 $\mathrm{kg\ m^{-3}}$, respectively (Figures 3.6 and 3.7). This high-performance level is a result of appropriately handling the drip method embedded in and supported by a bundle of interventions (pond, soil moisture monitoring and water optimization experiments of the farmer) as a combined package.

Additional agricultural inputs that resulted in increased yield or water productivity of cotton under drip were including (i) proper application of liquid fertilizer and primary macronutrients as Di-Ammonium Phosphate (DAP), (ii) early sowing, which allowed the crop to reach maturity before peak temperature occurred (this is important because flowers and pollination could be affected by a spike in temperature – an issue becoming even more important in future due to expected impact of climate change), (iii) using a good quality of cotton seed as BS18 that had better germination and featured resistance against peak temperature, (iv) management and reducing the effect of diseases such as attack of white fliers and Pink bollworm through regular application of sprays,(v) timely harvesting the cotton raw yield by hiring female harvesters, and (vi) adopting appropriate spacing between plants to give room for ventilation of the air. The farmer was testing and thereby improving the system layout and its performance; as an example, he informed that after testing during several years, he selected plant to plant distance as 30 cm and row to row distance as 150 cm.

The farmer achieved the highest yield under the realistic conditions of the study region and was confident of achieving even higher yields by using better quality seed, early sowing, developed pesticides, and finding female harvesters at the picking time of the yield. Despite higher yield, the drip farmer was not optimistic about the cultivation of cotton and did not grow the crop in 2020 due to constraints such as seed quality and price, unavailability of female harvesters, the low price of cotton, and attacks by whiteflies and pink bollworm (as stated by the farmer). Moreover, the owner of Field D cooperated with UAF to follow the academic suggestions on improving cotton yield and is willing to experiment with scientists and officials to further improve intervention packages.

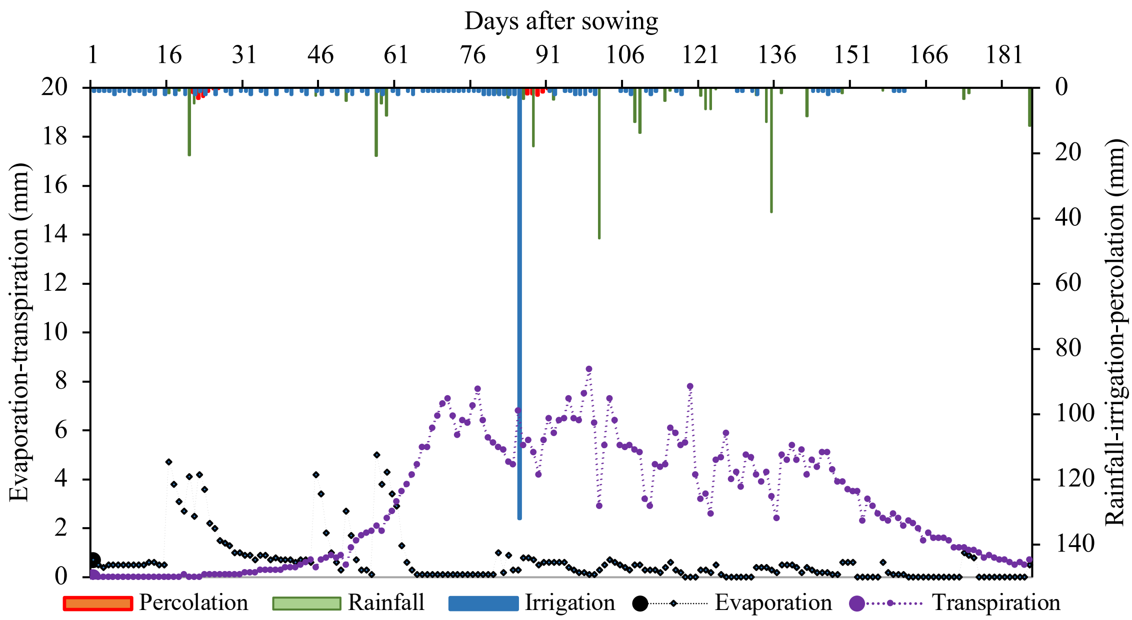


Figure 3.11: Field D temporal root zone water balance parameters over the cotton growth period.

Cotton irrigation in Field E

The farmer in Field E was considered a large farm holder and had the Warabandi allowance of around 13.3 mm of canal water per week (the canal water supply was not reliable due to the farmer’s location at the tail of the Mungi canal). The farmer irrigated the field in 10–20-day intervals using the cultivation method of the ridge-bed furrow.

The one-time gross irrigation water application was around 65 mm and the owner often irrigated cotton by abstracting groundwater. Because the farmer cultivated several crops on the large farm and was diverting weekly canal water to other crops rather than cotton as it did not correspond to irrigation timing required for cotton. Summing the gross irrigation applied by each event over the growth period of the crop resulted in a 635-mm season gross water application. Using the practiced irrigation events as input in the AquaCrop simulation leads to 364 mm (percolation) and 188 mm (evaporation) of non-beneficial use to the crop and 522 mm productive requirement of the crop fulfilled as actual transpiration (Table 3.4). The applied water in each event was beyond field capacity, the majority of non-beneficial use was due to deep percolation, and soil evaporation was higher at the beginning of the season (Figure 3.12). Despite this, the farmer achieved a rather higher seed lint yield of 2.31 $\mathrm{ton\ ha^{-1}}$ because of early sowing, water availability (access to a tube well), and proper usage of spray and fertilizers; these practices resulted in high ET and gross water productivity of 0.35 and 0.36 $\mathrm{kg\ m^{-3}}$, respectively (Figures 3.6 and 3.7).

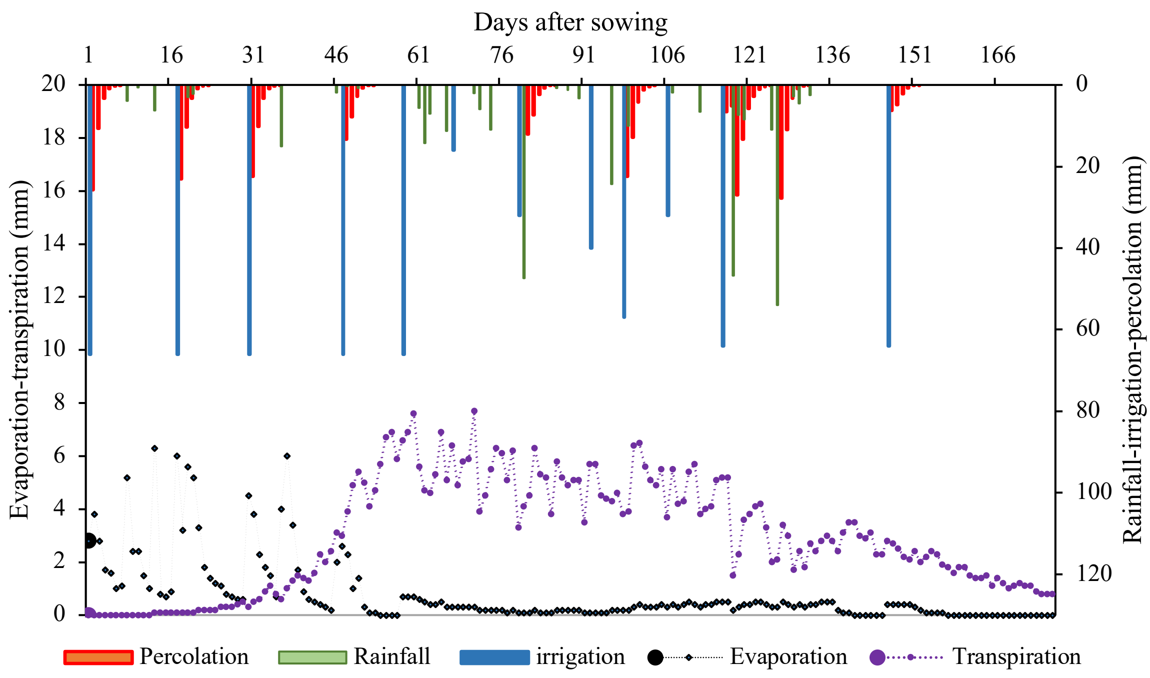


Figure 3.12: Field E temporal root zone water balance parameters over the cotton growth period.

Cotton irrigation in Field F

Field F was managed by a small-scale farmer whose farm was located at the tail of the Mungi Distributary canal. This farmer received irregular canal water due to sedimentation along the Mungi canal or higher water losses; therefore, the farmer bought groundwater from a large farm holder. In Field F, the ridge-bed furrow method was chosen for cotton cultivation to restrict water use; and the irrigation interval was on average after 20-day and each water application event was around 40 mm. The soil moisture was maintained within allowable depletion levels that resulted in a substantial reduction of percolated water, whereas soil evaporation was higher in the first 55 days and decreased in further development stages of the crop (Figure 3.13). Therefore, 509 mm was applied as gross water requirement by the farmer, while the actual evaporation was simulated as 225 mm and percolation was 187 mm over the cotton cultivation period (Table 3.4).

According to the farmer, the attack of whiteflies and pink bollworm were the limiting factors that led to a low seed lint yield of 1.98 $\mathrm{ton\ ha^{-1}}$, 0.31 $\mathrm{kg\ m^{-3}}$ ET water productivity, and 0.39 $\mathrm{kg\ m^{-3}}$ gross water productivity (Figures 3.6 and 3.7). Moreover, the farmer stated that it was difficult to fulfill the input cost of cotton, such as the cost for buying groundwater that is pumped by a large farmer as well as fertilizer and spray expenses.

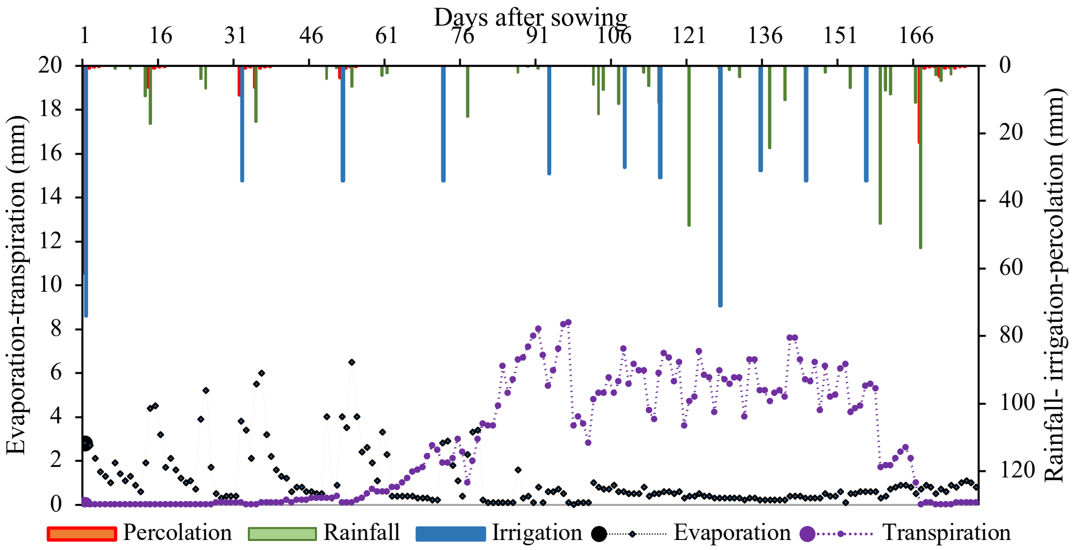


Figure 3.13: Field F temporal root zone water balance parameters over the cotton growth period.

3.5 Discussion

In this study predicted cotton ET water productivity by the model varied as 0.22, 0.29, 0.31, and 0.64 $\mathrm{kg\,m^{-3}}$for flood basin, raised-bed furrow, ridged-furrow and drip, respectively. Therefore, types of cultivation methods influenced the beneficial use of applied water in the fields. Furthermore, tube well owners were technically more efficient users of water than buyers in a study conducted among 172 cotton growers (92 tube well holders and 80 water purchasers) that were irrigating their fields using groundwater in Punjab (Watto and Mugera, 2015). In the current study also the farmers of fields B and E were holders of large farms and tube well owners; thus, the model predicted higher ET water productivity of 0.31 and 0.35 $\mathrm{kg\,m^{-3}}$ in their respective fields. In contrast, the farmers of fields C, and F were small farm holders and water buyers who attained slightly lower simulated ET water productivities of 0.22, and 0.30 $\mathrm{kg\,m^{-3}}$, respectively (Figures 3.6 and 3.7).

In addition to water management features, lower cotton yield in Punjab is caused by factors such as seed quality, fertilizer management, plant protection management and other factors. A number of studies informed that combined climate smart agricultural (CSA) interventions improved yield and water efficiency in cotton farming in Punjab. A combination of three major inputs, irrigation water, fertilizer, and pesticide improved cotton water productivity (Shabbir et al., 2012). Moreover, most of the CSA adopters in Punjab stated the reasons for practicing CSA techniques (plants in a bed, laser- guided land levelling, crop rotation, and developed crop varieties) for cotton cultivation were the limited availability of canal water, substantial pumping of groundwater, impact of climate change, decline of the groundwater table, and increase in salinity (Imran et al., 2018) . Also a set of interventions comprising capacity building and training of farmers, land preparation, mulching, drip, proper usage of seed, improved the yield and water productivity of the cotton and other crops (Bakhsh. et al., 2005; Qureshi et al., 2010). Therefore, a package of interventions (such as in case of Field D), including the use of a pond as decentral storage option, soil moisture sensor, and drip cultivation (which could be considered as CSA tools), could save water, minimize groundwater pollution, and increase cotton production.

The improvement of cotton yield is associated with multiple and inter-related factors such as water, seed quality, disease control, fertilizer usage, climatic conditions, soil characteristics, and crop cultivar. Managing and improving non-water agricultural inputs, such as disease and pests control, proper fertilizer application, and improved seed could increase the crop yield and enhance water input use towards higher water productivity.

The estimated cotton gross water productivity in this study under actual field practices ranged from 0.23 to 0.39 $\mathrm{kg\ m^{-3}}$(except Field D, which is located outside of the Mungi area and using drip irrigation), that matches the cotton gross water productivity 0.26 $\mathrm{kg\ m^{-3}}$attained in a study in the command area of four distributary canals in Punjab using CropWat model (Shabbir et al., 2012). While the Mungi cotton gross water productivity is relatively low when compared to the global average of raw cotton water productivity as 0.65 $\mathrm{kg\ m^{-3}}$ (Zwart and Bastiaanssen, 2004),and the values for other regions with a similar climatic condition such as the Ferghana valley of Central Asia, Turkey (under a drip method and also under surface methods in the Söke region), and Northwest China as 0.58, 0.84, and 0.62 $\mathrm{kg\ m^{-3}}$, respectively (Çetin and Kara, 2019; Reddy et al., 2012; Shareef et al., 2018). Moreover, the obtained seed lint yield of cotton in this study ranged from 1.19 to 2.47 $\mathrm{ton\ ha^{-1}}$ (except Field D) which is lower than the cotton seed lint yield revealed in Punjab India around 3 $\mathrm{ton\ ha^{-1}}$ (Singh et al., 2007), and 2.7 $\mathrm{ton\ ha^{-1}}$ for Khorezm region of Uzbekistan that has similar annual reference evapotranspiration of 1500 mm as Mungi area (Akhtar et al., 2013).

Technical complexities, the limited knowledge of farmers, and the high prices of low-quality irrigation equipment have hindered the improvement of on-farm water management. Moreover, despite the enhancement of on-farm water management for most farmers in Pakistan, farming is not a beneficial business due to low water productivity (Hasan et al., 2021). This is supported by the farmers' statements from this study (e.g., those from Fields D, B, and F), who proposed that cotton farming is no longer a profitable agricultural activity due to high input costs.

3.6 Conclusion

The study considered the entry point for more flexible and demand-orientated irrigation focused on water input as a package of interventions practiced in Field D to be introduced at farm level assuming that Warabandi will remain the guiding principle on water allocation to farms and at larger system scale in future. The irrigation practice of Field D involved (i) the provision of demand-based irrigation planning (it could be facilitated by utilizing the AquaCrop model to simulate pre- and within-season irrigation planning), (ii) advancing irrigation schedules by sensor-based soil moisture monitoring provides a strong intervention package to optimize on-farm irrigation management, which can unfold its potential by (iii) combining the storage option of Warabandi allowance during the potential surplus time in a pond at the farm to create an enabling environment for demand-based irrigation. In addition, using the drip method could considerably reduce the undersupply effect of Warabandi and improve water productivity. This combination will enhance flexible irrigation scheduling and support farmers within farm water allocation and in pre-season crop selection. For that reason, this study argues in chapter 5 that integrating interventions into a package for on-farm water management is the most promising approach to achieve higher water productivity at farm level given the framing conditions of Warabandi.

4 ASSESSING COTTON IRRIGATION SCHEDULING UNDER ROTATIONAL DELIVERY SCHEDULE IN PAKISTAN

4.1 Abstract

Limited water and rigid rotatioms of the Warabandi-guided water allocation led to unsustainable pumping of groundwater and relatively low field application efficiency and water productivity. The study assessed cotton irrigation scheduling under current practices and the planning options in context of the Warabandi principle. The farming practices of two cotton fields (raised-bed furrow) were intensively monitored at the Mungi Distributary canal command area in Punjab. The AquaCrop model was parameterized and validated for each field using 2019 and 2020 datasets and then applied to quantify four irrigation scheduling scenarios. Scenario 1 reflects the current irrigation practice under the canal and groundwater use, while for scenarios 2, 3, and 4, solely canal water allocation was considered and irrigation followed a fixed 7-days, 14-days rotations and flexible intervals, respectively. According to the results, scenarios 2, 3, and 4 resulted in a substantial reduction of percolation below the root zone and lowered actual evaporation enabling similar yields and higher gross water productivity compared to the current practices in both fields. Under the frame conditions of Warabandi, scenario 4 was a promising option of introducing more flexible and demand-oriented irrigation at the farm level. The study suggests storing canal water allowance in a pond during the potential surplus time (pre-cultivation period, initial stages of cotton growth, and rainy days) and adapting irrigation depth/interval using sensor-based soil moisture monitoring.

Keywords: cotton irrigation optimization, field water balance, water productivity, AquaCrop Model

4.2 Introduction

The AquaCrop model (Steduto et al., 2012) was specially developed to simulate the crop yield response to water (Tenreiro et al., 2020), and it was already applied for similar purpose of evaluating rotational delivery schedules in Argentina and Iran (Angella et al., 2016; Davarpanah and Ahmadi, 2021).The FAO AquaCrop is an atmosphere-soil-water-crop model including the function of irrigation scheduling. The model is used to estimate and analyze crop yield impacted by changing climate, soil conditions, and field management (Steduto et al., 2012). As an irrigation planning model, it enables the development of irrigation strategies under different deficit irrigation scenarios to assess and boost water productivity (Raes et al., 2018). The AquaCrop model was widely used under various agro-ecological conditions and its reliable simulations can be assured through its holistic calculation processes impeded in the model (Foster et al., 2017).

Several studies deliberated the deficit of canal water supply in Pakistan using various methods and proposed modification options to the Warabandi canal water distribution and its performance that could be implemented by the irrigation authorities as a top-down approach. Ahmad et al. (2019) assessed the supply of canal water based on actual field water requirements and suggested optimum water allocation by developing a Crop Water Allocation Model, while Ajmera (2013) showed seepage losses in the network of canals and proposed an increase in the amount of water distributed to tail farmers. Moreover, Ruigu (2016) considered conjunctive use of water (canal and groundwater) under the Warabandi system and the contribution of capillary rise for irrigation of cotton at different planting dates using the AquaCrop model (yet, the model was neither calibrated nor validated) and revealed that early planting of cotton resulted in better yield. Qureshi et al. (2002) irrigated sugarcane by applying canal and groundwater in three rotational intervals of 7, 10, and 15 days using the SWAP93 model (Van den Broek et al., 1994) at experimental treatments in Sindh province, Pakistan. The study revealed that the application of gross water input of 1,650 mm after 15 days of fixed intervals led to the best option in terms of yield and water use efficiency. However, this study considers a bottom-up approach in utilizing canal water allocation at farm level.

This chapter aimed to evaluate cotton irrigation under four scenarios. The current irrigation planning and management practices (scenario 1) by farmers, i.e., conjunctive use of canal water obtained from Warabandi allowance and pumping groundwater. In contrast, scenario 2 represents irrigation scheduling after each 7-days cycle, i.e., the existing features of Warabandi principle (canal water allocation and 7-days rotation) placed in Punjab. Scenario 3 considers the existing water allowance, but with an irrigation interval of 14 days (the interval is feasible since sufficient storage features of the soil in fields are observed), while scenario 4 was based on flexible and demand-oriented irrigation intervals taken into account the Warabandi allocation throughout the cotton irrigation period. The application of groundwater in scenarios 2, 3, and 4 was not considered. The chapter delivered detailed information about irrigation scheduling of cotton for on-farm water management based on the bottom-up approach in Punjab.

4.3 Materials and Methods

4.3.1 Study site description

Field A and B were selected to represent the common irrigation method for cultivating cotton in the Mungi area as raised-bed furrow shown in Figure 4.1. Field A is located at the upstream part of the Mungi Distributary canal and monitored as 0.4 hectare (one acre) of the land plot in 2019 and 2020. Field B is located at the middle part of Mungi Distributary CCA and is considered a 0.4 hectare land plot in 2019 and 0.61 hectare (1.5 acres) plot in 2020 (the 0.61 hectare plot of the farmer had only one outlet for field water application). The electrical conductivity (EC) of Mungi canal water was tested as ~0.2 dS m^{-1}, while groundwater EC was as 1.1 and 1.8 dS m^{-1} for fields A and B, respectively.

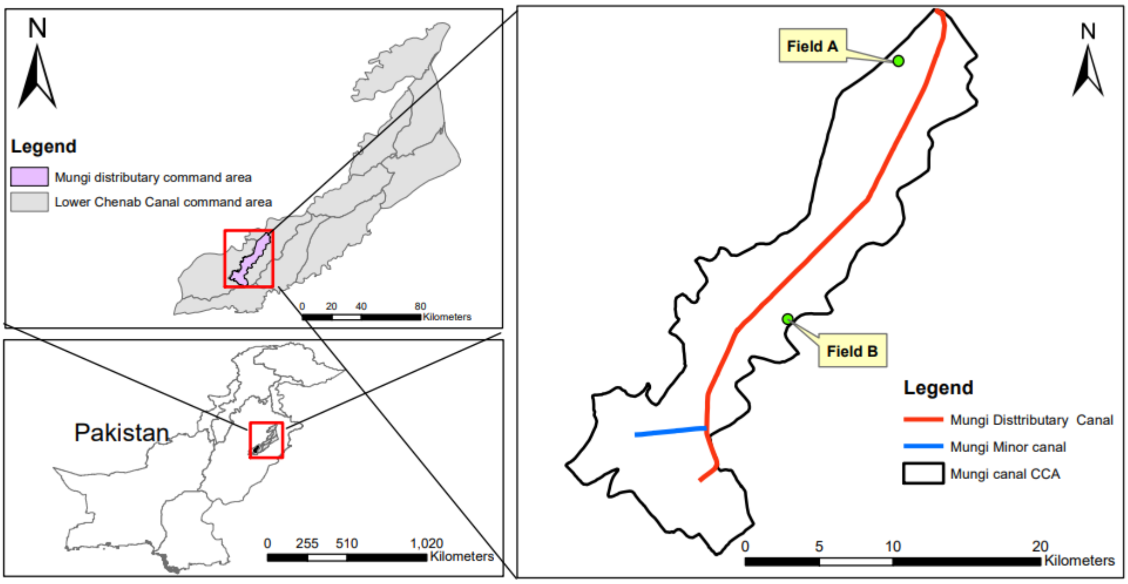


Figure 4.1: Geographical location of the study area (Mungi Distributary canal command area).

4.3.2 AquaCrop model application

The AquaCrop model was used to evaluate the field water balance parameters under cotton irrigation practices and to assess irrigation scheduling scenarios. For parameterization and validation of the AquaCrop model, intensive fieldwork at the two cotton fields (A and B) was conducted to closely monitor farmers' activities during the Kharif season in 2019 and 2020. Relevant field data were collected and used as input in the model next to information on climate, crop, soil, irrigation and field management. The data collection methods, input and model application are explained in detail in the following sub-chapters.

Meteorological data

Climatic data such as rainfall, solar radiation, maximum and minimum air temperature, relative humidity, and wind speed from 2008 to 2020 were collected from the meteorological station of the University of Agriculture Faisalabad (UAF) as shown in Table 4.1.

Table 4.1: Summary of climatic data: mean monthly maximum and minimum temperature, rainfall and reference evapotranspiration (ET0) for the period 2008-2020.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain(mm)	11.3	20.5	28.3	19.5	23.2	37.3	107.5	90.7	60.5	7.2	2.3	3.1
ET_0 (mm)	46.2	65.7	111.4	164.1	212.4	213.1	180.1	161.9	138.8	105.8	60.5	43.5
Tmin(°C)	5.9	8.8	14.2	19.6	24.5	27.3	27.9	27.4	24.8	18.8	12	6.9
Tmax(°C)	17.8	20.5	27.3	34.5	39.6	40.1	37.4	36.5	35.6	33	26.4	20.8

Measurement of soil water content

During the cotton cultivation season of Kharif in 2019 and 2020, periodic soil samples (before and after irrigation events) were collected and the SWC determined using gravimetric methods which are described in detailed in the previous chapter (under subsection of 3.3.2 AquaCrop model).

In addition, soil properties of both fields such as soil bulk density, permanent wilting points, field capacity, electrical conductivity and soil texture were determined and are depicted for Field A and B in Table 3.2.

Measurement of water application to the fields

The detailed information on measurement of water application to the field is provided in the previous chapter (under the subsection of 3.3.2 AquaCrop model). In this study, the groundwater contribution (capillary rise) and surface runoff from the fields were considered negligible because the groundwater depth was >10 m and farmers were practicing end blocked furrows.

Measurement of cotton phenology

Measurement of crop phonological stages discussed before (under the subsection of 3.3.2 AquaCrop model). In this chapter besides the yield, aboveground biomass was determined. For this purpose, plants during harvest time at a 1 m2 area in three random locations (head, middle, tail) in the fields were collected, weighed and transported to the laboratory. The plants were then dried at 65°C for three days in the oven to obtain the dry matter biomass.

Parameterization of AquaCrop model

The model parameterization is dependent on cotton conservative and non-conservative parameters which are deliberated in most recent chapter (under the subsection of 3.3.2 AquaCrop model).

For tuning of the model, the study considered the average values of the non-conservative parameters in growing degree days (GDD) from both growing seasons (2019 and 2020) in each field. GDD is an air temperature stress indicator in the model and calculated thermal time for crop development (Steduto et al, 2012). Afterword, the model was parametrized based on the crop, climate, soil, field management, and irrigation data attained in 2019 and 2020.

Model evaluation criteria

The study applied five statistical indicators to evaluate the relationship between the observed and simulated data for canopy cover development and soil water content in the root zone. These indicators were the normalized root mean square error (CV, RMSE), root mean square error (RMSE), coefficient of determination (R^2), the index of agreement (d), and the Nash–Sutcliffe model efficiency coefficient (EF). Whereas the match of simulated and observed data for aboveground biomass and raw yield were assessed using coefficient of determination. The detailed information on statistical indicators has already been discussed (under the subsection of 3.3.2 AquaCrop model).

Model application for quantifying irrigation scheduling scenarios

After parameterization and validation, the model was used to work out four irrigation scheduling scenarios for each field separately in 2019 and 2020 described in Table 4.2. Scenario 1 represents the current practice strategy on utilizing the Warabandi canal water allowance supplemented by intensively pumped groundwater to fulfil the crop demand (conjunctive use strategy). In the current practice, both farmers' irrigation intervals were usually according to Warabandi principle (after each 7-days) but occasionally varied from 5 to 10 days (on warm or rainy days). While scenario 2 follows the existing Warabandi features (water amount per 0.4 hectare and fixed 7-days rotation), and scenario 3 is based on doubling the current water allowance due to consideration of a 14-days fixed interval. The applicability of scenario 3 was to consider the future perspective of Warabandi and the pressure on Pakistan's water resources as a result of climate change, increased competition for water demand in various sectors (agriculture, industry, urban, and environment), reservoir sedimentation, deteriorating groundwater quality and dropping groundwater tables (Sarwar, 2019, Usman et al., 2018; Akhtar et al., 2022).

Moreover, scenario 4 reflects flexible and demand-oriented irrigation scheduling under the framing conditions of the Warabandi principle by utilizing weekly allowance in a storage facility at the farmers' farm. While irrigation application was adapted manually in the model to rainfall events and the soil was refilled during each irrigation event slightly below field capacity to minimize deep percolation below the root zone of the crop. Moreover, for 2nd, 3rd and 4th scenarios groundwater application was negligible and they were solely based on Warabandi canal water allocation throughout the cotton growth period.

In addition, each farmer's actual cotton irrigation period in 2019 and 2020 was the basis for all four scenarios. Therefore, the farmers' irrigation period for Field A was May 1st–September 4th, 2019, and March 25th–September 5th, 2020. While for Field B, it was April 24th–September 14th, 2019 and April 11th–September 20th, 2020. The total Warabandi water allowance over the crop growing period was considered to the number of weeks during the actual irrigation period for 2nd, 3rd and 4th scenarios in 2019 and 2020.

Overall, the model was applied to predict yield, gross and ET water productivity, actual transpiration, actual evaporation, actual evapotranspiration, and percolation below the root zone. Gross water productivity is the ratio of obtained yield to gross water applied, and ET water productivity is the ratio of seed lint yield to the amount of water evapotranspired.

Table 4.2: Irrigation scheduling scenarios for cotton for Field A and B in 2019 and 2020.

Scenario description	Irrigation frequency	Irrigation amount	Remarks
1st (Actual management)	Varied based on farmers' current practice	Considering farmers current practice	
2nd (7-days rotation)	7 days fixed rotation	Current Warabandi canal water allowance (20 minutes for 0.4 ha)	Based on current Warabandi principle
3rd (14-days rotation)	14 days fixed rotation	Doubling the amount of current Warabandi allowance (40 minutes for 0.4 ha)	Based on assumption for future scenario of Warabandi
4th (Flexible scheduling)	Varied	Total Warabandi allowance was considered throughout cotton growth period.	Adapting irrigation application to rainfall events and irrigating the soil slightly below field capacity level.

Moreover, the study generated long-term (2008–2020) three irrigation scheduling scenarios separately for each field based on the actual cultivation period of cotton in 2019 and 2020. For long-term assessment, the 2nd and 3rd scenarios remained with the same characteristics, while the first scenario was eliminated as the actual irrigation practices of the farmers differ throughout the years, and the 4th scenario was considered as an optimal irrigation scenario instead of flexible to make the long-term optimal scenarios comparable and uniform for both fields. For optimal scenario, a threshold was defined in the model to prevent water stress conditions. Therefore, irrigation was applied each time the soil lost 30% of total available water, which is the canopy growth threshold for cotton and it was suggested in the AquaCrop model (Hsiao et al., 2009; Farahani et al., 2009).

4.4 Results

4.4.1 Parameterization and validation of the model

Parameterization of the model

Adjustment of the crop's non-conservative parameters for each cotton cultivar used as BT-007 (Field A) and BT-490 (Field B) is shown in Table 4.3.

Table 4.3: Cotton nonconservative crop parameters.

Parameter description	Unit	Field A	Field B
Sowing to emergence	GDD	104	91
Sowing to maximum canopy cover	GDD	1611	1528
Sowing to flowering	GDD	1219	1204
Length of flowering	GDD	676	1004
Sowing to max rooting depth	GDD	1243	1528
Sowing to senescence	GDD	2434	2452
Sowing to maturity	GDD	3266	3402
Maximum canopy cover CC_X	%	90	94
Initial canopy cover CC_0	%	0.26	0.29
Maximum effective root depth	Meter	1	1
Reference harvest index(HI_0)	%	22	24

Validation of the model based on soil water content

Referring to quantification of water dynamics in the root zone of the crop, the AquaCrop model simulation overall matched well with the measured data from two fields considering 2019 and 2020 based on statistical indicators as shown in Figure 4.2. Compared to that in 2019, the model performed slightly better in predicting soil moisture content measured at both fields in 2020. Therefore, in 2020, for Field A, the relationship of observed and simulated data was showed by R^2 = 0.83, d = 0.79, similarly for Field B, it was attained as R^2 = 0.83, d = 0.88. While in 2019 for Field A, R^2 = 0.76, d = 0.75, and for Field B it was R^2 = 0.67, d = 0.73. The model slightly over-predicted the root zone moisture content at deep layers in both fields in 2019. This difference could be attributed to higher and an unusual one-time rainfall event especially in April, May, and June as 43, 20, and 17 mm, respectively, in 2019 compared to that in 2020 and could be associated with slight deviation in the recorded rainfall in the UAF meteorological station and the Mungi area in the selected fields because they were 62 km apart. Similar discrepancy in simulating soil water content in AquaCrop model has been documented in other studies (Tan et al., 2018; Hsiao et al., 2009).

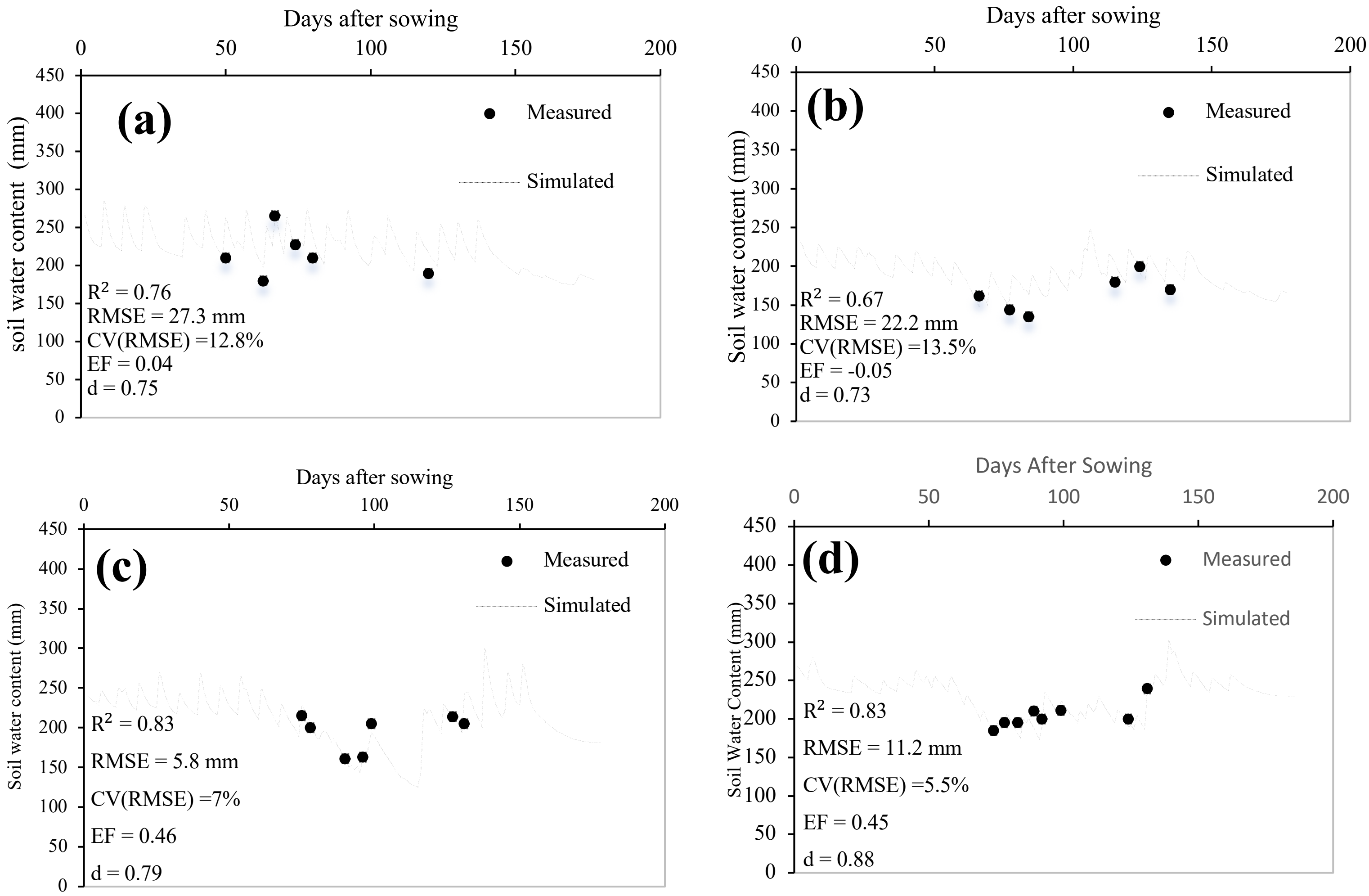


Figure 4.2: Simulated versus measured soil water content under field condition throughout cotton growth period: (a) Field A in 2019, (b) Field B in 2019, (c) Field A in 2020, and (d) Field B in 2020.

Validation of the model based on canopy cover development

The model performed very well considering the outcomes of statistical indicators in estimating the canopy development of cotton for both fields during the cropping seasons in 2019 and 2020 under Mungi conditions (Figure 4.3).

In reference to Figure 4.3, the model well simulated the canopy cover development during initial and mid stages of crop growth at both fields in 2019 and 2020, while in 2020, it slightly overestimated the canopy development in comparison to measured data, especially at the senescence stage of the crop. This unpredictability could be attributed to rapid increase of the temperature from anthesis onward that boosted the senescence stage and led to the decline of the canopy at the Mungi area (Andarzian et al., 2011), while the increase and decline trends of canopy cover were well simulated by the model.

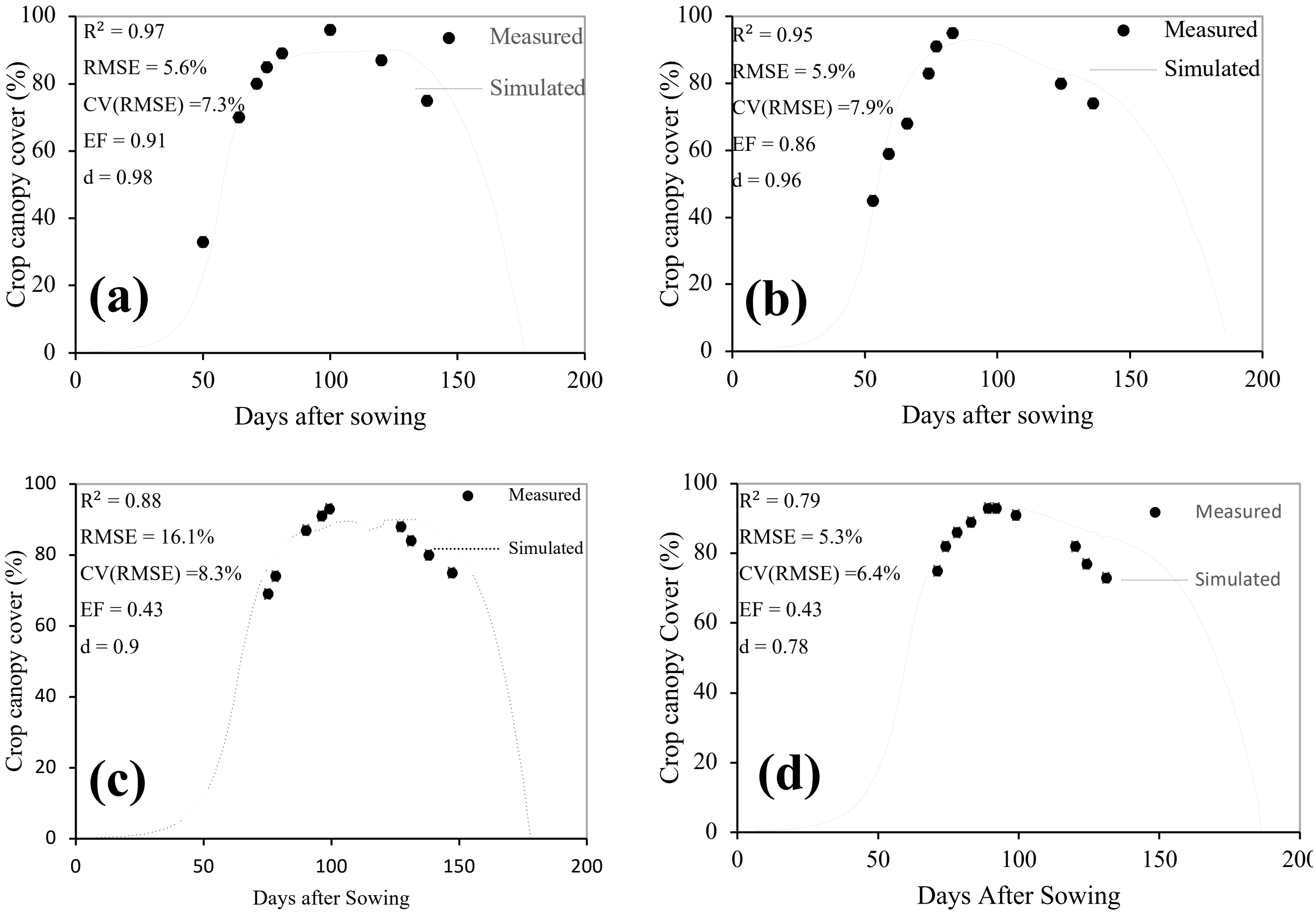


Figure 4.3: Simulated versus measured Canopy Cover of cotton for under field conditions during Kharif season: (a) Field A in 2019, (b) Field B in 2019, (c) Field A in 2020, and (d) Field B in 2020.

Validation of the model based on final seed lint yield and above ground biomass

For Field A, the measured seed lint yield decreased from 2.47 ton ha^{-1} in 2019 to 2.17 ton ha^{-1} in 2020 (simulated yield attained as 2.4 and 2.2 ton ha^{-1}, respectively). In comparison but for the same period, the observed yield for Field B increased from 2.17 to 2.4 ton ha^{-1}, while simulated yields were 2.19 and 2.44 ton ha^{-1}, respectively. The model accurately simulated the cotton yield using GDD in the study conducted by Tsakmakis et al. (2018). The final measured above ground biomass for Field A attained 9.5 and 9.7ton ha^{-1} , while the simulated biomass acquired in the model was 9.5 and 9.6 ton ha^{-1} for 2019 and 2020, respectively. Conversely, the measured biomass from Field B obtained 9.13 and 9.5 ton ha^{-1} and the simulated biomass was 9.2 and 9.5 ton ha^{-1} for 2019 and 2020, respectively. The model predicted very well the measured final aboveground biomass and yield for both fields as R^2 = 0.73 and R^2 = 0.64, respectively, as shown in Figure 4.4.

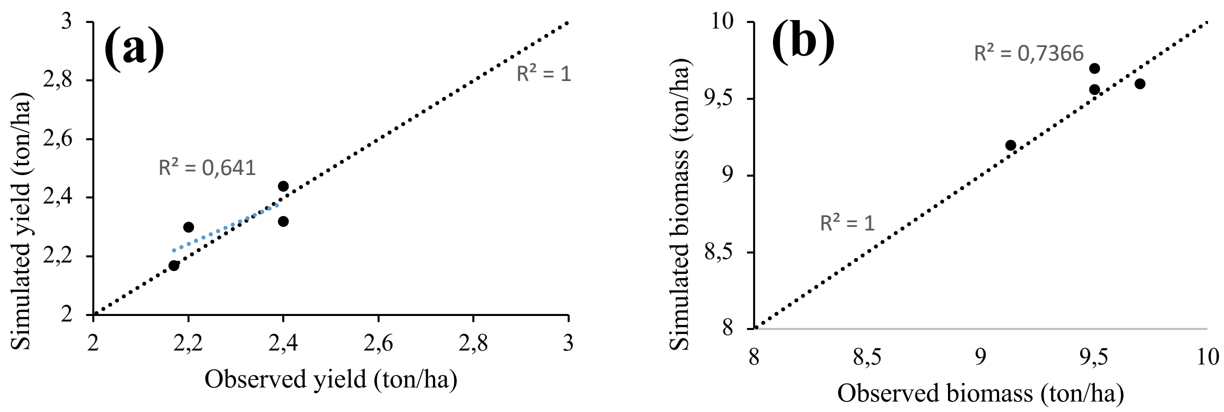


Figure 4.4: Simulated versus observed values of cotton (a) final seed lint yield, and (b) final above ground biomass.

4.4.2 Generating irrigation scheduling scenarios

Scenarios for field A

In reference to Tables 4.4 and 4.5, the results reveal that in the 1st (current practice) scenario for Field A in 2019 and 2020, the farmer applied his mode of water application based on observation of the field and the crop. The average gross irrigation depth per event was ~56 mm (mixed canal water with groundwater or applied solely groundwater). The Warabandi canal water allowance of the farmer was ~17 mm on a weekly basis; therefore, in the 2nd (7 days) and 3rd (14 days) scenarios, the gross water application per event was considered 17 and 34 mm, respectively. While in the 4th or flexible scenario, the irrigation depth varied based on adaption to rainfall events and irrigating below field capacity.

According to Table 4.4, throughout the cotton growth period in 2019, the farmer applied 1,081 mm gross irrigation depth in the 1st scenario, while it was 323 mm in the 2nd, 3rd, and 4th scenarios. Simulating the practiced irrigation under actual field conditions with the validated model leads to 632 mm estimated percolating below the crop's root zone and, therefore, was non beneficial to the crop. Compared to that considerable over irrigation in the 'business-as-usual practice', the percolation below the root zone was 30 and 48 mm for the 2nd and 3rd scenarios, respectively. However, it dropped down to zero in the 4th scenario. In addition, the number of irrigation events decreased significantly in the 3rd and 4th scenarios to 10 and 14 events compared to 18 and 19 events in the 1st and 2nd scenarios, respectively.

Similar results were obtained in Table 4.5, the same farmer applied 857 mm of irrigation depth during the cultivation period of the crop in the 1st scenario in 2020, which is less than 1,081 mm in 2019. As a reason, the farmer stated higher rainfall in 2020. During the crop growing season of 2020, the gross applied water for 2nd, 3rd, and 4th scenarios was 408 mm, and the predicted percolated water was reduced significantly to 12 mm in the 4th scenario, whereas it varied as 468, 71, and 130 mm for the 1st, 2nd, and 3rd scenarios, respectively. The substantial reduction of percolation water in the flexible (4th) scenario was because of adjustment of irrigation events (refilling soil moisture to a value below field capacity, in order to utilize a higher share of rainfall events by storing in the root zone), while in the case of the 2nd scenario, it was mainly due to smaller irrigation depths and more frequent irrigation compared to other scenarios. The slightly higher percolation in the 2nd and 3rd scenarios of 2020 was due to corresponding of rainfall and fixed irrigation events. Also, the higher percolation in cotton fields under rotational irrigation water supply was documented in the study by Angella et al. (2016).

Moreover, a shift from non-productive actual evaporation (E) to beneficial actual transpiration (T) was perceived in the irrigation scheduling scenarios. Table 4.4 presented that in 2019, for the 1st, 2nd, 3rd, and 4th scenarios, the actual E varied as 239, 201, 173 and 179 mm, while the actual T differed as 554, 462, 471, and 511 mm, respectively. Similarly, in 2020 considering the 1st, 2nd, 3rd, and 4th scenarios, the actual

E showed decreasing trend of 233, 220, 186, and 166 mm, while actual T varied as 585, 536, 507, and 590 mm, respectively (Table 4.5). The variation of actual transpiration and evaporation under deficit irrigation scenarios in cotton using the AquaCrop model was also reported in the study by Farahani et al. (2009).

The significant reduction in percolated water and shifting of actual E to actual T during irrigation planning scenarios affected the seed lint yield and harvest index. The 4th scenario simulation for Field A in both 2019 and 2020 resulted in a similar yield of 2.2 and 2.28 $\mathrm{ton\ ha^{-1}}$ compared to the recorded yield under the actual farmer's irrigation management (1st scenario) as 2.2 and 2.3 $\mathrm{ton\ ha^{-1}}$, respectively. This indicates that the current yield can be maintained despite a significant reduction in irrigation water input.

Moreover, slightly lower yields of 1.77 and 1.87 $\mathrm{ton\ ha^{-1}}$ in the 2nd and 3rd scenarios of 2019 compared to 2020 as 2.39 and 2.45 $\mathrm{ton\ ha^{-1}}$ was largely due to early sowing of cotton on March 25th, 2020 than that in first of May, 2019. Early sowing in 2020 allowed the crop to reach maturity before peak temperature in June over 40°C in the Mungi area. This is important because flowers and pollination could be affected by a spike in temperature–an issue becoming even more important in the future due to the expected impact of climate change (Li et al., 2020; Mudassir et al., 2021). Moreover, contribution of rainfall was 380 mm in 2020 as compared to that as 266 mm in 2019.

Table 4.4: Comparison of the irrigation scheduling scenarios for Field A in 2019.

Scenario description	No. of irrigation event	Applied water (mm)	T Actual (mm)	E Actual (mm)	ET actual (mm)	Drain below root zone (mm)	Biomass $\mathrm{ton\ ha^{-1}}$	Yield $\mathrm{ton\ ha^{-1}}$	Harvest Index (%)
1st current practice	18	1081	554	239	793	632	9.7	2.2	22.5
2nd 7-days rotation	19	323	462	201	663	30	8.2	1.77	21.5
3rd 14-days rotation	10	323	471	173	644	48	8.4	1.86	22.1
4th Flexible	14	323	511	179	689	0	9.1	2.2	23.8

**266 mm rainfall was considered over the crop growth period for all the above scenarios. The current practice irrigation period (May 1st– September 4th, 2019) was the basis for all the scenarios.*

Table 4.5: Comparison of the irrigation scheduling scenarios for Field A in 2020.

Scenario description	No. of irrigation event	Applied water (mm)	T Actual (mm)	E Actual (mm)	ET Actual (mm)	Drain below root zone (mm)	Biomass $\mathrm{ton\ ha^{-1}}$	Yield $\mathrm{ton\ ha^{-1}}$	Harvest Index (%)
1st current practice	19	857	585	233	818	468	9.6	2.3	24.1
2nd 7-days rotation	23	408	536	220	757	71	9.49	2.39	25.2
3rd 14-days rotation	12	408	507	186	693	130	9.23	2.45	26.6
4th Flexible	10	408	590	166	755	12	9.6	2.28	23.8

**380 mm rainfall was considered over the crop growth period for all the above scenarios. The current practice irrigation period (March 25th–September 5th, 2020) was the basis for all the scenarios.*

As depicted in Figure 4.5, the simulation of Field A in 2019 showed that the 4th scenario resulted in maximum ET and gross water productivity as 0.32 and 0.68 $\mathrm{kg\ m^{-3}}$ in comparison to all other scenarios, respectively. While in 2020, the 3rd scenario led to the highest ET and gross water productivity of 0.37 and 0.6 $\mathrm{kg\ m^{-3}}$, respectively. A slightly higher yield was predicted in 2020 for the 2nd and 3rd scenarios as 2.39 and 2.45 $\mathrm{ton\ ha^{-1}}$, when compared to the 4th scenario as 2.28 $\mathrm{ton\ ha^{-1}}$. This difference is due to slightly higher biomass and lower harvest index in the 4th scenario as 9.6 $\mathrm{ton\ ha^{-1}}$ and 23.8%, respectively, compared to biomass and harvest index obtained for the 2nd scenario as 9.49 $\mathrm{ton\ ha^{-1}}$ and 25.2% and for the 3rd scenario as 9.23 $\mathrm{ton\ ha^{-1}}$ and 26.6%, respectively. This indicates that the higher water stress in the vegetative growth period of the cotton crop in the 2nd and 3rd deficit irrigation scenarios demonstrated a positive impact on the harvest index which is in-line with findings documented in other studies on cotton growing (García-Vila et al., 2009; Steduto et al., 2009).

In both years, the gross water productivity was achieved higher in all three Warabandi deficit irrigation scenarios compared to the current irrigation management, while ET water productivity was slightly higher in 2019 for the 1st scenario as 0.3 $\mathrm{kg\ m^{-3}}$in comparison to the 2nd and 3rd scenarios 0.27 and 0.29 $\mathrm{kg\ m^{-3}}$, respectively (largely due to over irrigation that the crop did not go under water stress). The flexible irrigation (4th scenario) led to better performance (higher ET and gross water productivity) than all scenarios in 2019 and similar outcomes with the 2nd and 3rd scenarios in 2020. Moreover, several studies reported the improvement of water productivity considering deficit irrigation on cotton using the AquaCrop model under differing agro-ecological zones (Yang et al., 2015; Hussein et al., 2011; Akhtar et al., 2013; Jalota et al., 2006; Linker et al., 2016).

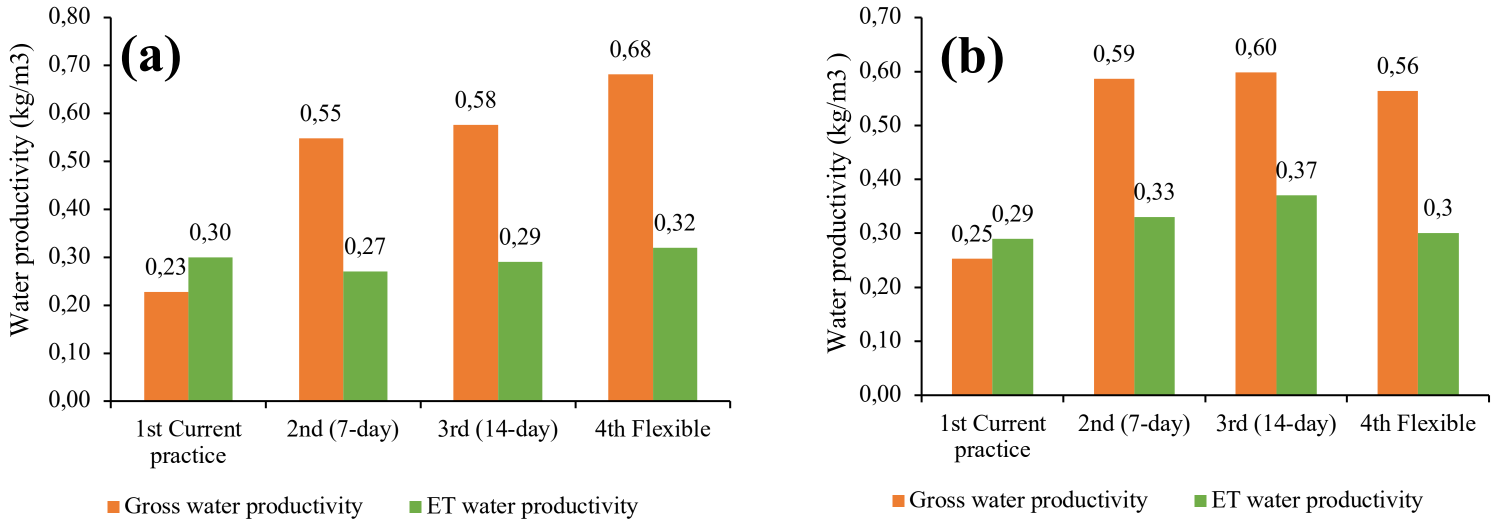


Figure 4.5: ET and gross water productivity under different irrigation scheduling scenarios for Field A in (a) 2019 and (b) 2020.

Scenarios for field B

Farmer of Field B gets a limited amount of 10 mm on weekly basis from canal water based on the Warabandi principle. The allocation of the farmer was reduced due to the construction of a bridge over the Mungi Distributary canal. The farmer's average gross water input per event was ~35 mm in the 1st scenario in 2019 and 2020, while it varied for the 4th scenario and the canal allocation was considered as 10 and 20 mm for the 2nd and 3rd scenarios, respectively.

The farmer applied 668 mm depth of water in 2019 under the current practice and a total of 210 mm gross water input was simulated for the 2nd, 3rd, and 4th scenarios throughout the cotton cultivation period (Table 4.6). The simulation outputs in Table 4.6 showed that the amount of water drained below the root zone was eliminated under the 4th scenario, while it decreased substantially as 260, 8, and 16 mm for the 1st, 2nd, and 3rd scenarios, respectively. In the same way, the farmer irrigated the cotton plot in 2020 by applying 527 mm during the growth period of the crop and 240 mm of applied water was considered for the 2nd, 3rd, and 4th scenarios as depicted in Table 4.7. The percolated water was higher in the 1st scenario as of 141 mm while it was simulated as null under the 4^{th} scenario and remarkably decreased to 16 and 21 mm for the 2^{nd} and 3^{rd} scenarios, respectively.

Water balance components in Field B also revealed a shift from actual E to actual T during both cultivation seasons in both years (Tables 4.6 and 4.7). In 2019, the simulation output indicated that actual E was similar in both (1^{st} and 2^{nd}) scenarios as 175 mm and it reduced to 160 and 134 mm for the 3^{rd}, and 4^{th} scenarios, respectively, while actual T increased to 402, 408, and 446 mm for the 2^{nd}, 3^{rd}, and 4^{th} scenarios respectively. A Similar tendency was revealed in 2020 and the model results for the 2^{nd}, 3^{rd}, and 4^{th} scenarios showed a decrease of actual E as 169, 170, and 140 mm and actual T improved such as 445, 447, and 535 mm, respectively.

The variation of actual E and actual T resulted in an improvement in yield across scenarios. For instance, for the 2^{nd}, 3^{rd}, and 4^{th} scenarios in 2019, the yield improved to 1.89, 2.02, and 2.1 ton ha^{-1}, while in 2020, the yield maintained for the mentioned scenarios as 2.69, 2.67 and 2.68 ton ha^{-1}, respectively. Furthermore, in 2020, despite a lower actual T of 445 mm in the 2^{nd} scenario compared to that of 535 mm under the 4^{th} scenario (Tables 4.6 and 4.7), both scenarios (2^{nd} and 4^{th}) resulted in similar yield of 2.69 and 2.68 ton ha^{-1} respectively. This difference in actual transpiration was attributed to a difference in the production of biomass for the 2^{nd} scenario as 9.39 ton ha^{-1} led to a harvest index of 28.7%, while, for the 4^{th} scenario, it was achieved as 9.5 ton ha^{-1} and resulted in harvest index of 28.3%. Therefore, in the AquaCrop model, the actual T was transformed into biomass and subsequently to yield in accordance with HI (Farahani et al., 2009). Differences in cotton yield across the deficit simulation scenarios were associated with the relationship between biomass production, yield formulation, and HI (Steduto et al., 2009), and were also attributed to actual transpiration during the cotton yield production stages, which are flowering and bud formation, while these stages are also sensitive to water stress (Himanshu et al., 2019; Jalota et al., 2006).

Moreover, obtaining similar cotton yield with lower ET and applied water (under deficit irrigating scenarios), in comparison with the current practice is attributed to a curvilinear relationship between cotton yield, ET, and applied water, where yield shortfall varies proportionally with the square of the relative deficit of applied water

(García-Vila et al., 2009, Orgaz et al., 1992; Steward and Hagan, 1973). Evidently, in the current study, the trend of cotton yield under current practices and deficit irrigation scenarios is in the range of findings reported in other studies (Linker et al., 2016; Akhtar et al., 2013).

Table 4.6: Comparison of the irrigation scheduling scenarios for Field B in year 2019.

Scenario description	No. of irrigation event	Applied water (mm)	T Actual (mm)	E Actual (mm)	ET Actual (mm)	Drain below root zone (mm)	Biomass $\mathrm{ton\ ha^{-1}}$	Yield $\mathrm{ton\ ha^{-1}}$	Harvest Index (%)
1st current practice	20	668	541	175	717	260	9.2	2.19	23.8
2nd 7-days rotation	21	210	402	175	576	8	8.2	1.89	22.8
3rd 14-days rotation	11	210	408	160	567	16	8.3	2.02	24.2
4th Flexible	11	210	446	134	581	0	8.44	2.1	24.6

**266 mm rainfall was considered over the crop growth period for all the above scenarios. The current practice irrigation period (24st April -14th September) was the basis for all the scenarios.*

Table 4.7: Comparison of the irrigation scheduling scenarios for Field B in year 2020.

Scenario description	No. of irrigation event	Applied Water (mm)	T Actual (mm)	E Actual (mm)	ET actual (mm)	Drain below root zone (mm)	Biomass $\mathrm{ton\ ha^{-1}}$	Yield $\mathrm{ton\ ha^{-1}}$	Harvest Index (%)
1st current practice	23	527	577	170	747	141	9.56	2.44	25.5
2nd 7-days rotation	24	240	445	169	614	16	9.39	2.69	28.7
3rd 14-days rotation	13	240	447	170	617	21	9.39	2.67	28.5
4th Flexible	12	240	535	140	675	0	9.5	2.68	28

**340 mm rainfall was considered over the crop growth period for all the above scenarios. The current practice irrigation period (11st April - 20th September) was the basis for all the scenarios.*

Figure 4.6 (a, b) indicated maximum values of gross water productivity in the 4rd scenario as 1 and 1.12 $\mathrm{kg\ m^{-3}}$ in 2019 and 2020, compared to all other scenarios. Moreover, ET water productivity of the 3rd and 4th scenarios attained the highest as 0.36 $\mathrm{kg\ m^{-3}}$in 2019, while in 2020 it was 0.44 $\mathrm{kg\ m^{-3}}$ for the 2nd and 3rd scenarios and 0.4 $\mathrm{kg\ m^{-3}}$ for 4th and the lowest as 0.33 $\mathrm{kg\ m^{-3}}$ for the business-as-usual scenario. As a result, scenarios of Field B revealed similar results as Field A that deficit irrigation planning of solely Warabandi water allowance, especially the 4th scenario as flexible irrigation resulted in better gross and ET water productivity compared to the actual practice by minimizing the percolation and evaporation as non-beneficial uses of water to the crop while maintaining similar yield.

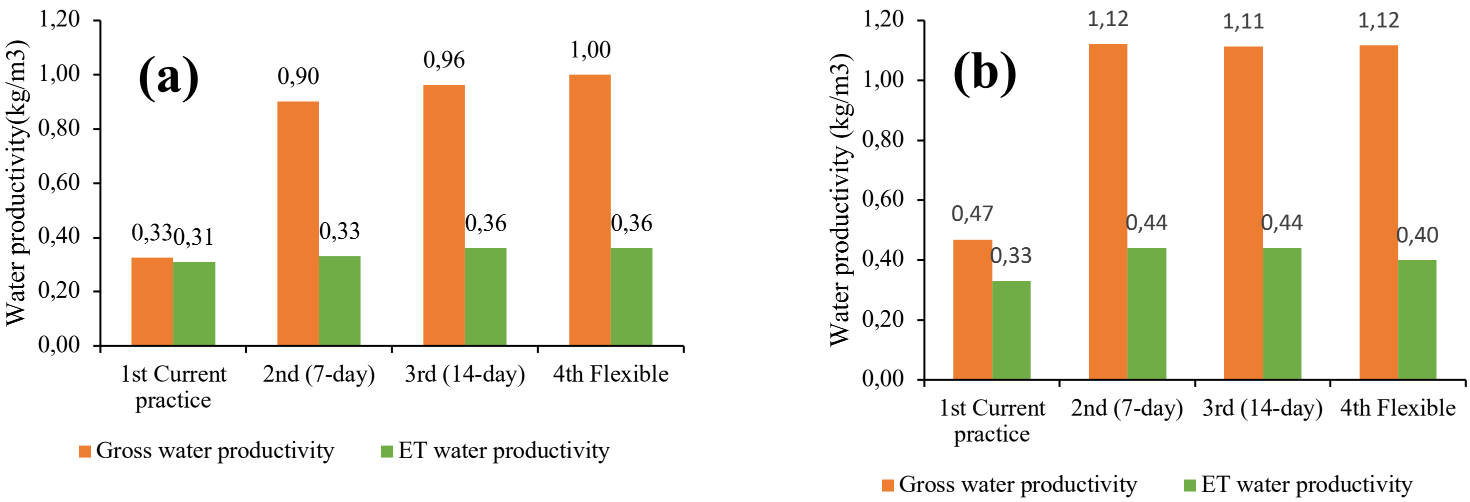


Figure 4.6: ET and gross water productivity under different irrigation scheduling scenarios for Field B in (a) 2019 and (b) 2020.

4.4.3 Long-term assessment of irrigation scheduling scenarios

Figure 4.7 presents the cumulative probability of cotton yield considering 13 years of simulation for three irrigation planning scenarios generated based on the cultivation of cotton practiced at fields A and B during the years 2019 and 2020.

The simulations over the years showed higher variability of cotton yields for 2nd and 3rd deficit irrigation scenarios due to climate variability especially rainfall and temperature, while it presented steadiness of yield for the optimal scenario (in long-term assessment of irrigation scheduling, scenario 4 changed from flexible to optimal) because it does not let the crop go under water stress and refill the soil to field capacity level each time the soil moisture reduces to 30% of the allowable depletion zone. Overall, the cumulative probability of cotton yield over 0.5 value for both fields considering 13 years of simulation reveals a similar yield in all scenarios. It indicates that the deficit irrigation scenarios as 2nd and 3rd in rainy growing seasons (wet years) of cotton could produce a similar yield as it produces in the optimal scenario; therefore, the cotton yield responses under deficit irrigation largely benefit from the seasonal rainfall (Himanshu et al., 2019). Moreover, early sowing of cotton resulted in better yield

(Ruigu, 2016), which is indicated by the increasing trend of yields in the 2nd and 3rd scenarios using an early sowing in both fields in 2020, compared to 2019 (Field A's sowing time was May 1st, 2019 and March 25th, 2020, while Field B's sowing timing was April 24th, 2019 and April 11th, 2020).

The focus of this study was on cotton yield response to the water input especially irrigation and rainfall, while cotton yield difference is largely diverse and linked to multiple interdependent factors including water, seed quality, disease control, fertilizer application, climatic conditions, soil characteristics, and crop cultivar. Non-water agriculture inputs including diseases control, adequate fertilizer application, and improved seeds could boost crop production and enhance water use efficiency. Therefore, several studies documented the variation of cotton yield under irrigation intensification as in this study (Aujla et al., 2005, Cetin and Bilgel, 2002; Onder et al., 2009).

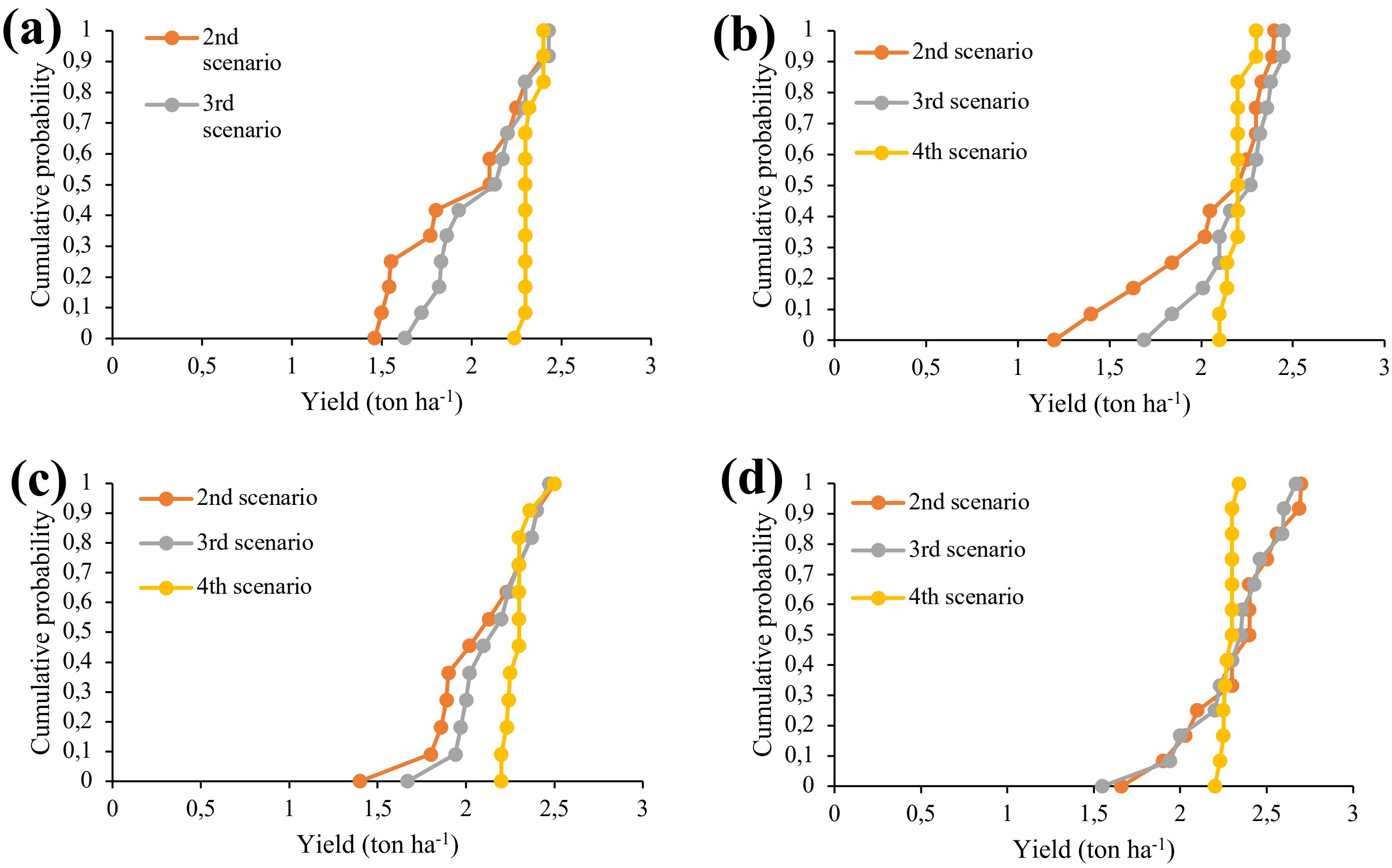
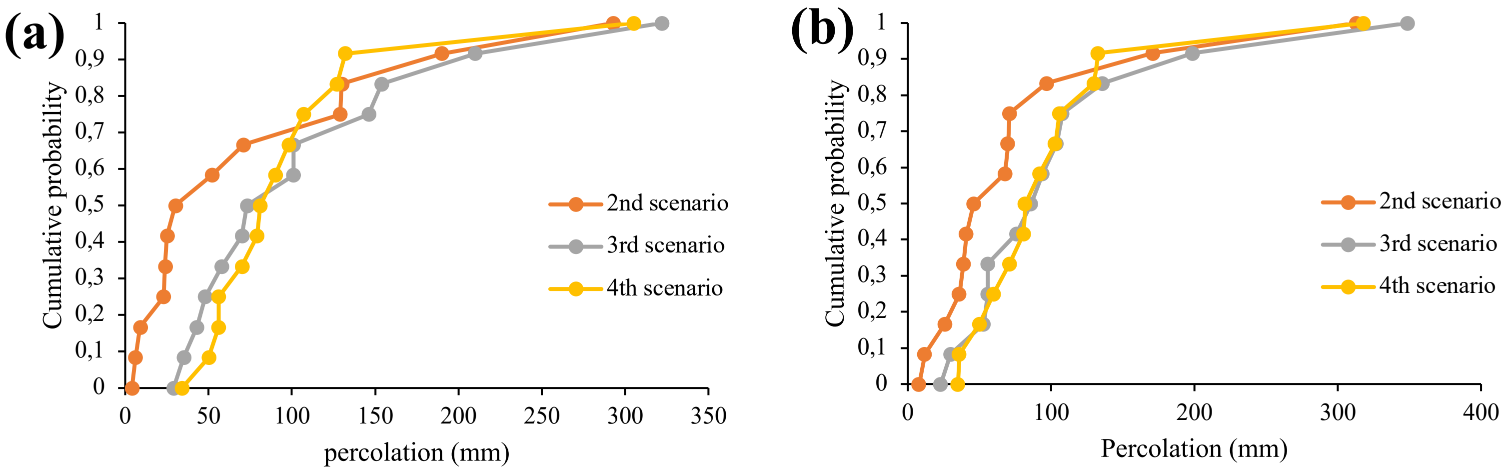


Figure 4.7: Cumulative probability of cotton yield for 13 years of simulations considering three irrigation planning scenarios under irrigation management of Field A in (a) 2019, (b) 2020, and Field B in (c) 2019, (d) 2020.

Figure 4.8 shows slightly higher percolation in the optimal (4th) scenario for Field B in 2019 and 2020 compared to Field A, which is associated with soil properties in Field B as sandy clay loam with lower water holding capacity compared to Field A exhibiting loamy soil which is shown in Table 3.2. While slightly lower percolation during the 2nd and 3rd scenarios of Field B in 2019 and 2020 is due to smaller depths of water application at each event such as 10 and 20 mm, respectively, whereas for Field A, it was 17 and 34 mm for the 2nd and 3rd scenarios, respectively.

Moreover, the percolation depths across the scenarios for both fields during 13 years ranged from 0 to 350 mm, which indicates the correspondents of irrigation to rainfall events. Even in the case of the optimal (4th) scenario that refilling the soil to field capacity could be followed by an intense rainfall event. Therefore, flexible irrigation scheduling could manage to eliminate the percolation amount completely and maintain the yield as depicted in Tables 4.4, 4.6, and 4.7.



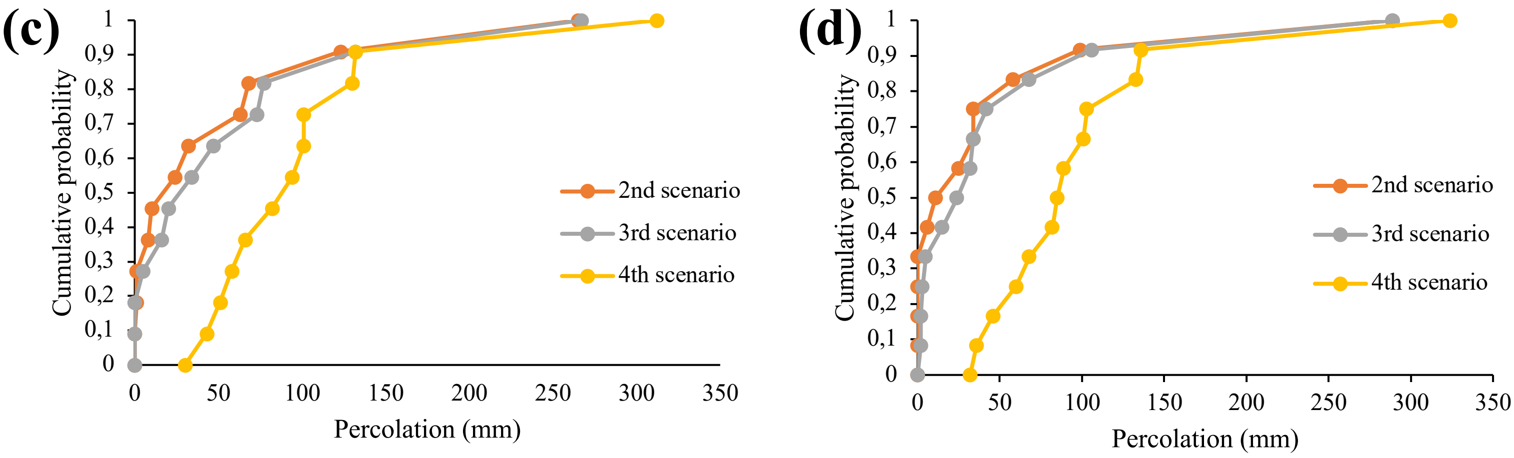
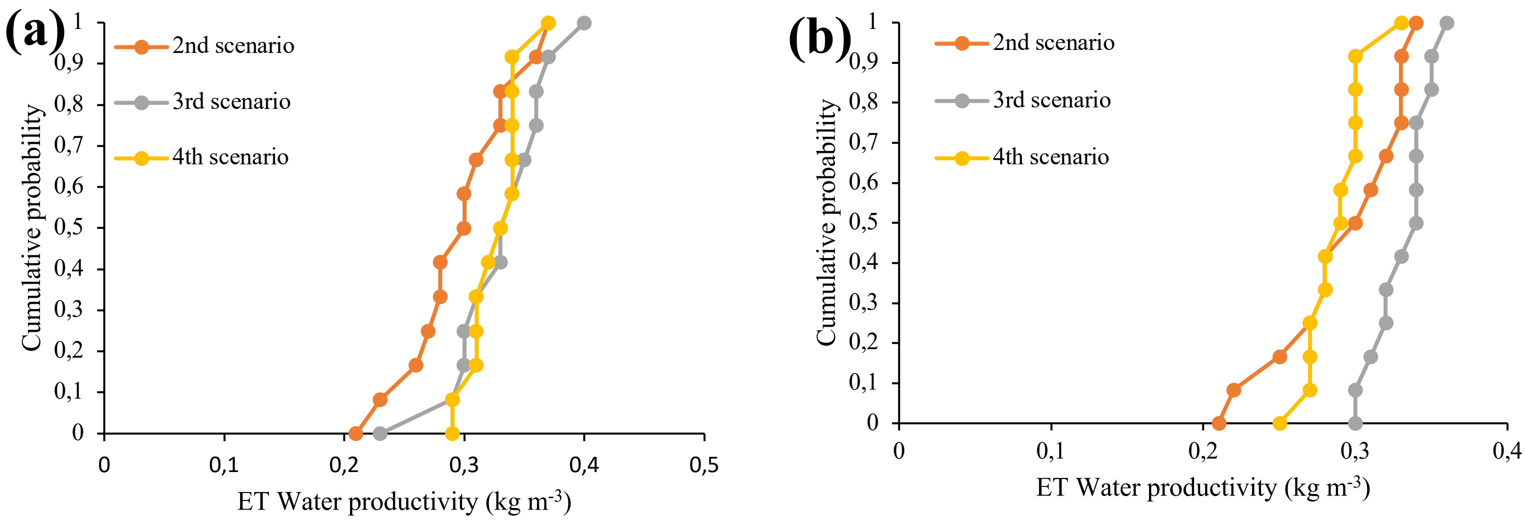


Figure 4.8: Cumulative probability of percolated water below cotton root zone for 13 years of simulations considering three scenarios under irrigation management of Field A in (a) 2019, (b) 2020, and Field B in (c) 2019, (d) 2020.

Figure 4.9 (a, b, c, d) highlighted the stability of ET water productivity of 4th scenario over the years, whereas higher ET water productivity is obtained in 2nd and 3rd deficit irrigation scenarios for both fields that resulted in better utilization of soil moisture content and rainfall events while maintaining the yields (Himanshu et al., 2019, Angella et al., 2016).



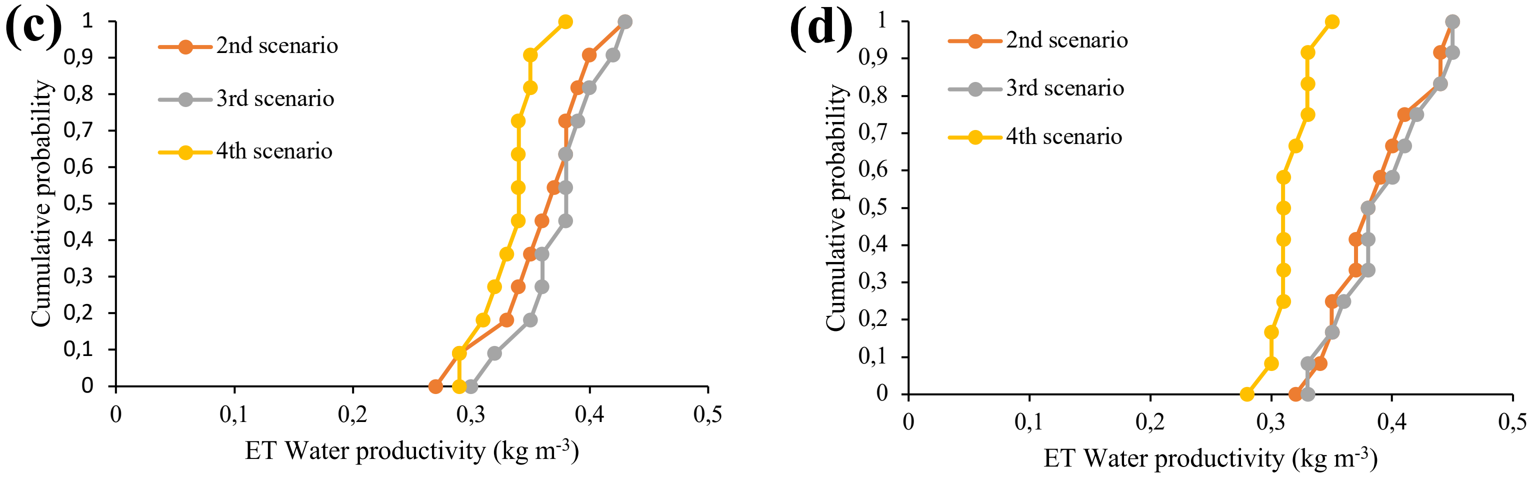


Figure 4.9: Cumulative probability of ET water productivity for 13 years of simulations considering three scenarios of Field A in (a) 2019, (b) 2020, and Field B in (c) 2019, (d) 2020.

4.5 Discussion and conclusion

The deficit irrigation planning scenarios as fixed (2nd and 3rd) and flexible (4th) resulted in higher gross and ET water productivity in comparison to that under current practices. Several studies investigated and addressed the relationship between deficit irrigation of cotton, its water stress stages and yields. Himanshu et al. (2019) imposed deficit irrigation on cotton at various growth stages in the Southern High Plains. They revealed that assigning a water deficit to cotton during the initial and late stages of growth exhibited little effect on decreasing yield or water use efficiency. The mid-season growth period, on the other hand, was highly sensitive to water stress, with a significant fall in yield reported. Similarly, Jalota et al. (2006) indicated flowering to boll formation growth stage in cotton was the most sensitive to water stress. Akhtar et al. (2013) conducted a similar study on applying deficit irrigation conditions to cotton in Uzbekistan. They demonstrated that reducing applied water by 12% (removing irrigation events) at the late development stages of cotton boosted yield by 8%.

This study considered scenario 4 (flexible irrigation scheduling) as the most promising option for utilizing Warabandi water allocation because it considered flexible and demand-oriented water application by targeting cotton's most water stress-sensitive stages, resulting in reduced percolation and non-productive evaporation and higher gross water productivity and yield (Tables 4.4, 4.6, and 4.7; figures 4.5 and 4.6). While fixed rotation intervals of 7 and 14 days corresponded to rainfall events and led to slightly higher percolation (Tables 4.4, 4.5, 4.6, and 4.7), also they did not consider the crop's critical stages of water stress. Furthermore, the storage characteristics of the soil, which is a realistic option for cotton fields (A and B) with mostly loamy soils mobilized and facilitated the potential of irrigating cotton with longer intervals and better performance of deficit irrigation scenarios (3rd and 4th). Additionally, the rigid rotation (7-days) of the current Warabandi principle is not too long and the cotton's initial stages are less sensitive to water stress (Li et al., 2019, Zonta et al., 2017; Himanshu et al., 2019).

Therefore, these features (soil texture and short rotation under the Warabandi) create an enabling environment for farmers to store the surplus Warabandi water allotment in a storage facility on their farms during the cotton's initial stages, pre-cultivation period, and rainy days (monsoon rains). The stored water then could be utilized to meet crop's demand at the most critical periods of cotton, which are flowering and boll formation. Furthermore, if farmers are assured (due to the existence of storage facilities on their farms) that they will be able to use the stored water in yield-sensitive periods, they are willing to preserve the surplus canal water and store it rather than apply it to the field at each rotation. While unfolding the potential of the storage facility using a sensor-based soil moisture monitoring could facilitate to adapt irrigation application slightly below field capacity level and after rainfall occurrence as in case of the 4th scenario (flexible) (Rivers et al., 2015; Blonquist et al., 2006).

Flexible and demand-oriented irrigation (4th scenario) not only closed the yield gap compared to actual practices (Tables 4.4, 4.6, and 4.7), but it also significantly lowered the percolation of water below root zone of the crop, which could greatly reduce the pressure on groundwater pumping using fuel energy and prevent aquifer contamination by percolated water from irrigated fields (loaded with fertilizers and plant protective agents) (Tischbein et al., 2013). Similarly, switching from rotational canal water supply to on-demand irrigation improved cotton yield by 20% and dramatically enhanced water productivity in Argentina's Rio Dulce irrigation system

(Angella et al., 2016). It also performed better in terms of water use efficiency than the conventional rotational canal system in Iran's Aghili irrigation network (Savari et al., 2016).

5 ASSESSING BARRIERS IN ADAPTATION OF WATER MANAGEMENT INNOVATIONS UNDER ROTATIONAL CANAL WATER DISTRIBUATION SYSTEM

This chapter has been published[2]. https://doi.org/10.3390/agriculture12070913

5.1 Abstract

This study assessed problems associated with irrigation water provisions and the potential barriers to the adaptation of the interventions (soil moisture sensors, on-farm water storage facilities and the drip method) under rotational canal water distribution in Punjab, Pakistan. Three groups of stakeholders were individually surveyed during September–December 2020: (i) 72 farmers, (ii) 15 officials, and (iii) 14 academicians. We used descriptive statistical analysis, cross-tabulation and the Fisher test to explore the pattern of responses across the groups. The main problems in the canal water distribution system were expressed by the farmers as limited water allocation, while academicians were concerned mostly with inflexibility and officials indicated discussion among neighbours. According to the farmers' responses, the conventional depth/interval of irrigation is flooding the field with water and observing the plants, indicating over-irrigation behaviour. Moreover, the most important barriers in the adaptation of the interventions that were highly rated by the three groups were low awareness, lack of training and financial resources. Additionally, farmers' education revealed a statistically significant influence on awareness of soil moisture sensors and water storage facilities, while large farm holders showed a positive relationship to conducting a joint experiment with scientists and farmers' associations on part of their land to improve water use efficiency.

Keywords: Rotational water distribution, water management intervention, adoption, obstacles

[2] Sajid, I.; Tischbein, B.; Borgemeister, C.; Flörke, M. Assessing Barriers in Adaptation of Water Management Innovations Under Rotational Canal Water Distribution System. *Agriculture* **2022**, *12*, 913. https://doi.org/10.3390/agriculture12070913

5.2 Introduction

This chapter focuses on the implementation of a package from water management interventions that includes soil moisture sensors, on-farm water storage facilities, and the drip technology. The performance of on-farm water storage has been assessed in India under the Warabandi conditions, indicating that on-farm water ponds have facilitated the implementation of sprinkler techniques and the pond-based sprinkler system resulted in improved water use efficiency, cropping yield, and net benefits (Amarasinghe et al., 2012). While Qureshi (2014) also recommended on-farm water storage intervention for canal water management in Pakistan that enables the storage of potential surplus water under rigid rotations. Moreover, it provides an enabling environment for efficient irrigation systems such as drip, which requires frequent irrigation of rather small amounts to unfold the full potential of that technique. Therefore, drip, as an advanced irrigation method, was highly recommended for improving water use efficiency in water stress conditions of Pakistan (Latif et al., 2016). Furthermore, sensor-based soil moisture monitoring supports farmers regarding when and how much water to irrigate, which has resulted in a substantial saving of irrigation water in other regions of the world (Blonquist et al., 2006; Rivers et al., 2015). The combination of an on-farm water pond, provision of irrigation scheduling and a drip technique have achieved higher water productivity at the farm level for cotton crop given the framing conditions of the Warabandi in Punjab, Pakistan (Weber et al., 2019).

A number of studies have addressed the on-farm water management issues and proposed interventions to the limited canal water allocation problems in the Warabandi-guided irrigation scheme. Khan et al. (2021) suggested introducing of low water demand crops, and adoption of efficient irrigation system. Similarly, Anwar et al. (2016) showed field layout improvements enabling the lowering of irrigation depths, thereby enhancing field application efficiency. In addition, another study supported the application of the laser grade profile and the furrow irrigation method (Anwar and Ahmad, 2020), while Latif et al.(2016) advised drip irrigation and Bakhsh et al. (2018) proposed bed planting method. However, they lack the consideration of barriers and obstacles in implementing these measures. Whereas, other studies assessed the potential barriers to the adaptation of several climate-smart agricultural practices for boosting the productivity of water and non-water agricultural inputs (Abid et al., 2015; Ali and Erenstein, 2017; Imran et al., 2018; Jamil et al., 2021; Khan et al., 2021; Shahid et al., 2021; Zardari and Cordery, 2010). Hence, the options for technical interventions are available; therefore, a major tasks which remains to be addressed is determining, how these interventions could be clustered and implemented, – which is basically the intention of this study with a focus on selected interventions forming a package.

Therefore, this study distinctively considered the evaluation of obstacles hindering the introduction of irrigation scheduling as a package of water management interventions for the farmers' farms under the rigid and erratic canal water supply. Thus, the main stakeholders (farmers, officials, and academicians) were involved and surveyed to reveal the integrated perspectives on the hurdles that require support to advance the understanding of the feasibility process for adopting the measures by farmers.

The study aims to assess the problems associated with the irrigation water provisions and the potential barriers to the adaptation of water management interventions on farmers' farms under the framing conditions of the Warabandi principle. This research attempts to support making the implementations more targeted by considering the requirements and views of the water users (farmers), water suppliers (officials of irrigation administration) and academicians.

5.3 Material and methods

5.3.1 Survey structure

The study designed a survey with a semi-structured, multiple-choice, rated, and open-ended format. During the months of September-December 2020, three different groups of stakeholders were surveyed: (i) 72 farmers were randomly selected in the command area of the Mungi Distributary canal, (ii) 15 government officials, and (iii) 14 academicians. The sample represents demographic attributes of a cross-section of farmers with differing schooling years, farm location along the Mungi Distributary canal, farm size, land ownership, and years of experience, whereas officials and academicians were selected based on their background related to irrigation water management.

The sample size was limited due to an ongoing wave of the Covid19 infection in the study area in 2020. The survey was conducted individually and face to face taking into account the Covid19 safety measures, with the assistance of a local language translator.

The survey questionnaires were broadly focused on the challenges of Warabandi water distribution faced by farmers in the fields/farms, the proposed water management interventions and the barriers to implementing these measures. The interventions led towards a more flexible irrigation strategy within the farms, taking into account the framing condition of the Warabandi in larger-scale water allocation.

Water management interventions were selected as water storage facilities, usage of soil moisture sensors and a combination of an on-farm water pond, soil moisture sensors and the drip technology. These interventions function as adaptation measures on farmers' farms to deal with the challenges associated with the unreliable and limited canal water supply versus a rising and increasingly variable water demand.

The experience during previous field work with the farmers and the literature permitted the identification of a set of potential barriers that may affect the implementation of selected interventions. They are summarized as follows: low awareness, lack of financial resources, operation and maintenance, and lack of training (Jamil et al., 2021; Shahid et al., 2021). The survey tried to quantify the relative importance of these barriers based on stakeholders' opinions (farmers, scientists, and officials).

5.3.2 Method of analysis

The study used descriptive statistical analysis, frequency tables, cross-tabulation and the Fisher test in order to compare and explore the impact and pattern of responses across three groups.

A cross-tabulation is a joint frequency distribution of incidents considering two or more categorical variables. The Fisher exact test can be used to assess whether the variables are statistically independent or whether they are associated by using the joint frequency distribution. It also compares the actual and expected data distribution within categories. If there is an association between variables, then other indicators of the relationship could be applied to explore the degree to which the values of one variable predict or differ from those of the other variable. A significance threshold of p=0.05 (De Veaux et al., 2008) was set. The more significant the finding is, the smaller the p-value is. The study explored whether a statistically significant relationship between independent variables (farmers' education, experience, land ownership, farm size, and field location) and the categorical variables exists or not. The null hypothesis (N_0) was that there is no relationship between independent and categorical variables. Stata statistical software was used for data analysis.

For rating questionnaires, participants from the three groups were asked to rate the strength of each potential barrier from 0 to 5 for the adaptation of a water management intervention. A rating of '0' indicates the barrier that does not affect the adaptation of the measure and a rating of '5' shows the strongest effect of the barrier on implementation of the relevant intervention. The study categorized the effect of barriers from 3 to 5 as strongest, while 1 to 3 indicated a moderate effect, and 0 to 1 showed a low effect. Spider graph presents the aggregated average rating as the perception of each group on strength of the effect of potential barriers identified for implementation of each measure. Categorization permitted to visualize the responses in a spider graph and compare the most or least important aspects agreed by all the groups.

5.4 Results

5.4.1 Descriptive statistics

Table 5.1 shows the demographic characteristics of the farmers and revealed that 52% of the farmers had a secondary school education, with an average of ~8 years of schooling, while 18% had no formal education. The respondents showed an average farming experience of ~12 years and the average farm size was ~4 hectares (10 acres), which is in line with the study that reported approximately 90% of Pakistan's farmers are small-scale, with landholdings of less than 5 hectares (Jamil et al., 2021). Moreover, the majority of the farmers (~75 %) were landowners, while the farms' distribution over the Mungi Distributary canal was scattered over the head, mid, and tail as 25, 40, and 34%, respectively.

Table 5.1: Heterogeneous attribution of the farmers (total participants= 72).

Farmers' characteristics	Indicators	Frequency	Percentage	Average	Standard deviation
Farmers education	No formal education	13	18.06	8.29	4.50
	Primary school	7	9.72		
	Secondary school	38	52.78		
	College	10	13.89		
	University	4	5.56		
Farmers experience	1-12 years	37	51.39	12.62	4.45
	>12 years	35	48.61		
Farm size	1-4 ha	39	54.17	10.45	8.28
	>4 ha	33	45.83		
Land ownership	Tenant	18	25		
	Land owner	54	75		
Field location along Mungi canal	Head	18	25		
	Middle	29	40.28		
	Tail	25	34.72		

On the question of environmental changes in the Mungi area over the past two decades considering multiple choice options, over 50 % of the farmers reported a decrease in canal water allocation. The dropping of the groundwater table, deteriorating in its quality and increasing land and soil salinity in the area have been observed by the farmers and were reflected in their responses as 43, 28 and 37%, respectively (Figure 5.1). Despite the efforts of the institutions in improving the performance of the irrigation infrastructure in recent years, the decrease in the canal water allocation is attributed to old water infrastructures and poor operation and maintenance resulting in high conveyance losses (Hussain et al., 2011), while increasing intensification and the introduction of new and water-demanding crops (e.g. sugarcane) have led to a higher demand (which is aggravating canal supply and demand gaps). Moreover, these factors could be associated with the impact of climate changes, the sedimentation of the reservoirs and sharpening competition for water use (agriculture, industry, domestic use and environment)(Sarwar, 2019). The deteriorating groundwater quality is attributed to the percolation of irrigation water loaded with fertilizers and agricultural substances into aquifers (Sajid et al., 2022).

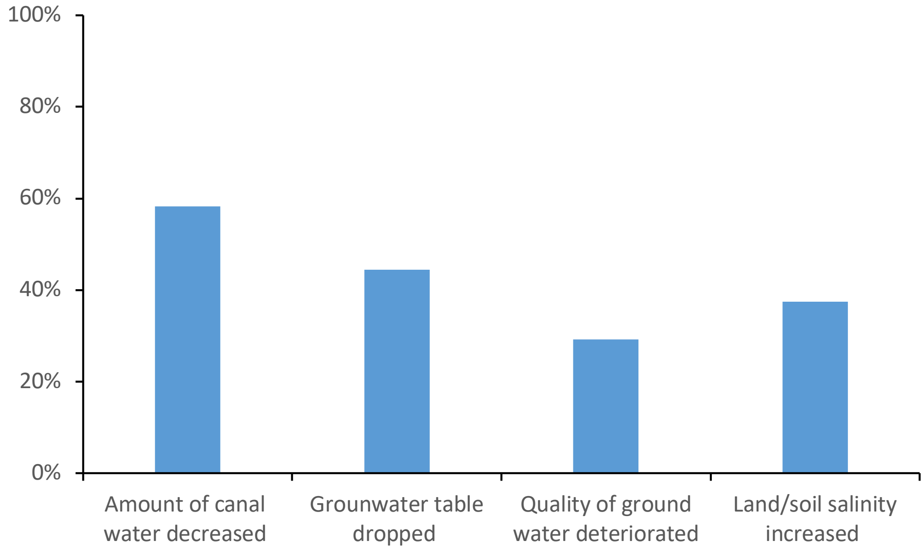


Figure 5.1: Responds of the farmers to environmental changes in Mungi area.

In reference to the respondents of Q1 in figure 5.2, the farmers stressed the limited canal water allowance in the Warabandi system as a major problem as 74% of the respondents, while rigid rotation and discussion with neighbors were rated as ~24 and ~2%, respectively. On other hand, considering Q2 in figure 5.2, the increase in the Warabandi allocation could enable farmers to grow high water demanding crops reflected by the farmers with 71% of the respondents. It implies that the increase in the allowance could change the cultivation behavior of the farmers to water-demanding crops, which does not lead to water saving and it might result in more pumping of groundwater to fulfil the demand of the crops.

Furthermore, for the past several decades, farmers have practiced irrigation scheduling under the fixed rotation of the Warabandi and have adapted to 7-day irrigation intervals for their common crops such as cotton, maize, and wheat. Therefore, for a question whether the farmers want a change in the 7-day rotation, around 67% of respondents conveyed ‘No’. Consequently, farmers choose alternative options for the using canal water allocation when it was not needed in their turns (Q3 in figure 5.2). The responses indicate that over 60% of the respondents use the canal water allowance in any case because they own big farms, while around 30% of the farmers sell it to another farmer and less than 10% exchange it with neighbours (Q3 in figure 5.2).

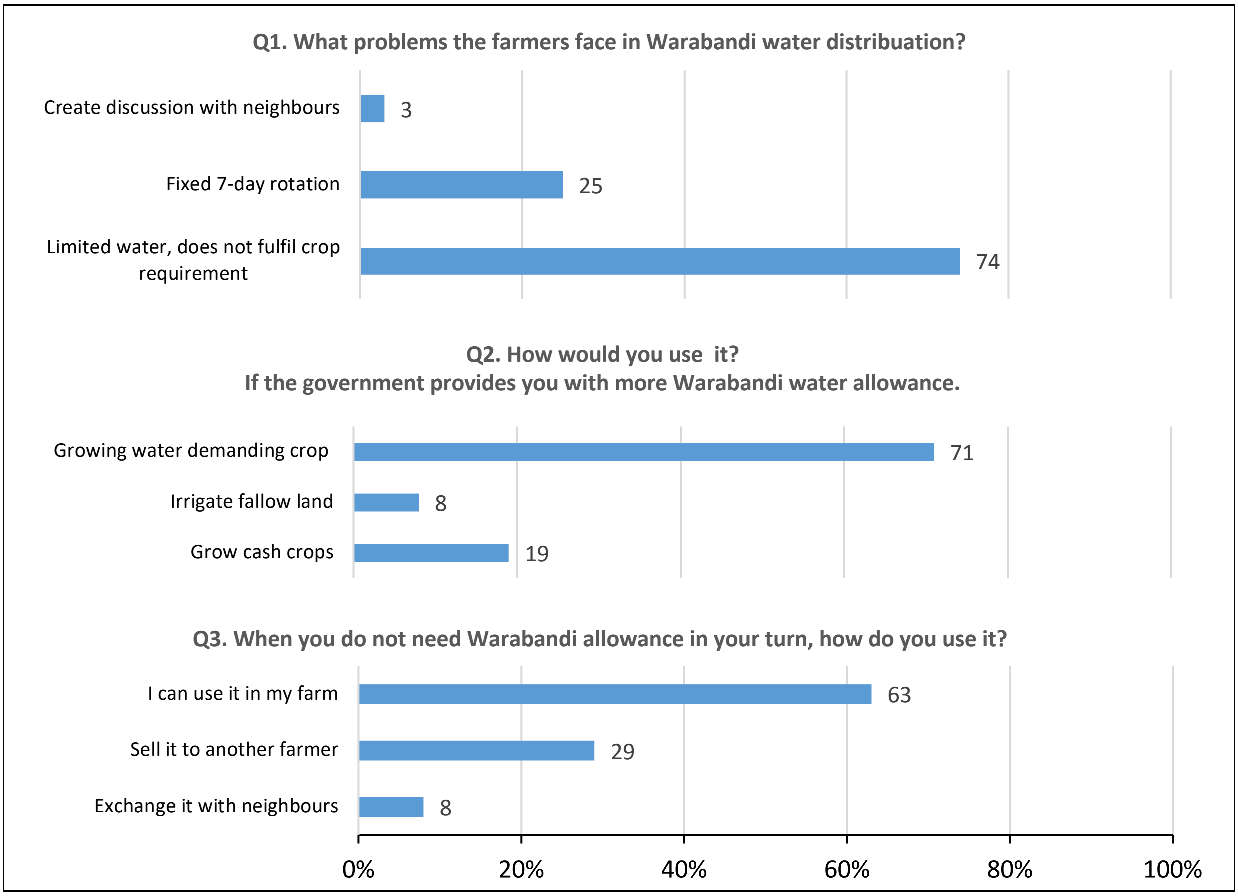


Figure 5.2: Percentage of 'Yes' respondents' related to Warabandi questionnaires.

The problems in the Warabandi principle were reflected by the three groups as depicted in figure 5.3. Most of the farmers (~70 %) expressed the limited canal water allowance as the main problem, while ~50% of academicians were concerned about inflexibility and ~60% of officials responded that creating discussion among farmers during the distribution of water under the rule of the Warabandi is the main problem. It implies a silo approach, which resulted in focusing on tackling existing problems in the canal water distribution system from each group's perspective, without collaborating with other groups in an integrative way in order to observe and solve the issue.

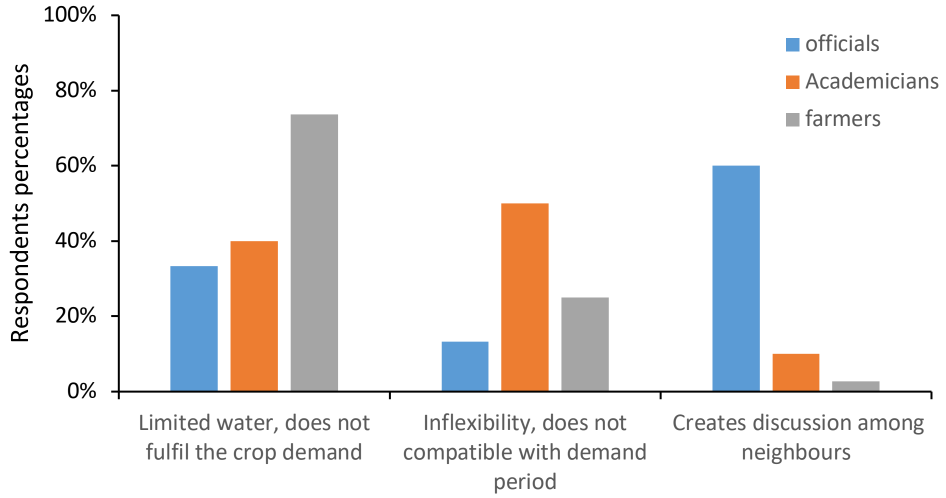
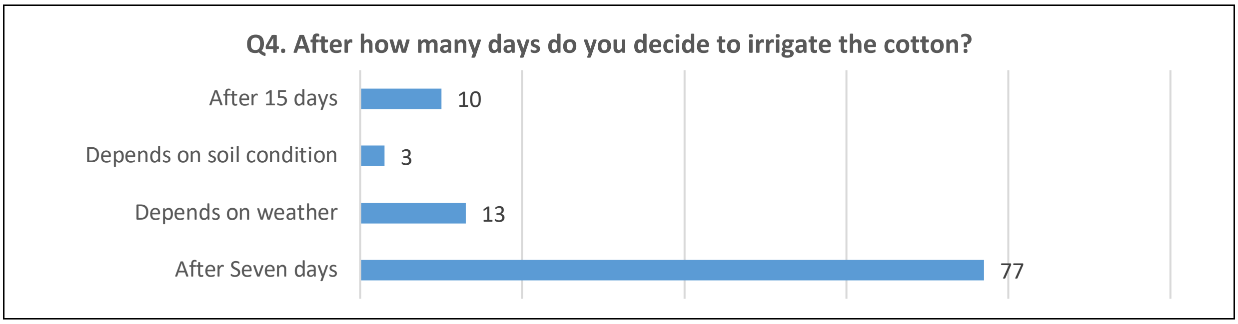


Figure 5.3: Reflection from the farmer, academicians and officials on problems relevant to the Warabandi.

To understand the perception of the farmers' irrigation behavior, the study narrowed down the questionnaires regarding the irrigating scheduling of cotton as a summer dominant and high-water-demanding crop in the Mungi area. According to figure 5.4 (Q4, Q5 and Q6), around 90% of the farmers responded that the irrigation timing of cotton was decided based on observation of the plant, whereas 85% responded that they fill the furrow depth with water and the irrigation interval usually takes place after 7 days (77% of the respondents). This indicates that conventional irrigation planning (time and depth) results in the over-irrigation behavior of the farmers. They do not consider the soil moisture content of the field and the time-dependent requirements of the crop. This implies the potential for intervention in irrigation scheduling to increase water use efficiency through performing joint experiments (farmers and scientists) and providing training options and facilities.



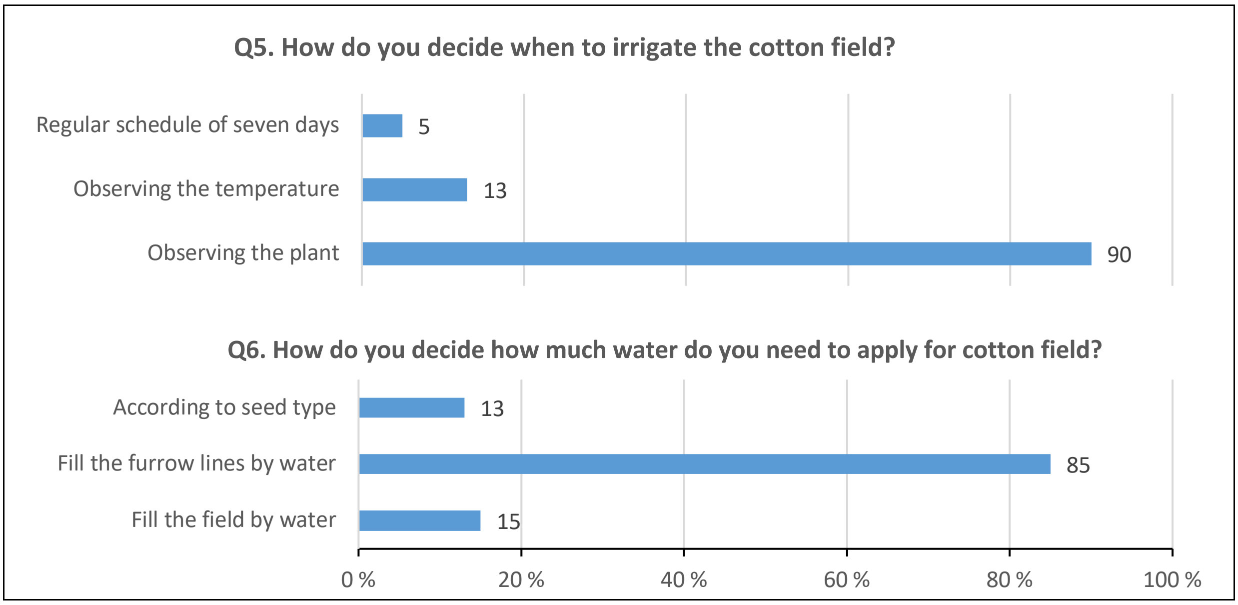


Figure 5.4: Percentage of 'Yes' responses relevant to cotton irrigation questions (It was open-ended question; 42 participants cultivated cotton crop and responded to the cotton-related questions).

Farmers have limited understanding and low awareness of water management interventions especially in the case of soil moisture sensors and on-farm water storage ponds, as evidenced by the 10 and 28% of 'Yes' responses in Figure 5.5. Furthermore, the institutions in Punjab provide farmers with a 60% subsidy for using drip technology, which could help farmers (Chaudhry, 2019). Therefore, 68% of farmers acknowledged that they could afford the drip system with a 60% subsidy. The adoption of drip technology in Punjab is related to numerous elements such as farmer training on its operation and maintenance, drip storage facilities, optimal integration with fertilizer application, and the drip design taking into account soil features (Weber et al., 2019).

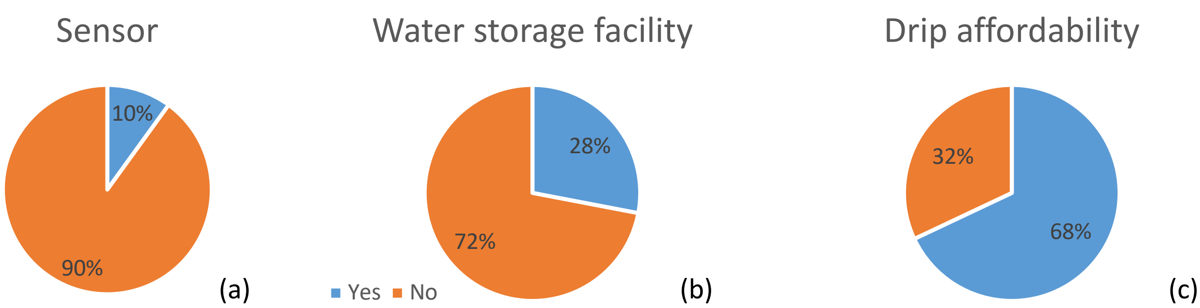


Figure 5.5: Respondent perceptions on (**a**) awareness about soil moisture sensors, (**b**) awareness about on-farm water storage facilities, and (**c**) affordability of the drip system by farmers receiving a 60% subsidy from the institutions.

When farmers were asked if they would participate in a joint experiment at a small plot of their land with scientists and farmers' associations to improve water use efficiency, and more than 53% of the farmers responded 'Yes'. This could enable further research on farmers' farm considering actual field conditions that reflect the real challenges and impacts caused by the implementation of proposed water management interventions. Furthermore, it supports the surrounding farmers to be inspired by the result of the experiment and easily adopting the measures (promising 'farmer-to-farmer' approach).

Regarding the most effective channels for approaching and providing guidance on water management to farmers in the Mungi distributary canal area, the private sector was most frequently mentioned (salespersons of the agricultural products), followed by the Agriculture Department and the Punjab Irrigation Department, with response rates of 46%, 32% and 24%, respectively.

5.4.2 Cross-Tabulation and Fisher test

The results of the cross-tabulation and Fisher test are provided in Table 5. 2.

Table 5.2. Cross-tabulation results for the categorical variables versus independent variables related to farmers.

Farmers'	Fisher test	Q.1: Is Drip a good cultivation method for cotton? (N=42)	Q.2: Do you want to conduct an experiment with scientists at your field? (N=72)	Q.3: Do you want a change in 7-day rotation of Warabandi principle? (N=72)	Q.4: Have you heared about soil moisture sensors? (N=72)	Q.5: do you have discussion with nieghbors on Warabandi water allocation? (N=72)	Q.6: Have you heard about on-farm water storage ponds? (N=72)
Education	p -value	0.377	0.63	0.52	**0.000**	0.713	**0.001**
Experience		0.142	0.233	0.619	1	1	1
Land ownership		0.669	0.417	0.094	0.181	0.495	0.362
Field location along the Mungi canal		0.136	0.912	0.071	0.408	1	0.200
Farm size		0.706	**0.019**	0.452	0.235	0.760	0.430

The findings revealed that the values of the Fisher test were greater than 0.05 as a significant interval for almost all the categorical variables. Therefore, we are unable to reject the null hypothesis and it implies that the incidence of all independent variables is not statistically significant with the categorical variable, which might be due to the limited sample size.

Furthermore, the results showed that the null hypothesis of no statistical association is rejected at the 5% level of significance, as reflected by p(a)= 0.000, p(b)= 0.001, and p(c)= 0.019. These figures correspond to farmers' education versus awareness of (a) soil moisture sensor and (b) water storage facilities and farm size in relation to (c) willingness of farmers to conduct a joint experiment at their plot of land together with scientists and farmers' associations, respectively. Thus, farmers with a university or a college degree had left their villages and to travel to nearby cities to attend schools and learn about innovative agricultural products such as soil moisture sensors and on-farm storage facilities. Farmers with larger amount of agricultural land, on the other hand, agreed to provide a small portion of their land for experimentation, but small landholders who rely on their land for a living did not want to risk it.

5.4.3 Constraints in the adoption of water management practices

The results in figure (5.6.a) demonstrated that farmers' reliance on tube-well water, exchange of Warabandi canal water with neighbors and lack of training were the strongest barriers to the adoption of an on-farm water storage at the farm level. They were rated between 3 and 5 by the three groups. While low awareness and lack of financial resources were moderate barriers according to farmers and academicians (rated between 1 and 3), officials perceived them as a strong hurdle. Furthermore, the barriers to operation and maintenance and using traditional methods were graded between 0 and 1, having a low effect. However, farmers rated operation and maintenance as a moderate obstacle. Therefore, creating an incentive for farmers to have a storage pond by increasing awareness and offering training on how to use canal water in a pond is critical. While farmers were not completely aware of the function of a pond. It creates an enabling environment for using higher irrigation technologies such as drip and sprinkler and storing the potential surplus water of the Mungi canal in

October, November, and December as well as during the shift from one season to another and on rainy days for later use (Sajid et al., 2022; Shabbir et al., 2012).

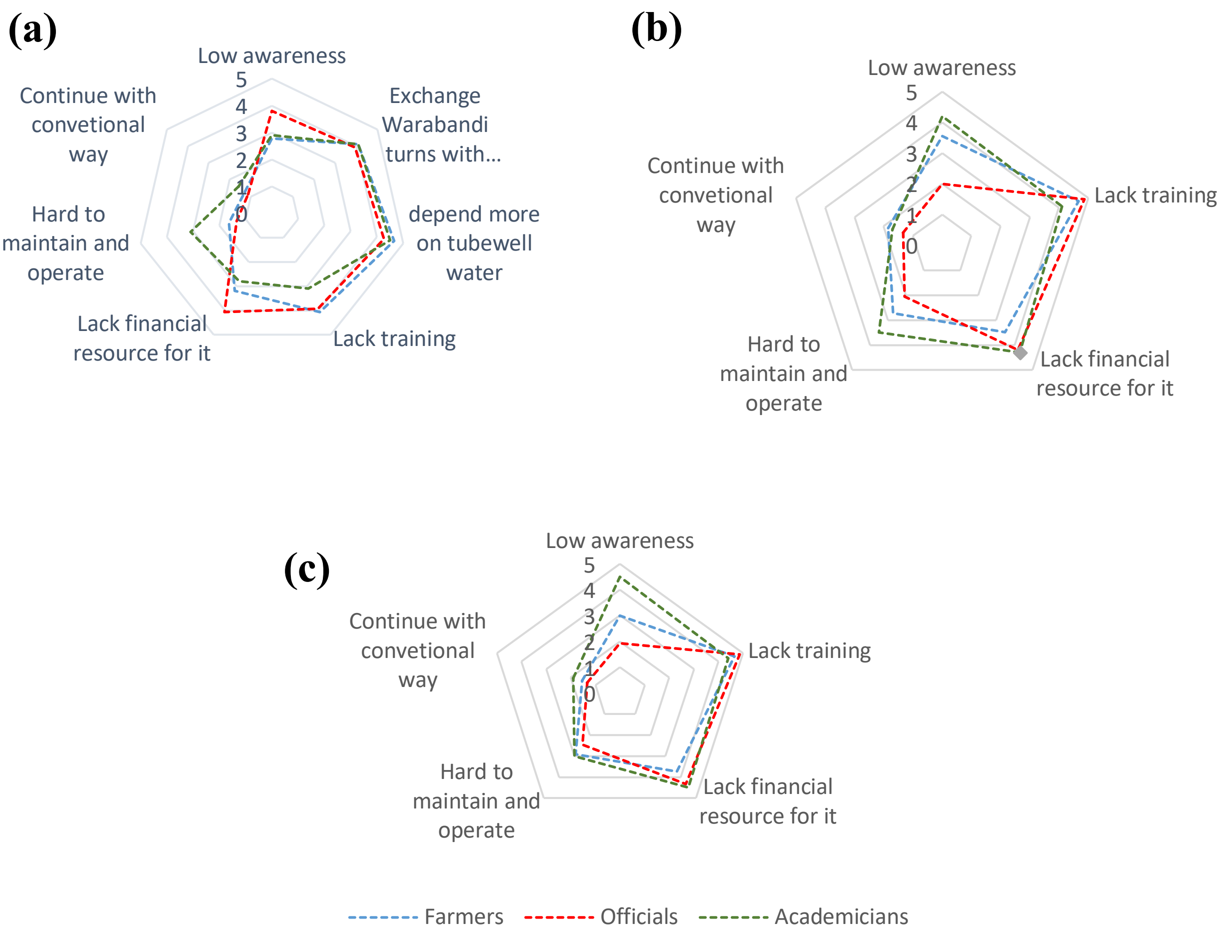


Figure 5.6: Perception comparison of three groups on barriers to ensuring the success of the adaptation process of (a) on-farm water storage facility (b) soil moisture sensors and (c) combination of a storage facility, soil moisture sensor and the drip method.

The adoption of soil moisture sensors in the field could improve irrigation timing and amount estimation. According to the ratings of the three groups, the strongest barriers to adopting this technique are a lack of training and financial resources (figure 5.6.b). There was a large difference in academicians' and officials' recognizing the importance of low awareness and the operation and maintenance of soil moisture sensors, because academicians rated them as having the strongest effect on adoption, whereas officials rated them as having a low impact. Practicing the conventional technique, on the other hand, was regarded as a low impediment to sensor implementation by the three groups.

Figure (5.6.c) presents the insight of the groups on a combination of water management interventions (soil moisture sensors, storage ponds and drip). All stakeholders agreed that the strongest barriers to the implementation of these interventions were a lack of training and financial resources, whereas academicians also rated low awareness as the strongest obstacle. Moreover, the three groups reported operating and maintenance as having a moderate effect and practicing conventional methods as having a low effect on barriers to the application of these interventions.

The assessment of barriers showed that since all the three groups - especially the farmers - rated conventional practices as low effect on adoption of the interventions, it indicates that the incentive of change already exists in farmers and are willing to adopt, yet face the need for being supported in addressing the hurdles. In addition to the identified obstacles, other factors could also be relevant as for example considering socioeconomic situation of the farmers and the equipment availability of each intervention. The assessment supports policy makers toward implementing the adaptation measures as these information reflects the real pictures of effectiveness and feasibility of the measures and development of the strategies.

5.4.4 Discussion

The development of agricultural policies necessitates understanding the perception of farmers and the socioeconomic factors affecting the implementation of the proposed adaptation measures (Li et al., 2017). The study's findings reveal that several obstacles influence the adaptation of water management interventions in the context of the Warabandi, with the strongest influences being low awareness, and lack of both training and financial resources. All of these factors have been identified and reported in other studies as barriers to adopting climate-smart agriculture practices in Punjab (Abid et al., 2015, Shahid et al., 2021; Imran et al., 2018). According to a recent study by Jamil et al. (2021), the main barriers to adopting sustainable land and water management measures (land laser leveling, bed planting, and minimum tillage) in cotton cultivation were low awareness, financial and resource constraints, irrigation water shortages, and the unavailability of the technological products.

In the current study, the farmers' education had a substantial influence on awareness of soil moisture sensors and storage ponds, whereas larger farm holders were more likely to be willing to conduct a joint experiment to improve water use efficiency. Similarly, the socioeconomic characteristics of the farmers influenced the application of the strategies documented in various studies. In study, Khan et al.(2021) revealed that the demographic attributions of the farmers, such as land size, experience, and education are significantly correlated with the adoption of high-efficiency irrigation techniques. In addition, Shahid et al. (2021) indicated in Punjab that farmers' experience in farming, education, land size, access to credit, and belief in climate change all have a positive impact on the implementation of measures such as on-farm water storage, soil conservation techniques, and efficient irrigation techniques. Furthermore, Ali and Erenstein (2017) demonstrated that farmers’ education, farm size, and access to credit were all positively associated with the acceptance of adaptation measures (e.g., adjustments in sowing time, changing to a new crop and shifting to drought-tolerant crops) in all four provinces of Pakistan. As a result, the farmers' socioeconomic characteristics collectively led to the adoption of the proposed techniques.

Farmers may continue to use traditional methods due to the accumulative influences of obstacles resulting from both farmer characteristics and external hurdles (Khan et al., 2021). Consequently, despite the fact that high-efficiency irrigation techniques (particularly drip) in Pakistan have shown a progressive impact in improving water use efficiency and were highly recommended for the country's water scarcity condition, adoption rates remained quite low (shah et all., 2004; Latif et al., 2016). In addition to other issues, the limited access to and availability of agricultural services and tools were reported in Punjab (Abid et al., 2015; Imran et al., 2018).

The driving forces for the farmers to enhance the utilization of Warabandi canal water in the Mungi area include the poor quality of groundwater, which can have a negative impact on crop yield, the increasing salinization, the high cost of pumping groundwater using fuel energy, and the high variability of environmental and climate change (erratic rainfall and rises in temperature) (Imran et al., 2018). In addition, issues associated with Warabandi could also influence farmers to adapt, for example, the issues of limited and unreliable water supply (Zardari and Cordery, 2010; Khan et al., 2021). Therefore, farmers are subject to change not only as a result of the pressures of environmental change, but also in order to maintain farming activities and attain greater economic benefits.

The majority of farmers in Pakistan (more than 90 percent) are small growers with less than 5 ha of land, which is one of the main reasons for the low adoption rate of climate-smart agricultural methods (Jamil et al., 2021), whereas offering subsidies has helped farmers, as in the case of the drip system and other farm machinery (Chaudhry, 2019). Thus, the institutions could provide subsidies for the recommended interventions (storage ponds, soil moisture sensors) while disseminating important information on these techniques through extension services and strengthening farmer association could raise awareness and overcome problems of small-scale farmers.

Furthermore, providing technical training has significantly assisted farmers in adopting the measures (Punthakey et al., 2016; Jamil et al., 2021). Therefore, the most promising point of the training that occurs at farmers' plots of land under real field conditions was considered to be related to the applicability and impact of the proposed management practices. The starting point could be from large farmers since they have indicated willingness to participate in the experiment in this study, while the surrounding small farmers would observe and benefit from joint experimentation.

Adapting particular water management measures requires the consideration of essential aspects of this study. It includes a limited sample size of the participants (farmers and especially academicians, and officials) and a lack of involvement of all the stakeholders in a focus group discussion which was planned, yet could not be realized due to Covid19 restrictions and precaution measures. Thus, a broader and in-depth survey of the participants could lead to a slight deviation from the results found in this study. For instance, a statistical conclusion from Table 5.2 necessitates more samples to test. Several studies in Pakistan have surveyed a higher number of farmers and showed a statistically significant association considering the adoption of climate-smart agriculture practices and farmers' experience, education, and farm size (Abid et al., 2015, Shahid et al., 2021; Imran et al., 2018). Furthermore, the selection and distribution of the farmers were random in the Mungi command area. Therefore, the findings of this study could provide insight into the irrigation problems of farmers which is an appropriate starting-point for further explorations.

5.4.5 Conclusion

The current study investigated the factors hindering the adoption of water management measures (on-farm water storage facilities, soil moisture sensors, and drip technology) that have the potential to significantly reduce the undersupply issue in the context of the Warabandi-guided irrigation scheme. According to the findings of this chapter, on-farm water management strategies should focus more on (i) improving farmers' awareness of intervention benefits, usage, and impacts in order to persuade them to take a step toward implementing such measures. (ii) Offering subsidies could increase the affordability of adaptation measures for farmers, and (iii) training could enable farmers to start using the measures. These obstacles are multi-institutional in scope and can be eliminated - or at least reduced - by the improvement of the services. It is vital to improve the farmers' socioeconomic situation, which is a long-term process, in order to increase their readiness to accept and implement the strategies. Farmers are inclined to adopt new measures as a result of increased water demand, erratic canal water supply, and high variability in the environment and climate, which might severely affect their production. Close collaboration between farmers, scientific communities, and administrative entities is essential in overcoming the constraints of the implementation of the measures. The development of water management adaptation strategies demands including and addressing farmers' perceptions of on-the-ground problems that could promote and sustain the application of the proposed techniques.

6 CONCLUSION AND OUTLOOK

6.1 Main findings of the thesis

The main findings of the studies conducted within the domain of this thesis are summarized, clustered into three groups and used to draw overarching conclusions as follows:

a) Key results derived from field measurements and empirical analysis

1. Despite the fact that the Mungi Distributary canal is undersupplied at ~68% and ~20% to meet the crops' demand cultivated in the Mungi CCA in both the Kharif and Rabi seasons of 2018/2019, respectively, there are periods with water availability that exceed the demand in the months of November and December. Here, the surplus water could be stored in water storage facilities at the farm level for later use.
2. Increasing the trend of erratic supply of canal water and groundwater quality deterioration have been observed from upstream to downstream of the Mungi Distributary canal.
3. In addition to water management features, the rather low cotton yields in the Mungi area are caused by factors beyond water management like seed quality, diseases, fertilizer management, plant protection management, and timing of sowing. Moreover, early sowing of cotton in the Mungi area resulted in achieving higher yields based on the farmers' practices in fields A, D, and F (mentioned in third and fourth chapters). Because early sowing allowed the crop to reach maturity before peak temperature in June as it crosses 40°C in the Mungi area. This is important because flowers and pollination could be affected by a spike in temperature–an issue becoming even more important in the future due to the expected impact of climate change.
4. Tube well owners were technically more efficient users of irrigation water than buyers in the Mungi area. In this thesis, farmers in fields B and E were tube well owners and achieved better ET water productivity of 0.31 and $0.35 \mathrm{kg\,m^{-3}}$, respectively, compared to water buyers in fields C and F with ET water productivity of 0.22, and $0.30 \mathrm{kg\,m^{-3}}$, respectively. The explanation for this

increased efficiency is related to the farmers' overall on-farm water management experiences, of which tube well ownership is only one component. In this thesis, tube well owners held larger farms with plenty of farming experience and invested more in enhancing agricultural production than the water buyers who owned limited land for cultivation, usually tenants with less farm experience. This argument was also supported in a study by Watto and Mugera (2015).

5. The soil moisture sensors facilitate lowering refill-limit of the soil slightly below field capacity level and adapting irrigation timing/amount after rainfall events as measures to better utilize available soil moisture in irrigation process (in case of Field D discussed in chapter three). While the major factor hindering the irrigation strategy (lower soil refill limit and adaptation to rainfall events) is the lack of canal water storage options on the farm to facilitate the storage of potential surplus canal water that can be used later as per crops' time-dependent demand.

b) Model-driven key results

1. The AquaCrop model predicted the temporal resolution of field water balance components throughout the crop growth period under the current practices. It highlighted the non-beneficial use of water as percolation (after over-irrigation events or an irrigation occurrence followed by rainfall) and evaporation, especially at the initial stages of the crop that can be the potential intervening points to save irrigation water in cotton fields.
2. Deficit irrigation scheduling scenarios in terms of irrigating solely by Warabandi water allowance under fixed intervals of 7 and 14 days rotations as well as flexible frequencies resulted in a substantial reduction of percolated water. In addition, these deficit irrigation schemes lowered actual evaporation and enabled similar yields together with higher gross water productivity comparable to current practice in the fields.
3. Deficit irrigation scenarios such after 7 and 14 days of interval in the rainy growing seasons (i.e., in wet years) of cotton could lead to similar yields

compared to actual practice. Therefore, the cotton yield responses under deficit irrigation are largely benefitting from seasonal rainfall.

4. The features of soil texture with mostly loamy soils in the Mungi area and short intervals of Warabandi (7-days fixed rotation) will enable the environment to store the surplus Warabandi water allowance in storage facilities of farms at the cotton initial stages, pre-cultivation period and rainy days (monsoon period). The stored water can be utilized during the critical periods (stages with high water demand and periods with high sensitive yield response) of the cotton that are flowering and boll formation. Therefore, flexible and demand-oriented deficit irrigation under the Warabandi framework is likely to be the most feasible option to implement.
5. The field application efficiency in the Mungi area for cotton fields that is improved by advancing surface irrigation techniques going from flood basin (~35% technical efficiency) towards raised bed-furrow, and ridge-bed furrow (the efficiency varied from 44% to 83%). While substituting irrigation technology further boosted the efficiency, for example, in case of drip method by over 90%.

c) Key results derived from survey questionnaires

1. The main problems in Warabandi water distribution system were expressed by the farmers as limited canal water allowance. On the other side, academicians are mostly concerned about the inflexibility while officials from irrigation administration conveyed discussion among neighbours.
2. According to the farmers' responses, the conventional irrigation scheduling behavior in the Mungi area is based on observing the plant for deciding on the irrigation timing and filling the field with water to determine irrigation depth. It favors an over-irrigation practice of farmers which does not consider the soil water holding capacity and crops' demand stages. Thus, considering these issues by introducing demand-oriented and site-specific schedules is a promising entry point for influential on-farm water management interventions.

3. Participants of the groups rated the most important barriers in adaptation of the water management interventions as low awareness, lack of training, and limited financial sources.
4. Farmers' education level had a significant influence on application awareness of soil moisture sensors and water storage facilities. While large farm holders showed a positive relationship to a joint experimentation with scientists and farmers' association for improving water use efficiency.

6.2 Strengths and limitations of the thesis

The strengths of this thesis include the consideration of the following points that could enhance agricultural water management in the context of the rotational delivery schedules of canal water in Pakistan:

I. This thesis took an interdisciplinary approach, using the bio-physical system as starting-point for working out technical interventions (via improved irrigation scheduling and advanced handling of irrigation techniques). Yet, it explicitly considered effect of scales (on efficiency and productivity) and addressing the issue on how to embed technical solutions into the socio-economic and institutional context in order to enhance the implementation.

II. Repeated measurements, monitoring and evaluation of canal water and farmers' activities over a large area of roughly 20,000 hectares in a remote area of Pakistan such as Mungi CCA for two years (2019 and 2020), have a matter of high importance to reflect the actual field conditions. Moreover, the assessment of all cultivation methods practiced for cotton as a high water demanding crop in the area (to the best of our knowledge) together with location distribution of the fields along the Mungi canal (top- and tail situation) delivered a package of detailed information to improve cotton on-farm water management.

III. The AquaCrop as an atmosphere-soil-water-crop model capable of evaluating and estimating each water balance component separately in the crops' root zone. While the function of irrigation scheduling in the model enabled an advanced assessment of field water balance parameters under various irrigation cultivation/scheduling options considering the features of Warabandi (rotation and depth). Based on its simplicities, precision and robustness, the model greatly assisted to address the objectives of the thesis in introducing irrigation scheduling as the most promising option in achieving higher water productivity considering a bottom-up approach in Punjab. While the trust in the outputs of the model was built by validating it using limited required input data, which was attained through direct and relatively easy methods. Although all crop models including the AquaCrop are one dimensional, and do not consider the spatial variability of water application along fields (Tenreiro et al. 2020).

However, the thesis also had some limitations, which are described as follows:

I. Security reasons in 2019 and 2020 restricted the monitoring and measuring of farmers' irrigation activities in each field and slightly hindered the coordination with farmers since they frequently adapted their plans for irrigation. Also, some of the farmers were irrigating their fields at night time, which affected the field measurements.

II. The sample size of the farmers in the survey was limited due to national Covid-19 restrictions and the pandemic also interrupted some of the measurements of the soil moisture content and irrigation water application at farmers' fields during field work in 2020.

6.3 Outlook

This thesis builds a basis of a bottom-up approach for managing the Warabandi water allocation on a farm level. However, further research is necessary to advance the understanding and feasibility of deficit irrigation scheduling options under a rotational water distribution system at farm level while aligning and boosting the farmers' capabilities to implement these options. The current thesis recommends the following specific points for further investigations:

1. The inclusion of the impact of rising efficiency on groundwater quantity and quality in further research and in decision-making in order to improve canal irrigation schemes. In the second chapter of this thesis, it was shown that water quality was better in the canal than in groundwater, and also the current

efficiencies of the canal network and irrigated fields were highlighted and indicated a potential capacity for improving the current efficiency of the irrigation scheme. Therefore, improving conveyance and field application efficiencies would lower the recharge to the aquifer and impact groundwater quality questioning the function of the aquifer as an additional resource and buffer in terms of quality and quantity. While high priority should be given to the protection of groundwater as it is the main source of drinking water for the growing population in Punjab.

2. The trend of erratic canal water supply and deteriorating groundwater quality is from upstream to downstream of the Mungi canal. For this reason, a transdisciplinary research approach for capacity building is a promising option for awareness rising and for balancing the upstream and downstream farmers' dependencies on canal and groundwater quantity and their impacts on the groundwater quality considering technical, social and environmental aspects of the canal water management.
3. Further investigations are required at field level on inclusion of water storage facilities to support the implementation of more flexible irrigation and better utilization of water at farm (and eventually watercourse in a next step towards upscaling) level. Here, crop water stress-sensitive stages under different irrigation methods in the context of Warabandi should be considered. The current work focused on the application of on-farm water storage practiced for drip irrigation technique that resulted in better performance.
4. The estimated magnitude of pumped groundwater as obtained in this thesis could be used as an entry-point for further studies on the water-food-energy nexus by including the issues of energy (fuel) demand and CO_2-emissions.
5. The current thesis highlighted one of the most important barriers as training programs for farmers to implement water management interventions in their farms. Exploring holistic and targeted training programs is needed at field level on irrigation scheduling considering farmers' perception on how to integrate the interventions into a package to be easy for implementation.

6.4 Closing remarks

Rigid canal water supply based on Warabandi rule hinders the introduction of flexible and demand-oriented water applications in the Punjab area. Furthermore, the Warabandi principle is currently under discussion due to the impact of climate change, sedimentation of the reservoirs, and increasing competition for water in the agricultural, industrial, and domestic sectors as well as the environment. Therefore, surface water resources are under pressure in Pakistan. However, Warabandi will still guide the irrigation water distribution in the country in the near and mid future. This thesis considered the introduction of irrigation scheduling under a rigid Warabandi principle as a bottom-up approach where it turned out to become a win-win option as it enables the improvement of cotton irrigation in Punjab by mobilizing potentials going beyond water management. Flexible and demand-oriented irrigation planning by utilizing solely the allowance of Warabandi water not only close the yield gap compared to the present practices, but it also (a) considerably lowers the pressure on groundwater abstraction, (b) reduces pumping using fuel energy, and (c) prevents contamination of groundwater by percolated return flows from the irrigated fields that is often loaded with fertilizers and pesticides.

Further, this thesis considered the entry point for more flexible and demand-orientated irrigation and focused on on-farm water management as a package of interventions to be introduced at the farm level assuming that Warabandi will remain the guiding principle on water allocation to farms on a larger system scale in future. A promising option would involve (i) utilizing the AquaCrop model to simulate pre- and within-season irrigation planning, (ii) advancing irrigation schedules by sensor-based soil moisture monitoring complemented by a strong intervention package to optimize on-farm irrigation management, which can unfold its potential by (iii) combining the storage option of Warabandi allowance during the potential surplus time in a pond at the farm to create an enabling environment for demand-based irrigation. In addition, the use of drip irrigation method could considerably reduce the undersupply effect of Warabandi and improve water productivity, although the adaptation of the drip system is bound to the socio-economic situation of the farmers discussed in the 5^{th} chapter. A combination of these measures will very likely enhance flexible irrigation scheduling and in turn support farmers by adapting farm water allocation and pre-season crop selection. Hence, this thesis argues that integrating several interventions into a package for on-farm water management is the most promising approach to achieve higher water productivity at the farm level given the framing conditions of Warabandi.

The outcomes of this thesis are promising to support farmers in coping with increasingly variable conditions by enabling a flexible response at the farm level. This is one important component of concepts to deal with future challenges and a way towards sustainable water management in Punjab. Improving the performance of Warabandi-guided water distribution in the irrigation network by advancing operation and maintenance has the potential to increase the water supply available at farm level and thereby providing the possibility for farmers to increase yields. In this context, accompanying measures are of special importance which improve the provision as well as the management of other agricultural inputs like seed, fertilizer, and plant disease management.

Development of agricultural policies necessitates an understanding of the perception of farmers and the socioeconomic factors affecting the implementation of the proposed adaptation measures. Therefore, the thesis used the integrated perceptions of the three relevant stakeholder groups (farmers, academicians and officials) and assists to advance understanding of the implementation processes by assessing potential barriers in adopting water management measures in the context of the Warabandi principle.

Last but not least, this thesis provides detailed information on the actual irrigation practices of cotton in the Punjab area. Its results deliver information to policy makers, academics, private sector employees, and farmers on on-farm water management interventions that could contribute to ensuring that cotton farming transforms sustainable, beneficial, and productive for farmers in Punjab and beyond.

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Appendix

Table A. 1. Cotton conservative crop parameters (Raes et al., 2009)

Parameter description	Units	Value
Base temperature (T_{base})	°C	12
Upper temperature (T_{upper})	°C	35
Effect of canopy cover on reducing soil evaporation in the late-season stage		60
Water productivity normalized (WP*) for ETo and CO2 during yield formation	As % WP* before yield formation	70
Possible increase of HI(Harvest Index) due to water stress before flowering	%	10
Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	Moderate	10
Coefficient describing the negative impact of stomatal closure during yield formation on HI	Small	8
Allowable maximum increase of specified HI	%	30
Soil water depletion factor for canopy expansion - upper threshold ($T_{exp,lower}$)	Fraction of TAW	0.20
Soil water depletion factor for canopy expansion - lower threshold ($T_{exp,upper}$)	Fraction of TAW	0.70
Shape factor for water stress coefficient for canopy expansion	none	3
Soil water depletion factor for stomatal control - upper threshold (P_{sto})	Fraction of TAW	0.65
Shape factor for water stress coefficient for stomatal control	None	2.5
Soil water depletion factor for canopy senescence - upper threshold (P_{sem})	Fraction of TAW	0.75
Shape factor for water stress coefficient for canopy senescence	none	2.5
Soil water depletion factor for pollination - upper threshold (P_{pol})	Fraction of TAW	0.85

TAW: total available water. HI: harvest index (defined as the percentage ratio of seed cotton yield to total biomass.