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InoCottonGROW

Reducing the Water Footprint of the Global Cotton-Textile Industry towards the UN Sustainable Development Goals

Joint final report of the collaborative project

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GRoW WATER AS A GLOBAL RESOURCE

Joint research project
„Water as a Global Resource (GRoW)“

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Cotton-Textile Industry towards the
UN Sustainable Development Goals

02WGR1422A-M

InoCotton
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Network coordination

Forschungsinstitut für Wasser- und Abfallwirtschaft an der RWTH Aachen (FiW) e. V.
Kackertstraße 15 – 17
52072 Aachen
Dr. sc. Dipl.-Ing. Frank-Andreas Weber

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SUPERVISED BY

PTKA Projektträger Karlsruhe Karlsruher Institut für Technologie

Project Partners

German Partners

Forschungsinstitut für Wasser- und Abfallwirtschaft an der RWTH Aachen (FiW) e. V.
Kackertstraße 15 – 17
52056 Aachen, Germany
Dr. sc. Dipl.-Ing. Frank-Andreas Weber
Charel Baumann, M.Sc.
Fabian Nawrath, B.A.
Dr.-Ing. Wolfgang Kirchhof
Dr.-Ing. Henry Riße
Jean Ferox, M.Sc.
Wolfram Schröder, B.Sc.
Dipl.-Ing. Helmut Krist

Technische Universität Berlin
Dr.-Ing. Markus Berger
Natalia Mikosch, M.Sc.

Hochschule Niederrhein University of Applied Sciences, Krefeld
Prof. Dr. Boris Mahltig
Dipl.- Ing.(FH) Oliver Heß
Dr. Dipl.-Chem. Michael Korger

IWW Rheinisch-Westfälisches Institut für Wasserforschung gGmbH, Mülheim an der Ruhr
Dr. Tim aus der Beek
Rike Becker, M.Sc.
Kristina Wencki, M.Sc.
Dipl.-Kfm. Clemens Strehl

Julius-Maximilians-Universität Würzburg
Prof. Dr. Christopher Conrad
Dr.-Ing. Muhammad Usman
Talha Mahmood, M.Sc.

Rheinische Friedrich-Wilhelms-Universität Bonn
Prof. Dr. Christian Borgemeister
Dr.-Ing. Bernhard Tischbein

RWTH Aachen University
Prof. Dr. Holger Schüttrumpf
Lennart Schelter, M.Sc.
Dipl.-Ing. Caroline Ganal

Hochschule Ruhr West, Mülheim an der Ruhr
Prof. Dr. Mark Oelmann
Jonathan Schulze, M.Sc.
Nora Zimmermann, M.A.

Thies GmbH & Co. KG, Coesfeld
Hermann Freericks

A3 Water Solutions GmbH, Saerbeck
Dipl.-Biol. Ulrich Brüß

LAR Process Analysers AG, Berlin
Dr. Ulf W. Naatz
Dipl.-Ing. Sina Balke
Dipl.-Ing. Agnes Eilers

SEBA Hydrometrie GmbH & Co. KG, Kaufbeuren
Dr. Philipp Theuring

Lippeverband, Essen
Björn M. Grün

CHT Germany GmbH, Tübingen (associated partner)
Christian Baggi

Universität Stuttgart (subcontractor)
Dr.-Ing. Harald Schönberger
Dipl.-Ing., Akad. Oberrat Ralf Minke

International Partners

University of Agriculture (UAF), Faisalabad, Pakistan

Punjab Irrigation and Power, Punjab Irrigation & Drainage Authority (PIDA), Lahore, Pakistan

National University of Sciences and Technology (NUST), Islamabad, Pakistan

National Textile University (NTU), Faisalabad, Pakistan

Pakistan Council Of Research in Water Resources (PCRWR), Islamabad, Pakistan

WWF Pakistan, Lahore, Pakistan

Kohinoor Mills Limited (KML), Kasur, Pakistan

Style Textile, Lahore, Pakistan

Sapphire Fibres Limited, Lahore, Pakistan

Pakistan Textile Exporters Association (PTEA)

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The Urban Unit (UU), Urban Sector Planning & Management Services Unit, Pakistan

Environment Protection Department, Government of the Punjab, Pakistan

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GIZ Pakistan

Water Use Association Söke (WUA Söke), Turkey

İstanbul Üniversitesi Merkez Kampüsü, Turkey

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LIST OF ABBREVIATIONS

Abbreviation	Description
AE	Application Efficiency
anMBBR	anaerobic Moving Bed Bio-Reactor
BMBF	German Federal Ministry of Education and Research
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CRU	Caustic soda Recovery Unit
DALY	Disability Adjusted Life Years
EoL	End-of-Life phase of a product
ETP	Effluent Treatment Plant
FEFLOW	Finite Element subsurface FLOW system (Diersch, 2014)
GDP	Gross Domestic Product
IWRM	Integrated Water Resource Management
LAI	Leaf Area Index
LCC	Lower Chenab Canal in Punjab, Pakistan
MAR	Managed Aquifer Recharge
RCP	Representative Concentration Pathway
Rechna Doab	Area between Chenab and Ravi rivers in Punjab, Pakistan
RO	Reverse Osmosis
SEBAL	Surface Energy Balance Algorithm for Land (Bastiaanssen *et al.* 1998)
SWAT	Soil & Water Assessment Tool (Arnold *et al.* 1998)
TFI	Textile Finishing Industries
UASB	Upflow Anaerobic Sludge Blanket digestion
UN-SDG	UN Sustainable Development Goals
WF	Water Footprint
WSF	Water Scarcity Footprint
WUA	Water Use Association
ZDHC	Zero Discharge of Hazardous Chemicals
ZLD	Zero Liquid Discharge

LIST OF CONVERSION FACTORS

Unit	Conversion to SI units	Description
cusec	1 cusec = 28.317 L/s or 0.028317 m³/s	cubic feet per second
raw cotton to lint cotton ratio	2.86 kg_{raw} / kg_{lint} (0.35 kg_{lint} / kg_{raw})	The amount of lint cotton produced from raw cotton depends on the quality of raw cotton and local conditions. We used a global conversion suggested by Mekonnen and Hoekstra (2011).

Note on Numbers: In this report, we use English SI number format (with decimal point instead of comma): 1 234 567.89 (https://en.wikipedia.org/wiki/Decimal_separator).

0 EXECUTIVE SUMMARY

0.1 English Summary

InoCottonGROW aims at contributing to sustainable water use along the cotton-textile value chain from cotton fields to textile industry and wastewater treatment. In case studies in Pakistan and Turkey, both major suppliers of German textile demand, our goal was to advance the water footprint (WF) concept to become a meaningful regional steering instrument in managing scarce water resources. Producing documentary videos, providing an internet-based WF tool, organizing roadmap workshops, and assessing the integration of the WF concept into textile labels, the aim was to improve national water-policy decision-making and raise the awareness of internationally operating brands, retailers, and German consumers for sustainable textile consumption.

Methods

Case studies were conducted in the Lower Chenab Canal irrigation system (LCC, 15,700 km², irrigation water entitlement approx. 8 billion m³/year, 12 million inhabitants) in the Indus Basin in Punjab, Pakistan, and at Water Use Association Söke in the Büyük Menderes Basin, Turkey.

We applied complementary methods, including (M1) satellite remote sensing, (M2) field experiments and crop-irrigation modelling, (M3) hydrologic and (M4) hydraulic modelling, (M5) survey on the institutional framework of water use in cotton farming, as well as (M6) textile company audits, and (M7) laboratory and full-scale dyeing trails in textile finishing.

Five demonstrations investigated strategies for WF reduction: (D1) flexible irrigation strategies to increase water productivity, (D2) water-saving textile machinery, (D3) resource-efficient dyestuffs, (D4) textile wastewater treatment by anaerobic treatment of highly polluted wastewater of desizing, (D5) pollutant analysis and regulatory enforcement of wastewater effluent standards.

Key Results

Cotton Irrigation: Allocation of irrigation water among farmers in Pakistan is organized by certain formal and informal rules known as the Warabandi system, in which water is allocated proportionally to each farm size in strict rotation. Our models confirmed that LCC is undersupplied: water demand exceeds supply. Field demonstrations concluded that – besides irrigation technology and scheduling – farmer training is key to minimize unproductive losses. In spite, canal lining is not the ultimate solution, since groundwater serves as intra- and inter-annual storage for irrigation wells. More flexibility is needed within Warabandi to cope with climate change starting bottom-up at farm-level. Comparing cotton yields achieved in Turkey with those in LCC, we observed about three-fold higher yields given the same actual evapotranspiration. Low cotton yield in LCC is only partly due to water stress. Scattered, lower-income farmers find it hard to afford quality inputs like good-quality seeds. Despite water stress, we find heat stress to likely dominate under climate change.

Textile industry: We demonstrated that a water-use reduction of up to almost 20 % is feasible in reactive black shade dyeing by installing water efficient textile machinery. Introducing advanced dyestuff can further reduce water use up to 40 % under certain conditions but Pakistani companies are rarely in a position to pay higher prices despite water and energy savings. We find process-integrated measures to often go along with energy savings, but little WF reduction.

Wastewater treatment: Functioning effluent treatment plants are key for reducing the grey WF, but only a few textile mills in Pakistan afford operating aerobic activated sludge treatment due to energy cost, poor maintenance, and lack of regulative enforcement. We demonstrated that low-hanging fruits do exist by operating a pilot-scale anaerobic moving bed bioreactor (anMBBR) for energy-efficient pretreatment of textile desizing effluent for biogas production. Despite the positive amortization of investments, we were not yet able to initiate full-scale application of this technology in Pakistan.

Water Footprint: Region-specific water scarcity footprints (WSF) was calculated for 17 irrigation subdivisions in LCC. The average WSF amounts to 2,333 m³ deprived per ton of cotton. These results are on average about 40 % higher than the WSF calculated by means of country-level scarcity factors. A free accessible web-based water footprint tool (http://wf-tools.see.tu-berlin.de/wf-tools/inoCotton/#/) is online for users to calculate their specific WF reduction potential, such as implementing improved irrigation technology or wastewater treatment.

Outlook & Future Applications

InoCottonGROW identified several feasible measures to increase the efficiency and productivity of water consumption and to reduce water pollution along the cotton-textile value chain. Combining measures in consistent policy scenarios, we conclude that their implementation is not only crucial for achieving UN-SDG 6 but also provides synergies for achieving other UN-Sustainable Development Goals (SDGs) targets as well.

The Water Footprint approach provides opportunities for science-based water policy, promoting coherent policy across different sectors (agriculture, textile, water, trade). Good water governance is key and groundwater governance must not be neglected. Our research indicates that the time to act is now: Far more ambitious approaches are needed to set the global framework for sustainable cotton-textile consumption.

0.2 Deutsche Zusammenfassung

InoCottonGROW will einen Beitrag zur nachhaltigen Wassernutzung entlang der Baumwoll-Textil-Wertschöpfungskette vom Baumwollfeld über die Textilindustrie bis zur Abwasserbehandlung leisten. In Fallstudien in Pakistan und der Türkei, beides wichtige Exportländer für in Deutschland verkaufte Textilien, war es unser Ziel, das Konzept des Wasserfußabdrucks (WF) zu einem regionalen Steuerungsinstrument für ein nachhaltiges Management knapper Wasserressourcen weiterzuentwickeln. Durch die Produktion von Dokumentarfilmen, eines internetbasierten Wasserfußabdruck-Tools, die Organisation von Roadmap-Workshops und die Bewertung der Integration des Wasserfußabdruck-Konzepts in Textillabels versucht InoCottonGROW dazu beitragen, die nationale wasserpolitische Entscheidungsfindung zu verbessern und internationale Brands & Retailers, Einzelhändler und deutscher Verbraucher für nachhaltigen Textilkonsum zu sensibilisieren.

Methoden

Fallstudien wurden im Bewässerungssystem des Lower Chenab Canals (LCC, 15.700 km², Zuteilung von Bewässerungswasser ca. 8 Mrd. m³/Jahr, 12 Mio. Einwohner) im Indus-Flussgebiet im Punjab, Pakistan und beim der Water Use Association Söke im Büyük-Menderes (Großer Mäander) Flusseinzugsgebiet, Ägäisregion, Türkei, durchgeführt.

Dazu wurden verschiedene, komplementäre Methoden angewendet, darunter (M1) Satellitenfernerkundung, (M2) Feldexperimente und Modellierung der Bewässerungsproduktivität, (M3) hydrologische und (M4) hydraulische Modellierung, (M5) Umfrage zum institutionellen Rahmen der Wassernutzung im Baumwollanbau sowie (M6) Audits in Textilunternehmen und (M7) Färbeversuche im Labor und in der industriellen Textilveredlung.

In fünf Demonstrationsvorhaben wurden Strategien zur WF-Reduzierung untersucht: (D1) flexible Bewässerungsstrategien zur Erhöhung der Wasserproduktivität, (D2) wassersparende Textilmaschinen, (D3) ressourceneffiziente Färbemittel, (D4) Abwasserbehandlung durch anaerobe Behandlung hochbelasteter Abwässer aus der Entschlichtung, (D5) Schadstoffanalyse und Vollzug von behördlich festgesetzten Einleitungsgrenzwerten.

Ergebnisse

Baumwollbewässerung: Die Zuteilung von Bewässerungswasser wird in Pakistan durch bestimmte formelle und informelle Regeln organisiert, die als Warabandi-System bekannt sind, in dem Wasser proportional zu jeder Farmgröße in strenger Rotation an die Farmer zugeteilt wird. Unsere Modelle bestätigten, dass im LCC der Wasserbedarf das Angebot übersteigt. Felderhebungen ergaben, dass neben der Bewässerungstechnik und der zeitlichen Zuteilung (Scheduling) das Training der Farmer entscheidend ist, um unproduktive Wasserverluste zu minimieren. Die Abdichtung der Bewässerungskanäle hat sich nicht als die erwartete Lösung herausgestellt, da die Infiltration aus den Kanälen in den Grundwasseraquifer als innerjährlicher und mehrjähriger Speicher für die Bewässerungsbrunnen dient. Im Warabandi-System wird mehr Flexibilität benötigt, um die Bewässerung an den Klimawandel anzupassen; beginnend lokal auf Farm-Ebene. Vergleicht man die in der Türkei erzielten Baumwollerträge mit denen in LCC, so stellt man ca. dreimal höhere Erträge bei gleicher tatsächlicher Evapotranspiration fest. Niedrige Baumwollerträge in LCC sind nur teilweise auf Wasserstress zurückzuführen: Kleinbauern mit geringem Einkommen können sich nur schwer hochwertige Betriebsmittel wie qualitativ hochwertiges Saatgut leisten. Neben Wasserstress wird mit voranschreitendem Klimawandel wohl der Hitzestress dominieren.

Textilindustrie: Wir haben gezeigt, dass eine Reduzierung des Wasserverbrauchs um bis zu 20 % bei der reaktiven Schwarzfärbung durch die Installation wassersparender Textilmaschinen möglich ist. Die Einführung ressourcensparender Farbstoffe kann den Wasserverbrauch unter bestimmten Bedingungen um bis zu 40 % weiter reduzieren, jedoch sind pakistanische Unternehmen trotz der damit zu erzielenden Wasser- und Energieeinsparungen nur selten in der Lage, die höheren Preise der Farbstoffe zu zahlen. Wir stellen fest, dass prozessintegrierte Maßnahmen oft mit Energieeinsparungen einhergehen, aber wenig zur Reduktion des Wasserfußabdrucks beitragen.

Abwasserbehandlung: Funktionierende Textilabwasserbehandlungsanlagen sind der Schlüssel zur Reduzierung des grauen Wasserfußabdrucks, jedoch können sich nur wenige Textilfirmen in Pakistan den Betrieb einer aeroben Belebtschlamm-Behandlung leisten, aufgrund von Energiekosten, schlechter Wartung und mangelnder Durchsetzung von Einleitungsgrenzwerten. Wir haben gezeigt, dass es vergleichsweise kostengünstig zu realisierende Lösungsansätze gibt, indem wir einen anaeroben Fließbettbioreaktor (anMBBR) im Pilotmaßstab zur energieeffizienten Vorbehandlung von Abwässern aus der Entschlichtung mit Biogasproduktion betrieben haben. Trotz der positiven Amortisation der Investitionen konnten wir die großtechnische Anwendung dieser Technologie in Pakistan noch nicht initiieren.

Wasserfußabdruck: Für 17 Bewässerungsgebiete in LCC wurde ein regionsspezifischer Wasserknappheitsfußabdruck (water scarcity footprint, WSF) berechnet. Der durchschnittliche WSF beläuft sich auf 2.333 m³ Bewässerung pro Tonne Baumwolle. Diese Ergebnisse sind im Durchschnitt etwa 40 % höher als der WSF, der mit Hilfe von Knappheitsfaktoren auf Länderebene berechnet wurde. Ein frei zugängliches, webbasiertes Wasserfußabdruck-Tool (http://wf-tools.see.tu-berlin.de/wf-tools/inoCotton/#/) steht Nutzern online zur Verfügung, um ihr spezifisches WSF-Reduktionspotenzial zu berechnen, z. B. durch die Implementierung einer verbesserten Bewässerungstechnologie oder Abwasserbehandlung.

Ausblick & Zukünftige Anwendung

InoCottonGROW identifizierte mehrere umsetzbare Maßnahmen zur Steigerung der Effizienz und Produktivität des Wasserverbrauchs und zur Reduzierung der Wasserverschmutzung entlang der Baumwoll-Textil-Wertschöpfungskette. Durch Bündelung von Maßnahmen in konsistente Politikszenarien zeigte sich, dass deren Umsetzung nicht nur entscheidend für das Erreichen von UN-Nachhaltigkeitsziel 6 „Sauberes Wasser und sanitäre Einrichtungen" beitragen kann, sondern auch Synergien für das Erreichen anderer UN-Nachhaltigkeitsziele bietet.

Der Wasserfußabdruckansatz bietet Möglichkeiten für eine wissenschaftsbasierte Wasserpolitik, die eine kohärente Politik über verschiedene Sektoren hinweg (Landwirtschaft, Textil, Wasser, Handel) fördert. Wasser-Governance ist entscheidend; das Grundwasser darf dabei nicht vergessen werden. Unsere Forschung zeigt, dass zeitnah ehrgeizige Ansätze erforderlich sind, um den globalen Rahmen für einen nachhaltigen Baumwoll-Textilkonsum zu setzen.

1 INTRODUCTION

(F.-A. Weber)

Germany is about to implement new legislation, the co-called Supply-Chain-Act (*Lieferkettengesetz* in German) that will require German companies to take responsibility for any labour or environmental abuses in the global supply chain of their products, if contractors and sub-contractors abroad were found to violate human rights or environmental standards. The Supply-Chain-Act is planned to be phased in for all companies with more than 3,000 employees (about 600 companies in Germany) in 2023 and extended to companies with more than 1,000 employees (about 2,900 companies) in 2024, including major brands and retailers from the German textile sector (BMZ, 2021).

Germany is generally considered a country rich in water. However, our demand for water-intensive cotton textiles (jeans, T-shirts, towels, bedclothes, and many more) has a major impact on water scarcity and water pollution in the mainly Asian manufacturing countries, where additional pressures such as climate change and the population growth exacerbate the water-related challenges. The irrigation of cotton plants as well as dyeing and finishing processes in textile manufacturing often require large quantities of water. In addition, rivers, soil, and groundwater may be polluted by salinization, application of pesticides and fertilizers, and the discharge of poorly treated textile wastewater to streams and natural habitats (Niinimäki *et al.* 2020).

Several labels and initiatives have been launched to support sustainable textiles, including the German government-run certification label Green Button (*Grüner Knopf* in German), multi-stakeholder initiatives like Partnership for Sustainable Textiles (*Textilbündnis*), Better Cotton Initiative (BCI), Zero-Liquid of Hazardous Chemicals (ZDHC), bluesign®, and Global Organic Textile Standard (GOTS), among others. Most label addresses water issues from a sectoral point of view in one way or the other, for example by restricting pesticide usages, restricting certain substances in manufacturing or requiring certain wastewater effluent standards to be met (FAO 2015; ZDHC 2018). Some brands have started to assess water consumption in their supply chain (e.g. Water Footprint Network, 2013; Levi Strauss, 2019, C&A, 2020).

However, an integrated approach is still under way that considers the impacts of water consumption and contamination. For national water-policy decision making managing scarce water resources an understanding of the impacts is essential to improve water efficiency and productivity where it matters most to minimize local water conflicts with competing water usages such as food production, energy generation, wetland protection and ecosystem regeneration. Likewise, pollution control must be prioritized where it matters most to avoid impacts on human health and environmental quality.

The volumetric water footprint (WF) concept has been applied to integrate water consumption to calculate green, blue, and grey water footprints (Text Box 1). Due to the complexity of water consumption, different assumptions and different scales, there has been a range of values published for the cotton-textile value chain. So far, the WF concept is more directed towards comparing cotton to synthetic textile fibres (e.g., Niinimäki *et al.* 2020) or comparing hydrological conditions among different cotton growing countries (e.g., Chapagain *et al.* 2006), rather than using it as a steering instrument for decision makers in managing scarce water resources.

In the global textile industry, decisions on cotton prices, production locations and standards may tremendously affect the livelihood of millions of people. Worldwide, 26 million tons of cotton worth 44 billion Euros are produced annually. More than 100 million farmers in more than 80 countries are involved in production, with cotton picking often by hand rather than machinery. Almost 75 % of cotton farmers are smallholders with an average farm size of two to four hectares, often in remote rural areas. Weaving, knitting, and wet-processing manufacturing capacity ranges from small-scale factories to highly automated fully integrated enterprises.

Figure 1.1: Some impressions of the cotton-textile value chain in Punjab, Pakistan. © FiW

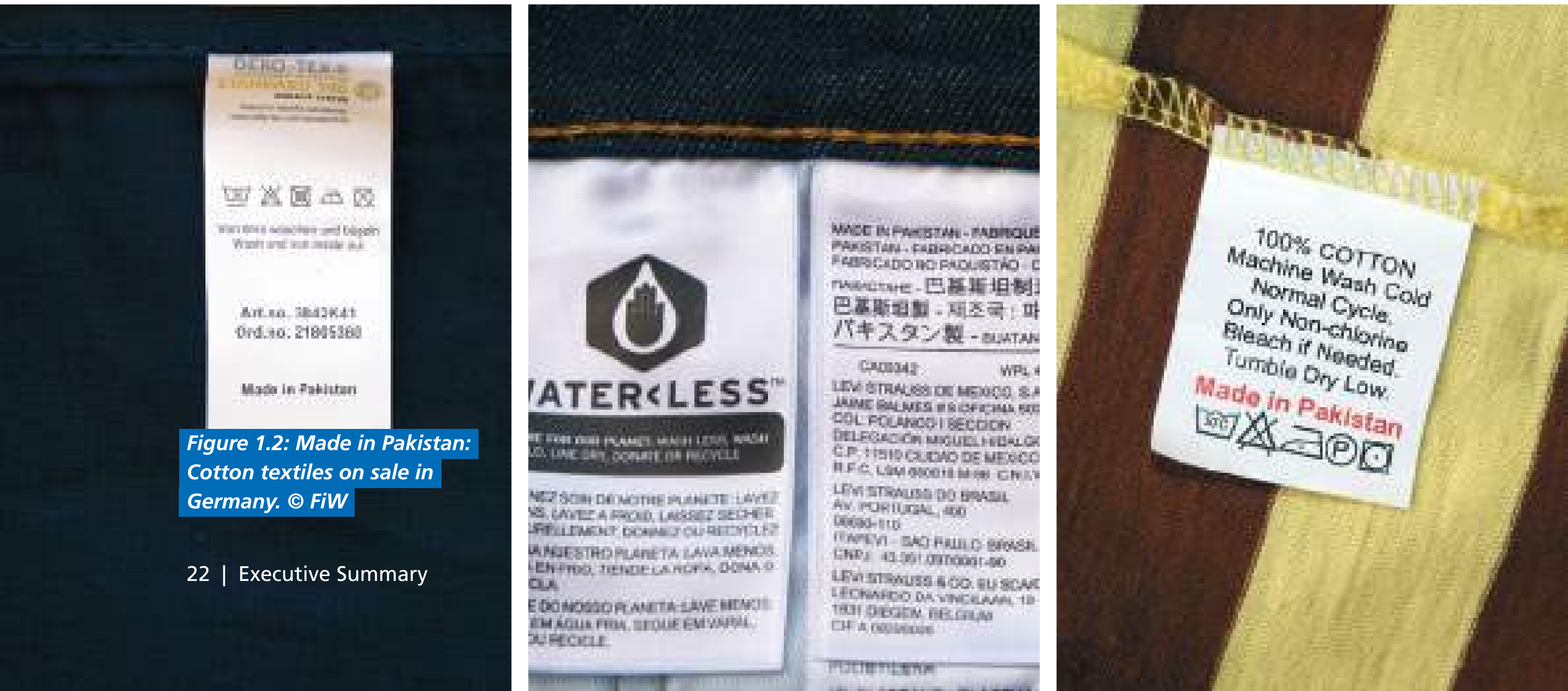


Figure 1.2: Made in Pakistan: Cotton textiles on sale in Germany. © FiW

Text Box 1:

What is the Water Footprint and Virtual Water Trade?

The concept of virtual water was the first attempt towards product water footprinting and was developed in the early 1960s (Allan, 1998). The method accumulates all quantities of water that have been consumed along the production chain of a product. Hence, it comprises water consumed in the actual manufacturing processes as well as water consumed in background processes such as material or energy production (Berger and Finkbeiner, 2010). The virtual water concept includes three dimensions: green water (soil moisture from precipitation), blue water (surface and groundwater) and grey water (water pollution) (Hoekstra *et al.*, 2011). As water intense products are shipped around the globe, water associated with their production is virtually traded between world regions (Figure 1.3), e.g. from developing countries to the European Union via cotton textiles.

Unlike some other environmental pressures, e.g. climate change, water related impacts strongly depend on the region where water is consumed due to unequal distribution of freshwater resources around the globe. For example, 1 litre consumed in water-abundant Sweden is significantly less severe than 1 litre consumed in water-scarce Pakistan. To address this issue, the water footprint calculation considers local conditions in the region of water consumption, e.g. water scarcity (ISO 14046:2014). A water footprint analysis can reveal the volumes of water associated with trade and resulting impacts in the exporting countries (GRoW, 2019).

Figure 1.3: Global water footprint of German commodity imports. © TUB

Within InoCottonGROW we focused on a case study in Punjab, Pakistan. A second case study in the Büyük Menderes Basin, Turkey, was conducted for comparison. Both Pakistan and Turkey are among the largest cotton producing countries worldwide ranking 5th (1,655,000 tons/a) and 6th (806,000 tons/a of lint cotton) after India, USA, China, and Brazil (U.S. Department of Agriculture, 2019). Both countries host significant national textile manufacturing capacity producing textiles for the European market (Figure 1.2).

In Pakistan, the local cotton production is the foundation of the textile industry, which is Pakistan's most important industrial sector representing about a quarter of the total industrial value creation. By far, it is the most important export sector of the country. It accounts for roughly 60 % of the total exports employing about 40 % of the industrial labour force (Pakistan Economic Survey, 2017).

Germany imported textile and textile goods from Pakistan worth 1.3 billion Euros in 2017 and 2018 (Pakistan Bureau of Statistics, UN Comtrade). Due to the EU-funded GSP+ (Generalized System of Preference) textile exporting countries like Pakistan strive to improve the sustainability of their domestic industries.

Given the importance of the cotton-textile sector in Pakistan and its dependency of water, strategies to increase water efficiency and productivity seem crucial for Pakistan´s commitment to achieve the UN Sustainable Development Goals (Text Box 2). The National SDGs Framework prioritized UN-SDG 6, among SDG 2 "No Hunger", SDG 3 "Good Health and Well Being", SDG 4 "Quality Education", SDG 7 "Affordable and clean energy", SDG 8 "Decent work and Economic Growth" and SDG 17 "Peace and Justice" to be achieved in the short run (Government of Pakistan, 2017). In a Voluntary National Review the first Local Government Summit on the UN Sustainable Development Goals (SDGs) identified water among education, employment, energy, and peace and governance as major issues to address (Government of Pakistan, 2019).

Advancements in water and sanitation may thus not only be mandatory for the achievement of the UN-SDG 6 targets itself, but may be a prerequisite, or at least provide synergies and minimises trade-offs for achieving most – if not all – 17 UN-SDG targets as well. Table 1.1 provides a selection of UN-SDG 6 and related targets for Germany, Pakistan, and Turkey.

Table 1.1: Selected UN-SDG 6 and related targets for Germany, Pakistan, and Turkey in 2017 (data from UN-STAT (2019), unless otherwise noted).

UN-SDG Indicator		Germany	Pakistan	Turkey
Population (national census)		83.2 million	216.6 million	83.6 million
GDP as purchasing power parity per capita (World Economic Outlook Database)		$56,956	$5,160	$32,278
1.1.1	Employed population below international poverty line	No data	2.0 %	0 %
2.1.1	Number of undernourished people	Non-relevant	24.8 million	Non-relevant
3.2.1	Infant mortality rate (deaths per 1,000 live births)	3.3	58.8	9.8
3.9.2	Mortality due to unsafe water and sanitation per 100,000 population	0.6	19.6	0.3
6.1.1	Population using safely managed drinking water	99.8 %	35.3 %	No data
6.2.1	Proportion of population practicing open defecation	0 %	10.4 %	0.3 %
6.2.1	Proportion of population with basic handwashing facilities on premises	97.2 %	59.6 %	65.2 %
6.3.2	Portion of river water bodies with good ambient water quality	35.1 %	No data	No data
6.4.1	Water Use Efficiency (US dollars per cubic meter)	109.8	1.44	13.6
6.4.2	Level of water stress	33.5 %	122.7 %	44.7 %
6.5.1	Degree of integrated water resources management	88.0 %	49.8 %	69.5 %
6.a.1	Total official development assistance for water supply and sanitation (millions of US dollars)	No data	306.6	53.2
7.1.1.	Proportion of population with access to electricity	100 %	71 %	100 %
7.2.1	Renewable energy share in the total final energy consumption	15.2 %	42.0 %	11.4 %
8.1.1	Annual growth rate of real GDP per capita	2.0 %	3.4 %	5.8 %
9.5.1	Research and development expenditure as a proportion of GDP	3.0 %	0.2 %	1.0 %
15.1.2	Freshwater Key Biodiversity Areas covered by protected areas	81.3 %	35.9 %	4.3 %
17.3.1	Foreign direct investment inflows (millions of US dollars)	60,354	2,496	11,020

Text Box 2:

What are the UN Sustainable Development Goals?

Recognizing that ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs, while tackling climate change and environmental protection, on January 1, 2016, all UN Member States adopted a common set of 17 Sustainable Development Goals (UN-SDGs) to be achieved until 2030. This Goals are part of a 15-year plan that describes how to achieve these goals, called the "2030 Agenda for Sustainable Development". All goals were again specified in 169 targets to be achieved by all poor, rich and middle-income countries.

To track the progress of the target´s achievement and to support decision-making, the adoption of UN SDGs was accompanied by the definition of a set of 231 accountable indicators by the „Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs)", a working group, in which 28 UN member states were represented with their respective statistical officers. An overview of the world's implementation efforts to date, highlighting areas of progress is provided in the annual Sustainable Development Goals Report. All countries are additionally invited to provide further information on their national achievements in individual voluntary reports.

Many – if not all – goals are strongly interconnected. Advancement in one goal – and UN-SDG 6 in particular – has the potential to foster advancement in other SDGs. At the same time, progress in some goals may also obstruct advancement of others, if policy strategies are not designed carefully. A core problem in using the UN-SDG indicator for prioritizing policy interventions is that not all indicators have a clear data collection and/or defined calculation methodology defined, and thus there is still a lack of reliable data for assessment.

For further information: https://www.un.org/sustainabledevelopment/

Figure 1.4: UN-SDG are interconnected: UN-SDG 6 as a prerequisite for achieving other goals. © FiW

2 PROJECT AIMS

Within InoCottonGROW, we were fortune to work in close cooperation between fourteen German research and industry partners and more than thirteen Pakistani and two Turkish partner organizations. The goal was to identify technically, economically, and institutionally feasible ways of increasing the efficiency and productivity of water consumption along the entire cotton-textile value chain "from cotton field to cloth hanger". The aim was directed towards identifying best-practise approaches under given hydrological conditions in each country, foreseeing that climate change will put additional pressure on limited water resources in the years to come (Figure 2.1). More specifically, the project aims were:

- How to make the water footprint a meaningful steering indicator for decision-makers, retailers & consumers (Chapter 3)
- How water-intensive is the cotton-textile value chain really? From inventory analysis to impact assessment in Punjab, Pakistan (Chapter 4 and 5)
- How to improve: five demonstration projects (Chapter 6)
- Are findings transferable to other cotton-textile producing countries: case study on cotton farming in Aegean region, Turkey (Chapter 7)
- Calculating the water footprint: current practise and options for improvement (Chapter 8)
- Towards achieving the UN-SDGs: Scenario analyses of consistent strategies for interventions (Chapter 9)
- Outreach: Support national decision makers and European consumers in sustainable consumption (Chapter 10)
- Overall conclusions: Which policy recommendations must be drawn from our research findings (Chapter 11)

We applied a combination of methods in WF inventory analysis and impact assessment:, including (M1) satellite remote sensing, (M2) field experiments and crop-irrigation modelling, (M3) hydrologic and (M4) hydraulic modelling, (M5) survey on the institutional framework of water use in cotton farming, as well as (M6) textile company audits, and (M7) laboratory and full-scale dyeing trails in textile finishing. The five demonstration projects we implemented to examine strategies for WF reduction were:

- (D1) flexible irrigation strategies to increase irrigation water productivity
- (D2) water-saving textile machineries
- (D3) resource-efficient dyestuffs
- (D4) textile wastewater treatment by anaerobic treatment of highly polluted wastewater of desizing
- (D5) pollutant analysis and regulatory enforcement of wastewater effluent standards.

Figure 2.1: Reducing the blue and grey water footprint to best-practice levels under given current and future hydrological conditions. © FiW

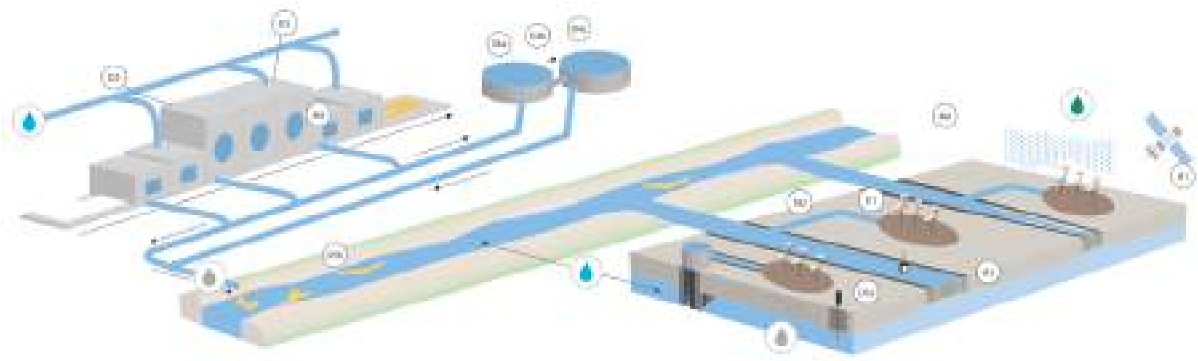


Figure 2.2: Methodology M and demonstrations D conducted in the study area integrating both cotton faming and textile manufacturing in a system approach. © FiW


National Textile University
Faisalabad, Pakistan
InoCotton
GROW
WATER FOOT PRINTS OF GLOBAL
COTTON-TEXTILE INDUSTRY

3 METHODOLOGY: MAKING THE WATER FOOTPRINT A MEANINGFUL STEERING INDICATOR

(N. Mikosch, M. Berger)

Water Footprint (WF) is widely applied as a tool to quantify impacts associated with the water use throughout the products' life cycle. The volumetric WF includes the volumes of directly and indirectly consumed (green and blue) and polluted (grey) water (Hoekstra *et al.*, 2011). Despite the relevance of the volumetric WF for awareness rising, it has been criticized for the lack of environmental and socio-economic meaning. For example, 1 litre water consumed in water-abundant Sweden does not have same consequences as 1 litre consumed in water-scarce Pakistan.

In order to advance the water footprint concept to an instrument that can support decision-making, methods have been developed within the scope of life cycle assessment (ISO 14046:2014).The latter requires conducting an impact-assessment step, which includes modelling local consequences of the water use by means of cause-effect chains. Existing WF models provide cause-effect chains for the impacts of the water consumption and pollution on the following:

- Freshwater scarcity (Berger *et al.* 2018; Boulay *et al.* 2017; Pfister *et al.* 2009)
- Human health due to malnutrition (Motoshita *et al.*, 2014), infectious diseases (Boulay *et al.* 2011) or diseases attributed to water toxicity (Rosenbaum *et al.*, 2008))
- Ecosystems (Verones *et al.*, 2013)
- Freshwater resources (Pfister *et al.*, 2009).

Currently available WF methods provide cause-effect chains usually on a world region, country or water-basin level (Figure 3.1). Although this resolution serves well for identification of hotspots on a global scale, it is insufficient to reflect local differences in water-use related impacts within individual countries.

Within the InoCottonGROW project, the inventory (water consumption and pollution) and impact assessment were regionalized to better address local conditions in Punjab, Pakistan. Including region-specific aspects allows

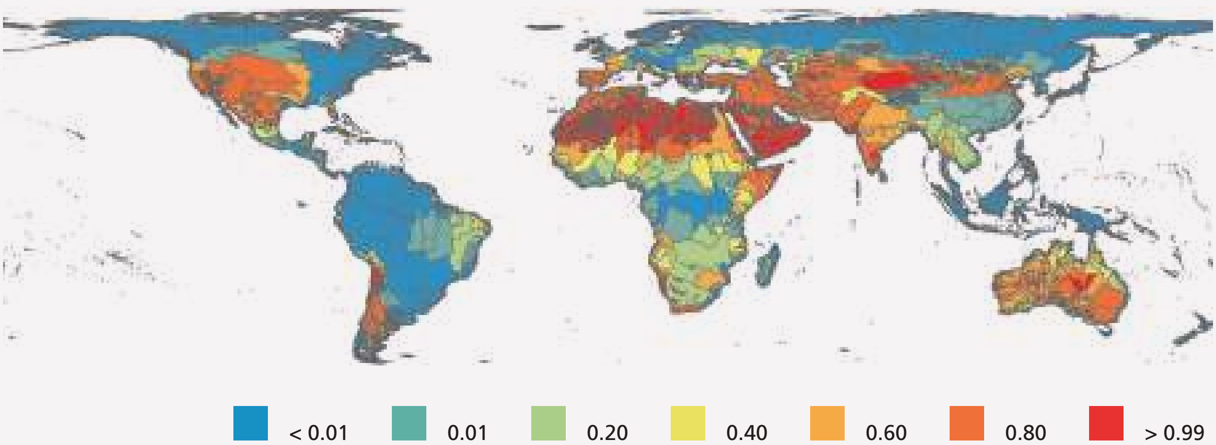


Figure 3.1: Monthly water scarcity factors are provided by the WAVE+ model (Berger et al. 2018). Shown here is the annual average water scarcity factor for each basin in [m^3 deprived / m^3 consumed]. © TUB

to enhance the WF as a management instrument for the decision-making in water governance, textile trade, and consumption.

The research design of InoCottonGROW includes the following tasks (Figure 3.2):

- inventory analysis (region-specific water consumption and pollution in cotton farming and textile production)
- impact assessment by means of the regionalized cause-effect chains for water scarcity, human health, and ecosystems
- development and evaluation of options for WF reduction in cotton farming and textile manufacturing, including advanced irrigation techniques and optimization of the textile manufacturing
- development and evaluation of intervention strategies
- assessment of its contribution for achieving UN-SDG targets

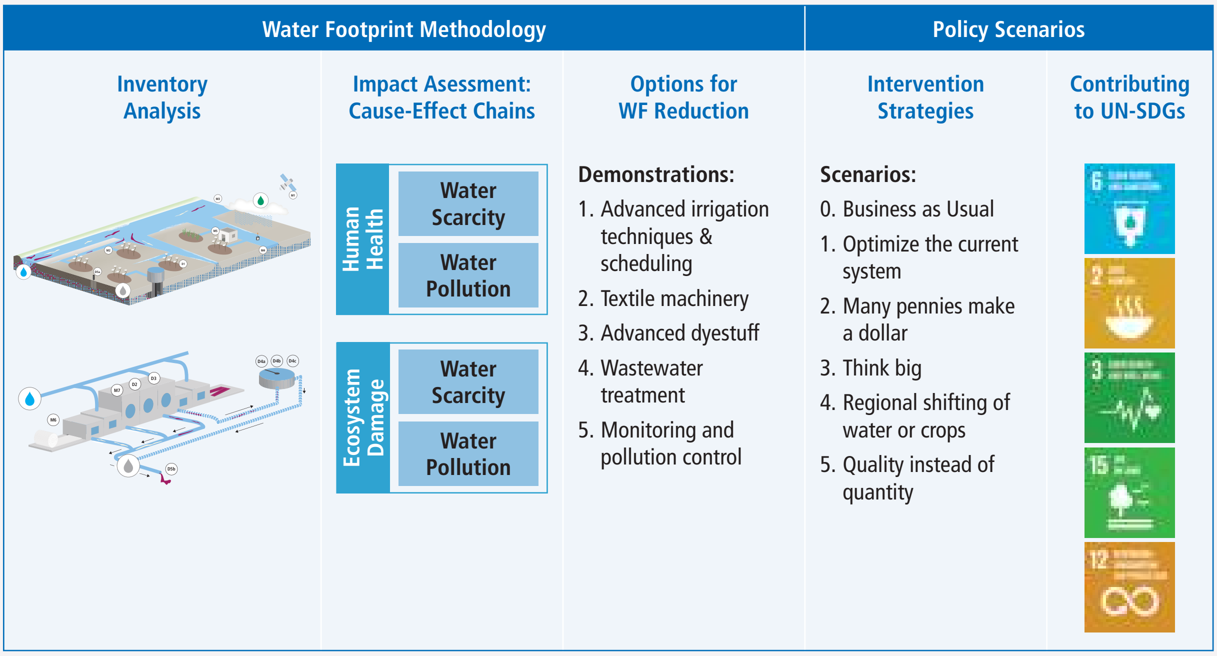


Figure 3.2: Research design of InoCottonGROW. © FiW

The inventory for the cotton cultivation in the study area we compiled based on the results provided by the hydrologic model SWAT (see chapter 4.3.3) and hydraulic groundwater model FEFLOW (see chapter 4.3.4). The water consumption of cotton crops was calculated based on irrigation data (Figure 3.3). The water scarcity was calculated based on the water availability data (surface water generated by the precipitation, groundwater and irrigation water provided by the canals) and the agricultural water consumption (total irrigation water consumption). Domestic and industrial water consumption were not considered due to its low relevance in the study area (Mikosch *et al.* 2020).

The inventory for textile manufacturing was compiled based on data acquired in audits conducted on behalf of GIZ in ten textile mills located in Punjab. The data includes the water with-drawal and discharge as well as wastewater quality analysis for the pollutants (chapter 4.4).

For impact assessment, cause-effect chains for water scarcity, human health, and ecosystems provided by existing models were regionalized to better represent local conditions in Punjab. Detailed information on the impact assessment and cause-effect chains modelling is provided in chapter 5.

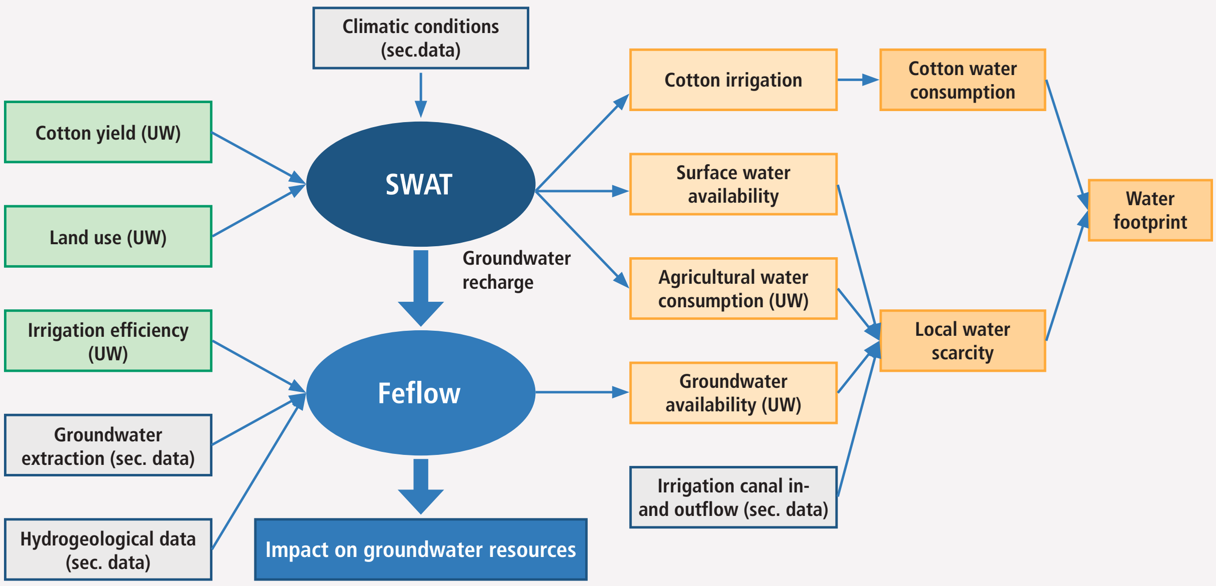


Figure 3.3: Inventory analysis of cotton framing: data flow for SWAT and FEFLOW modelling, impact assessment on groundwater resources, and water footprint calculation. © InoCottonGROW Team

4 INVENTORY ANALYSIS IN THE COTTON-TEXTILE INDUSTRY IN PUNJAB, PAKISTAN

4.1 The Indus-Basin Irrigation System

The Indus Basin Irrigation System (IBIS) is the largest contiguous irrigation system in the world. It was designed about a century ago. The core objective of its design was to avoid famine through curbing crop failure and expanding settlement opportunities by constructing irrigation infrastructure including reservoirs, barrages and main canals. IBIS is serving an area of 16 Mha with some 172 billion m³ of river water flowing per year (Aslam and Prathapar 2006). Originally, the IBIS was designed for an annual cropping intensity (ratio of effective crop area harvested to the physical area) of about 75 % that has grown up to 200 % (Kazmi *et al.* 2012).

The major reason is rising food demands due to accelerated population growth and better nutrition requirements. This has put a tremendous pressure on the irrigation demands and resultantly serious consequences to the ecosystem balance. On the other side, the canal supplies has either remain stagnant or decreased over time due to climate change and many canals have lost their design capacity due to siltation and erosion of their banks (Badruddin 1996). The result is over dependence on groundwater resources. Canal irrigation dominated the irrigated agriculture in IBIS by the end of 1990s, but in the early 1990s, irrigation using groundwater had surpassed canal irrigation (Van der Velde and Kijne 1992). According to Chaudhary *et al.* (2002), more than 50 % of irrigated lands in IBIS are irrigated by groundwater resources, and more than 70 % of the farmers in the Punjab province rely directly or indirectly on groundwater for raising their crops (Qureshi *et al.* 2003).

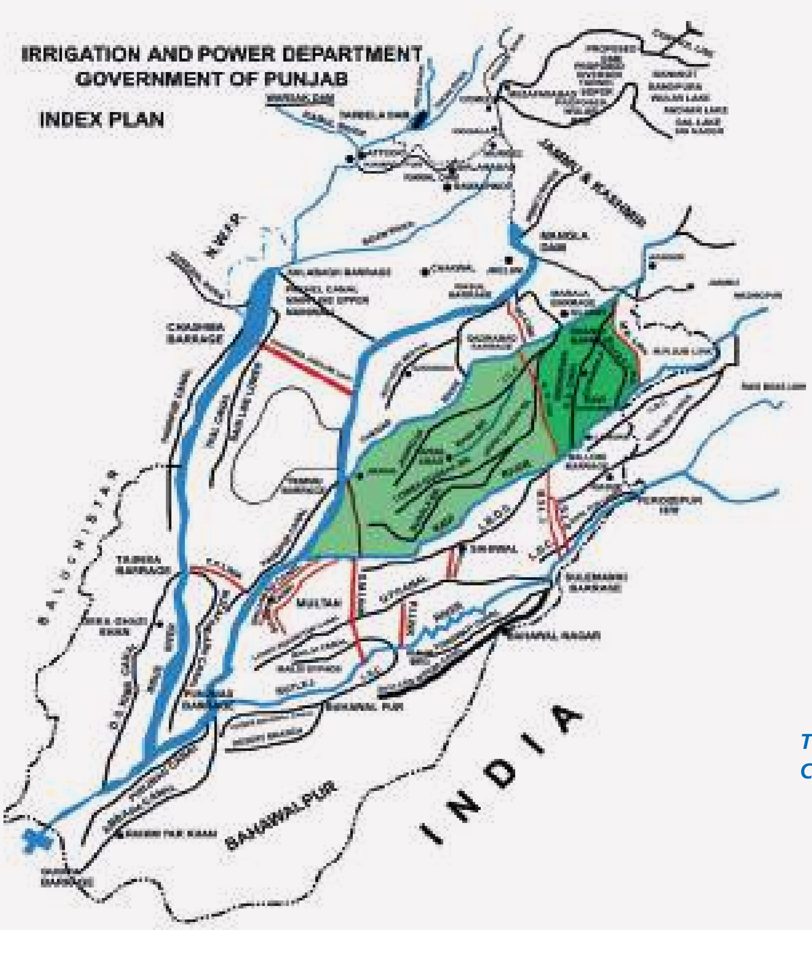


Figure 4.1: The Indus-Basin Irrigation System administrated by Punjab Irrigation & Drainage Authority (PIDA). The core study area of the Lower Chenab Canal (LCC) is highlighted (brown shade). The larger Rechna Doab extends from Marala-Ravi Link canal to the Trimmu-Sidhnai canal (both green and brown shaded areas). Adapted from PIDA.

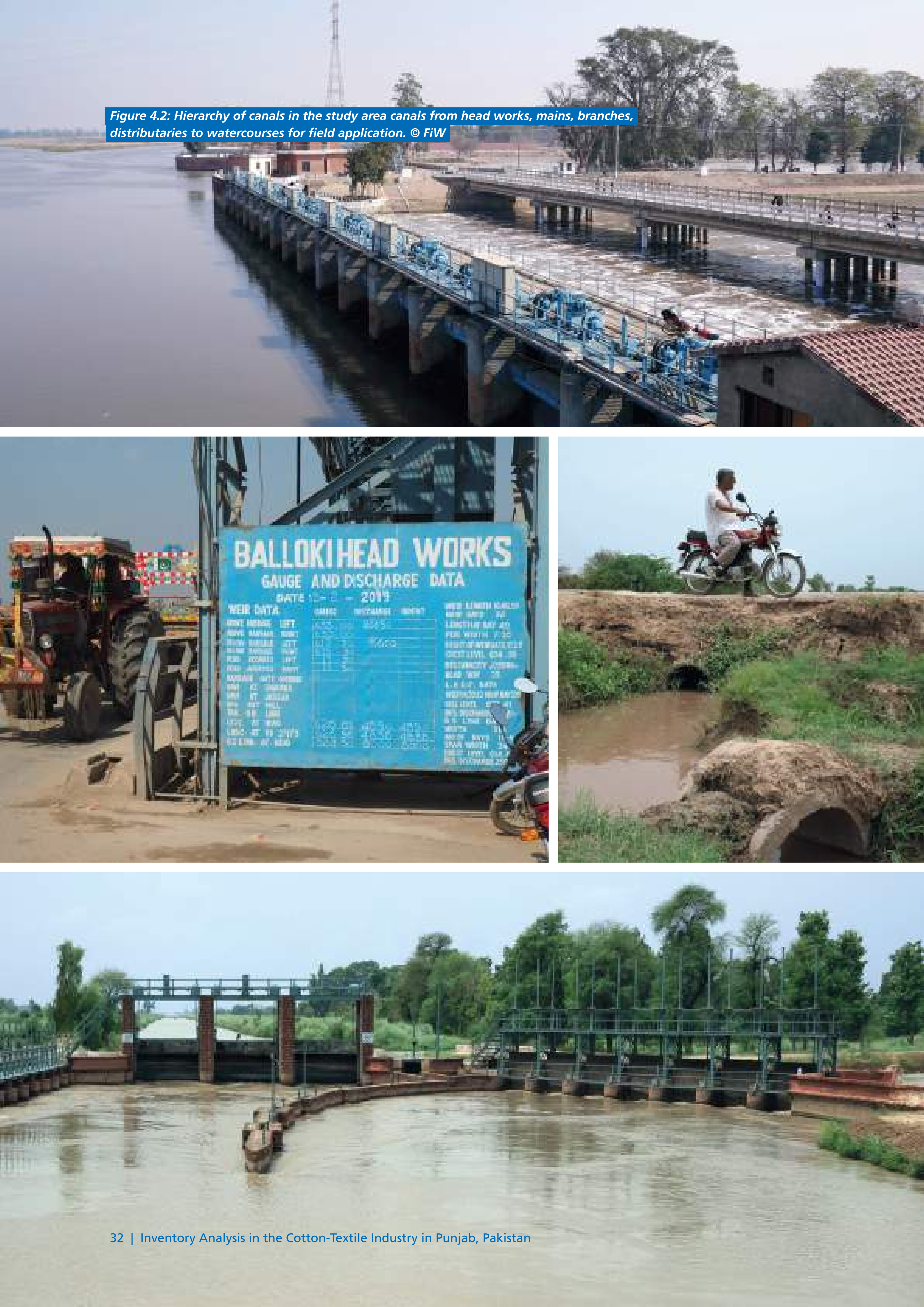


Figure 4.2: Hierarchy of canals in the study area canals from head works, mains, branches, distributaries to watercourses for field application. © FiW

4.2 Study Area Rechna Doab and Lower Chenab Canal

(M. Usman, R. Becker, L. Schelter)

Rechna Doab, one of the biggest and largest irrigation schemes of the IBIS is selected for the current study that lies between Ravi and Chenab rivers. The gross command area of this irrigation system is about 2.98 million hectares (Mha), out of which 2.3 Mha is cultivated and irrigated land. Whole Rechna Doab is further subdivided in to 28 irrigation subdivisions that are considered as the smallest irrigation management unit of irrigation system in this study area. The structuring of irrigation subdivisions is to guarantee the equitable distribution of canal water among various users. Lower Chenab Canal (LCC) irrigation system constitutes a major portion of Rechna Doab, which off-takes from Khanki headwork on the river Chenab, and is divided into two parts, LCC East and LCC West that constitutes the districts of Faisalabad, Jhang and Toba Tek Singh.

The study area is categorized as agricultural land with various crops are grown throughout the cropping year including rice, wheat, sugarcane, fodder, cotton and vegetables etc. The cropping year can be sub-divided into two seasons namely Kharif and Rabi, where Kharif season generally starts from April/May and ends in September/October. Rice and wheat are the two major crops during Kharif and Rabi seasons, respectively. The other major crops cultivated during Rabi season are Rabi fodders (mainly barseem and oat), while cotton and Kharif fodders (mainly sorghum, maize and millet) are grown in Kharif season. Sugarcane is another major crop in the region that is annual crop, which is cultivated in the months of September and February (Usman *et al.* 2015).

The climate of the area is arid to semi-arid. The climate conditions fluctuate in terms of temperature and rainfall. Four types of weather seasons prevail that include summer, winter, spring and autumn. The summers are hot and long lasting with temperatures ranging between 21 and 50 °C. Daytime temperature ranges between 10 and 27 °C during winter, whereas it may drop to zero at night. The average annual rainfall in Rechna Doab varies from 290 mm in the southwest to 1046 mm in the northeast. Highest rainfalls occur during monsoon months from July to September that accounts for about 60 % of total annual rainfall (Usman *et al.* 2015).

The spatial variability of precipitation is analyzed in Figure 4.3.

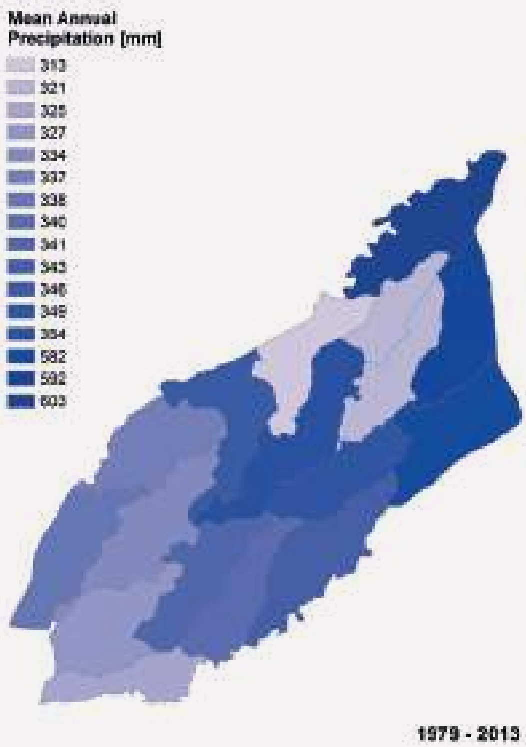


Figure 4.3: Spatial variability of precipitation data in the LCC region. © IWW-MH

Geological and hydrogeological settings

Rechna Doab is a part of an abandoned flood plain with the deeper sections formed by the underlying metamorphic and igneous rocks of Precambrian age. The settling material mainly consist of highly stratified unconsolidated alluvial composed of sands of various grades interbedded with discontinuous lenses of silt, clay and nodules of kanker – a calcium carbonate structure eroded and deposited by tributaries of the Indus River (Sarwar and Eggers 2006). The sediments in the upper regions of Rechna Doab consist of medium to fine sand, silt and clay, whereas the gravel and coarse sand are uncommon. The origin of clay deposits have not yet been identified specifically, but they are presumed to be the repeatedly reworked loess deposits of the hills at the north and northwest regions. Hydrogeological investigations carried out during the 1957–1960 period show that maximum thickness of alluvium is unknown, although the test wells logs show the thickness is over 200 m or more nearly everywhere in Rechna Doab. The alluvial complex is of heterogeneous nature and forms a transmissive aquifer system, however in some areas, the soils are homogeneous containing high percentage of silt and fine to very fine sand. Clay contents are higher in depression areas (Rehman *et al.* 1997). Accordant to lithological mapping details presented by Usman *et al.* (2015) of various boreholes indicate that thickness of alluvium complex is relatively higher in lower parts compared with upper parts that contain small lenses of clay and gravel throughout the area. It also shows that aquifer is mainly composed of sand with deposits of clay, gravel and silt at different depths. The horizontal permeability is an order greater than vertical (Bennett *et al.* 1967). The porosity of the water bearing material ranges from 35 to 45 % with an average specific yield of around 14 %. Khan (1978) has summarized the results of pumping tests and lithological, mechanical analyses of test holes, according to which hydraulic conductivity varies from 24 to 264 m/d and specific yield values vary from 1 to 33 % in Rechna Doab.

Groundwater in the Rechna Doab is an active part of the water cycle as most farmers rely on it as a supplement for their share of canal water supply. The groundwater table in the doab lies around 6 m below ground and can therefore easily be reached using fairly cheap and readily available well technology. The homogeneous and highly conductive aquifer underlying the entire Rechna Doab further facilitates the use of groundwater. Since the early 1900s, through the construction of the first larger irrigation canals and high seepage rates from these canals into the ground, the groundwater table in the doab rose dramatically leading to water logging in many areas. During the 1960s the water table could be stabilized using state-organized pumping campaigns to extract groundwater for use as irrigation water. The introduction of affordable pumps and the consequent rise of groundwater abstraction by farmers led to falling groundwater tables around the turn of this century.

4.3 Cotton Farming

(B. Tischbein, M. Usman)

Cotton is dominating the cropping pattern of the Kharif season in terms of area (together with rice and fodder crops) ranging between 2.5 to 3.1 Mha during the last decade. Due to the huge area and a rather long vegetation period (Figure 4.4), cotton cultivation accounts for a considerable part of irrigation water in the study region; vice-versa, improvements in cotton irrigation towards higher efficiency and productivity have a high potential to lower the currently tremendous – and in future due to climate change even further rising – pressure on water resources in Punjab.

Monsoon rainfall during Kharif season in Punjab (around 240 mm at Faisalabad in April-October) is by far not sufficient to cover the potential evapotranspiration of cotton (in the range of 700 mm) and therefore, cotton cultivation depends on irrigation. The irrigation water is provided by a hierarchy of canals from mains, branch, and distributaries to watercourses for field application following the the Warabandi principle. Yet, canal water supply is complemented by pumping groundwater for two major reasons: firstly, the capacity of the canal system does not allow to match the water requirements caused by the increase in copping intensity compared to the intensity level of the canal system design; secondly, farmers use the aquifer as a buffer to achieve some flexibility from the Warabandi system in order to meet the time-depending irrigation water demand.

At farm level, irrigation water received from watercourses and/or pumped from groundwater is conveyed in most cases by unlined farm canals to the fields. The methods for application of the water to the field (or more precisely, to the root zone of the crop) consist in basin or border irrigation ('flat sowing'), conventional furrow, raisedbed technique ('bed planting') or, at few farms, by drip irrigation (Figure 4.4).

Basin/border and furrow irrigation are conventional techniques, raisedbed is an advanced version of gravity-driven irrigation techniques. The technical efficiency of these methods (relation between the amount of water brought into and stored in the root zone for beneficial use by the crop and the amount of water directed to the field) depends mainly on:

- appropriate determination of the net irrigation demand (in general for filling soil moisture from current level up to field capacity),
- spatial uniformity of water application within the field
- avoiding of surface runoff from the field
- minimizing of evaporation during application process
- proper dosage of application discharge.

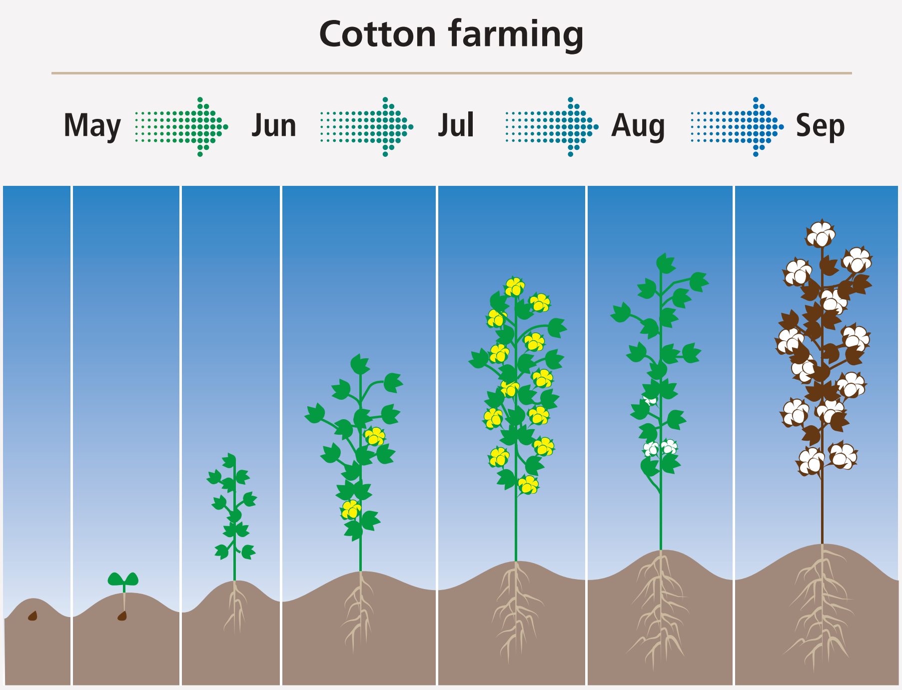


Figure 4.4: Cotton growing period in the Kharif season from May to September. © FiW

As the gravity-driven methods use the surface of the field for water application, the uniformity of the slope within the field has a crucial influence on the uniformity of water distribution in the field, efficiency of these methods can be enhanced by laser-guided field leveling. Combining raisedbed and laser-guided leveling a powerful combination of interventions creating an enabling environment to foster irrigation efficiency.

Drip irrigation has the highest potential to raise efficiency due to targeted application to the crop, frequent irrigation water application with high uniformity, lowering evaporation and enabling proper dosage. In combination with fertilizer application, the drip system can achieve high productivity (Table 4.1).

Text Box 3:

What is the Warabandi system?

The Warabandi (the term Warabandi means "turns" (wahr) which are "fixed" (bandi) is a fixed-rotational cycle, which normally repeats every week to achieve the most uniform and equitable allocation of water. All farmers who are landowners or tenants are entitled to water in proportional relation to their field size (Bandaragoda, 1998). The cycle of Warabandi starts from the head and proceeds to the tail of the watercourse. During each turn, the farmer has the right to use all of the water flowing in the watercourse at his specified turn (Bandaragoda, 1998).

The main canals, distributaries, and minors are managed by the provincial Irrigation Departments and deliver water to the head of the watercourses through a fixed cross-section outlet, which is designed to provide a quantity of water proportional to the cultivable command area of the watercourse. In order to meet its objective to distribute water equally the design concept of Warabandi assumes that each distributary canal, by and large, maintains a flow close to 75 percent of the full supply capacity.

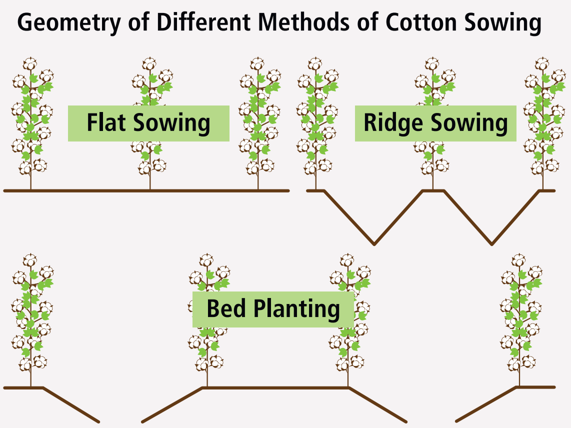


Figure 4.5: Major irrigation methods and related cotton planting (basin/border, furrow, raised-bed, drip). © FiW

Table 4.1: Comparison to application efficiencies (AE) reported in literature.

Irrigation Practice	Application	Comment	Reference
Uncontrolled flooding (Basin)	40 – 50 %	Based on soil and discharge	Brouwer *et al.* 1989
Sprinkler	75 – 80 %	Based on soil types	Brouwer *et al.* 1989
Drip	90 – 95 %	Based on soil & irrigation	Brouwer *et al.* 1989
Border (gravity)	55 %	Based on field applications in wheat crop	Shahid (2009)
Furrow ridge (gravity)	55 – 60 %	Based on about 30% water saving in bed-furrow as compared to ridge-furrow, and assuming AE of bed-furrow as 75 %.	Ahmad *et al.* (2011)
Bed furrow (gravity)	67 % 65 – 75 %	Based on field applications in wheat crop. Based on 40 – 50% water saving, observed in comparison to conventional flooding with 40 – 50% efficiency.	Shahid (2009) Ahmad and Mahmood (2005); Ahmad *et al.* (2007); Shahid and Ahmad (2008)
Furrow ridge with drip	90 – 95 %	Similar to Drip	Own estimation
Furrow bed with drip	90 – 95 %	Similar to Drip	Own estimation

4.3.1 Satellite Remote Sensing (M1)

(M. Usman, C. Conrad)

Remote sensing data are fundamental input for hydrological and hydrogeological distributed models. In the InoCottonGrow project, we have used remote sensing data and techniques for achieving three major objectives, including (i) land use land cover classification (ii) consumptive water use modeling, and (iii) cotton crop biomass and yield estimation.

4.3.1.1 Land-use land-cover mapping

We have used both unsupervised and machine-learning classification approaches for mapping land-use land-cover using MODIS and Sentinel 1&2 data. All major crops of spring (Rabi) and monsoonal autumn (Kharif) cropping seasons including cotton, wheat, rice, and sugarcane are classified from 2005 to 2017. For unsupervised classification, we have utilized MODIS NDVI data at 250 m resolution (both Aqua&Terra) at 8 days temporal resolution. Data quality check and other pre-processing was performed before running the k-means algorithm. We generated NDVI temporal profiles of different major crops in the regions for different cropping seasons. As a last step, the accuracy assessment of the modelled results was performed by comparing results with state crop inventory and internet-based map services. Figure 4.6 shows the obtained land-use land-cover map of the Punjab for all major crops including cotton.

We also utilized various machine learning algorithms including the Random Forest and Support Vector Machine for Sentinel 1&2 data at 20 m spatial resolution to generate the land-use land-cover information. We downloaded Synthetic Aperture Radar (SAR) data (i. e. Sentinel 2) by the European Commission for the cotton cropping year 2016–2017 free of cost from https://scihub.copernicus.eu/. The processing of data was performed using SNAP (http://step.esa.int/main/toolboxes/) and PolSARpro (https://earth.esa.int/web/polsarpro/home) tools. We also used SAR data in combination with optical data from Sentinel to achieve better classification results. The results

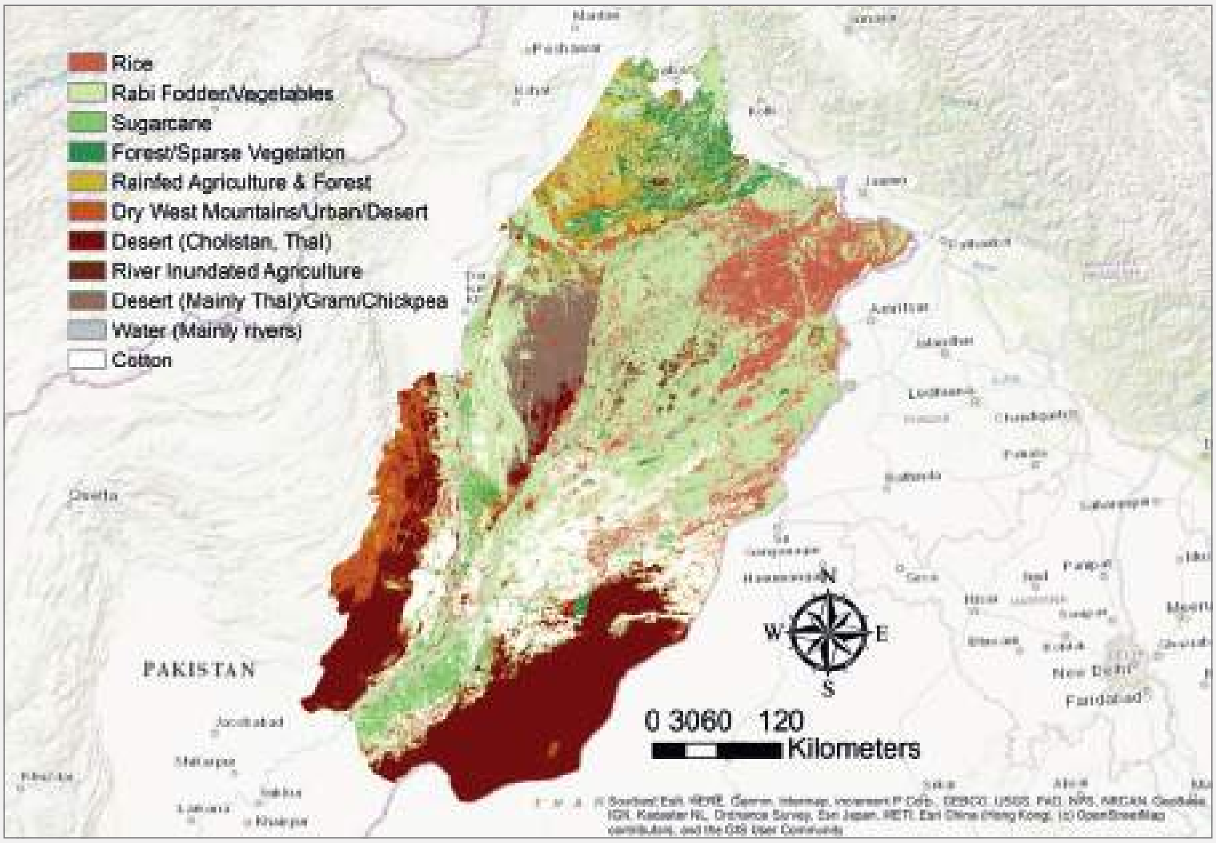


Figure 4.6: Land-use land-cover mapping results of Punjab for unsupervised classification. © UW

were verified, based on 1400 field points collected in the region, through different tests including error matrix, kappa coefficient, and McNemar test. The results are utilized to devise detailed land-use land-cover scenarios for the hydrological modelling using SWAT model. Figure 4.7 shows the land use land cover map of the entire LCC at 20 m spatial resolution.

The results of the whole Punjab (Figure 4.6) show that during the Kharif cropping seasons, Kharif fodder/vegetable is the largest class by area followed by desert and cotton at the second and third places, respectively. The other crop classes during Kharif seasons include rice (at 4th place), sugarcane (at 9th place), and rainfed agriculture at the 5th place. Whereas, for Rabi cropping seasons, wheat is predominantly the largest class followed by Rabi fodder/vegetable at the second place. Desert is the third largest class followed by dry mountains/urban areas, rainfed agriculture, forest/sparse vegetation, desert agriculture, sugarcane, water, and river inundated agriculture. During the period from 2005–2017, cotton was grown in Punjab province on 2.35 ± 0.21 million ha (47 % of cultivated irrigated land).

From the results based on LCC region, rice is dominated in the upper regions whereas fodder and sugarcane are dominant in the mid regions along with other classes including cotton, and settlements. It is also evident that in LCC cotton is less dominant and mainly grown in the tail reaches of the irrigation system (Figure 4.7).

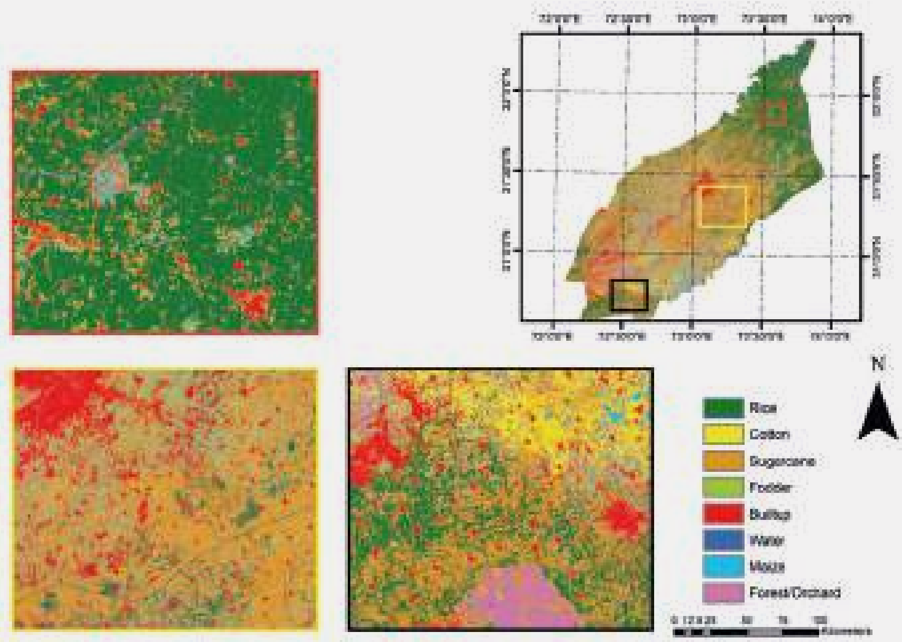


Figure 4.7: Land-use land-cover mapping results of LCC for machine learning using SAR and optical data. © UW

Text Box 4:

How is water consumption calculated from satellite remote sensing?

Energy balance for ET:

$$ET = R_n - G - H$$

where ET ist the latent heat flux (W/m²), R_n is the net radiation flux at the surface (W/m²), G is the soil heat flux (W/m²), and H ist the sensible heat flux to the air (W/m²)

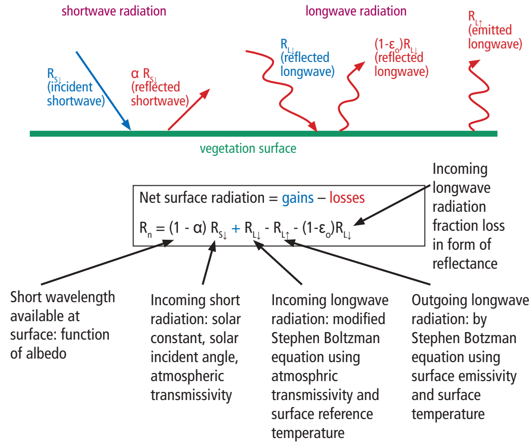
$$EF = LE/(R_n - G)$$

EF behaves temporally stable during the diurnal cycle. Since EF ~ EF24, i.e. the 24 hour latent heat flux can be determined as:

$$LE_{24} = EF * R_{n24}$$

For simplicity, the 24 hour value of G is ignored

Reference: Bastiannssen et. al. (1998)



4.3.1.2 Consumptive water use estimation

We have used Surface Energy Balance Algorithm (SEBAL) for the estimation of actual evapotranspiration (I. e. consumptive water use) devised by Bastiannsen *et al.* (1998). Table 4.2 shows the summary of the data utilized for the purpose. As a first step, we performed pre-processing of MODIS data including rescaling, resampling, sub-setting, re-projecting and different data quality checks using various specialized codes written in R programming. About 1500 GB data were downloaded and processed, from 2005 to 2018, free of cost from https://modis.gsfc.nasa.gov/data/.

Table 4.2: Summary of MODIS data downloaded and pre-processed for SEBAL.

Data Product	Spatial Scale	Temporal Scale	Sensors	Variables
MOD13A2	1000 m	16 days	Aqua, Terra	NDVI, Rely
MOD15A2	1000 m	8 days	Terra	LAI
MOD09Q1	250 m	8 days	Terra	Red, NIR, Surf-ref-qc
MOD11A1	1000 m	Daily	Terra	LST, Day-view-time, Day-view-angle, Emissivity B31, Emissivity B32, QC_Day

For validation of SEBAL results we utilized multiple approaches including comparison of SEBAL results with advective-aridity (AA) and Penman Monteith (PM) approaches for the period from 2005–2016 (Figure 4.8). The results of SEBAL ET usually underperformed than AA during summer months but the results are contrary for cooler months. The results are in accordance with other studies, including Usman *et al.* (2014; 2015) and Waqas *et al.* (2016).

Moreover, various energy and soil flux sensors were installed at a test site located in the research field of the University of Agriculture, Faisalabad. The results of net radiation and soil heat flux were compared with the results from SEBAL (Figure 4.9), which shows R^2 values of 0.86 and 0.96, Nash Sutcliff Efficiency (NSE) of 0.82 and 0.81, and Root Mean Square Error (RMSE) of 55.28 and 9.2, respectively. The results can be considered satisfactory considering a spatial difference of comparison between 1 km x 1km SEBAL based results to point specific results from the installed sensors.

Figure 4.10 shows the spatial distribution of during Kharif and Rabi cropping seasons. Water consumption is usually higher in northern regions. During Kharif season, it is mainly associated to rice cropping in these areas due to relatively better canal water availability and higher rainfall in the northern reaches.

The spatial analysis of consumptive water use was performed at different scales including irrigation circles, irrigation divisions, and irrigation subdivisions of LCC. At the scale of irrigation circles, the most upstream irrigation circle (rice dominant area) show significantly different ET patterns than the other irrigation circles of the study area. The higher spatial difference of ET patterns (upstream-downstream) occur at the level of irrigation subdivisions, followed by irrigation divisions, irrigation circles and the whole Rechna Doab.

Text Box 5:

How to calculate crop yield from satellite remote sensing?

The Light Use Efficiency (LUE) model relies on plants absorbing light energy (photosynthesis), which is depicted in form of photosynthetically active radiation (PAR). If we know the fraction of light which is absorbed (i.e. FPAR), then we know the energy available for the increase of biomass (i.e. APAR). The biomass increase (NPP) is determined by the factor, which states how efficient absorbed energy is converted into biomass, which is known as light use efficiency. The accumulated NPP can then be converted into a crop yield through introduction of harvest index (HI).

Light Use Efficiency Model based on Monteith (1972 & 1977)

$APAR = FPAR * PAR$

$NPP = APAR * LUE_{act}$

$Crop\ Yield = NPP * HI$

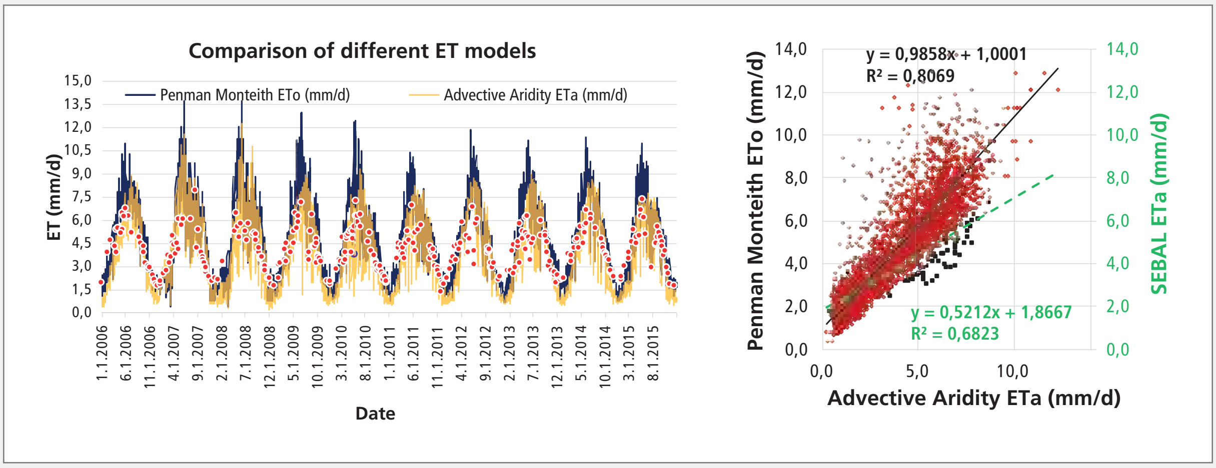


Figure 4.8: Comparison of SEBAL-based ET results with AA and PM. © UW

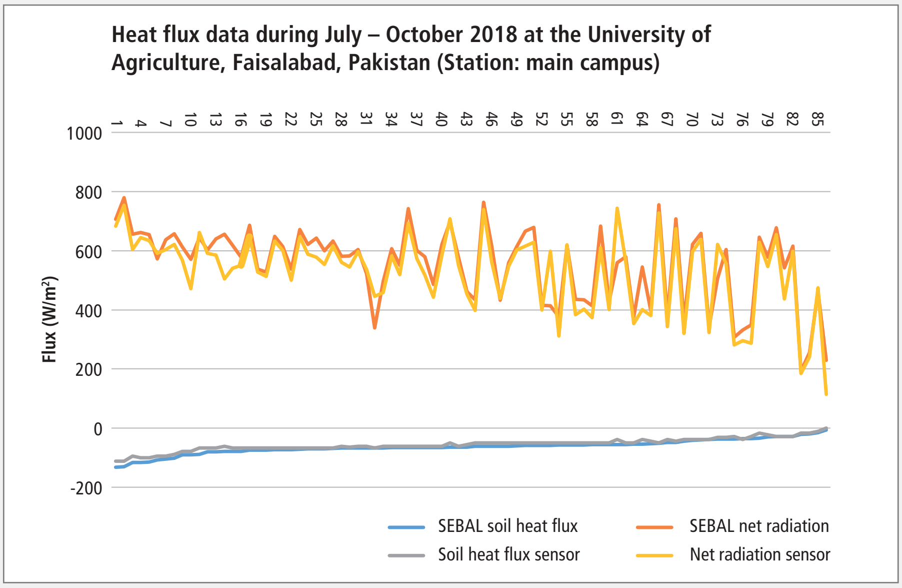


Figure 4.9: Comparisons of SEBAL results with head flux data at UAF main campus measured July to Oct. 2018. © UW

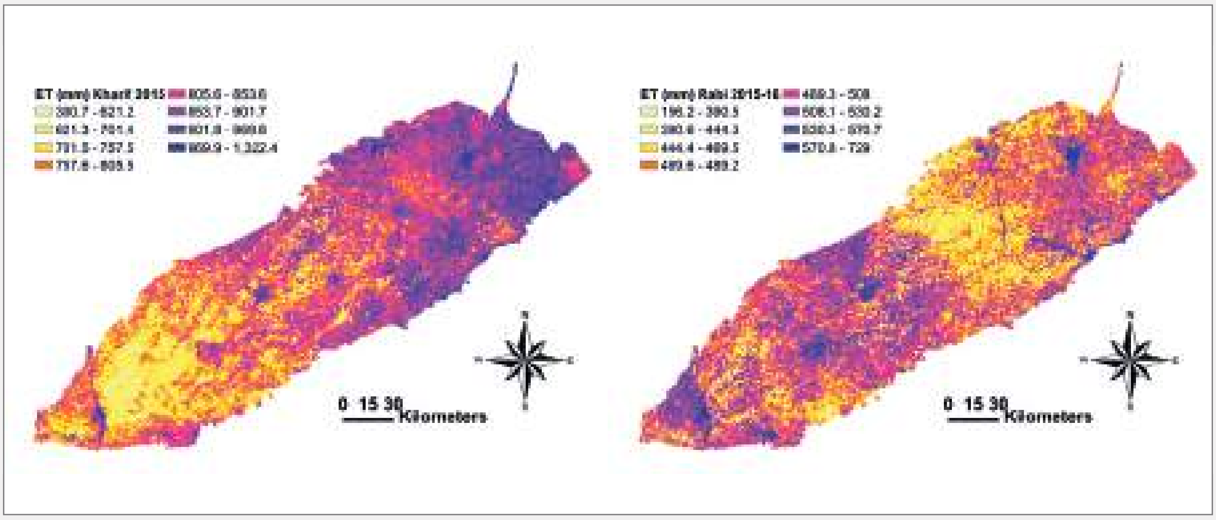


Figure 4.10: Spatial distribution of consumptive water use during Kharif and Rabi cropping seasons. © UW

4.3.1.3 Crop yield estimation

We have utilized the Light Use Efficiency (LUE) model for modelling of cotton yield in Punjab for the period from 2005–06 to 2015–16, using MODIS Normalized Difference Vegetation Index (NDVI) data along with Photo Synthetic Active Radiation (PAR) and temperature data from the European Centre for Medium-Range Weather Forecasts (ECMWF). The NDVI data of 250 m spatial resolution were attained free of cost from https://modis.gsfc.nasa.gov/data/, whereas the PAR and other climatic data were downloaded from https://www.ecmwf.int/ free of cost at a spatial scale of 0.5 degree. The land-use land-cover information of the target crop cotton was attained from the land-use classification results presented above.

Different values of light use efficiency were utilized in a loop function to fit results to yield data observed in the field. HI value of 0.08 is used as reported by FAO for lint cotton. Initially the model was calibrated and validated for major cotton producing districts of Punjab including Khanewal, Multan, Lodhran and Vehari. Later the estimation was done for the whole Punjab. The best results were attained for light use efficiency value of 2.5 (g C/MJ) as can be seen from the Figure 4.11.

Based on these results, Figure 4.12 shows the spatial distribution of cotton yield in the whole Punjab and major cotton producing districts for the cropping season 2016. It is evident that the cotton is dominant in the lower-middle regions of the province. The upper-middle Punjab regions including the LCC were majorly cultivated with rice with random cultivation of cotton.

4.3.2 Irrigation Efficiency and Productivity from Field to Distributary-Canal Level (M2)

(B. Tischbein, A. Bakhsh, I. Sajid, M. Fareed)

The goal to "reduce the water footprint' translated in an objective to guide irrigation management leads to the target of 'increasing water productivity'. Major terms for assessing the current status of irrigation performance are clarified in the following.

Water productivity is formulated as yield per gross water input. Tackling these factors, water productivity can be optimized by irrigation management basically by

1. providing irrigation (in terms of amount and timing) sufficient to avoid any water stress ('appropriate irrigation')
2. with lowest possible water losses ('highest technical efficiency').

Appropriate irrigation is considered in case the actual transpiration is at potential level (no water stress). **Technical irrigation efficiency** is the amount of irrigation water brought into and stored in the root zone (and beneficially used by the crop) in relation to the gross water directed from the source to the irrigation unit. In order to assess the handling of major irrigation system components, efficiency terms are related to the process of applying the water to the field (**field water application efficiency**) and to the process of conveying water in the irrigation network (potentially further differentiating according to canal hierarchy).

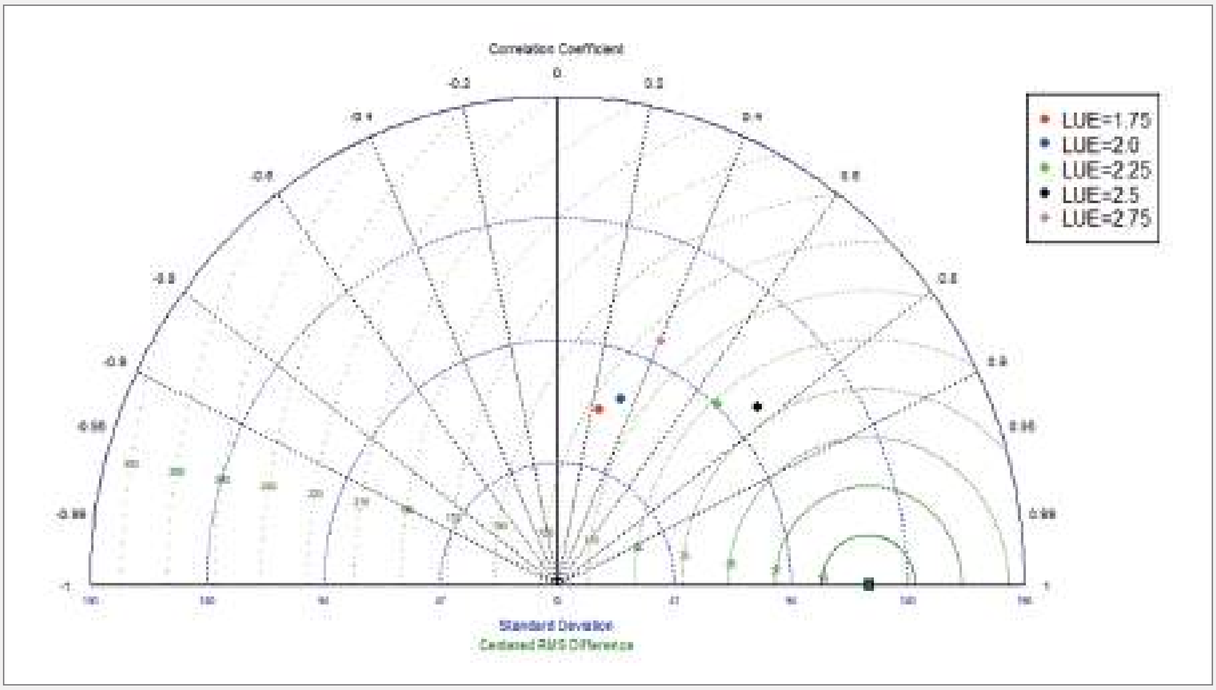


Figure 4.11: Taylor diagram for comparative statistics of yield estimation using the Light Use efficiency model. © UW

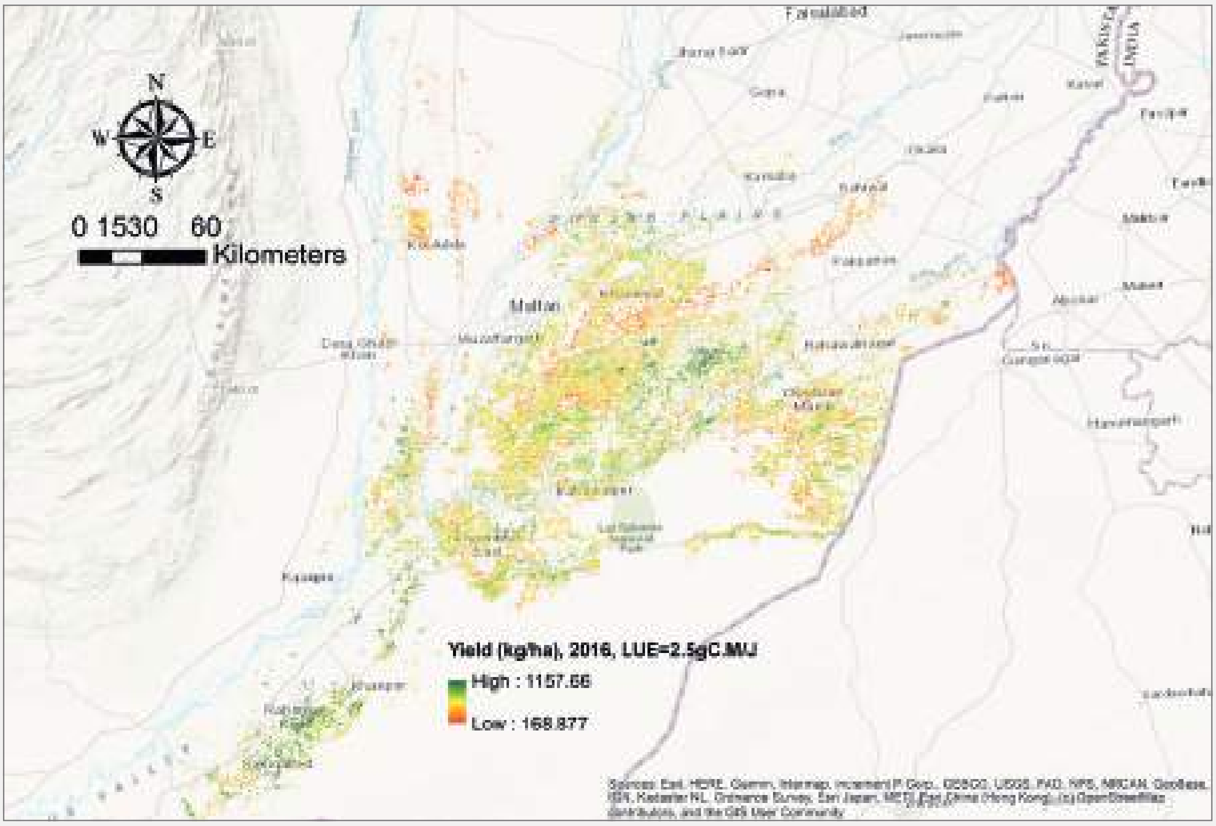


Figure 4.12: Spatial distribution of lint cotton yield (kg/ha) for year 2016 in major districts of Punjab. © UW

Text Box 6:

How do irrigation scheduling models work?

The major purposes of agricultural irrigation consist in realizing (1) soil moisture over the vegetation period in the root zone of the crops high enough to avoid water stress, and (2) soil salinity low enough not to exceed salt tolerance limits of the crops. Under arid and semi-arid conditions, reaching these objectives requires application of irrigation water (fulfilling purpose 1) and realizing leaching (meeting purpose 2). Irrigation scheduling is the procedure to determine plans providing the **information on when and how much to irrigate** and when and by which amount to realize leaching. This Text Box 6 is focusing on purpose 1, whereas Text Box 9 below provides information on leaching for salt management (purpose 2).

Water stress occurs when the soil moisture drops below the level of 'allowable depletion' that means root water uptake is limited by low soil moisture leading to a reduction of actual transpiration below potential level which in turn is causing reduction of yield. The core of irrigation scheduling models consists **in water balancing related to the root zone with high temporal resolution** (daily time-steps). Contrasting water inputs (rainfall, irrigation, capillary rise) versus water outputs (evaporation, transpiration, percolation below root zone, surface runoff) for the root zone of an irrigation field at daily time-steps provides the daily soil moisture in the root zone. When the soil moisture reaches the lower limit of the allowable depletion, irrigation is needed and the net irrigation is the amount to fill current soil moisture up to field-capacity level. Following that approach, irrigation scheduling models deliver the information when and how much to irrigate (irrigation plan or irrigation schedule).

In order to deliver the irrigation plan, scheduling models such as FAO AquaCrop process data on: (a) atmosphere (temperature, air humidity, wind speed, solar radiation in order to estimate evapotranspiration as well as rainfall), (b) soil water storage characteristics (field capacity, permanent wilting point) and features controlling water fluxes (mainly: hydraulic conductivity), (c) biomass and yield development under the influence of transpiration in order to derive the irrigation time and amount from the soil water balance.

With respect to available water supply, two cases may occur: sufficient supply and limited supply. In case of sufficient supply, irrigation schedules avoiding water stress by maintaining the soil moisture within the allowable depletion can be derived and, therefore, these schedules enable to mobilize the full yield potential related to the input 'water'. In case of **limited supply**, water supply is not sufficient to keep soil moisture within the range of allowable depletion, water stress and in turn yield reduction is unavoidable. In this case, the task of applying irrigation-scheduling models consists in minimizing the effect of unavoidable undersupply on the yield (**controlled deficit irrigation**).

Water allocation in Punjab is guided by the Warabandi principle leading to a fixed rotational water provision (canal water provided each 7 or 10 days with a fixed amount). Although irrigation schedules are determined by the supply side, irrigation scheduling models (basically starting from demand-side) have the potential to support farmers by enabling the following options:

- supporting pre-season selection of crops based on simulated impact of the fixed rotation on the yield under expected soil-crop-atmosphere conditions
- water allocation within the farm can be optimized
- in case of undersupply regarding the canal water, additional irrigation events (timing, amount) supplied by groundwater pumping to avoid or minimize water stress can be determined.

4.3.2.1 Current status of irrigation in Mungi distributary area

In order to assess the current status of irrigation, we applied an approach combining modeling (irrigation scheduling model: FAO AquaCrop) and monitoring of irrigation practices (Mungi Distributary area in LCC study area). The FAO-AquaCrop is an atmosphere-soil-water-crop model capable to perform irrigation scheduling by (i) providing time and net amount of the irrigation events to be executed over the vegetation period, and (ii) deliver an estimation of the yield to be expected by these schedules under the crop, soil, and atmosphere conditions at the site under consideration.

Monitoring of cotton irrigation of three farms in the area supplied by the Mungi Distributary during the cotton seasons 2018 and 2019 led to following major results:

- Although water input to the monitored cotton fields and the respective yields achieved show wide ranges (gross water input ranging from: 275 mm up to 1081 mm; with average around 600 mm; yields: in the range between 1.10 up to 2.82 ton raw cotton/ha, the irrigation in general is in a deficit situation (mainly in terms of yield and in turn regarding productivity). Yet, there is an example of drip irrigation in combination with a pond for water storage performing at a level which marks the realistically achievable optimum productivity.
- (Technical) field application efficiency by conventional furrow and raisedbed technology is in the range of 51 up 68 % (with higher values achieved by well managed bed-furrow systems); in case of basin or border irrigation methods, application efficiency is lower with around 40 %.
- Network efficiencies were analyzed (by inflow-outflow method) for watercourses and irrigation ditches within farms. Table 4.3 provides the losses per unit wetted area and time, which are then transferred into a conveyance efficiency related to a 1 km canal reach. Losses of the unlined canals are high and especially relevant in the farm ditches. By canal lining, the losses (mainly by percolation and seepage; to a small degree also by evaporation and transpiration of vegetation in the canals) can be lowered by 70 % (i. e., to one-third) representing a huge water saving potential, yet having implication on the groundwater recharge as discussed below.

In order to approach the current irrigation practice in the Mungi region, we applied the irrigation scheduling model FAO AquaCrop by utilizing inflow data at Mungi Disty, meteo, soil data, and practiced Warabandi schedule as input. As depicted in Figure 4.13, a gross irrigation amount of 377 mm was provided by the inflow to Mungi from May 9th to Nov. 11th 2017 in addition to 184 mm of effective rainfall (May 1st to Nov. 30th, 2017 amounts to 421 mm). Based on a technical scheme irrigation efficiency of 50 % and assuming that 90 % of the irrigation losses recharge groundwater and are pumped back for irrigation, 358 mm net irrigation amount is available (Figure 4.14).

Based on a 7-day Warabandi schedule, we allocated this net irrigation amount in the simulation at each Warabandi turn (7 days irrigation interval) and at each second turn (14 days irrigation interval) taking into account soil, meteo and crop data for Mungi situation. Figure 4.15 provides the field water balance components and the yield of the AquaCrop simulation. Besides approximating the reality in Mungi, the simulation reveals that the model can be used to optimize temporal within-farm water allocation.

Under typical soil conditions in Punjab (loam with a rather high storage characteristics), it is possible to use the canal water provided in a 7-day Warabandi each second turn for irrigating cotton (14 days irrigation interval) and thereby to reduce non-productive actual evaporation and raise productive actual transpiration leading to a higher yield with same irrigation amount.

The higher water input monitored at specific farms in relation to the simulation based on average conditions in Mungi can be made plausible by following explanations: due to water deficit situation, not the entire farm area is irrigated (as confirmed by representatives of Punjab Irrigation) increasing the water input per area; farmers may prioritize cotton).

Table 4.3: Losses in studied watercourses and farm ditches.

	Length (m)	Discharge capacity (L/s)	Loss in (L per m2 wetted area * hour)	Conveyance efficiency per 1 km
Watercourse (unlined)	1780	79	23.1	88.6 %
Field ditch (unlined)	620	44	41.8	70.6 %

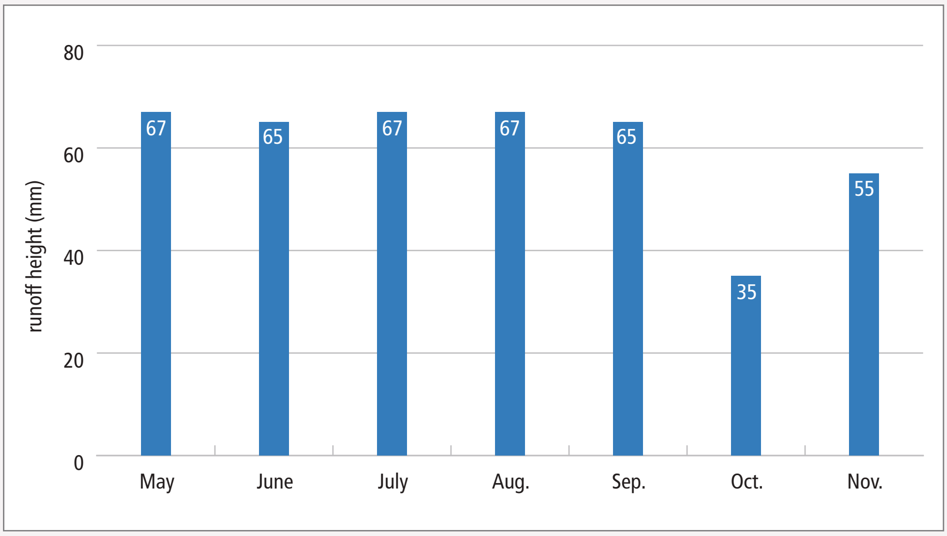


Figure 4.13: Inflow to Mungi area from (runoff-height calculated by daily values and summed to months).

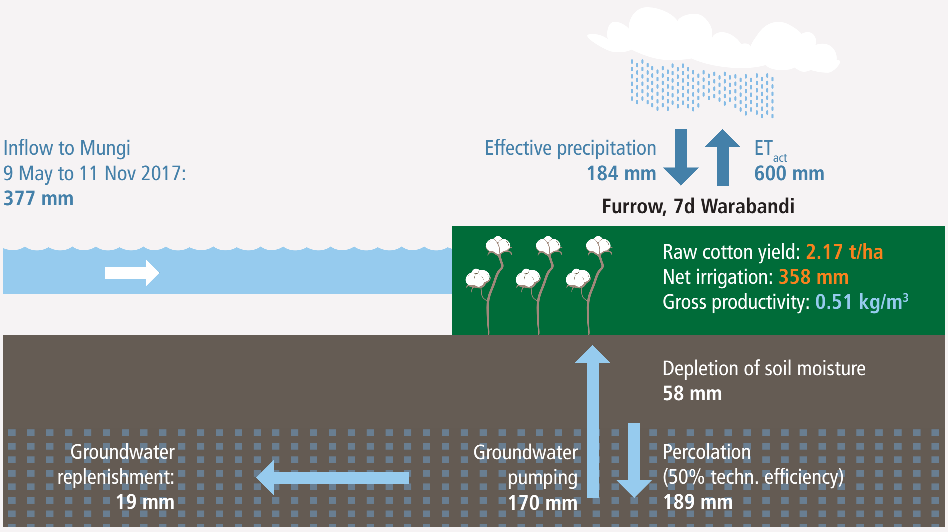


Figure 4.14: Schematic field water balance calculated for 7-day Warabandi for Kharif cotton season from May 9th to Nov. 11th, 2017. © FiW.

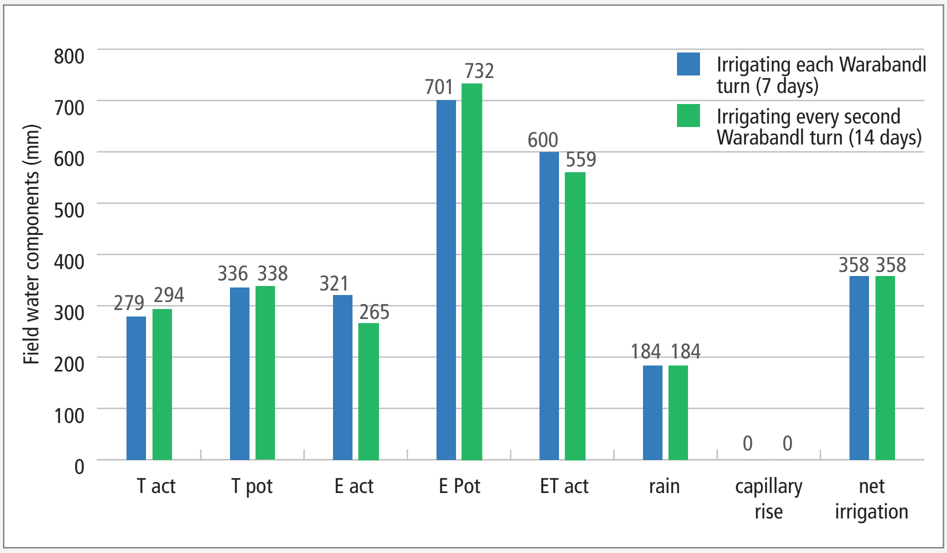


Figure 4.15: Field water components comparing 7-day Warabandi (each turn) to 7-day Warabandi (irrigating only every second turn, 14 days) shifting from (non-productive) evaporation E_{act} to (beneficial) transpiration T_{act} raising raw cotton yield from 2.17 to 2.29 tons per ha.

4.3.2.2 Options of irrigation scheduling towards improving water productivity

Basically, options for improving irrigation towards higher water productivity comprise of: (1) interventions in field-water management (irrigation scheduling; modification and handling of water application techniques; storage facilities as a component of 'creating an enabling environment' for advanced scheduling), (2) upgrading the canal network (mainly: lining), and (3) measures advancing agricultural inputs as well as processes towards higher yield which is enhancing the utilization of irrigation water applied. For reaching high impact, combining interventions into 'packages' is the most promising and effective approach.

Field water management

We used the AquaCrop model adapted to the conditions in Mungi as a tool to model improved water productivity via advancing irrigation scheduling. Shifting the partitioning of evaporation and transpiration towards productive transpiration is one option to raise productivity (Figure 4.15). A further option to raise productivity consists of realizing water savings of practiced schedules keeping the yield at the current level. In the following, we give an example summarized by Table 4.4.

*Table 4.4: Practiced and optimized irrigation schedules (*not considering non-uniformity along the furrows or raised-bed lines).*

	Practiced irrigation	Optimal schedule	Warabandi (irrigation at each second turn, 14 days)
Number of irrigation events	18	11	11
Water applied (mm)	1081	405*	300*
Potential Transpiration (mm)	496	490	485
Actual Transpiration (mm)	488	490	425
Potential evaporation (mm)	463	433	472
Actual evaporation (mm)	252	220	221
Percolation below root zone (mm)	682	18.2	0.6
Biomass (ton per ha)	9.3 (9.45)	9.36	8.7
Yield (ton raw cotton per ha)	2.03 (1.97)	2.06	1.9

As reference situation, 'practiced irrigation' (18 irrigation events; 1081 mm water input in the cotton season) was monitored at a farm in Mungi leading to a measured yield of 2.03 ton per ha. Water balance components were simulated by AquaCrop with soil, crop, and meteorological input data of the location; simulated yield (1.97 ton per ha) is close to the observed amount. The 'optimal schedule' represents a flexible and demand-based irrigation (not considering restrictions by Warabandi), whereas the simulation scenario 'Warabandi' is embedded in the Warabandi schedule using the water at the cotton field at each second turn (14-day irrigation interval). Basically, the water saving potential can be derived from a comparison of the water balance component 'percolation below root zone'. An amount of 682 mm in the practiced schedule reveals a clear over-irrigation. In the 'optimal' and the 'Warabandi' scenarios, these percolation losses can be strongly reduced as simulated percolation is small ('optimal') and zero ('Warabandi'). The yield levels are maintained ('Optimal'; 2.06 ton per ha) or slightly lower (1.9 ton per ha) as a consequence of slight deficit irrigation under Warabandi conditions, a high gain in water productivity can be achieved. As AquaCrop is a one-dimensional model, non-uniformity of water application along the furrow/raisedbed lines is not considered; therefore, not the full difference in 'percolation below the root zone' between the reference situation and the scenarios can be saved in reality.

Besides – and in combination with scheduling – options for modifying application techniques and their advanced handling have a potential to raise productivity by lowering gross water input (reducing irrigation losses and rising irrigation efficiency). For that purpose, our partner UAF carried out irrigation experiments considering modification of techniques (raisedbed instead of conventional furrows), technology change (stepping from surface irrigation methods to drip technology) and full as well as controlled deficit irrigation strategies (see chapter 6.1).

Canal network

Lining of watercourses and field ditches is reducing seepage and percolation losses. The losses in unlined versus lined canals given in Table 4.3 can be reduced to one-third, enabling a considerable water saving potential. Yet, lowering of canal percolation losses leads to reducing the groundwater recharge and thereby impacting the groundwater potential.

When conceiving options for rising efficiency at field and canal network level, it should be taken into consideration that – to a high share – the efficiency rise is caused by lowering percolation which is recharging groundwater. As a consequence, groundwater potential currently used as a storage 'buffer' for more flexible irrigation is reduced and in terms of water quantities nearly 'zero-sum games' between efficiency gain in the surface system versus lower groundwater potential are played.

Yet, we suggest to include in decision-making processes external effects of groundwater pumping (compared to more efficient use of irrigation water in the surface system) which mainly consist in costs for pumping and in CO_2 emissions of diesel pumps. A further aspect deserving consideration while conceiving interventions towards efficiency rise via lowering of percolation refers to the impact on groundwater quality within the linked water quantity-quality interface; that means avoiding percolation of water polluted with fertilizers and plant protective agents may help to conserve groundwater quality (priority for efficiency gain and reducing percolation), whereas percolation from sources with low pollution (canal water) is recharging groundwater quantitatively with a low risk towards quality reduction in the aquifer (less priority for efficiency gain from perspective of groundwater quality conservation).

Enhancing the agricultural system

The yield of cotton is caused by a mix of manifold and interdependent factors (e.g., water, crop features, soil, atmosphere, nutrient availability, diseases, agricultural practices). Going beyond managing the input 'water' by irrigation as considered above in (1) and (2), interventions on other factors aiming at higher yield can enhance the utilization of the input 'water' in terms of higher water productivity. Tackling such non-water factors currently causing under-performance in yield generation reveals that improving seed quality, fertilizer application, management of diseases and pests can clearly improve production – and in turn for a given water input – contribute to enhancing water productivity.

Text Box 7:

Why are pesticides used in cotton farming?

Cotton is a marvelous crop with renewable, recyclable and biodegradable properties. It is a difficult crop to grow particularly under severe weather situation (i.e. both droughts and flooding). Many insects, nematodes, spider mites and disease-causing microorganisms feet on cotton. Its successful raising demand vast use of pesticide and insecticides, for instance, despite only 2.4% share of this crop in world's cultivated land, it utilizes 16% insecticide and 6% pesticides of the world's agriculture usage. The major pesticides/ insecticides used from cotton in Pakistan include Organophosphate, Bifenthrine, Emamectin, Trizophos, Acefate, Leufereon, Triazophas, Acetamapirid, Karatay, Olala, and Polytrinc, whereas, in Turkey, Akariside, Aphisgossypii, Bemisia Tabaki, Lygus Spp and Heliothis Armigera are heavily used. Pesticides use – even when used according to instructions – can harm through poisoning farm workers, drift into neighboring areas and communities, contaminate surface and groundwater resources and kill beneficial insects and soil micro-organisms.

More than 90 % area in Pakistan is under BT cotton. BT cotton use lepidopteran control and has no direct role for climate change and water shortage. Generally, BT varieties has more yield potential than non-BT varieties so we may say they have high resource use efficiency like water and nutrients. BT varieties are more responsive to nutrients as well. Nevertheless, these all varieties are not performing so good in Punjab due to high stress like heat and insect pest complex.

Figure 4.16: Pesticide used by a farmer in Punjab. © FiW

4.3.2.3 Drip irrigation in combination with water storage facility

We analyzed the performance of a drip irrigation system fed from a pond at the farm in Samundri region. Cotton was grown and irrigated with high frequency (daily) in the period from April 25th to August 27th, 2018. By achieving a raw cotton yield of 2.82 ton/ha with a gross water input of 275 mm, the farmer reached a level, which we consider as upper limit of practically reachable water productivity.

We simulated the irrigation by AquaCrop with water balance components as depicted in Figure 4.17. The simulation confirmed that the rather high productivity is achievable by a package of drip irrigation and a pond enabling high frequency irrigation at a controlled deficit level and utilizing depletion of the soil storage.

4.3.2.4 Implementation factors other than water

The major challenge regarding implementation of advanced irrigation schedules consists in the need to introduce a more flexible as well as demand-oriented irrigation in order to cope with an increasingly variable environment (due to climate change and a sharpening competition for water driven by land use dynamics) under the condition of the Warabandi principle assumed to guide water allocation in future in Pakistan.

We see the entry-point for implementation of a more flexible and demand-oriented irrigation at the level of a farm. Taking the water input into the farm according to the Warabandi as fixed, the application of irrigation scheduling can support farmers in pre-season crop selection, in-season and within-farm water allocation and minimizing the impact of water stress on yield in case of non-avoidable under-supply (expected to become a realistic challenge due to climate change in tendency rising the water demand (higher evapotranspiration) and lowering the water supply or at least increasing its variability. Melting glaciers are expected to reduce their buffer function on water supply.

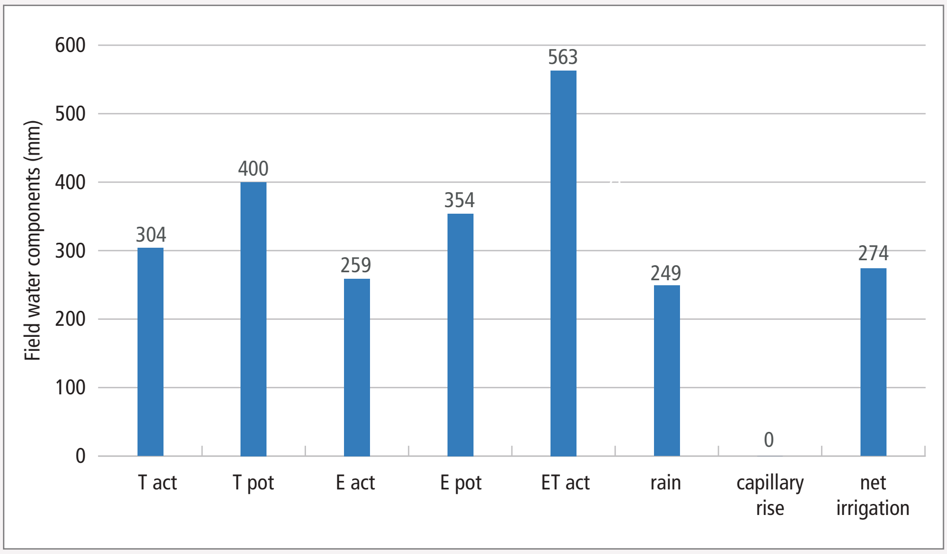


Figure 4.17: FAO-AquaCrop simulated field water components of a practiced drip irrigation (cotton season 2018) at a farm in Samundri region. Raw cotton yield observed was 2.82 ton/ha, simulated 2.75 ton/ha. (Controlled) deficit irrigation utilizing soil storage depletion approaches a realistic upper limit of productivity.

4.3.2.5 Outlook on future challenge by climate change

Climate change is expected to raise the irrigation demand due to enhancing evapotranspiration driven by rising temperature. In addition, there is high uncertainty on changes in further influential factors on actual evapotranspiration (ET_a).

In order to approximate the magnitude of increasing evapotranspiration, we preformed simulation runs as given by the alterations in Figure 4.18. Basically, we consider two groups of simulations: (1) impact by rising temperature as a rather sure corridor of change and (2) impact by altering air humidity and wind speed (high uncertainty). As reference scenario we used meteo data from UAF campus station of 2018. Alternative scenarios considered a temperature raise by 2 °C and 4 °C, respectively; a lowering of air humidity (RH) by 5 % and 10 %, respectively; a raise in wind seed by 0.3 m/s and by 0.5 m/s; and finally the combined effect of lowering air humidity and raised wind speed on reference evaporation ET_0 and net irrigation water demand (actual ET – rain) referring to the cotton Kharif season.

As depicted in Figure 4.18, the rise in ET_a above the reference situation in 2018 in a scenario consisting in lower air humidity plus higher wind speed is numerically stronger (from 592 to 654 mm) than the ET_a raised by 4 °C higher temperature (592 to 638 mm). As the changes in air humidity and wind speed are rather uncertain – yet lead to comparatively high increase in ET_a (compared to the rise in temperature) – the need to answer the in future increasingly variable environment by a more flexible irrigation scheduling is further underlined.

An option to cope with higher net irrigation demand (as a consequence of rising ET_a) in a situation with the given supply consists in increasing the irrigation efficiency. Our simulation show that a rise in technical irrigation efficiency from currently 50 to 57 % is needed to compensate the 4 °C-driven increase in ET_a, whereas even 59 % are required to cope with an increase in ETa caused by a combined effect from air humidity and wind speed.

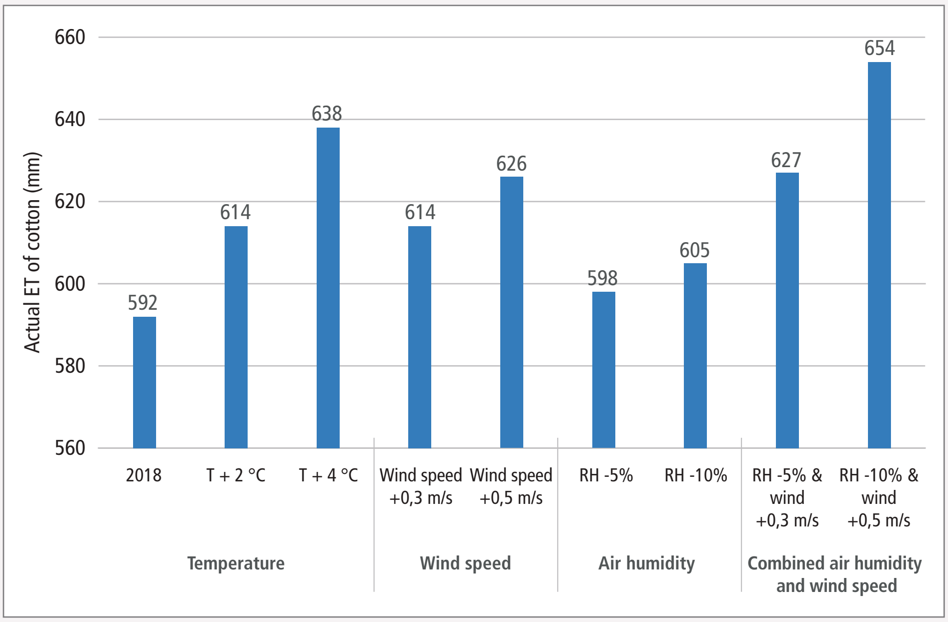


Figure 4.18: Scenarios evaluating the impact of climate change on actual evapotranspiration of cotton (contrasting rather sure corridor of temperature rise versus altering air humidity and wind speed).

4.3.3 Hydrological Modelling on the Basin Scale (M3)

(R. Becker, T. aus der Beek)

The calculation of a regional specific water footprint needs detailed and spatially distributed information on water availability, water demand and water consumption. To investigate these variables for cotton agriculture in our study area, we set up a hydrological model for the entire study region of the LCC irrigation system. Because of its strengths in simulating hydrological dynamics of agricultural areas, we chose the widely used Soil & Water Assessment Tool (SWAT) model software (Arnold *et al.*, 1998). By applying the SWAT model we were able to incorporate detailed management strategies into the analysis, accounting for spatially distributed land use and management changes and their effects on the local hydrology. Due to its spatially differentiated output, it is possible to use this model to upscale the results obtained in M2 (chapter 4.3.2) to the entire study region and provide hydrological data at the scale needed for a regional specific water footprint calculation.

4.3.3.1 Data sets and models used

The principal focus of the hydrological modelling is twofold: (1) the modelling approach is used to answer questions on changes in water demand due to climate and land use changes, and (2) it helps to define changes in water demand due to improved irrigation efficiencies and management strategies. Because of the differences in these two research areas, with one being more focused on environmental changes and the other one being more focused on technical improvements, we set up two distinct SWAT models, each with question specific model assumptions. We thus make sure, that despite some constraints of the modeling software in representing the LCC-irrigation system with all its dynamics and processes, each model output is, as a result of its unique assumptions, as close to reality as possible. See Text Box 8 for a description of assumptions, strengths and weaknesses of each model.

Basic datasets required to set up the SWAT model for the LCC study region are topographic information, land cover data, soil characteristics and meteorological time series. In addition, we consider crop rotation patterns as well as specific planting and harvesting dates for the agricultural crop types (Figure 4.19). Remote sensing and ground station evapotranspiration measurements are used to calibrate and validate the model (Becker et al. 2019). Climate change data based on the medium and high CO_2-emission scenarios RCP 4.5 and RCP 8.5 are taken from climate models of the CMIP5 project. Here, we use the downscaled CMIP5 climate data from the CORDEX project (www.cordex.org).

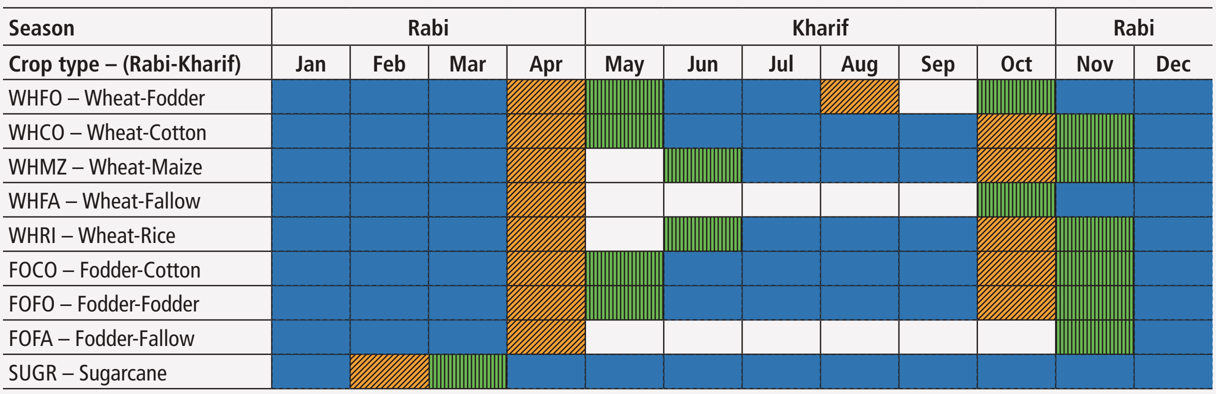


Figure 4.19: Agricultural land-use classes in the study area and their planting (green/hatched), irrigation (blue/dotted), and harvesting (orange/crosshatched) times. (White refers to fallow / no irrigation). © IWW-MH

Text Box 8:

What are strengths and limitations of the hydrologic models developed?

Due to the differences in our modeling goals (simulation of environmental changes vs simulation of technical improvements of the irrigation system), we set up two distinct SWAT models each with question specific model assumptions. The main assumptions, strengths, and weaknesses of these two models are summarized as follows:

Plant Demand Model: used for climate change and land-use change assessment

Assumptions:

- Water availability for irrigation comes from a source outside of the catchment and is unlimited.
- Irrigation is based on water demand.

Strengths:

- The model reacts flexible to changing climate conditions and shows how climate change will change irrigation water demand, biomass production, yield, etc.
- Assuming the constant availability of water allows to assess the impacts of climate change apart from water shortage issues.
- The model is more realistic in terms of the spatial distribution of irrigation events (assuming that in reality the farmers irrigate where water is needed and they do not irrigate every Warabandi turn the same field).
- The model shows an "optimal" system, flexible and demand based irrigation and can serve as upper limit for potential improvements.

Weaknesses:

- Irrigation amounts are unrealistically high because unlimited water supply assumed.
- Irrigation scheduling is not following the Warabandi system and thus not adequate to asses any irrigation system related questions.

Warabandi Model: used for irrigation efficiencies assessment

Assumptions:

- Water availability for irrigation comes from a source outside of the catchment but is limited.
- Water allocation is following the Warabandi system. Irrigation amounts are fixed and are in line with the farmer survey conducted in this project.
- Surface and groundwater irrigation are both considered in the total irrigation amount (differentiation is not possible for now).
- According to the "rebound-effect" we assume that with increasing irrigation efficiencies there is more water available for irrigation.

Strengths:

- Irrigation amounts are closer to reality in this model as they are fixed according to the survey.
- This setup enables the assessment of changing irrigation efficiencies, as the volume of applied irrigation water can manually be changed.
- Different irrigation schedules can be assessed, as the timing of irrigation can manually be adjusted.
- Crop yield will be more realistic in this model, as water availability and allocation is closer to real conditions (lower than in the Plant Demand Model)

Weaknesses:

- Even though irrigation depths and frequencies can be manually set they are still fixed within each scenario and don't react flexible to environmental changes. The model can therefore not be used to assess changes in water demand due to changes in environmental conditions (climate change or land-use change).
- Fertilizer application is overestimated because maximum fertilizer application is assumed.
- Changes in groundwater storage can't be assed with this model because it neglects pumping from the basin itself (irrigation source is outside of the catchment).

4.3.3.2 Results: water availability, water demand and water consumption

The assessment of agricultural water availability, water demand, and water consumption in the study area (Figure 4.20) shows a high irrigation demand for cotton plants, which is above the average demand of other summer (Kharif) crops, such as maize, corn, sugarcane, and rice. Considering the overall limited water availability in the study area, the results show a strong need for additional irrigation water supply. The high water consumption (ET_{act}) in cotton agriculture puts strong pressure on surface water and groundwater resources. According to our model results, approx. 40 % of the irrigation demand for cotton has to be fulfilled through groundwater pumping.

The pressure on surface water and groundwater resources varies throughout the growing season and is highly dependent on rainfall rates (Figure 4.21). Especially during the central monsoon months, July and August, over two-third of the irrigation demand can be met by precipitation, while during the first months of the growing period rain water availability is negligible and nearly the entire water demand for cotton growth has to be fulfilled by the limited surface water availability and – to the largest extend – by groundwater supply.

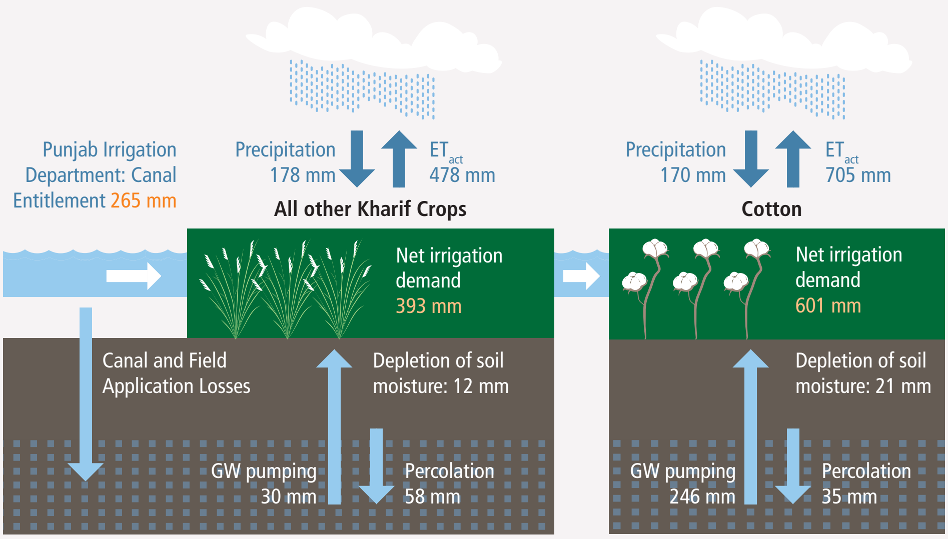


Figure 4.20: Water availability, demand, and consumption in Kharif season May to September based on the Plant Demand Model (Mean of 2004-2013). © FiW

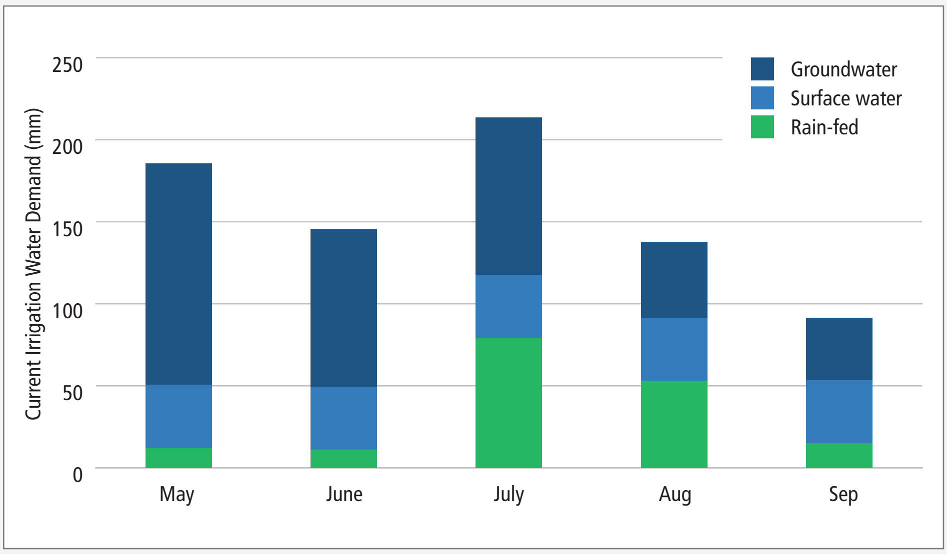


Figure 4.21: Contributions of groundwater, surface water, and rain to fulfill the irrigation demands of cotton estimated by the SWAT-model under current climate conditions. © IWW-MH

4.3.3.3 Effects of land-use change and climate change

Our spatial assessment reveals a strong spatial northsouth gradient in water demand as well as in future temperature changes in the study region (Figure 4.22). This leads to important regional differences in estimated current and future water footprints with the LCC area (see chapter 8).

Our modeling results confirm that in a hypothetical scenario in which cotton farming is intensified across the whole LCC region the water demand would significantly increase while the overall cotton yield would slightly decrease. Main reason for the increased water use is the above mentioned higher irrigation demand of the cotton plants compared to food crops. The reduced yield on the other hand assumes that cotton farming is extended to areas with less suitable growing conditions, showing the sensitivity of agricultural production to "optimal growing areas", also entitled as "eco-agrological zones". This aspect is already widely discussed in Pakistan, especially with respect to future climate change, which shifts these optimal growing zones and affects water resources as well as productivity levels.

Our results show the following climate-change impacts for water demand and agricultural productivity of cotton farming in the LCC area: The high sensitivity of water availability to precipitation rates and the highly uncertain estimates of future rainfall amounts make a prediction of future irrigation water availability very challenging. Yet, the predicted significant temperature increases in the LCC area, of up to +2 °C until the year 2050, let assume with high certainty that pressures on water resources will further aggravate. One reason is the earlier plant development due to higher temperatures, which is represented in the following by the leaf area index (LAI).

The model results (Figure 4.23) show that, with warmer temperatures, cotton plants will reach maturity and especially leaf senescence faster than in the past and thus the growing period is expected to reduce significantly (Figure 4.23: lines "Past LAI" vs. "Future LAI"). This leads to surprisingly low increases in future water demand, in spite of the strong temperature increase. This result can be seen in the low differences of the bar plots in Figure 4.24. Howev-

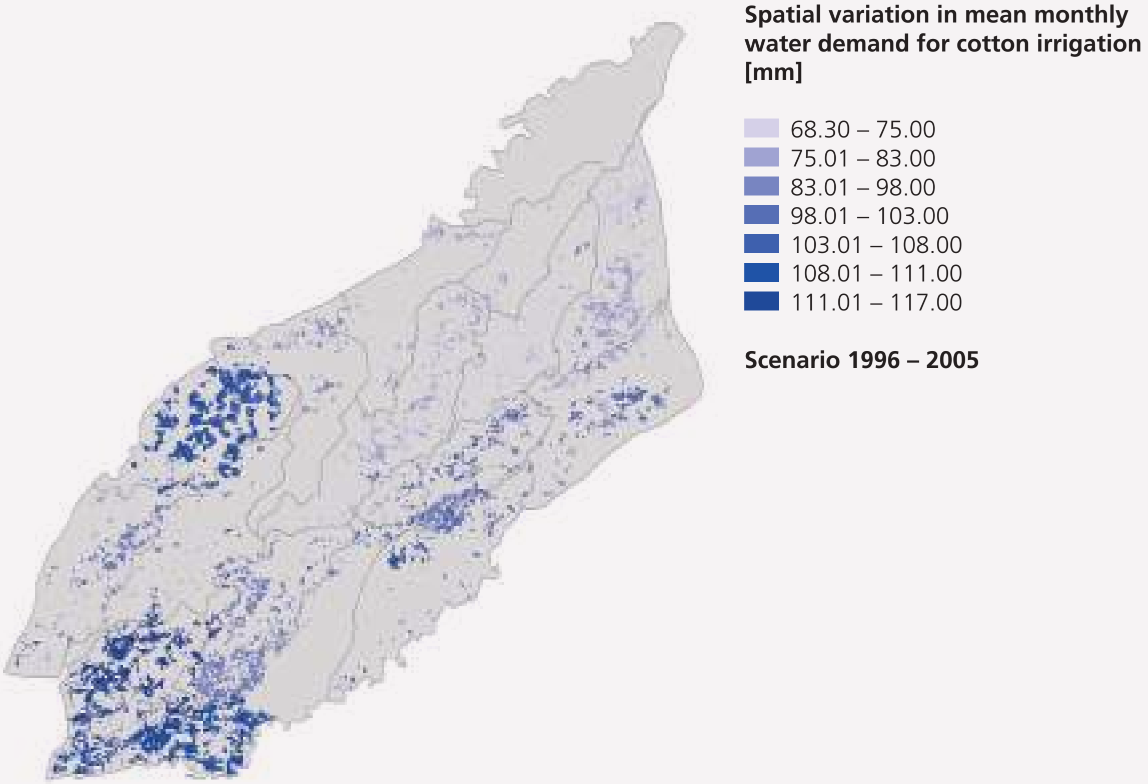


Figure 4.22: Spatial distribution of irrigation demand over cotton areas in the Lower Chenab Canal System. © IWW-MH

er, it might negatively affect the contribution of groundwater and surface water needed to meet the overall irrigation demand. The faster growing cycle will lower the water demand towards the end of the growing period, where rainfall contributions are large. However if planting dates are shifted to earlier dates, as can already be seen in the study area (Figure 4.23, lines "Future LAI early planting"), it will increase water demand at the beginning of the season, where rainfall amounts are negligible. This means that even if the overall seasonal water demand will not change significantly, surface water and especially ground water resources will have to cover a higher share of the overall irrigation amounts needed for cotton growth.

Furthermore, the results revealed that even under the assumption of sufficient water supply and a negligible increase in irrigation demand, yield will be significantly reduced in future due to increased plant temperature stress. Figure 4.24 shows that, in spite of the presumed sufficiency in water availability, cotton yield will decrease substantially in the short-term (2020–2030) as well as in the medium-term (2040–2050) both under medium (RCP 4.5) as well as under high (RCP 8.5) CO_2-emission scenarios. The stronger the temperature increase, the stronger will be the negative impact on yield. This is an important finding regarding water management in the area, since it shows the limitations of the resource "water" to mitigate climate change impacts. Temperature stress related adaption strategies (e.g., more heat tolerant crops) are under these circumstances more important than increasing irrigation intensities.

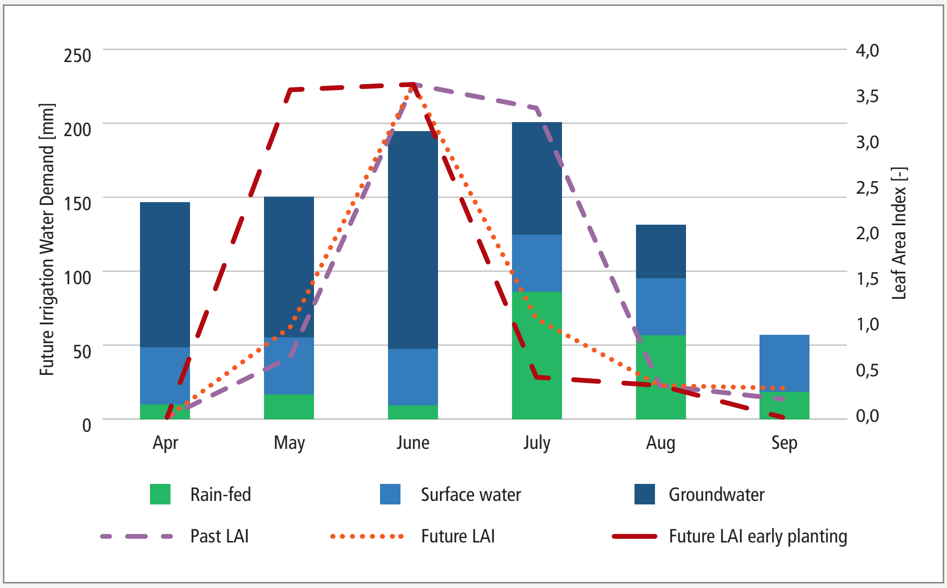


Figure 4.23: Effects of planting schedule on the share of irrigation water sources. Contributions of groundwater, surface water and rain to fulfill the estimated irrigation demands of cotton (SWAT-model) under future climate conditions. © IWW-MH

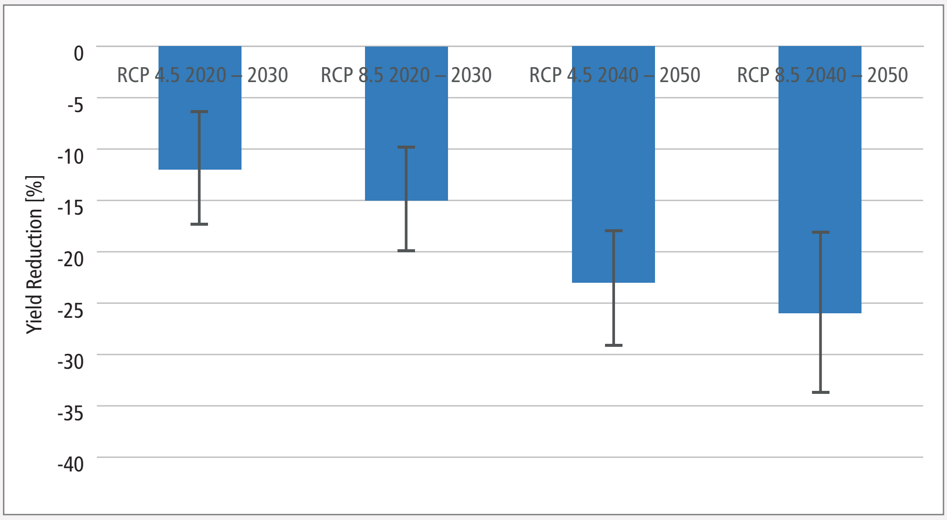


Figure 4.24: Climate-change effects on cotton yield. The uncertainty arises due to the variability in the 9 selected climate models. © IWW-MH

4.3.3.4 Effects of irrigation management changes

To assess the impacts of technical improvements of the irrigation system, we run the SWAT model with different irrigation efficiencies, representing the findings from the project method M2 on improving irrigation management to reduce the water use in cotton production. Here, we do not assume sufficient water supply. Instead, we assume that the reported irrigation efficiency for the LCC system of 70 % is the most realistic scenario. In line with the results from M2, we then increase the efficiency to 80 % and 90 %. These are optimistic scenarios under the hypothesis that current irrigation practices of furrow and flood irrigation are turned into bed irrigation, sprinkler irrigation, or even drip irrigation practices. We then run the efficiency scenarios with current and one future climate scenario (RCP 8.5, 2040–2050).

The modeling results (Figure 4.25) clearly show that cotton yield can be significantly increased with better irrigation practices. This can also positively affect groundwater pumping rates, which can be reduced due to the higher availability of surface water resources. According to our results, yield can be increased by 15 % if an irrigation efficiency of 90 % can be achieved. Climate change, however, will counter-act these positive effects and will lead to a reduction in cotton productivity compared to current yield levels, even under an improvement in irrigation efficiency to 90 %. This shows again that enough water availability alone cannot be the only adaption strategy against climate-change impacts. Nevertheless, Figure 4.25 displays noticeably that improvements in water-use efficiency can help to reduce the negative impacts of climate change as it shows smaller yield losses with increasing efficiencies.

4.3.3.5 Summary and conclusions

The central results of the hydrological models used for this project are summarized as follows:

- Temperature stress on plant growth will increase significantly.
- A substantial reduction in cotton crop yields are observed in future, which can mainly be ascribed to a shortened growing period due to higher temperatures.
- The shorter growing period leads to a comparably low future increases in the overall irrigation demand.
- Even though overall changes in water demand are surprisingly low, higher pressures on surface water and groundwater resources can be expected due to changes in plant growing cycles: Future temperature patterns are expected to speed up the plant growing cycle and increase irrigation demands during the early growing stages. In LCC study area, this alters the share of irrigation water supply sources (i. e. rain, surface water, and groundwater) and leads to higher demands of surface water and particularly groundwater resources while the contribution of rainfall is expected to decrease.

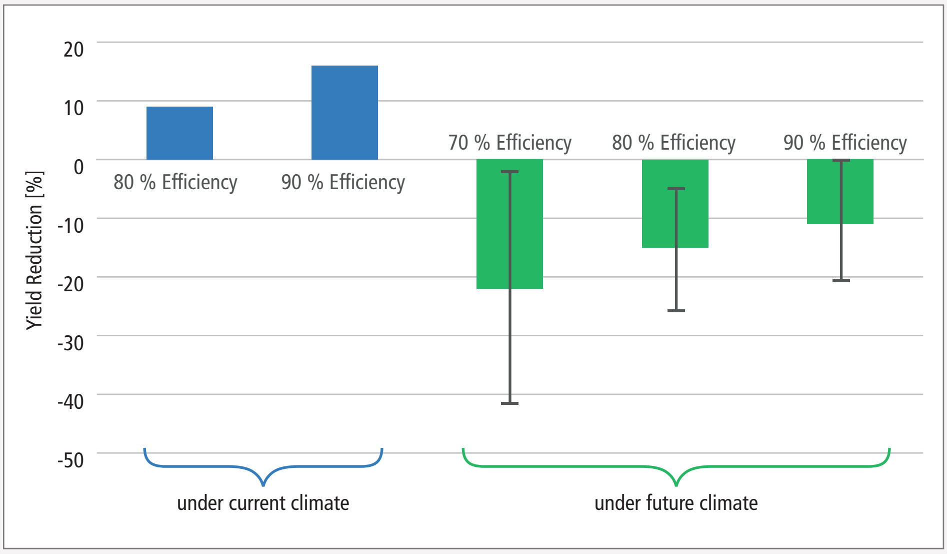


Figure 4.25: Changes in yield due changes in irrigation efficiency under current and future RCP 8.5 climate conditions. © IWW-MH

- Improving irrigation efficiency will help to mitigate negative climate-change impacts on agricultural productivity, but cannot prevent an overall reduction in future yield.
- Plant-type related adaption strategies, such as more heat tolerant crops or crops with shorter growing periods, could help to reduce water demand and prevent production losses.

Further reading

Becker, R., Koppa, A., Schulz, S., Usman, M., aus der Beek, T., Schüth, C., (2019). Spatially distributed model calibration of a highly managed hydrological system using remote sensing-derived ET data. J. Hydrol. 577, 123944. https://doi.org/10.1016/j.jhydrol.2019.123944

Schulz, S., Becker, R., Richard-Cerda, J.C., Usman, M., Beek, T., Merz, R., Schüth, C., 2021. Estimating water balance components in irrigated agriculture using a combined approach of soil moisture and energy balance monitoring, and numerical modeling. Hydrological Processes. https://doi.org/10.1002/hyp.14077

Text Box 9:

How does salt management work in cotton farming?

Any irrigation water contains to some degree salts. Supplying irrigation water is therefore always causing input of salt into the root zone. The amount of salts in the root zone of irrigated fields is a result of salt inputs and outputs mainly driven by water fluxes. Salt input consists in the amount as well as salt content of the irrigation water, a possible capillary rise in case of shallow groundwater, fertilization, and to a very small extent precipitation. In contrast, percolation below the root zone, surface runoff, lateral water exchange and removing biomass during harvest, drive the output of salts. Differences between input and output cause either an increase (salt accumulation) or decrease (leaching of salts) in the balancing period (e.g., the vegetation period).

Salinity control aims at keeping the salt content (often measured as electrical conductivity ECe in the saturation extract) below plant tolerance limits, which would lead to salt stress reducing crop yields once exceeded. Conceiving salinity control by water management builds on consideration of two major processes: (1) estimating the salt accumulation from the balance of the above components, and (2) determining leaching water quantities, which compensate and discharge the salt input by the corresponding output.

Practically assessing the magnitude of salt input and output components reveals that precipitation does not lead to any significant salt input and contribution by fertilization is rather small; surface runoff on irrigated fields is largely avoided, lateral exchange is low and salt output with harvested biomass is numerically not high. In case of deep groundwater (no capillary rise), salt input is driven by irrigation water amount (and its salt content) and salt output depends on the water percolating below the root zone and its salt content. In order to keep salt content in the root zone below crop salt tolerance limits, salt output via water percolating below the root zone must balance the input by irrigation water. The share of the percolation water in relation to the irrigation water input is the leaching fraction equaling in the above formulated simplified case the relation between salt content of irrigation water and percolation water (assumed to be in the range of drainage water in case of an artificial drainage system.

Realizing leaching requires purposely irrigation above field capacity in order to create percolation through the root zone taking accumulated salts. The amount of percolation water is the above-mentioned leaching fraction. A further condition to effectively perform leaching consists in discharging the leaching water after percolating through the root zone and reaching / recharging groundwater out of the irrigation scheme. As in most cases natural groundwater flow is not sufficient to realize that outflow, an artificial drainage system needs to be installed.

Two factors ease salt control in cotton irrigation in Punjab: firstly, salt tolerance limit of cotton is rather high (ECe of 7.7 dS/m) and secondly, the monsoon rainfall is leading to percolation realizing a natural leaching.

Yet, in regions with a high share of groundwater used for irrigation (with comparatively higher salt content than canal water), southern Punjab with low rainfall and lower reaches of canals with a tendency towards water stress (adding up with salt stress) are under risk towards salinization and require estimation of a leaching fraction to be considered in irrigation schedules.

4.3.4 Hydraulic Model: Groundwater-Surface Water Interaction (M4)

(L. Schelter, H. Schüttrumpf)

Groundwater is an active and integral part of the water cycle in the Punjab. Due to a groundwater table fairly close to the surface (less than 10 m in most of the Rechna Doab), the groundwater is easily accessible for farmers with private tube wells (Figure 4.26). Therefore, it can and is already being used as a reliable and stable resource to supplement irrigation when canal water is not sufficient. Therefore, we set up a hydraulic groundwater flow model to evaluate the impact of different climate change and management scenarios on this important resource.

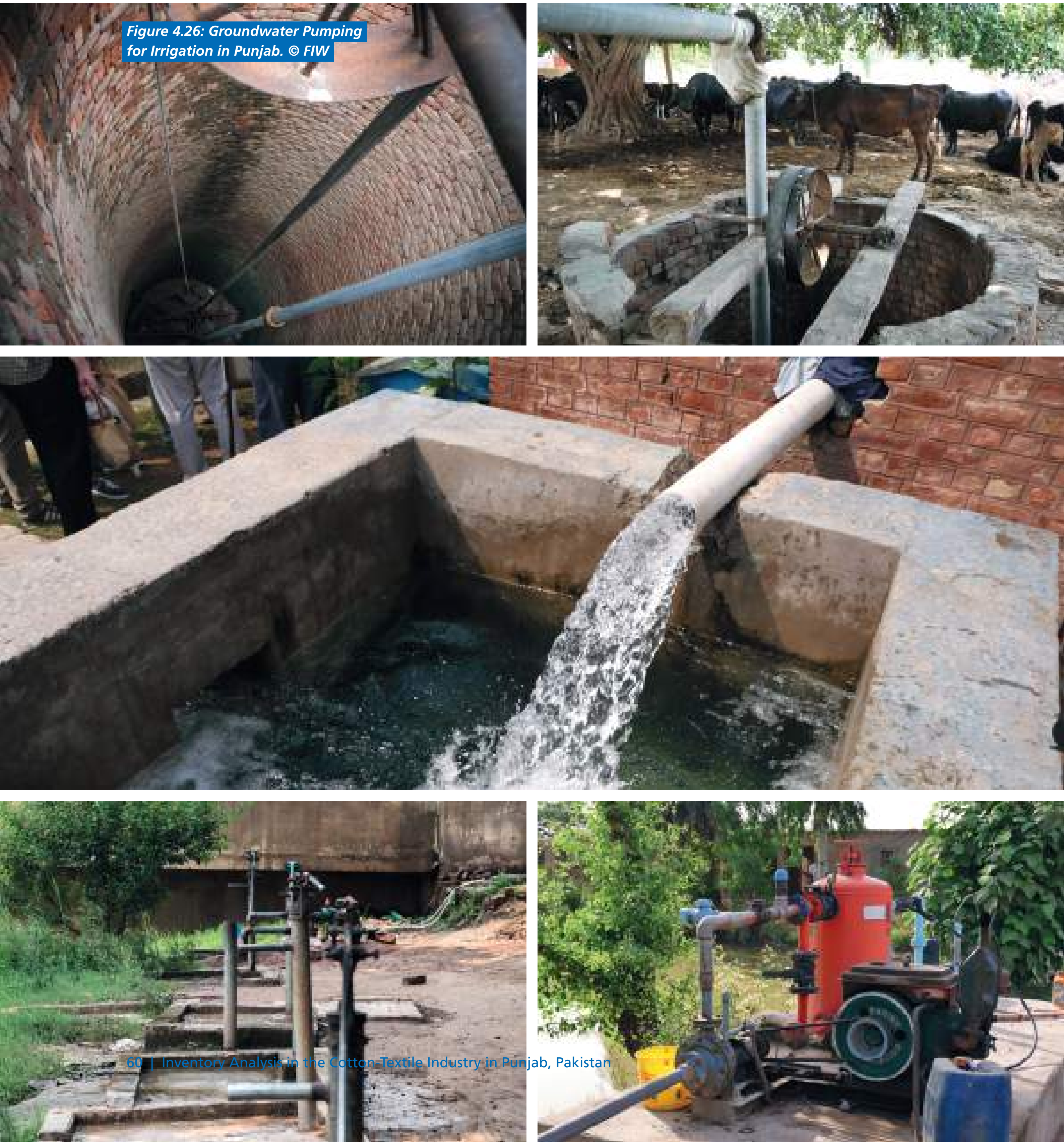


Figure 4.26: Groundwater Pumping for Irrigation in Punjab. © FIW

4.3.4.1 Hydrogeological situation

For Rechna Doab, data of 588 wells is available. Groundwater hydraulic head hydrographs of these wells suggest constant or even rising groundwater levels for the last decade. Trends of falling groundwater are observed in only 33 % of the wells, located partly in the tail end of the irrigation system. Figure 4.27 shows the average depth to water table in the Doab with a significant negative trend indicating rising groundwater levels for the observation period from 2005 to 2015. The monsoon flood of 2010 is clearly visible in the peak from pre-monsoon to the post-monsoon season 2010, when groundwater was notably recharged by the flood waters.

The commonly reported high rates of groundwater recharge from the irrigation canals would suggest a stronger increase of groundwater in the proximity of the bigger channels. However, as shown in Figure 4.28, there is no clear correlation between the groundwater table trend and the distance to the large irrigation channels in the area. Nonetheless, this underlines the geographic assessment of the region as a very conductive, mostly homogeneous aquifer.

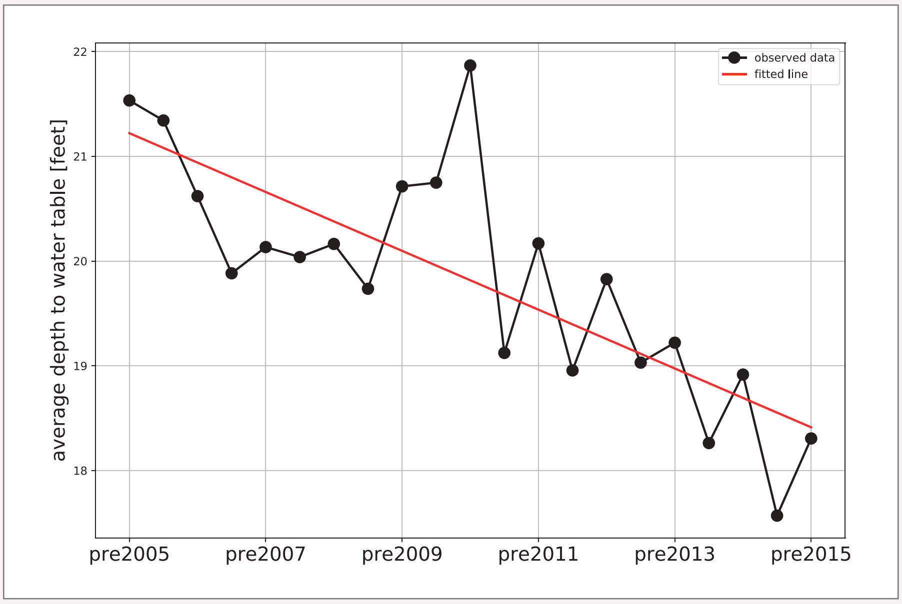


Figure 4.27: Mean depth to water table of 588 wells with two values per year, pre- and post-monsoon. A negative trend of -0.14 feet/ season can be seen and is significant (p=3e-05). This suggests an average rising of the groundwater table by 8.5 cm/year for the observed period 2005 to 2015. © RWTH-IWW

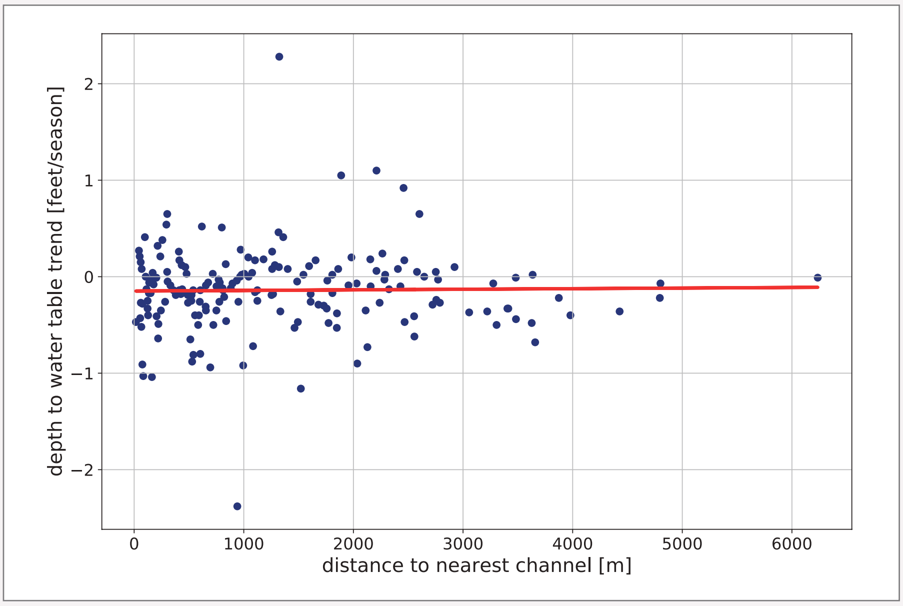


Figure 4.28: Relation of groundwater table trend to distance to the nearest channel. The red line visualizes that there is no significant trend. © RWTH-IWW

4.3.4.2 Model setup and calibration

We set up a numerical groundwater model using FEFLOW that considers all major irrigation channels in the Rechna Doab. The rivers Chenab and Ravi form the northern and southern border of the model area which includes three link canals, two main canals, 12 branch canals and two drains in total. From the Marala-Ravi Link canal to the Trimmu-Sidhnai canal it covers an area of about 30.000 km².

The model uses the finite element method with a two-dimensional, triangular mesh that is vertically projected and includes more than 250.000 nodes, shown in Figure 4.29.

To better capture the infiltration of the surface water, the mesh is refined around the channels. Flow in the model is calculated using Darcy's law for a saturated aquifer at automatically determined, optimal time steps that are very short, only minutes long, at the beginning of the simulation and develop into monthly time steps once the simulation becomes more stable.

Input data regarding geological properties of the ground is taken from documentation of the United States Geological Survey campaign throughout the 1960s that provides drill cores for the entire Rechna Doab (Greenman *et al.* 1967). Groundwater recharge data is provided as simulation output of the hydrologic model of project method M3. Classified land-use data is created through remote sensing in M1, and groundwater abstraction rates are calculated and extrapolated from the farmer surveys produced in M5.

The canals and rivers in the model are defined as Cauchy boundary conditions at water level height in the streams with an in-transfer rate that represents the leakage factor and controls recharge into the model by these boundary conditions.

Calibration of the model is performed using the PEST algorithm with 151 selected wells with two measurements per year each, giving a total of 3020 data points between 2005 and 2015. Calibrated parameters are hydraulic conductivity of the ground, specific storage, in-transfer rate of the canals and the water level of the canals and streams. The calibration target is the hydraulic head at the locations of the calibration wells.

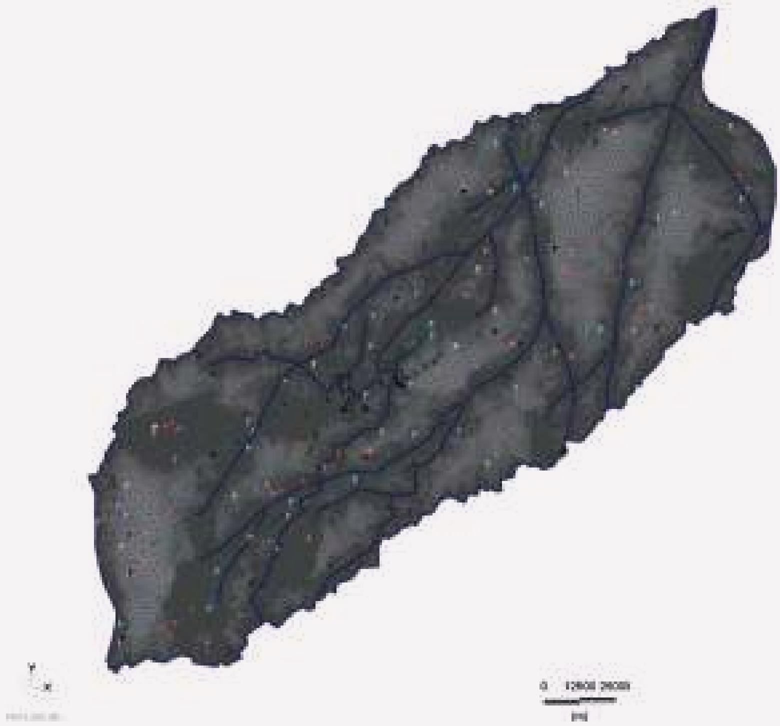


Figure 4.29: Overview of the model area with the triangular finite elements mesh of more than 250.000 nodes. The colored flags represent the locations of the calibration wells. © RWTH-IWW

4.3.4.3 Sensitivity analysis

The results of a sensitivity analysis of the model can be seen in Figure 4.30. It is clear that the abstraction rate, the amount farmers are pumping, is by far the most potent parameter in the model affecting the mean hydraulic head in the model more strongly than any other parameter.

Since the abstraction rate depends on hundreds of individual farmers whose pumping activity is not monitored, it remains an estimate. Therefore, we compared three different estimates of abstraction rate to be able to assess the impact on the aquifer.

The first estimate is provided by Cheema (Greenman *et al.* 1967) and is calculated as a mean abstraction rate of 469 mm annually over the entire Rechna Doab. This value is a rather high estimate given that mean irrigation depth in the area is 710 mm annually. With an average of 47 % of irrigation water coming from groundwater, Cheema's estimate probably overestimates groundwater abstraction when compared to the reported quantities by the farmers in the Rechna Doab (334 mm annually from groundwater).

Qureshi *et al.* (2003) estimated groundwater abstraction in the entire Indus Basin from which it can be calculateed proportionally to be 229 mm annually over the entire Rechna Doab, which is a little more than half the value proposed by Cheema *et al.*

The most detailed account is provided by the 69 farmer surveys that report the amount of irrigation per year and the percentage of irrigation sourced from groundwater, making it possible to calculate annual groundwater abstraction for each crop type. These farmer survey results are extrapolated to the entire model area using the land use classification data.

For each scenario, we started the model in October 2005 with a mean hydraulic head of 185.02 m. Results were extracted after 30 years and show an overall increase in hydraulic head for all three pumping estimates. Cheema *et al.*'s 469 mm annual abstraction rate led to a mean hydraulic head of 189.88 m, Qureshi *et al.*'s 229 mm estimate produced a mean hydraulic head after 30 years of 190.08 m while the abstraction rates from the farmer's survey produced a groundwater level increase to 192 m.

While these scenarios do not consider behavior change of farmers in the future nor do they account for increases in irrigation efficiency or other changes in water management, they highlight a key finding of this study: The quantity of groundwater might not be the biggest problem.

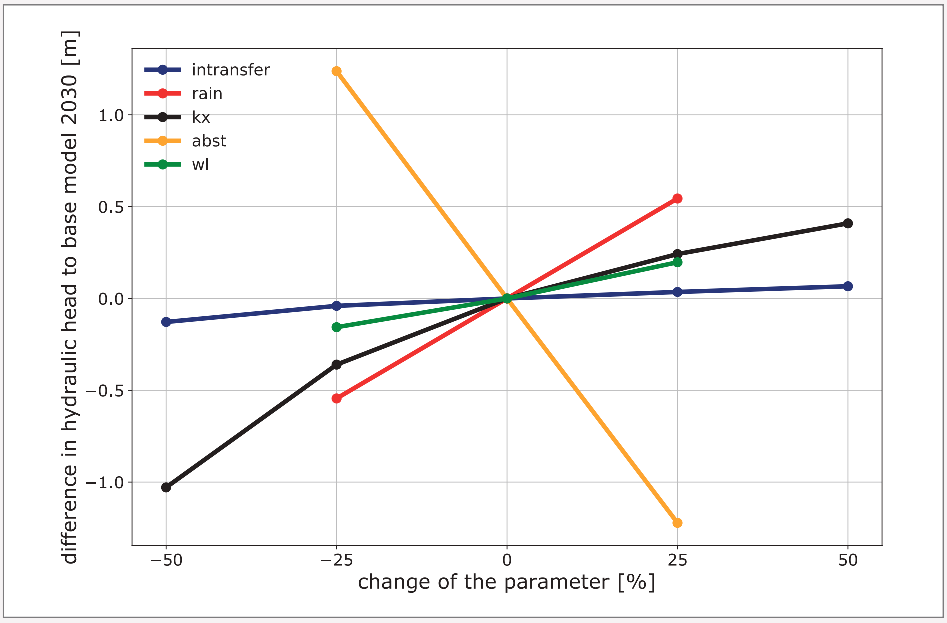


Figure 4.30: Results of a sensitivity analysis in which in-transfer rate, percolation, hydraulic conductivity, abstraction rate and water level in the canals were modified and the effect on the mean hydraulic head after 30 years was compared. © RWTH-IWW

4.3.4.4 Model scenarios and results

The purpose of the model was to simulate and represent two main parameters: on the one hand, the expected future development of the groundwater level under different scenarios and, on the other hand, the water exchange between individual regions as input data into the calculation of the region-specific water footprint.

Three scenarios were considered. Two scenarios with identical management but different underlying climate projections and a third scenario assuming extensive governmental interventions to reduce the seepage in the canals and to increase the overall irrigation efficiency. The widely used scenarios RCP4.5 and RCP8.5 of the Intergovernmental Panel on Climate Change (IPCC) were used as climate scenarios. Based on the scenarios developed in the project consortium, the third scenario is called the "ThinkBig" scenario and the RCP4.5 scenario serves as the underlying climate projection.

Figure 4.31 shows the model result for the height difference of groundwater levels in 2056 and 2015 in metres for scenario RCP4.5 in the entire model area, the Rechna Doab.

Positive values show an increase in groundwater levels over this 41-year simulation period, whereas negative values show a decrease. In the southwestern part of the model a local, significant increase can be observed, whereas the rest of the model is quite balanced. A direct influence of the channels in the sense of a significant increase in the immediate vicinity of the channels is not discernible. However, the large seepage losses of the channels have been proven in many studies. The explanation here is the spatial resolution of the model. With a minimum distance between two calculation nodes of at least 250 m, even in the immediate vicinity of the channels, such a direct influence on the groundwater level is no longer detectable. In addition to the coarse resolution, this is also due to the high permeability of the entire aquifer, which consists mainly of sand, which is why the groundwater level can adapt to changes comparatively quickly and over a large area and why such fluctuations are distributed over the area. The irrigation channels, therefore, have a strong influence on the development of the groundwater level and the water balance, but this is not limited to the area surrounding the channels; due to the high permeability of the aquifer, the entire model area is affected. Overall, it is interesting that the model does not show a dramatic drop in the groundwater level, as was often expected. On average, the groundwater level in the RCP4.5 model is 189.22 mNN in the pre-monsoon period 2056. In 2015 this value was 184 mNN. However, the usual assumptions of falling groundwater levels do not fit with the observed data from 2005 to 2015, as was explained above. The simulation results also suggest that even under the assumption of a climate change scenario, overuse and the

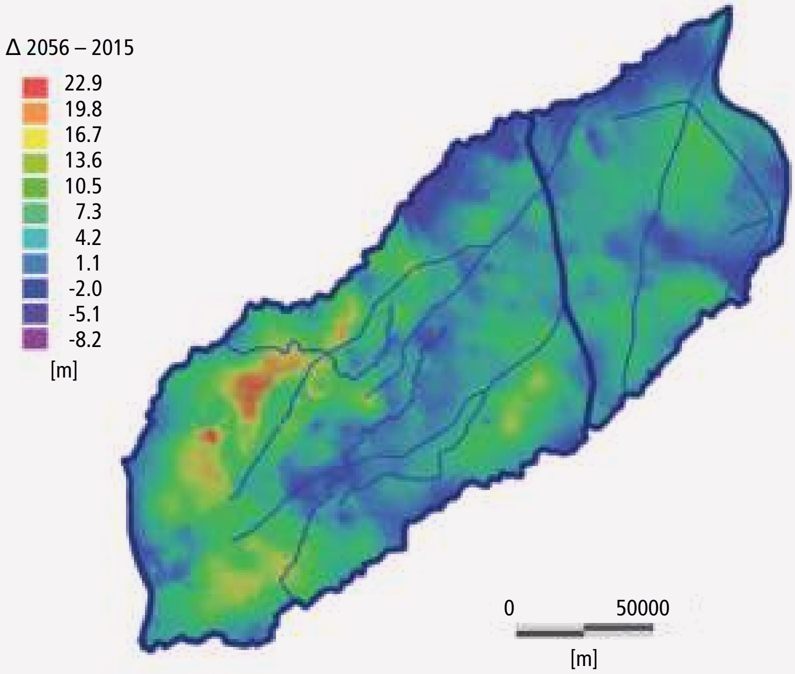


Figure 4.31: Difference of hydraulic head in the pre-monsoon season of 2056 in comparison to 2015 under RCP4.5 conditions in meters. Boundary conditions (canals) of the model are drawn in blue. © RWTH-IWW

consequent lowering of the groundwater level may be overestimated in general opinion. For comparison: Even in the RCP8.5 climate scenario, which assumes much stronger impacts and changes due to climate change and a much steeper temperature rise, the groundwater level reaches a height of 189.53 mNN, not half a meter of difference from the RCP4.5 model.

Table 4.5: Simulated Hydraulic Head values in the pre-monsoon season of 2056 for RCP4.5 and ThinkBig in mNN.

Model	Hydraulic head mean	Hydraulic head minimum	Hydraulic head maximum	Hydraulic head std. deviation
RCP4.5	189.2	138.093	238.699	22.949
ThinkBig	189.5	139.741	239.12	22.858

Table 4.5 shows data on groundwater levels also in the pre-monsoon period 2056 for the RCP4.5 and the ThinkBig scenario, which is based on the identical climate change assumptions but includes extensive measures to increase irrigation efficiency. This is done through large-scale government backed lining of more than half of the canals using concrete slabs. For the Think Big scenario, the infiltration rate in all canals was reduced by 70 %, and the pumping rate was reduced by 50 % in the entire model, since more irrigation water is available from the canals and less has to be pumped from the groundwater due to lower infiltration from the canals.

It is striking that even after 41 years of simulation, the difference in the mean groundwater level in the model area for the ThinkBig scenario is only 30 cm higher, with a similar division into minimum and maximum values. The extremely extensive measures on which the model version is based, therefore, seem to have little effect on the long-term development of the groundwater level. In view of the enormous costs for the practical implementation of these measures, their cost-benefit should therefore be weighed up even more carefully. Here, other measures, such as the introduction of drip irrigation systems over a wide area, could be more effective and feasible at lower cost, i. e. the extensive lining of most channels with bitumen seals, which lose a large part of their function after a few years if they are not continuously renewed and repaired.

4.3.4.5 Discussion and conclusion

With steady or even rising groundwater levels in many areas of the Rechna Doab, the question becomes: Is the quality of the groundwater sufficient for irrigation and what can be done to improve groundwater quality.

A popular solution that is often advocated for is lining of the canals. This would reduce seepage from the canals, at least for the first couple of years because the lining is usually not maintained and deteriorates over time which drastically diminishes its effects. However, groundwater recharge from canals as well as from field percolation helps improve groundwater quality and provides an opportunity to store and protect water from unproductive evaporation.

Groundwater recharge improves quality of the groundwater by diluting it and in doing so reducing salinity and contamination. Reducing seepage from the canals would lead to a massive decrease in groundwater recharge possibly leading to severe salinization in many areas as the salt left behind by falling groundwater would not be leached out of the ground anymore.

Another important function of the aquifer is storage. Due to a groundwater table fairly close to the surface, less than 10 m in most areas of the Rechna Doab, the groundwater is easily accessible for farmers with private tube wells. Therefore, it can and is already being used as a reliable and stable resource to supplement irrigation when canal water is not sufficient. This could be due to the seasonal variability of the surface water supply or because of the rigid Warabandi system, which is supply-driven, rather than demand-driven, as has been explained above.

For these reasons, we advise to carefully examine the situation and the intended outcome before considering large-scale lining projects. Immense costs, long-term maintenance responsibilities and possible drawbacks due to groundwater quality issues require substantial benefits on the surface water supply side of the equation. If done, lining efforts should focus on the wastewater drains that transport highly polluted water from domestic sources as well as industry first to protect the health of the local population and the quality of the freshwater resources.

Further reading

Cheema, M.J.M., Immerzeel, W.W., Bastiaanssen, W.G.M. (2013): Spatial quantification of groundwater abstraction in the irrigated Indus Basin. Groundwater 52(1), 25–36. https://www.doi.org/10.1111/gwat.12027

Greenman, D.W., Swarzenski, W.V., Bennett, G.D. (1967): Groundwater hydrology of the Punjab, West Pakistan, with emphasis on problems caused by canal irrigations. Geological Survey Watersupply paper 1608-H.

Qureshi, A.S., Shah, T., Akhtar, M. (2003): The groundwater economy of Pakistan. Pakistan Country Series No. 19, Working Paper 64, International Water Management Institute, Pakistan. ISBN:92 90 90 530 1.

4.3.5 Institutional Framework of Water Use (M5)

(J. Schultze, N. Zimmermann, M. Oelmann)

Over the last decades the increasing population growth in Pakistan has put additional pressure on the already scarce water resources of the Indus Basin Irrigation System to produce more food (Amir and Blackmore, 2005). To meet this new food demand farmers have introduced more water intense irrigation methods that also require a much more flexible application of water. Farmers have responded to their sincere water scarcity situation either by tapping groundwater or by illegally increasing their share of surface water at the expense of the other farmers (water theft). Both of these responses have weakened the ability of the irrigation department to enforce its water allocation rules along with its ability to uphold its physical infrastructure (Briscoe *et al.*, 2005). Consequently, a considerable share of farmers have no longer been supplied by the irrigation system and thus had to rely on pumping groundwater (Government of Pakistan, 2012). However, even though the development of groundwater has prevented the irrigation system from its collapse, groundwater is 15 to 20 times more expensive than canal water for irrigation due to drilling, pumping, and energy costs, creating a massive income gap between farmers with good access to water from the canal system and those with poor or no access at all (Briscoe *et al.* 2005). Moreover, in some areas, groundwater is of inferior quality and hardly suitable for irrigation. Another negative aspect of the excessive pumping of groundwater is that it has substantially increased Pakistan's CO_2 emissions in agriculture (Briscoe *et al.* 2005).

The bottom line is that farmers in Pakistan need a reliable supply of water from the irrigation system and that the organization of the irrigation system by the centrally organized public irrigation bureaucracy has been struggling to do that. There are multiple reasons why the irrigation system has been deteriorating and why the way water has been priced and allocated has been dysfunctional. Overall, besides the fact that the irrigation department has been notoriously underfunded, those reasons can be traced back to a lack of transparency and accountability due to the unchallenged authority the irrigation department has over the water resources (Briscoe *et al.* 2005). All together those three aspects have resulted in the following institutional shortcomings:

- a disregard and underinvestment for maintenance,
- low water fee collections,
- a bad quality of services,
- a high level of systemic corruption
- a dysfunctional organization where costs and benefits are not assigned in a way that those people who are doing the work have an incentive to perform well.

To address those management deficiencies Pakistan introduced in 1997 an irrigation reform (PIDA Act 1997). The cornerstone of the reform was to include farmers in the management of the irrigation system with the purpose to bring down costs and at the same time to make the system more transparent and accountable. Another goal of the reform was to decentralize decision-making as much as possible to a local level so that the rules and activities are better in line with the needs of the farmers.

4.3.5.1 The irrigation reform evaluated by the Ostrom criteria

Usually participation – at least in theory – is something that is pushed by grassroot movements that consist of groups of people that feel disenfranchised from political decisions that directly affect their lives (Marshall, 2005). Pakistan's irrigation reform, however, had not been advocated by the affected people – the farmers – in a bottom up approach but had been introduced by the Pakistan government on the recommendation of the World Bank (Qureschi, 2015). Thus, in order to make sense of the reform, the most obvious first question to examine was: Do farmers actually want to participate, and if so: Are they capable of taking over vital management tasks? The first question could relative easily be answered. During our first field visits in Punjab in 2017 all interviewed farmers welcomed the possibility to take over more responsibility and to have a say in irrigation matters. However, the second question was harder to examine since it could not be addressed in a simple yes/no dichotomy. The capacity to govern themselves was evaluated by Elinor Ostrom's 8 design principles, examining whether a community is able to govern itself and manage its natural resources in a sustainable way (Ostrom, 1992).

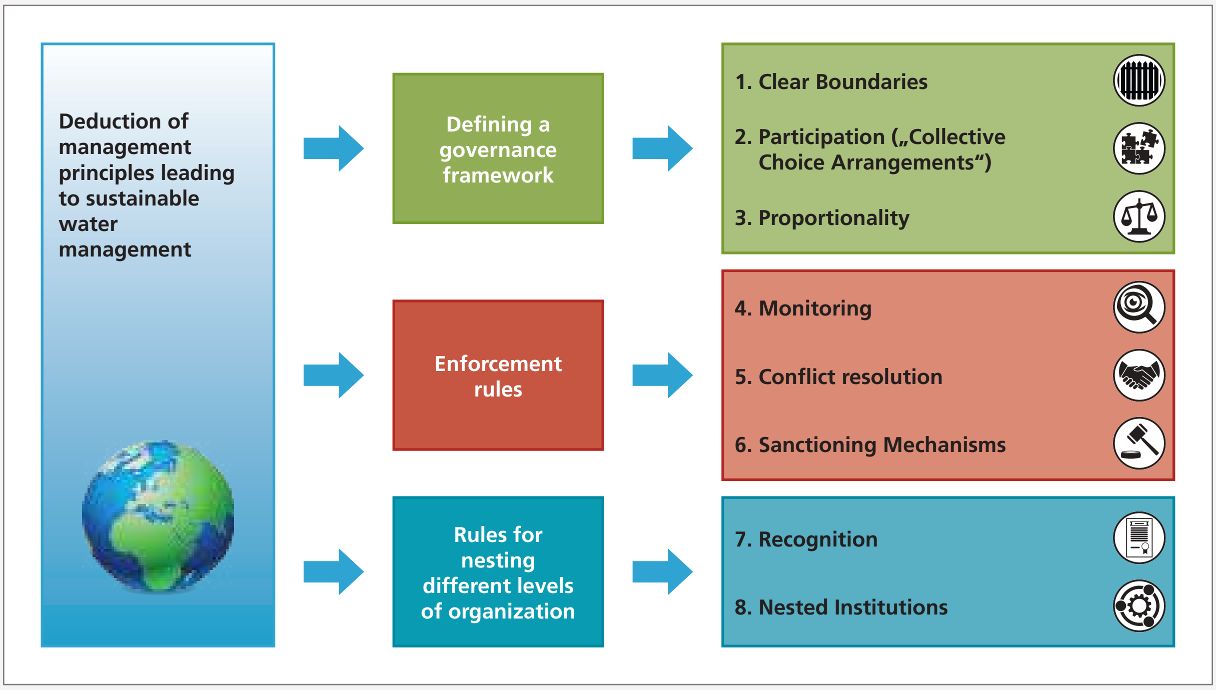


Figure 4.32: Methodology: Applying Elinor Ostrom's 8 Design Principles. © HRW

Conceptually, those 8 principles can be put in 3 different categories (Figure 4.32). The first category defines certain factors that enable communities to agree on collective rules and actions; the second category defines factors that enable communities to make sure that those rules and actions are followed and respected, and the third category deals with aspects that enable small communities to align their rules and sovereignty with their attached larger organizational levels such as regional, provincial and national level of organization, as well as their ability to coordinate their resources and interests with neighbouring communities.

During our various workshops and field trips with farmers it became clear that the biggest obstacles to self-organization was a lack of enforcement rules as well as a lack of coordination horizontally and vertically – meaning with other communities and with higher level organizations. In particular the issue of monitoring becomes vital. For example, farmers on a local level do not know how much water is available for their watercourse nor do they know at the next higher hydraulic level how much water is available for the neighbouring watercourses with whom they share a distributary canal. The lack of reliable information on the available water in the canal system along with inadequate sanctioning mechanisms for rule violators make it for small communities almost impossible to effectively govern themselves.

4.3.5.2 Farmer interviews

Those findings from our interviews and workshops were confirmed in a farmer survey we conducted in 2018 in three different cotton regions in Punjab: Verhari, Toba Tekh Singh, Dera Gazi Khan with a total of about 150 interviewed farmers. The survey questionnaire contained 52 questions about the status quo of agricultural water usage, the allocation infrastructure, organizational patterns, and individual behaviour. The questions were bundled in five different clusters, consisting of the basic information of the respondent, current situation of water allocation, ground water and canal water situation, involvement of different actors, and current farming methods. Some results are summarized in Table 4.6.

Table 4.6: Selected results of the farmer survey interviewing about 150 farmers in Punjab.

	Average	(Range)
Age	42	(19 – 80)
Schooling	10 years	(0 – 19 years)
Land ownership	2 ha	(0 – 40 ha)
Net income (converting Pakistani Rupees to Euro by 2018 exchange rate)	1768 EUR/a	(177 – 42440 EUR/a)
Water shortage	70 % experience water shortages (mainly April/May and winter)	
Water theft	26 % complain when upstream farmers use more water than allowed in Warabandi system	
Raw cotton yield	2499 kg/ha ± 1500 kg/ha	
Groundwater abstraction in Kharif season	184 mm ± 27 mm	

4.3.6 Synthesis and Conclusions

This survey gave valuable insights into the social, economic, and cultural fabric of farmer communities and completed the information we gathered from previous research. In this context we also identified other management gaps at the local level such as a water pricing system that works on a flatrate tariff basis, and thus does not consider scarcity aspects. Clearly, such a water tariff model undermines attempts to motivate farmers to conserve water. However, developing a pricing system that considers the actual water usage of farmers would require a functioning monitoring system that provides farmers with real time information on water availability.

This is not only a technical but also an institutional challenge to implement such a monitoring system at all hydraulic levels. In particular this means that farmers need to put more emphasis in coordinating their management efforts with neighboring watercourses as well as with the irrigation department.

Thus, we recommend that Punjab restructures its organizational structure on a horizontal as well as on a vertical level. This means that the federations of farmer organizations along a distributary and even along a main canal need to be established to mutually coordinate water management along the canal – as it was intended by the irrigation reform.

Further Readings

Oelmann, M., Schulze, J., Zimmermann, N., Roters, R. (2020): Water management below the outlet – a survey-based analysis on the Indus Basin irrigation system in Pakistan. *Int. J. Environmental Policy and Decision Making* 2(4), 2019.

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4.4 Textile Manufacturing

4.4.1 Inventory of Textile Industry in Punjab (M6)

(F.-A. Weber, J. Ferox, W. Kirchhof)

Groundwater pumping is the main source of water for the textile industry in Punjab. Owning land in Pakistan also entitles the owner to the free use of the underground groundwater resources. As a result, only very few textile companies have implemented a continuous monitoring of water use and discharge. To assess the impact of the textile industries on water resources in Punjab, we estimated the amount of groundwater used by the textile industries and the amount of wastewater discharged based on a compilation of textile industries in the Greater Faisalabad Area.

A comprehensive list of textile industries in the Greater Faisalabad Area was compiled based on an extensive internet review and screening of various textile associations as well as textile exporters, including the *All Pakistan Textile Processing Mills Association* (APTPMA), the *All Pakistan Textile Mills Association* (APTMA), and the *Pakistan Textile Exporters Association* (PTEA). Once filtered for textile processing companies, the overview of corporate members provided by the Faisalabad Chamber of Commerce & Industry served as an additional source of information. Company financial reports usually include the amounts of textiles produced throughout a financial year and hence provided further insight into company production quantities. The Pakistani partners helped to refine the company overview, counting a total of 236 companies (Figure 4.11).

In a second step, wet processing textile industries were selected from the dataset, reducing the list of relevant companies to a total of 88. Production capacity and actual production was calculated from available data. To allow for use in other work packages, especially the hydraulic model, the data was georeferenced using ArcGIS and Google Earth Pro but then anonymized for further use.

Water efficiency audits conducted by GIZ GmbH were provided anonymously for companies in Faisalabad and Lahore. Several reports were in a draft state and hence incomplete, and a general over-estimation of production capacities was apparent. Regardless of these short-comings, these reports were the only available unbiased source of measured data and as such the best available data source. The reports offered figures for water use and wastewater discharge for a total of 17 companies. An extrapolation of the water consumption and wastewater discharge to all recorded wet-processing textile companies in Greater Faisalabad area is provided in Table 4.7.

Table 4.7: Extrapolation of water consumption and wastewater discharge to all recorded wet-processing textile companies in Greater Faisalabad area.

	Water consumption [m³/a]	Water consumption [L/kg]	Wastewater discharge [m³/a]	Wastewater discharge [L/kg]
Median of 17 studied plants	1,178,500	129	918,213	112
Extrapolation to all wet-processing plants in Greater Faisalabad area	100,172,500		78,048,105	

The onsite analysis in Pakistan suggests that little to no water reuse is implemented in the factories in Punjab. The comparison of the water consumption and wastewater generation hence gives an indication of the losses through evaporation in the factories. Based on the values presented in the GIZ reports, evaporation losses in the factories range from a minimum of 4 % up to maximum of 22 %, with a mean of 14 %.

In a 2018 workshop with the Water and Sanitation Agency (WASA) and the Irrigation Department of Faisalabad, the Environmental Protection Department (EPD) of Punjab presented the flow rates in the wastewater drains around Faisalabad. Two major drains pass through the city of Faisalabad, the Paharang Drain in the northwest, which ultimately discharges the wastewater into the northern river Chenab, and the Madhuana Drain in the southeast, which ultimately discharges the wastewater in the southern river Ravi. According to the EPD, a total of 33,933,685 m³ of wastewater leave the city through the Paharang drain each year, while an annual 102,694,940 m³ are discharged through the Madhuana drain. According to EPD, the textile industry in Faisalabad accounts for roughly 68 % of industrial polluters. It follows that textile industries account for a total wastewater volume in both drains of 92,907,465 m³ per annum. With stormwater also being discharged through these drains, and a certain amount of water coming from upstream Faisalabad, the order of magnitude presented in Table 4.7 is confirmed.

While the EPD estimates less than 10 % of the water used in Pakistan is attributable to the industry, they acknowledge the pollution footprint is manifold greater than that of the agriculture. While ten of the 88 wet-processing companies assessed appeared to operate treatment plants based on their own claim, the analysis of various audits, the correspondence with the partners in Pakistan, and on-site analyses suggest few companies actually operate treatment plants, or have the capability of effectively purifying textile wastewater. The lack of effective wastewater treatment in textile companies is evident and stimulated the efforts in demonstration project D4.

4.4.2 Water Use of Exhaust Dyeing Machinery (M7)

(H. Freericks, O. Heß, M. Korger, B. Mahltig)

The amount of water needed during dyeing processes strongly depends on the age and type of the used machines, technology, and colour shade. Thies examined the water use and water consumption of different reactive dyeing processes for cotton of their own exhaust dyeing machines used in Pakistan by several dyehouses. With a water meter that is part of all THIES iMaster systems, it is possible to routinely record the total amounts of water used and wastewater produced in the dyeing process.

As result, water use varies from 15 L to almost 70 L water per kg cotton fabric (Figure 4.33) due to several reasons. The liquor ratio (ratio between textile product and water) varies, also the dyed colour shade makes a remarkable difference in water use. The darker the shade the more water is used because more dyestuff and added chemicals are needed absolutely. Therefore, darker shades need more rinsing bathes to remove unbound dye from the fabric. The wide range of water consumption for the very dark colours is related to different chemical characteristics of the dyes used in the dyehouses. Depending on the dye used, the fixation rates range between 65 % and approx. 95 %. A corresponding amount of excess unfixed dye must be rinsed out.

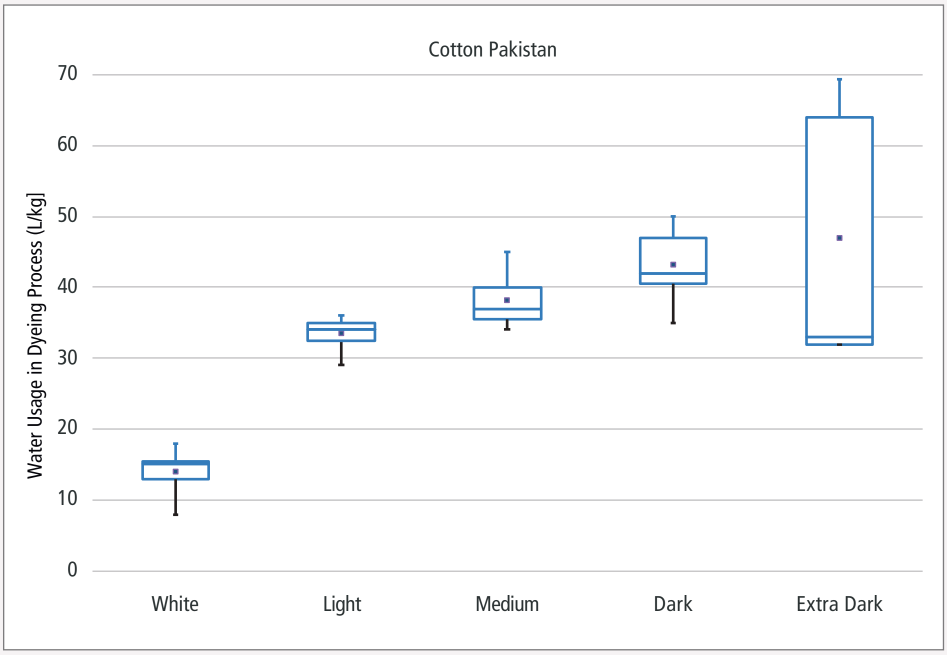


Figure 4.33: Box plots of measured water use of exhaust dyeing machinery THIES iMaster H_2O operated routinely by textile mills in Pakistan (data base n = 7–9). © THIES

4.4.3 Industry Audits: Identifying Options to Improve Water and Energy Efficiency (M7)

(C. Baumann, H. Schönberger)

The Federal German Ministry for Economic Cooperation and Development (BMZ) has commissioned the Agency for International Cooperation (GIZ) to implement water and environmental management systems to reduce, preferably to mimimise, the use of water consumption for textile finishing (wet processing such as textile pre-treatment , dyeing, printing and final finishing). Therefore, the project “Water Efficiency in the Textile Industry (WETI)” was developed aiming at appropriate and efficient use of the limited water resources for textile finishing (wet processing). As the Pakistan textile finishing industry consumes about 70 % of the industrially used water, the substantial improvement of water efficiency is of high relevance. In Pakistan, textile finishing industries (TFI) increasingly perceive the scarcity of water resources (especially groundwater) as an operational and strategic risk to their business. The key causes of the inefficient water use and high water consumption by TFI is lack of awareness and incentives for water saving measures, the low costs for intake water as well as for wastewater discharge, outdated production technologies, and a lack of monitoring of water use in production processes. It is important to see that high water consumption is associated with a higher consumption of chemicals and energy.

In the following, important techniques to minimise water (and energy) consumption are presented which were gained from the WETI Project carried out in 15 TFI in or near Lahore and Faisalabad.

Any water conservation/minimisation measures require an adequate water management plan which is, together with water audits, part of the environmental management system (EMS). It includes:

- flow diagrams and a water mass balance as a result of proper water consumption monitoring
- establishment of water efficiency objectives and development of actions to achieve them
- implementation of water optimisation techniques (e.g. control of water usage, reuse/recycling of certain individual wastewater streams, detection and repair of leaks)

Water and energy audits are carried out at least annually to ensure that the objectives of the water and energy efficiency plan are met. First, an annual mass stream overview (Figure 4.34) shall be generated indicating all relevant input streams. My means of such an overview, important environmental performance indicators can be calculated such as the specific water consumption in [L/kg textile], specific wastewater generation in [L/kg textile], specific consumption of primary energy in [kWh/kg textile] and of electricity in [kWh/kg textile]. Such an overview requires a minimum of monitoring. For the total annual water consumption, the flow has to be measures at least for the main pipes. However, in order to develop targeted measures for reducing/ minimising of water consumption, also all main consumers, i. e. the different machines, shall be monitored for water consumption. In the final stage, the annual mass stream overviews is not only available for the whole TFI but also for relevant machines and processes operated.

In the following, important technical measures based on the aforementioned management approach are mentioned concerning the reduction/ minimisation of water consumption. As the finishing of woven fabric dominates in Pakistan, an examples is described more in detail, also to show that the reduction of water consumption requires an integrated approach taking into account different processes and the interrelations between them.

Figure 4.34 below shows a typical example of the pretreatment of woven fabric with cotton as the main fibre consisting of desizing, scouring, bleaching and mercerisation. Here, whenever possible with respect to product quality, scouring and bleaching may be combined to save one process. Then, the specific water consumption for the different processed mentioned should not exceed 4 L/kg textile, i. e. about 4 /kg each for desizing, scouring and bleaching and 7 – 12 L/kg for mercerisation. In addition, washing water from bleaching can be reused for scouring, washing water from scouring can be reused for desizing, and washing water from mercerisation can be reused for desizing, scouring or bleaching (Figure 4.34). No intermediate tank is required as the different machines work at the same time. The only measures are to install additional pipes to carry out the connections at and between the machines and the removal of fibres by continuously operated drum separators (“lint collectors” in Figure 4.34).

Further measures to reduce water consumption are briefly mentioned below.

- Collection of cooling water from singeing, from cooling padders or drums (e.g. last drum of cylinder driers) to reuse it in any of the process machines as its quality concerns that of pre-treated raw water.

- In case raw water has high content of dissolved solids (neutral salts), which is usually the case in Pakistan, it is treated by reverse osmosis (RO). The permeate (about 70 % of the input flow) is of high quality and is used for processing or as boiler feed water whereas the concentrate (about 30 % of the input flow) is usually discharged. The permeate flow can be increased by installing a second RO stage that requires much higher pressure and is therefore more costly. The concentrate can be stored and used for low quality purposes such as in the colour kitchen for washing floors and pre-cleaned chemical drums or for showering water at coal fired boiler wet scrubber and toilets.
- A caustic soda recovery unit (CRU) is used to concentrate dilute caustic soda solution (weak lye) of 5–10°Bé concentration into 20–25°Bé concentration by evaporating water from the weak lye through evaporators. The vapors from weak lye is condensed into hot water through condensers. This hot water is at a high temperature of about 80°C with alkaline pH. Generally this hot alkaline water is wasted in the industry. This water may be collected and reused as washing water for post-mercerization washes, desizing, scouring and bleaching washes. This water can also be used as dilution water for preparing caustic soda solution from 50°Bé–25°Bé. A significant amount of energy will also be saved
- The condensate from CRU is hot and at alkaline pH. Often, this hot alkaline water is wasted but can be reused for mercerisation. The same is true for water from vacuum ejectors to create vacuum in the CRU evaporators. This water can be used for washing after the mercerisation process or for washing after bleaching.
- In case of mercerisation, caustic soda is cooled through ammonia chiller. Cooling water is used at ammonia chiller's condenser to condense ammonia gas. This cooling water is a clean water stream and can be collected and reused in the process.
- For exhaust dyeing of cotton and cotton blended knitwear, in addition to use low liquor ratio machines, the number of baths can be significantly reduced by using improved dispersing systems. Thus, a total specific water consumption of 30–40 L/kg textile can be achieved.

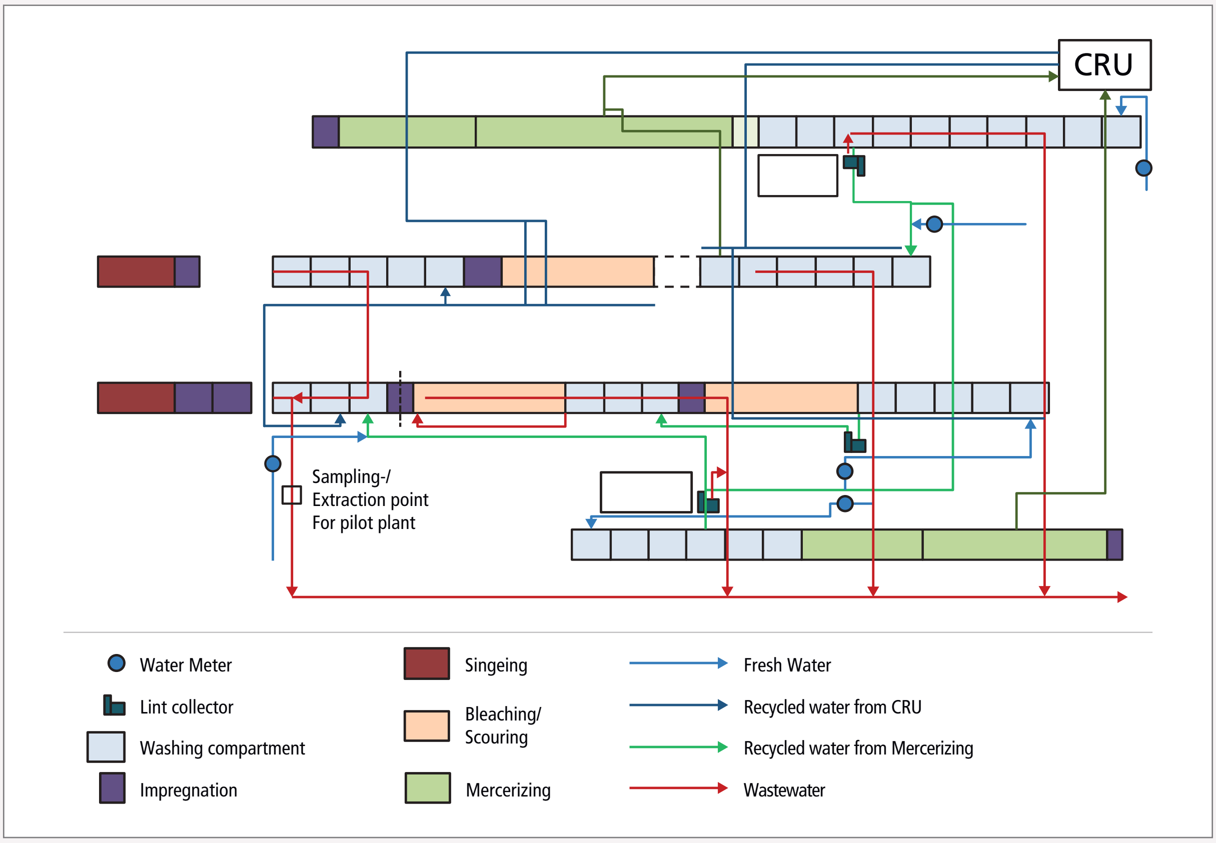


Figure 4.34: Floor plan with fresh water, re-used water and wastewater sewers. © FiW

4.4.4 Wastewater Treatment in Textile Industry (M8)

(C. Baumann, F.-A. Weber, H. Schönberger)

Quality standards for liquid effluents from textile producers are regulated in Pakistan by the National Effluent Quality Standards (NEQS, 2000). While the limit values for key wastewater parameters set in the NEQS are comparable to other national regulations, such as the German Wastewater Ordinance (Table 4.8).

Apart from national wastewater regulations, customer specific demands have become more important in the last years, especially since the publication of the ZDHC (2016) wastewater guidelines. The guidelines distinguish between three levels for conventional wastewater parameters: foundational, progressive and aspirational. While producers were expected to achieve the foundational limits within a year from the publishing date of the guidelines, aspirational limits are expected to be met by January 1, 2020 (ZDHC, 2016).

Table 4.8: Comparison of different textile wastewater limit values (AbwV, 1997; NEQS, 2000; ZDHC, 2016)

	NEQS	AbwV	ZDHC Foundational	ZDHC Progressive	ZDHC Aspirational
Temperature [°C]	≤3*		Δ15**/ ≤35	Δ10**/ ≤30	Δ5**/ ≤25
COD [mg/l]	150	160	160	80	40
BOD5 [mg/l]	80	25	30	15	5
TDS [mg/l]	3500				
TSS [mg/l]	200		50	15	5
Total-N [mg/l]		20	20	10	5
NH4-N [mg/l]	40	10	10	1	0.5
Total-P [mg/l]		2	3	0.5	0.1
Sulfite [mg/l]		1			
AOX [mg/l]		0.5	5	1	0.1
Color (436nm) [m-1]		7	7	5	2
Color (525nm) [m-1]		5	5	3	1
Color (620nm) [m-1]		3	3	2	1
Oil and Grease [mg/l]	10		10	2	0.5
Phenol [mg/l]	0.1		0.5	0.01	0.001
Colifom [bacteria/100 ml]			400	100	25

*The effluent should not result in temperature increase more than 3°C (…) (NEQS, 2000)
**Degrees above ambient temperature of receiving water body (ZDHC, 2016)

The reference document on best available techniques for the textile industry by the European Commission (2003) contain descriptions of several wastewater treatment plants operated in the textile industry. The best available techniques (BAT) derived from these systems recommend to, as far as possible, separate different wastewater streams on-site according to their contaminants and loads in order to treat them separately. In cases where wastewater streams with high concentrations of non-biodegradable compounds cannot be treated separately, the European Commission (2003) recommends a combination of an activated sludge system at low food-to-microorganisms ratio and tertiary treatment processes such as activated carbon adsorption, precipitation using iron salt, wet oxidation or ozonation. However, as discussed in Schönberger (2018), even with the use of the BATs for textile wastewater treatment, it requires a well-designed and well-operated treatment plant to even comply with the progressive levels of the ZDHC guidelines, especially for water efficient textile plants.

Upcoming technology are Zero Liquid Discharge (ZLD) treatment plants designed to recycle most of the liquid effluent by use of membrane and reverse osmosis while evaporating the water in the remaining concentrate. However, this entails high investment and running costs.

In fact, currently only a small fraction of textile processing mills in Punjab have functioning wastewater treatment plants installed, and even if installed, activated sludge treatment processes are hardly operated due to high energy costs. Based on anonymized data by GIZ surveys of 9 textile processing mills in Punjab, wastewater composition varies widely, with parameters often not complying to national or international standards (Figure 4.35). Thus, mainly untreated wastewater is thus discharged via open, partly unlined central drains into the river Ravi and Chenab (Figure 4.36, Figure 4.37). Percolation of untreated wastewater contaminates downstream ecosystems, groundwater pumped for irrigation and drinking water supply.

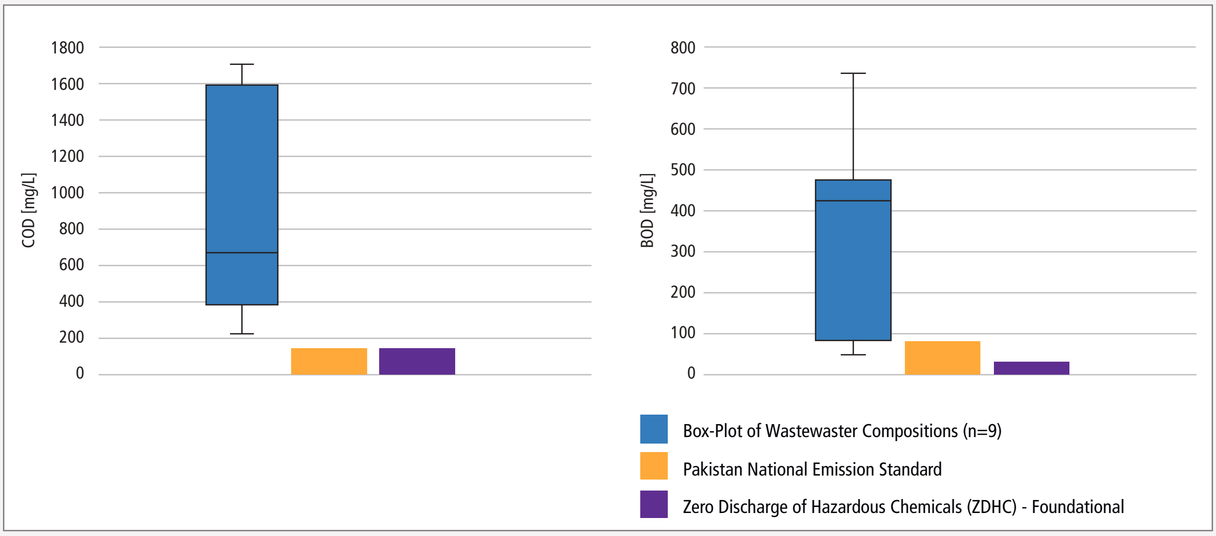


Figure 4.35: Composition of untreated textile wastewater based on nine company surveys conducted in Punjab. © FiW

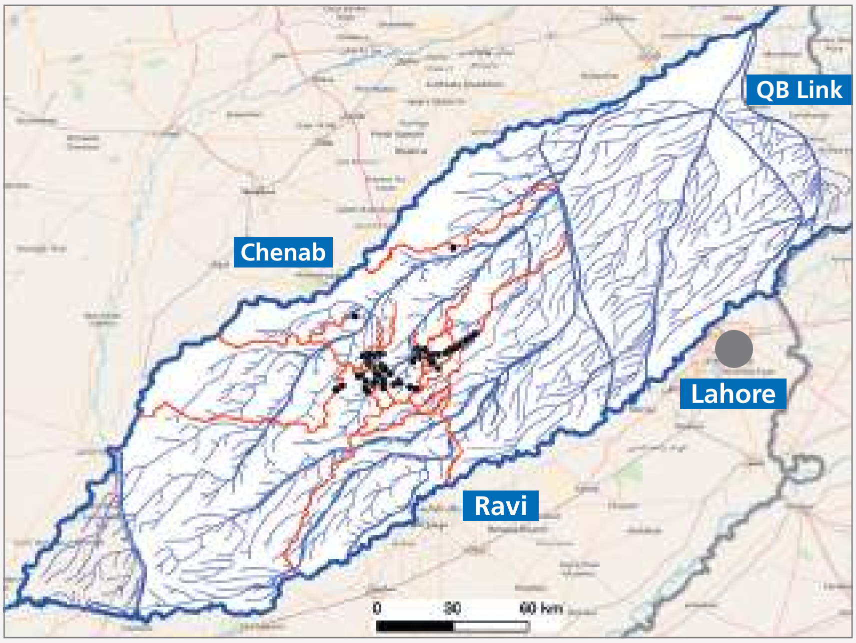


Figure 4.36: Based on member lists of textile associations, internet search, and satellite images, 85 textile mills in LCC were identified (black dots), of which approx. 10 show nearby wastewater treatment plants in satellite images. Treated and untreated industrial and municipal wastewater is channelled via partly unlined central drains (in red) to the receiving rivers Chenab and Ravi. © FiW

Figure 4.37: Central Drains, discharging mainly untreated wastewater to river Chenab and Ravi. © FiW

Text Box 10:

What makes textile wastewater toxic?

Many textile treatment processes require its own specialized chemicals to meet the requirements of the final product. Usually it starts with a pre-treatment and ends with a finishing process. Therefore, the generated textile wastewater from the mill contains a wide range of different chemicals used for textile treatment, their transformation and degradation products. When untreated, these chemicals may directly or indirectly cause several health hazards to humans, animals, plants, as well as microorganisms. Degradable compounds high in Biological Oxygen Demand (BOD) may result in oxygen depletion of the water body. Phosphates and nitrogen compounds such as urea, thiourea and derivatives lead to river eutrophication.

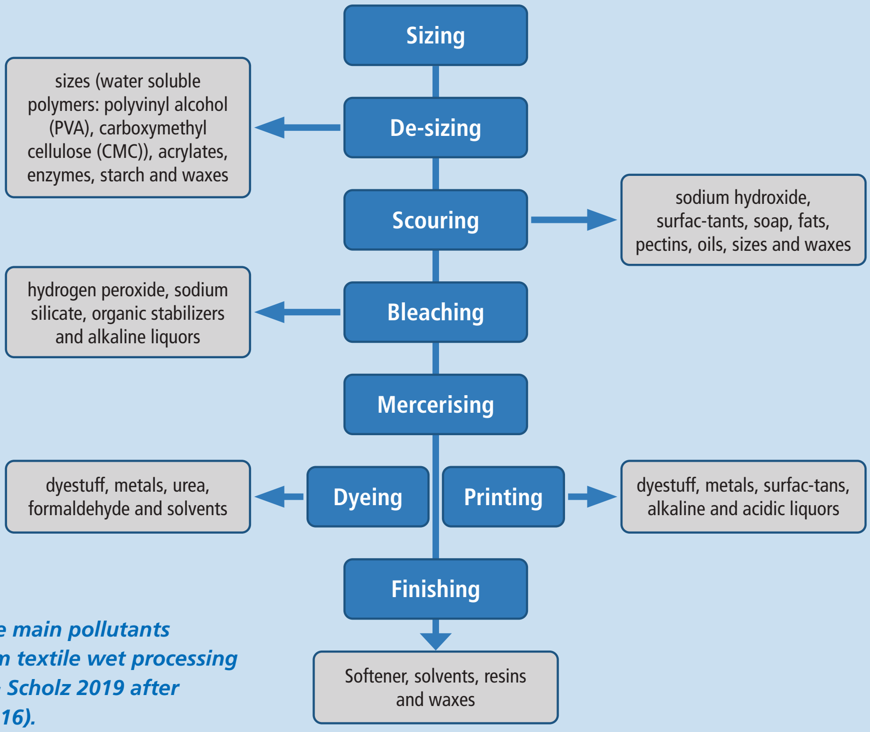


Figure 4.38: The main pollutants discharged from textile wet processing (from Yaseen & Scholz 2019 after Holkar et al. 2016).

For example, 700,000 tons of synthetic dyes are produced worldwide. Up to 200,000 tons of these dyes are lost to effluents every year during dyeing and finishing operations of textiles, due to the inefficiency of the dyeing processes (Drumond Chequer, 2013). High concentrations of textile dyes in water bodies cut off sunlight, thereby upsetting biological activity photosynthesis process of aquatic plants or algae. Most of the colorants used in the textile industry are soluble dyestuffs, 70–80 % of them are azo dyes (Rawat *et al.*, 2016). Azo dyes are popular because they dye textiles at 60°C, while other dyes require higher temperatures up to over 100 °C. They are cheap and offer an extensive range of colours and have good colour fastness. In textiles dyeing up to 50 % of the azo dyes can be washed out. With the factory discharges they end up in water bodies as they can be hardly removed by standard waste water treatment processes. Dyes tend to accumulate in solid mediums due to their resistance to biodegradation, which is related to their synthetic origin and complex molecular structure. Today, they are produced for the most part in China and India, followed by Korea, Chinese Taipei and Argentina (OECD 2005). According to the section 43 (azo dyes and azo colorants) of annex XVII of REACH legislation some are banned since 2002 throughout the EU, if the dyed product comes into direct and prolonged contact with the human skin or oral cavity. In Germany they have been partly banned already since 1996. Nevertheless, textile products still contain the globally banned azo dyes or respectively aromatic amines as degradation products, because of gaps in the production chain and a lack of knowledge.

5 IMPACT ASSESSMENT OF THE COTTON-TEXTILE INDUSTRY IN PUNJAB, PAKISTAN

(F.-A. Weber)

Water consumption and pollution associated with the cotton and textile production may result in impacts on the water resources, human health, and ecosystems within and downstream of the study area (Figure 5.1). Enhanced evapotranspiration from irrigated cotton fields may cause water scarcity in the downstream regions, potentially resulting in yield reduction, which in turn may cause malnutrition of the local population when food is already in short supply. In addition, over-abstraction of freshwater for irrigation purposes may cause degradation of aquatic ecosystems, loss of natural habitats and biodiversity. Several cases of degradation are documented in the Indus Basin, notably the Indus river falling partly dry below Kotri Barrage in Sinth, the endangering of the Indus river dolphin, and seawater intrusion into Indus Delta, listed as a wetland of international importance on the Ramsar List of Wetlands (Kalhoro *et al.* 2016, WWF 2020).

Water pollution is caused by application of pesticides and fertilizers in cotton cultivation as well as the discharge of untreated wastewater from the textile production. This affects both human health and ecosystems through the ingestion of and contact to the toxic substances such as heavy metals and dyestuffs' residues applied in the textile processing. Once discharged in the drains, the contaminants are discharged into rivers. Downstream, pollutants may reach downstream aquatic ecosystems and potentially drinking water resources. Furthermore, since the river water is used for irrigation, the contaminants may accumulate in the food crops.

In rural areas in Punjab, drinking water is mainly supplied by bank filtration along irrigation canals, while groundwater is saline deteriorated by agriculture by sewage and central drain infiltration. Therefore, families, often children are sent to collect water from shallow wells alongside the banks of the irrigation canals (Figure 5.2). Only large cities like Faisalabad and Lahore opperate centralized water supply, which is currently extended by additional tube well galleries along branch canals with support of Japan International Cooperation Agency (JICA), (Roohan Javaid 2019). Bottled water and soft drink supplied from sources upstream in the mountains of Punjab are popular for those who can afford it.

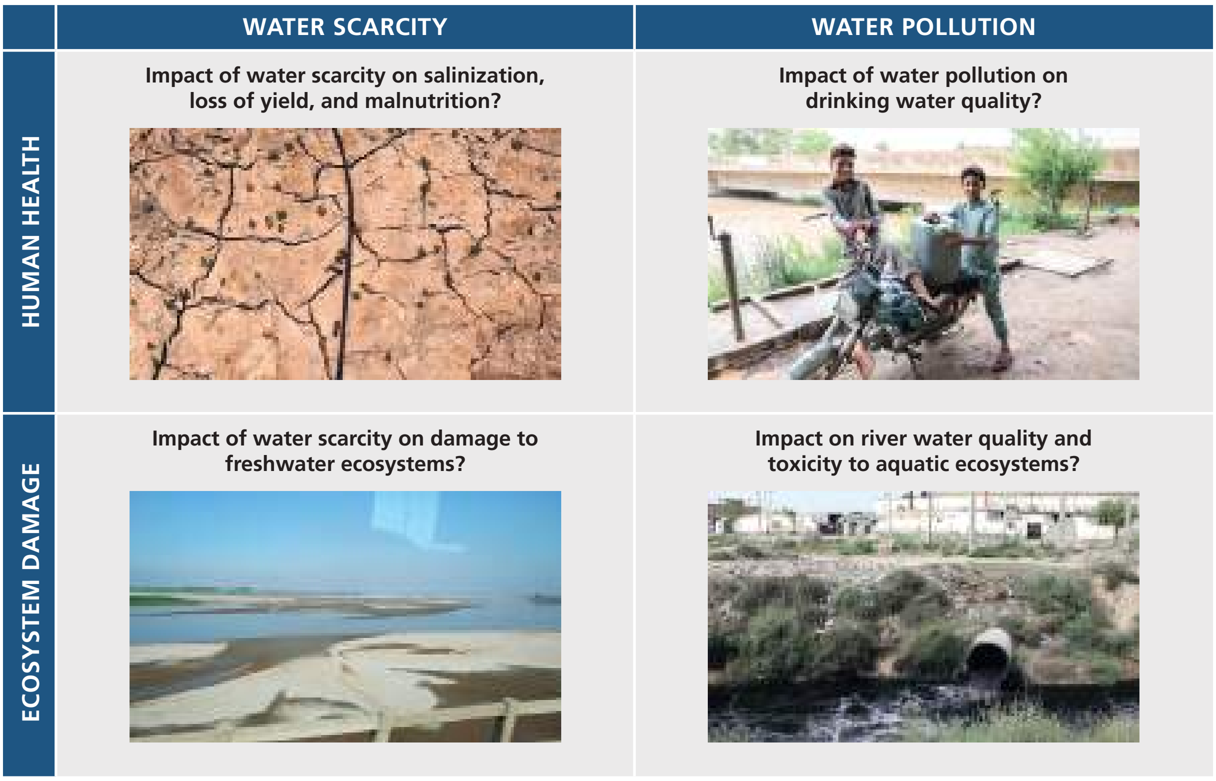


Figure 5.1: Potential cause-effect chains on human health and ecosystem damage. © FiW.

Figure 5.2: Children collecting drinking water from bank filtration in Punjab. © FiW

5.1 Cause-Effect Chains

(N. Mikosch, M. Berger)

Cause-effect chain modelling allows for a quantitative assessment of the impacts on the human health and ecosystems associated with the water consumption and pollution. Human health damage assessment models applied in water footprinting include two types of water use: water consumption and pollution. Two general impact assessment approaches exist in water footprinting: deprivation based (impacts due to the lack of water) and pollution based (impacts due to the intake of pollutants) (Mikosch *et al.*, 2020b).

The cause-effect chains are regionalized by means of physical parameters (e.g. landscape data and water scarcity) and socio-economic factors such as Human Development Index (HDI) that reflect the adaptation capacity of the population to environmental pressures, e.g. through using bottled water for drinking when domestic water is polluted. Existing models for the human health damage assessment provide regionalization on the country or world region level. So far, it was not investigated how well the impacts occurring on a local scale can be reflected by existing WF models. For this reason, within the InoCottonGROW project, the consistency between the locally occurring and modelled cause-effect chains was evaluated in the study area. Based on the results, recommendations for adjusting existing and developing new cause-effect chains were provided.

Based on the analysis conducted in the study area, three cause-effect chains were identified for the human health damage related to the agricultural water deprivation:

1. Malnutrition damage due to the loss of the yield. The impacts include loss of the yield of food crops, resulting food shortage and finally malnutrition. This cause-effect chain is relevant particularly when short-term interruptions in food supply cannot be compensated by food stock and/or imports.
2. Malnutrition damage due to the income loss. This cause-effect chain reflects the economic damage associated with the loss of yield of both food (e.g. rice) and cash crops (e.g. cotton) resulting from the water deprivation. Income loss in its turn reduces the purchasing power of farmers and their families and therefore may cause malnutrition.
3. Diseases due to usage of the wastewater-impacted water resources for irrigation purposes. Applying contaminated water resources may lead to the exposure of the local population to the contaminants either via direct contact to polluted water or indirectly through contaminated food crops and drinking water. Intake of the contaminants (e.g. heavy metals) mayin the spread of toxicity-related diseases (Mikosch *et al.* 2021).

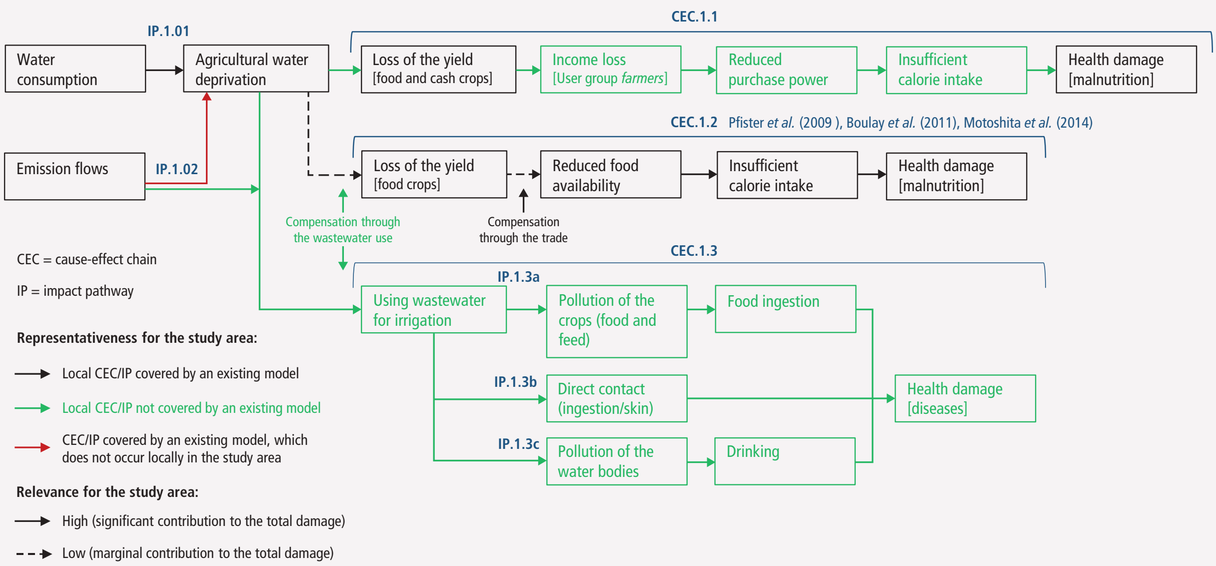


Figure 5.3: Existing and recommended cause-effect chains for the human health impacts associated with agricultural water deprivation (based on Mikosch et al. (2021)).

Out of the three aforementioned cause-effect chains, only the one for the malnutrition damage related to the reduced food availability is addressed by existing WF models (Figure 5.3). Therefore, we recommend integrating other cause-effect chain in water footprinting.

Wastewater generated in the textile production may discharge contaminants including heavy metals and organic compounds to downstream drinking water resources and the food chain, e.g. via polluted irrigation water. The intake of the contaminants may lead to the subsequent health impacts. These cause-effect-chains identified on the local scale are addressed by existing WF models. To improve the representativeness of the cause-effect chain for the exposure via drinking water, groundwater compartment should be included in the model (which is currently missing). Furthermore, we recommend to introduce an adaptation capacity factor to better evaluate the exposure via drinking water, e.g. through considering socio-economic status of the local population or the availability of water supply systems (Figure 5.4).

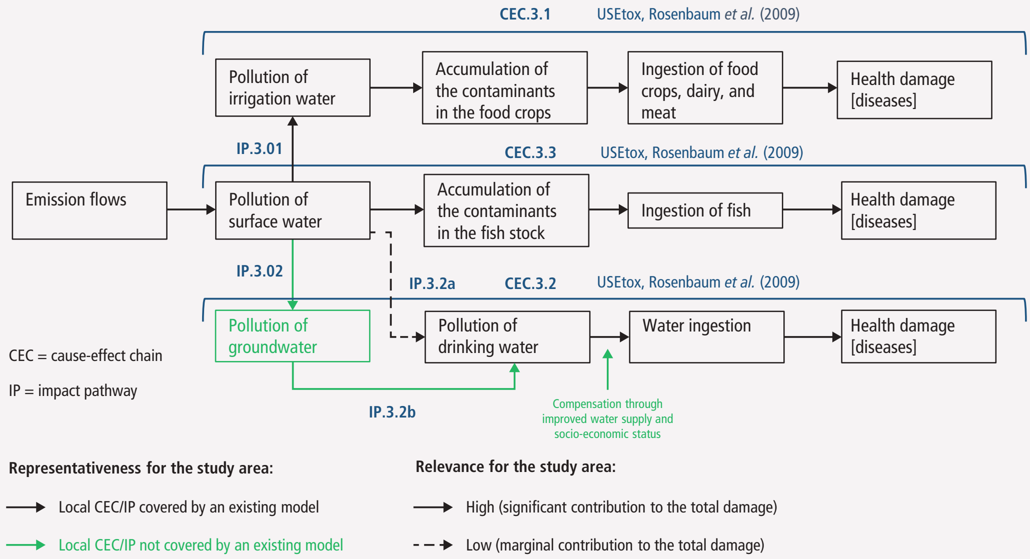


Figure 5.4: Existing and recommended cause-effect chains for the human health impacts associated with water pollution (based on Mikosch et al. (2021)).

The cause-effect chains for the damage on the aquatic ecosystems include the impacts of both water deprivation and pollution (Figure 5.5). Due to the irrigation of the cotton fields, amounts of freshwater withdrawn from the rivers are evapotranspirated by the cotton plants, removing the water from the river basin. This leads to the reduction of the environmental flow needed to sustain downstream aquatic ecosystems and loss of the habitat of local aquatic species. Water pollution leads to eutrophication and toxicity-related damage on the aquatic ecosystems. These locally identified cause-effect chains are addressed by existing WF models. To provide a region-specific analysis, the models need to be adjusted for the local conditions, e.g. the response of the local ecosystems to water shortages needs to be modelled. Providing eco-toxicity data for a broader range of contaminants generated during the textile production, particularly dyestuff' residues and auxiliary compounds, could significantly enhance the assessment of the ecosystem damage related to the water pollution.

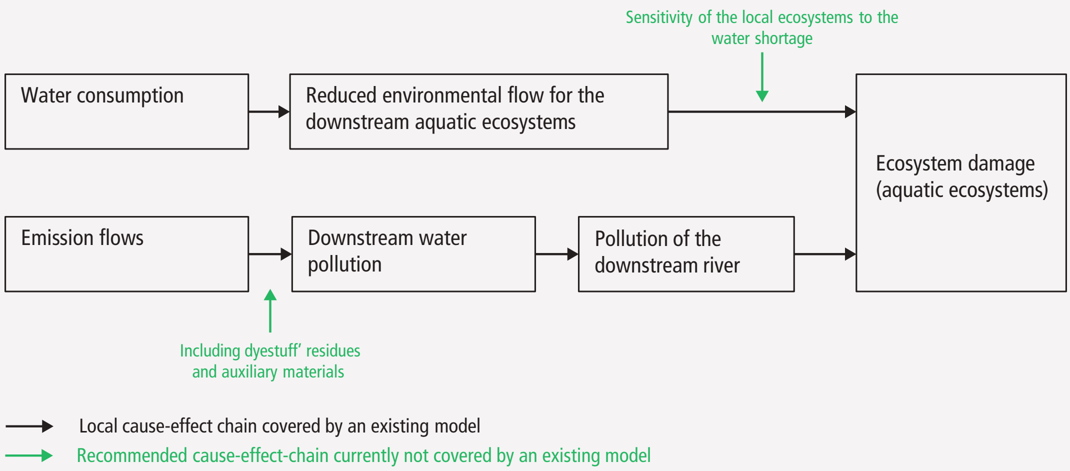


Figure 5.5: Cause-effect chains for the ecosystem damage.

6 FIVE DEMONSTRATION PROJECTS: OPTIONS FOR REDUCING WATER CONSUMPTION

Five demonstration projects illustrate strategies to reduce the water footprint of the cotton-textile production: (D1) flexible irrigation strategies to increase irrigation water productivity, (D2) water-saving textile machineries, (D3) resource-efficient dyestuffs, (D4) textile wastewater treatment by anaerobic treatment of highly polluted wastewater of desizing, (D5) pollutant analysis and regulatory enforcement of wastewater effluent standards.

6.1 Optimizing Cotton Productivity (D1)

(B. Tischbein, A. Bakhsh, M. Fareed)

As derived in chapter 4.3 we combined performance assessment of irrigation under real conditions at farms in the Mungi Distributary with irrigation experiments carried out by our partner UAF at the Water Management Research Centre (WMRC) in order to derive pragmatic strategies to improve field water management towards higher productivity.

The irrigation experiments aim at testing options by modifying (advanced bed-furrow) and changing irrigation application technology (drip irrigation) and by irrigation strategies (full irrigation; deficit irrigation at different levels).

Text Box 11:

What are criteria to assess water productivity in cotton farming?

appropriateness of irrigation
irrigation schedules avoiding water and salt stress $(E)T_{act} = (E)Tpot$ (or minimizing the impact of water stress on the agricultural yield in case of undersupply)

(technical) irrigation efficiency
ratio of water supplied into the root zone (for use by crops as actual evapotranspiration) in relation to the amount of water withdrawn from the source (per: system component)

water productivity
ratio of agricultural yield per gross water input of irrigation water and leaching water

effectiveness of salt management by leaching
amount of irrigation (leaching) water to maintain a soil salt content below crop tolerance limits

Crop water productivity (CWP)
yield over the amount of total water applied for a crop.

Figure 6.1 provides net irrigation demand (green bars) and gross irrigation input (blue bars) for drip irrigation and bed-furrow with full, 10 % and 20 % deficit (related to input) in the upper part and the respective yields achieved in the lower part of Figure 6.1.

As depicted in Figure 6.2, drip irrigation reaches an application efficiency of 83 % and a water productivity of 0.684 kg raw cotton per m^3 gross water input. Bed-furrow method leads to 64 % application efficiency and a productivity of 0.48 kg raw cotton per m^3 gross water input. Stepping into deficit irrigation of 10 and 20 % could raise efficiency (71 % and 80 %), yet efficiency gain was compensated at the price of lower yield in deficit irrigation; therefore, water productivity was rather constant at approximately 0.48 kg raw cotton per m^3 gross water input.

An application efficiency of 83 % by drip method leaves some space for improvement. For that purpose, we adapted the irrigation scheduling model AquaCrop to the conditions of the drip irrigation plots as a starting-point to simulate options to enhance application efficiency. Due to systematic performance of the drip experiments (irrigation each third day), the soil moisture after rainfall events is above field capacity. Basically, two strategies can be applied to raise application efficiency: either to postpone irrigation events after heavy rainfall or to lower the refill limit of irrigation slightly below field capacity leading to a higher share of effective rainfall and in turn to saving of irrigation water.

As depicted by Figure 6.3, it is possible to lower the gross irrigation input from 475 mm to 403 mm without reducing the yield and thereby increasing application efficiency up to 95 %.

The experiments can support farmers in: (i) modifying the surface irrigation method (towards bed-furrow), (ii) assessing an eventual change in application technique (towards drip irrigation), and (iii) performing controlled deficit irrigation to cope with undersupply situations enabling to minimize the yield loss due to non-avoidable water stress expected to become more frequent in future as an impact by climate change and a sharpening competition for water.

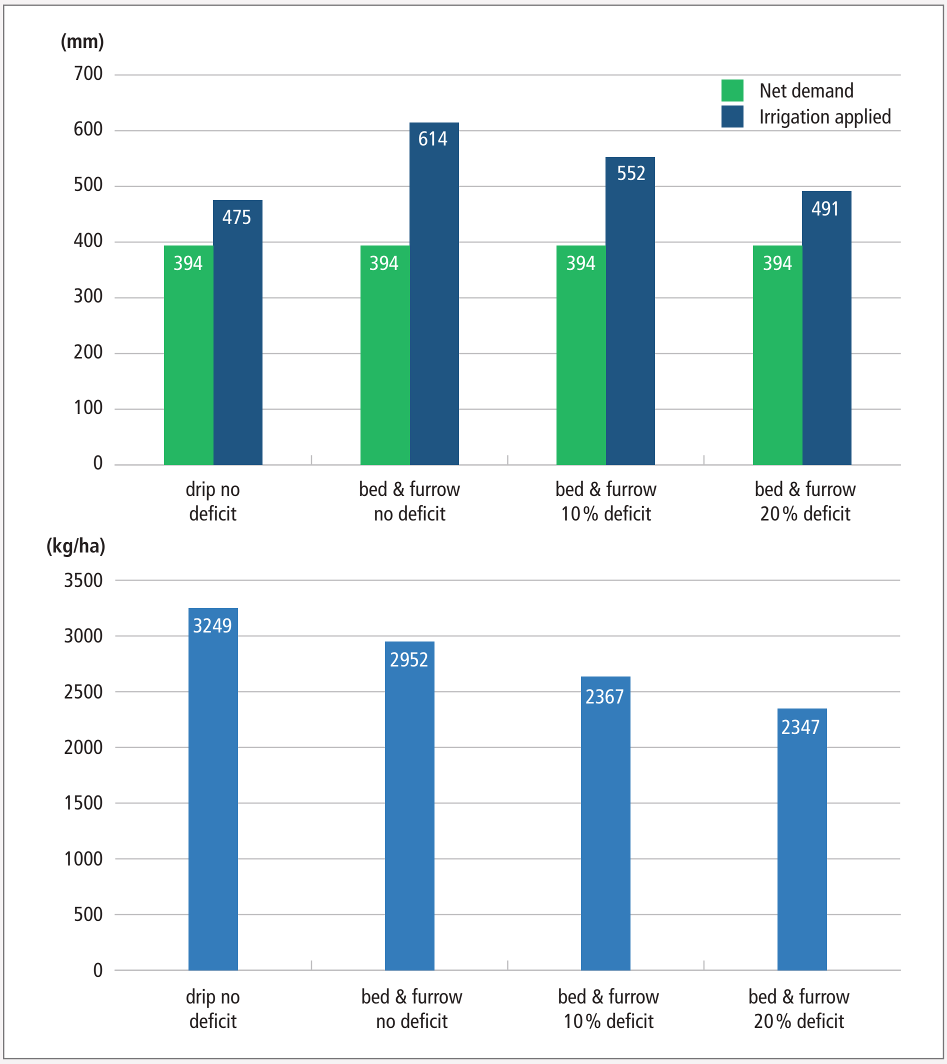


Figure 6.1: Net irrigation demand, gross irrigation applied and recorded yield in irrigation experiments conducted 2017 by UAF at WMRC.

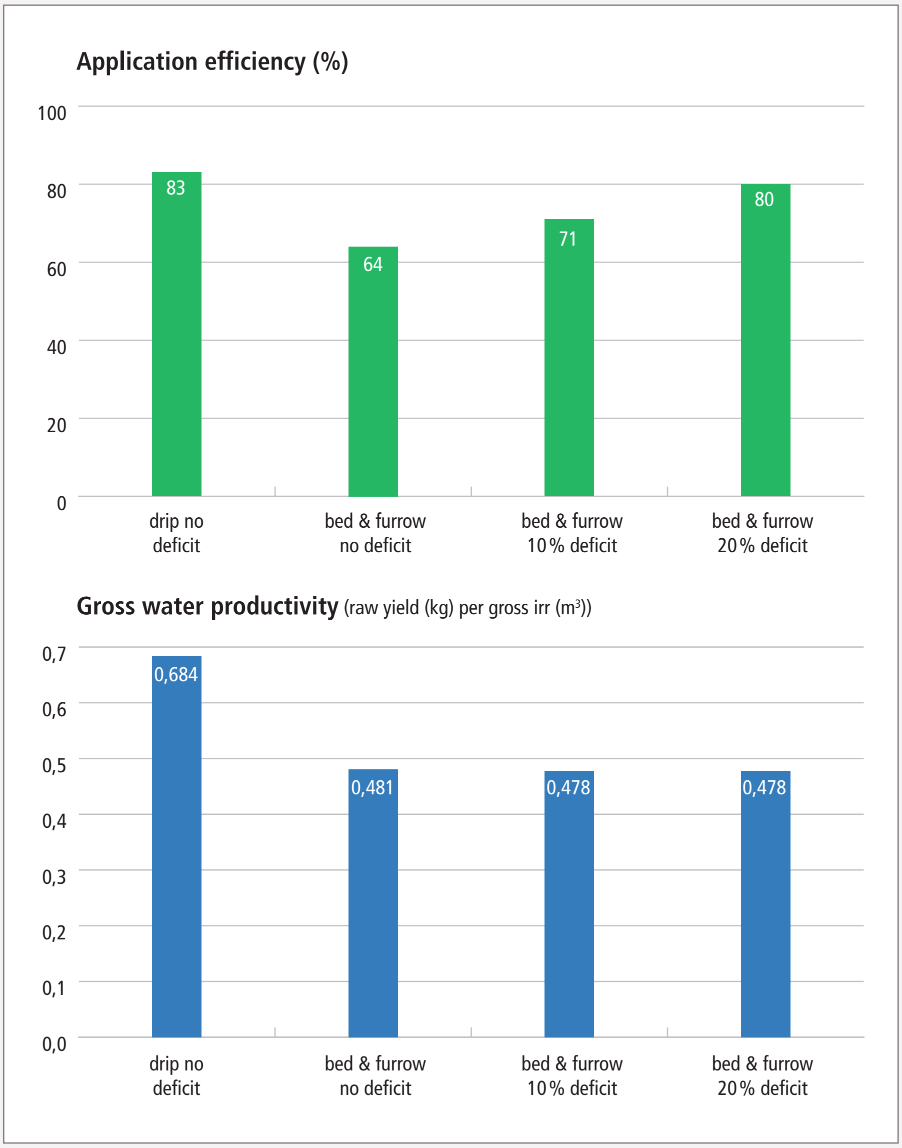


Figure 6.2: Application efficiency and gross water productivity of irrigation experiments yield in irrigation experiments conducted 2017 by UAF at WMRC.

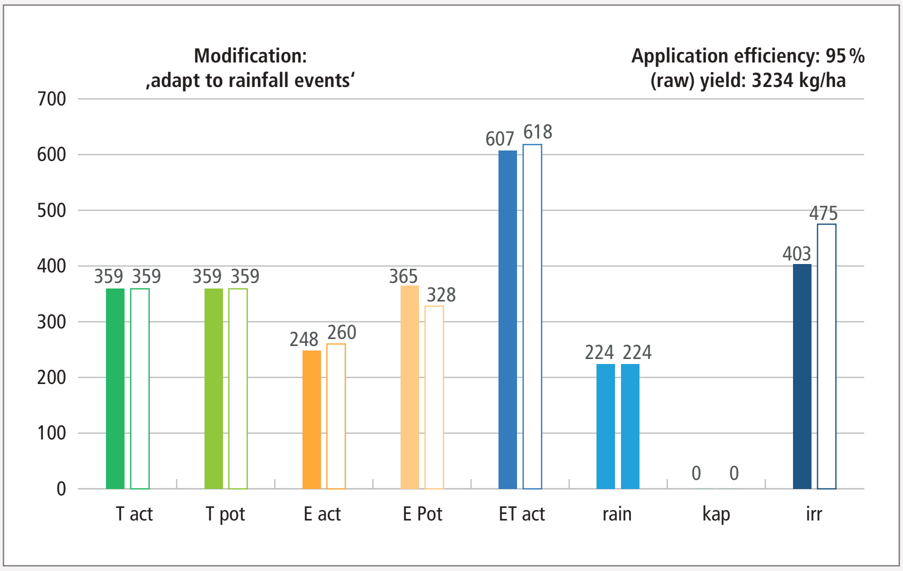


Figure 6.3: AquaCrop modelled field-water balance components of a simulated flexible irrigation schedule integrating / utilizing rainfall to enhance application efficiency (example: drip irrigation).

Text Box 12:

Why is implementation of drip irrigation technology slow in Punjab despite governmental support?

Compared to surface irrigation methods (basin, furrow), drip irrigation has the potential to enabling clear advantages mainly in terms of high efficiency and targeted high frequency irrigation enhancing uniform crop growth. Yet, for full utilization of that potential, requirements need to be fulfilled:

- storage facilities to provide supply for frequent irrigation by the drip system
- appropriate combination with fertilizer application
- cropping pattern ideally consisting of point or row crops
- proper design of drip systems in relation to soil and crop conditions
- availability of funds for investing in drip systems
- providing funds, knowledge and training for operation and maintenance of drip systems
- training on estimating the irrigation requirement and the operation of drip systems

Besides providing subsidies (as realized by the government in Punjab), supporting spreading of drip irrigation systems requires to create an enabling environment in terms of fulfilling abovementioned prerequisites:

- supporting to establish storage facilities
- providing appropriate fertilizer
- training and demonstration projects

Due to limitation of funds and restrictions by cropping pattern, implementation of drip systems could be concentrated on priority areas (with storage facilities available; cultivation of point- and row cash crops; soils non-appropriate for surface irrigation methods; availability of training facilities and willingness of farmers to cooperate). After successful implementation there could be expanded to further sites in a joint effort by farmers, their organizations and scientists.

There is a mixed opinion on the success and failure of this technology in Pakistan although government has provided 60 % financial support drip irrigation system installation. The following point can be considered as their pros and cons:

Pros:

- Best methods for orchards, vegetables and desert regions
- Saving of 50 – 60 % fertilizer application

- Saving of up to 50 % water as compared to conventional flood irrigation
- Better crop yield achievements compared to flood irrigation
- Solar operated groundwater system improving the drip system adoption

All above benefits primarily rely on the personal commitments by the individual farmers on-farm. Nevertheless, following are the challenges in the promotion of drip irrigation in Pakistan

- Low water pricing system of canal water itself is an obstacle in adoption of drip
- Lack of on-farm canal water storage end up utilizing groundwater for drip irrigation, which is expensive and energy dependent
- Many agricultural regions in Pakistan are still not connected with national grid, therefore farmers must rely on diesel operated system to run drip system, which is expensive
- The system is more successful in canal irrigated regions due to mix irrigation by canal and drip system. This is mainly true in case of grown orchards because a newly designed drip irrigation system does not cope root water uptake requirements
- The manufacturing of drip system is not done locally therefore it is still expensive even after subsidy by the government, also lacks expertise on the part of local industry
- Poor service by the companies on doorsteps of farmers after selling the system
- Non-availability of drip system spare from local market
- Lack of training for governmental staff and end users I. e. farmers
- Farmers are interested to earn more money from the system through growing cash crops but advisory is missing on part of service providers for successful selection and growing of such crops
- No ownership and interest by workers on-farms in the absence of landlords/ owner
- There must be a care during the advertisement for drip regarding environmental issues
- Solar operated tube wells without groundwater cost can lead to overutilization of the resource
- Since no manufacturing of drip system/ parts is done locally, after lifetime of lateral/ pipes in absence of recycling facilities, the country could be a graveyard of plastic material

6.2 Water-Efficient Textile Machinery (D2)

(O. Heß, M. Korger, B. Mahltig, H. Freericks)

Modern technologies allows to interact individually in programmed sequences of closed tank dyeing systems. Thies Textilmaschinen developed Thies DyeControl (Figure 6.4), an additional measurement system for analysis and optimization of dyes and treatments for the exhaust procedure. It offers a visual display of the treatment curves. This allows control of liquor clarity as well as the determination of dye exhaust from the liquor. The dyer recognizes if and when dyes migrate from the aqueous phase to the fibre.

At a textile finishing plant in Lahore Thies installed DyeControl in an existing and running iMaster H_2O exhaust dyeing machinery. The new option of online opacity measurements of the liquor optimizes the rinsing time and the number of rinsing baths resulted in a decrease of water use for black shade dyeing from 69 L/kg to 52 – 62 L/kg textile (Table 6.1).

By the use of optimized dyeing machines in combination with optimized recipes for dyes, additional water savings of 10 to 19 % have been achieved in experiments only by the use of DyeControl. As a main result, the amount of process water was reduced by measuring the opacity of the dye liquor during the dyeing process with the monitoring tool. The quality control of dyed fabrics of all four trials on a full-scale production machine type iMaster show identical results.

Table 6.1: Water savings trails T1 shows the standard reference process without DyeControl, T2 to T4 are optimized processes and recipes with Dye-Control.

Trial	Liquor-Ratio [:1]	Water Use [L/kg]	Water Saving [%]	Trial
T1	6	69	Reference	T1
T2	6	62	10.1	T2
T3	5.5	62	10.5	T3
T4	5.5	56	19.2	T4

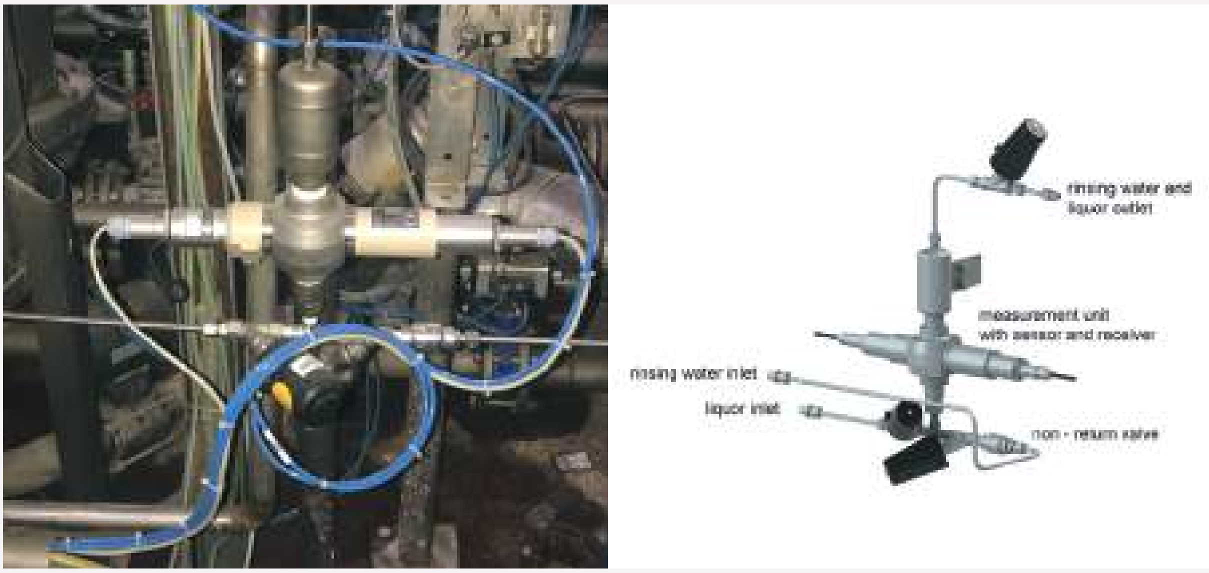


Figure 6.4: Thies DyeControl installed in an existing iMaster H_2O exhaust dyeing machinery at a textile finishing plant in Lahore. © Thies

6.3 Advanced Dyes and Process Chemicals (D3)

Exemplary for reactive dyeing processes we examined and optimized a local exhaust dyeing process (P0) for cotton single jersey (a typical fabric for T-shirts) in colour black from a Pakistan dyehouse with international customers. Within four interrelated processes (P1 – P4) and the participation of German companies, the textile machine manufacturer Thies and textile chemical supplier CHT, dyeing recipes and technologies were developed and tested under laboratory and full-scale conditions in Germany. By modifying dyestuff, chemicals, and processes, the major goal was to maintain the quality parameters for colour fastness of the textiles with less water use.

All major parameters for the comparability of the final dyed fabrics for garments got defined by standardized test. We made tests with the dyed fabrics regarding fastness to rubbing, washing, light and perspiration (Figure 6.5). The results got compared with black T-shirt samples bought in German department stores to find out if the changed dyestuff and methods obtain comparable results. The tests carried out have shown that changes in processes can achieve adequate results in comparison to conventional dyes and associated auxiliaries (Table 6.2).

Table 6.2: Examination of reactive dyeing processes in colour black (100 % cotton single jersey)

REACTIVE DYEING PROCESS	P0	P1	P2	P3	P4
Recipe / Auxiliaries	STANDARD	STANDARD imitated	1st	2nd	3rd
			improvement	improvement	improvement
Liquor ratio	01:06	01:06	01:05	01:05	01:06
Water use [L] per kg textile	61	56	39	37	29
Water saving [L] per kg textile	-	5	22	24	32
Water saving [%]	-	8	36	40	53
Processtime calculated [h:min]	13	11:30	09:05	07:03	06:31
Used black dye [g] per kg textile	unavailable	38	52	50	50
Dye fixation rate black only [%]	unavailable	82 – 83	88-89	90	68 – 79
Unfixed black dye [g] in drain per kg textile	unavailable	6.8 – 6.5	6.2 – 4.6	5	16.0 – 10.5

Key to table above:

- P0 is the local dyeing reference process (standard recipe) dyed onsite at Pakistani dyehouse in Lahore with Synozol Dyestuff from supplier Kisco: Synozol Ultra Black DR, SYN YELLOW K-3RS 150 %, SYN RED K-3RS 150 %.
- P1 – P4: all four Processes got dyed at Thies Textilmaschinen in cooperation with CHT in Coesfeld Germany.
- P1 is the imitated process P0 with the use of conventional dyes from CHT (ranges BEZAKTIV S and S-MATRIX: BEZAKTIV Cosmos S-MAX, BEZAKTIV Yellow S-MATRIX 150, BEZAKTIV Red S-MATRIX 150.
- P2 – P4 were dyed with the use of advanced dye systems 4SUCCESS© with Bezaktiv GO© dyes: BEZAKTIV Velvet Black GO, BEZAKTIV Golden Yellow GO.
- P4 shows a process without a bleaching of the fabric (it can be avoided because we dyed a dark shade). Also P4 was carried out in one dye bath only.

The dye fixation rate got identified after determination of black dye remains in collected and filtered drains using UV-VIS spectroscopy measurements.

The conducted trials lead to following results:

The imitated standard process P1 equals the local dyeing reference process P0 without changing any process conditions, but shows a reduced water use of 8 %, only based on the proper implementation by keeping to numbers and duration of rinsing baths.

The highest water use reduction (> 29 L/kg) is seen in P4. Accordingly, water saving is > 50 % for a black jersey T-shirt (weight 200 g). This means water consumption of only 6 litres instead of 12 litres due to changes in the use of chemicals and processes. As an important side effect, reduction of the process time of > 40 % is achieved which directly results in lowering the production costs.

The dye fixation rate increases from P1 to P3 by changing to advanced dyes. The best achieved fixation rate is 90 % in P3, which means about 10 % less dye stuff in the waste water compared to P1.

Our recommendation is process P3 with advanced dye system due to highest dye fixation rate considering a reduced water use. When dyeing unprepared raw fabric, we do not recommend P4 by using only one dye bath due to quite low dye fixation rates.

Ensuring a reliable production is the first goal of any entrepreneur. Introducing changes, e.g. a new dyestuff or new dyeing process, is generally not easy because no one is willing to change an established and properly running system. It is even more difficult if a dyehouse has to pay higher prices for advanced dyestuff compared to the approved one. As demonstrated within laboratory and full-scale demonstrations in Germany, water, energy and time can be saved in textile dyeing processes. However, the entrepreneur needs to be convinced to perform more sustainable dyeing processes.

Efforts to eliminate toxic substances from textile finishing become more and more evident by changes in European law and a changing consumer behavior that results in process changes of the textile production chain. The improved dye system works out well and gets more and more established in Pakistan. According to CHT, this advanced dye process has already been running at some CHT customers. Looking at absolute sales at the end of 2019, Pakistan and Turkey are among the top five user countries using the improved dye systems.

Figure 6.5: Dyeing results at HN-FTB. © HN-FTB, Carlos Albuquerque

6.4 Anaerobic Treatment of Desizing Wastewater (D4)

(C. Baumann, H.M.A. Shahzad, S.J. Khan, H. Schönberger, U. Brüß, H. Riße, W. Kirchhof, F.-A. Weber)

This chapter is taken in part from Baumann (2018).

Desizing wastewater stream from woven textile finishing plants often carry about 50 % of the Chemical Oxygen Demand (COD) load in a comparatively low wastewater volume, no anaerobic pretreatment plants dedicated to this stream exist in Pakistan to this day. However, full-scale anaerobic plants for desizing wastewater are operated in other countries, such as Germany (Minke and Schönberger, 2017).

Anaerobic pretreatment of industrial wastewater is an established technology in many industries that emit effluents with high organic pollution loads, especially in the food and beverage industry. Anaerobic processes have several advantages over the more commonly applied aerobic systems, most importantly (i) less energy consumption, (ii) less sludge production, and (iii) production of combustible biogas. However, as their removal efficiency commonly ranges between 65 to 95 %, a subsequent aerobic system is necessary in most cases to comply with the relevant effluent standards in western countries (Dinsdale *et al.*, 2007).

A pilot scale anaerobic treatment of desizing wastewater has been planned, build, shipped, commissioned, tested, and optimized at Kohinoor Mills Ltd. (KML) textile factory at Kasur south of Lahore to demonstrate the effectiveness of anaerobic pretreatment of heavily organically polluted wastewater of the desizing process. The purpose of this pilot research was to demonstrate the anaerobic technology under on-site conditions and to provide practical data on the removal efficiency and biogas production. This data is used to estimate the efficiency of a full-scale anaerobic pretreatment plant for desizing wastewater and the resulting load reduction on subsequent treatment steps.

6.4.1 Layout and Commissioning of AnMBBR Pilot Plant

The anaerobic pilot wastewater treatment plant used in this study is a containerized moving bed biological reactor (MBBR) with a maximum capacity of 20 L/h. Figure 6.6 shows a simplified Piping and Instrumentation Diagram (P&ID) of the anaerobic wastewater treatment plant.

The wastewater used for the pilot research is pumped from a drain next to the desizing washboxes of both bleaching lines into the transfer tank, an Intermediate Bulk Container (IBC) with a volume of 1 m³. After reaching a temperature of less than 40°C, the wastewater batch is filled through a bag filter with a pore size of 250 µm into the acidification tank. After filling the acidification tank with a new batch, the usually high pH of 10 – 11 is adjusted as necessary using hydrochloric acid. The wastewater is then continuously pumped into the recirculation stream via an adjustable peristaltic pump. The recirculation flow is driven by a progressive cavity pump with a variable flow of 100 – 150 L/h. The combined stream of the feed and the recirculation flows into the reactor where it is spread by a horizontal perforated pipe.

The reactor contains 300 L of carrier material (EvU-Pearl®) with a density of 0,98 g/cm³ which can easily be held in suspension by the mixer.

The water that is displaced by the inlet flows through a sieve, designed to keep the carrier material from exiting the reactor, into the bottom halve of the adjacent column. The column fulfils two main tasks. It prohibits the generated biogas from escaping through the wastewater outlet. Potentially washed out sludge particles can settle and will be brought back into the reactor by the recirculation. From the column, the pretreated wastewater exits the plant by overflowing into the outlet ending up in the textile factory sewer.

The biogas captured at the top of the reactor is dried in a gravel filter before being stored in a biogas bag. The biogas bags have a volume of 1.2 m³ and are especially designed for use in small-scale biogas plants. The connected bag inflates through pressure equalization with the reactor. Once the connected bag is full, it is switched with an empty bag and its content is burned in a gas stove. The amount of biogas produced is recorded by a gas meter installed behind the gravel filter.

In order to lower the startup time of anaerobic systems, reactors are usually inoculated with sludge from existing anaerobic treatment plants. As no anaerobic sludge was available in this case, cow manure was used instead to assure a sufficient initial anaerobic bacterial count.

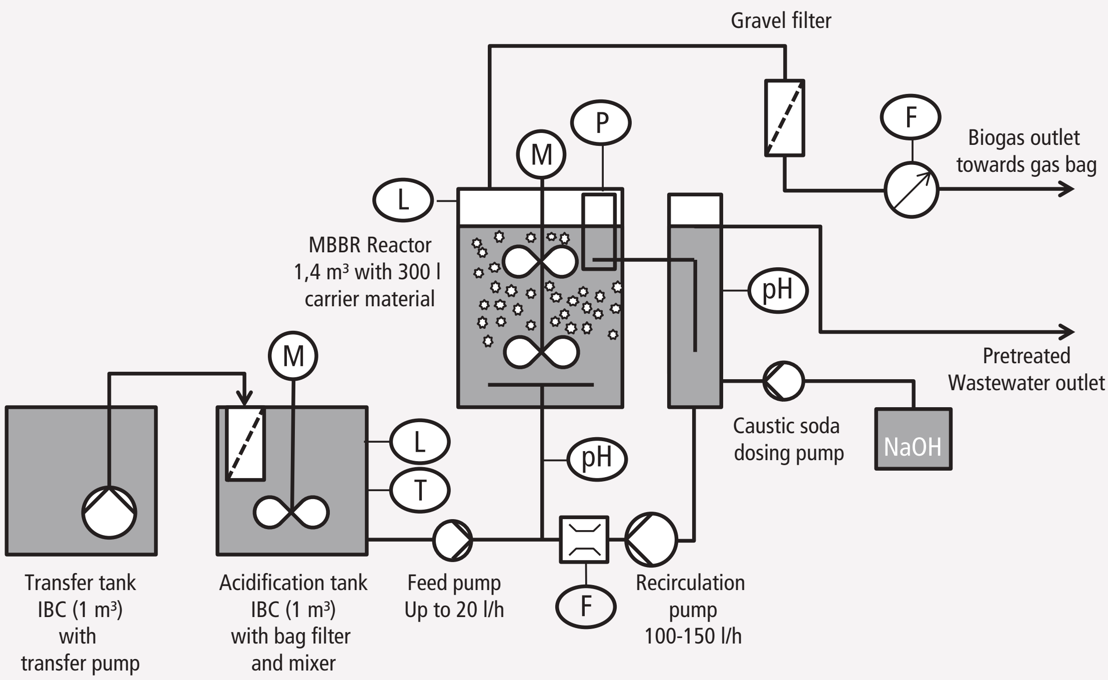


Figure 6.6: Schematic of the anaerobic pilot wastewater treatment plant. © FiW

Figure 6.7: AnMBBR pilot-plant in operation at KML in Kasur producing biogas for water heating. © FiW

6.4.2 Results of AnMBBR Pilot Plant Operation

During its operation phase of 76 days, the pilot-scale anaerobic MBBR achieved a COD removal of 55.7 %, which is slightly lower than reported removal rates of full-scale plants in literature. However, significant potential for improvement was determined due to not considered COD degradation in the acidification tank as well as non-degraded organic acids in the pilot plant outlets. Therefore, a removal rate significantly higher than 60 % seems possible. Based on the biogas production, the specific methane yield during the pilot study was determined at 0.25 m³/kg COD. A highlight was burning the produced biogas to boil a pot of tea in front of the factory employees to proof that wastewater can produce energy (Figure 6.7). Despite the satisfactory COD removal rates, the reactor did not achieve the intended hydraulic retention time (HRT) of 3 days due to unstable conditions, probably caused by a lack of biomass retention in the system. High H_2S concentrations due to the sulfate load and inhibitory effects of the present detergents were identified as potential reasons for the insufficient biofilm on the carrier.

6.4.3 Projection to Full-Scale Implementation

The actual data from the pilot study was used for the projection of a full-scale plant. The removal efficiency of a full-scale plant can be expected to surpass the results of the pilot plant. Based on the assumed daily wastewater flow of the desizing wastewater, the estimated COD inlet load of a full scale plant calculated to 3750 kg COD/d. Based on the experimentally determined removal rate of about 56 % the expected COD load removal is 2100 kg COD/d. Applying the experimental data on the biogas conversion rate, the expected biogas and methane production are calculated to 700 m³ Biogas/d or 525 m³ CH_4 per day.

In order to assess the effects of a full-scale anaerobic plant on the subsequent treatment processes, the current situation is further examined. Based on the small amount of available data, the inlet COD load of the existing effluent treatment plant (ETP) is estimated at 7200 kg COD/d. Figure 6.8 depicts a Sankey diagram of the current situation of the ETP based on the COD load streams estimated.

As seen in chapter 6.4.3, based on the pilot study, a COD Load removal of at least 2100 kg/d can be estimated for a full-scale anaerobic plant at KML. This means that the COD inlet load of the ETP would be reduced to about 5100 kg/d.

Under aerobic conditions, only 5% of the removed organic compounds are used to build biomass. The anaerobic sludge production can thus be estimated as about 200 kg/d while, as seen in the previous chapter, 700 m³ of biogas would be produced per day.

In order to precisely assess the effect of the reduced inlet concentration to the existing aerobic effluent treatment plant, a full design calculation is necessary. In an idealized case, the COD load reduction capacity of the aerobic ETP is assumed to remain equal to the current state. However, due to the presumably lower ratio of readily degradable organic matter in the reduced load to the ETP, the capacity of the ETP would most probably be lower than in this idealized case. However, as can be seen in Figure 6.9, even in this idealized scenario, the final outlet of ≥ 250 mg_{COD}/l would still surpass the limit values of both NEQS and ZDHC. This means that the construction of a full-scale anaerobic plant would most probably not be sufficient to reach the relevant limit values without further modifications to the wastewater treatment system. Therefore, an update to the current ETP system will most likely be necessary, with or without an anaerobic pretreatment plan.

To showcase the advantages of the anaerobic pretreatment, Figure 6.10 shows the COD load streams of an improved aerobic reaching the same overall removal efficiency (87,5%) as the idealized case in Figure 6.9.

As is evident from Figure 6.10, the higher COD removal in the aerobic system leads to an increase in oxygen demand of 2100 kg_{O2}/d, which is equal to the COD removal by the anaerobic pretreatment in the case of Figure 6.9. Assuming a Specific Standard Oxygen Transfer Rate (SSOTR) of 18 $g/(m^3_N \cdot m)$ and using the depth of the current activated sludge tank of 4.5 m, the difference in necessary air flow rate can be calculated to 18.0 m³/min.

Concerning the sludge production, it is shown that the aerobic system produces about 950 kg/d more sludge then the system with anaerobic pretreatment. This is evident, considering that the removal of 2100 kg_{COD}/d produces 1050 kg/d of aerobic sludge while the same removal only produces 200 kg/d of sludge under anaerobic conditions. Another advantage of the anaerobic pretreatment plant is the ability to use its pH increasing processes to partly neutralize the caustic wastewater from the oxidative desizing, resulting in a lower overall chemical use.

It is very unlikely that an anaerobic pretreatment plant for desizing wastewater would be sufficient to comply with the relevant limit values. For this reason, it is necessary to implement a comprehensive wastewater management concept for all effluent streams at the company level or even at textile cluster level using an appropriate combination of decentral pretreatment and centralized effluent treatment technologies.

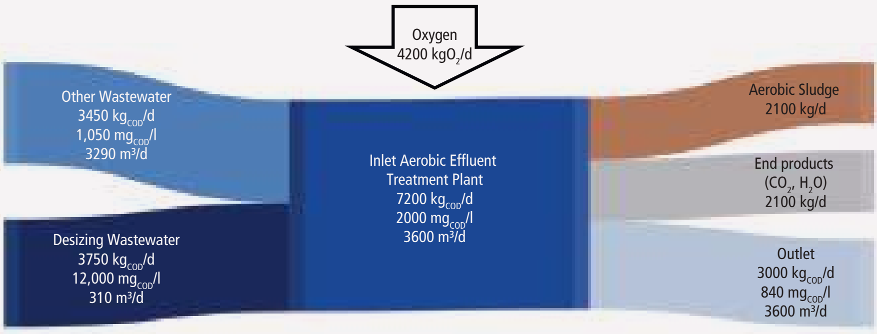


Figure 6.8: Sankey diagram of current COD load streams at the ETP.

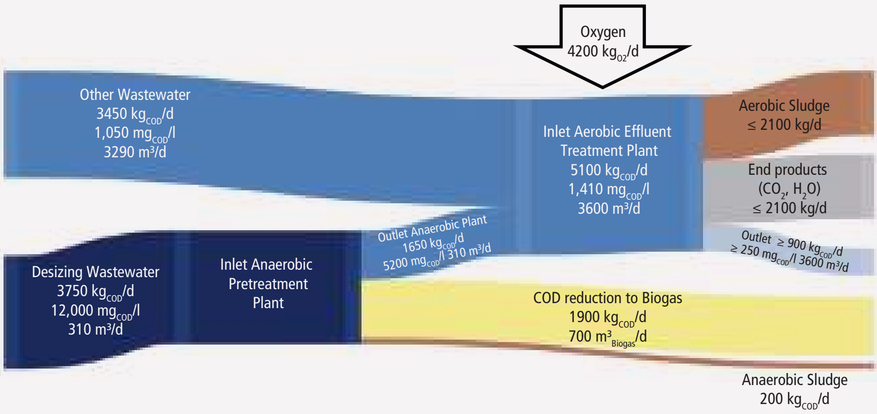


Figure 6.9: Sankey diagram of COD load streams at the ETP with anaerobic pre-treatment of desizing wastewater (idealized scenario).

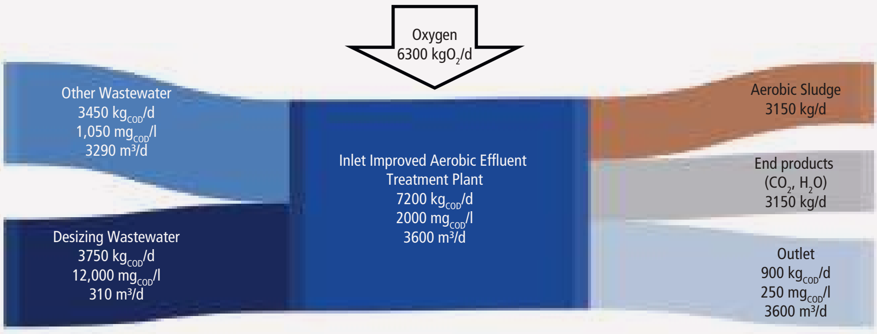


Figure 6.10: Sankey diagram of COD load streams at an optimized aerobic ETP.

6.4.4 Economic Efficiency of a Full-Scale Implementation

In order to give a first estimation of the costs and benefits of a full-scale plant as well as for the potential payback period, the investment costs are estimated to range between 750,000 EUR and 1.5 Mio EUR. This large price range is based on statements of multiple internationally active anaerobic plant manufacturers in 2018.

Two scenarios for the use of the produced biogas are considered:

- Direct use of the biogas in the mineral gas powered machinery (e.g. singeing, thermo oil boiler, etc.)
- Use of the electricity and heat, generated from a combined heat and power system (CHP)

Large amounts of mineral gas are consumed in the dyeing and finishing plant, mostly in form of regasified liquefied natural gas (RLNG). The main consumers are the singeing range, the thermal oil boilers as well as the stenters. According to the manufacturers of those machines, the biogas can in principal be used as a supplementary fuel, provided that the gas is treated accordingly. However, in all cases, the biogas use would first require elaborate and expensive modifications of the machines.

In case of the singeing range, the modifications at the machine level are expected to be small as compared to the other machines. However, according to the manufacturer, it would be very difficult to assure the flame quality in terms of uniformity along the fabric width. As this might have adverse effects on the product quality, the manufacturer discourages the use of biogas in singeing ranges that have not been specifically designed for its use.

For the use of biogas in the thermal oil boilers or stenters, both manufacturers state that elaborate modifications, especially at the gas intake, would be necessary. In both cases, the manufacturers state that they have only limited experience with the use of biogas in their machines, so that the costs involved would have to be determined after a detailed investigation.

The direct use of the biogas in the production thus entails a separate investigation and invest

A cost-benefit analysis conducted suggests that a projected full-scale anaerobic plant is financially viable given Pakistani energy prices, although payback period of ≥ 16 years is long. Table 6.3 shows an overview of the costs and benefits of an anaerobic pretreatment for desizing wastewater at KML, for the different investment cost and biogas use scenarios discussed in the previous chapters. It also differentiates between the profit, i.e. the revenue from the biogas minus the running costs of the plant, and the monetary benefits, which additionally include the cost savings compared to a similar capacity aerobic system, without anaerobic pretreatment. For the sake of completeness, the table also contains the discussed cost benefits that could not be quantified within this project.

Table 6.3: Overview of the cost and benefit calculation

Investment [EUR]						
Anaerobic plant	750,000	750,000	1,125,000	1,125,000	1,500,000	1,500,000
Machine upgrade for biogas	50,000	n/a	50,000	n/a	50,000	n/a
Combined Heat & Power Plant	n/a	150,000	n/a	150,000	n/a	150,000
Running costs [EUR/year]						
Maintenance Anaerobic plant Machinery	9,375	9,375	14,063	14,063	18,750	18,750
Maintenance Anaerobic plant Civil works	3,750	3,750	5,625	5,625	7,500	7,500
Maintenance CHP	n/a	16,484	n/a	16,484	n/a	16,484
Energy	7,653	7,653	7,653	7,653	7,653	7,653
Staff	4,000	4,000	4,000	4,000	4,000	4,000
Revenue [EUR/year]						
Biogas production	52,079	59,526	52,079	59,526	52,079	59,526

Sub-Total [EUR/year]						
Direct profit	29,177	20,139	23,552	14,514	17,927	8,889
Payback period [yr]	29.3	49.3	56.7	109.0	109.3	321.1
Cost savings compared to an improved aerobic ETP [EUR/year]						
Blower savings at ETP	17,893	17,893	17,893	17,893	17,893	17,893
Chemicals for pH equalization	+	+	+	+	+	+
Sludge treatment & disposal	+	+	+	+	+	+
Total [EUR/year]						
Total Monetary benefits	48,944	39,907	44,257	35,219	39,569	30,532
Payback period [yr]	16.3	22.6	26.5	36.2	39.2	54.0

6.4.5 Technical and Financial Viability

A functional anaerobic pretreatment plant for desizing wastewater at KML would considerably lower the COD inlet and outlet of the current ETP, however even in the most optimistic scenario, this would most likely not be sufficient to respect the relevant limit values. Therefore, the construction of an anaerobic plant should only be conducted as a part of a comprehensive wastewater management concept accounting for all liquid effluents from the textile pretreatment and dyeing facilities.

Although the payback time may seem excessively long when only considering the profits from the biogas production, it has to be noted that an anaerobic plant would not only lower the running costs of the wastewater treatment system as a whole, bringing down the payback time to 16 to 54 years. Including an anaerobic pretreatment plant into the wastewater management concept would also most likely entail lower investment costs for the improvement of the remaining ETP.

It is therefore recommended to conduct technical and financial comparisons of wastewater treatment technologies on a full concept basis. In order to eliminate some of the currently prevailing uncertainties, binding technical and financial offers should be requested from renowned wastewater treatment system suppliers an compared.

Further reading:

Shahzad H.M.A., Baumann C., Khan S.J. Schönberger H., Weber F.-A. (2019): Performance evaluation of the first anaerobic moving bed bioreactor (AnMBBR) for pretreatment of desizing wastewater in Pakistan. Desalination and Water Treatment, accepted for publication.

Baumann, C. (2018): Anaerobic Digestion of Desizing Wastewater in Pakistan. Master thesis, Chair of Environmental Engineering, RWTH Aachen University (Mentor: Frank-Andreas Weber, Supervisor: Prof. Dr. Johannes Pinnekamp, Dr. Regina Haußmann).

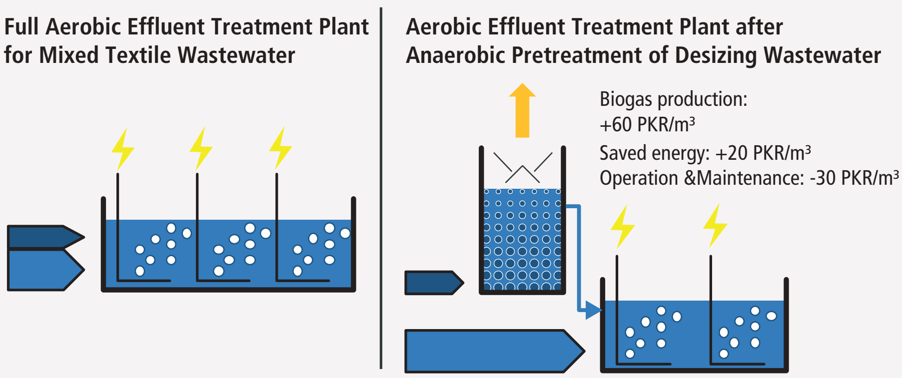


Figure 6.11: Comparison between current aerobic ETP and improved concept with anaerobic pretreatment of desizing wastewater followed by aerobic ETP. © FIW.

6.5 Water Quality Monitoring and Control (D5)

6.5.1 Monitoring of Groundwater Quality and Quantity

(P. Theuring, F.-A. Weber)

In order to continuously monitor the influence of water abstraction for irrigation and the impact of fertilization on both the quantity and quality of the groundwater in agricultural areas, 4 stations were installed at both the campus and the agricultural test site of UAF (Figure 6.12). These stations were equipped with SEBA LogCom-2 loggers and multiparameter sensor (MPS) sensors that automatically measure the water level, temperature, electric conductivity, total dissolves solids, salinity, and water density, store the data and allow the measurement values to be automatically transmitted via GPRS to UAF university. Groundwater percolation was monitored under the fields to detect salinization due to fertilization. To get a more detailed understanding on the precise water quality pressures on the groundwater, a more advanced multiparameter groundwater sensor SEBA MPS-K16 was installed additionally at the UAF test site (Figure 6.13). The sensor measured, logged and transmitted data on water level, temperature, pH, electric conductivity, total dissolves solids, salinity, water density, redox potential, nitrate, ammonium, calcium, and chloride. These measurements are highly sensitive and allow for an immediate detection of intrusion of fertilizer or waste water in groundwater.

Since especially the advanced monitoring with a multiparameter sensor requires frequent maintenance by local personnel, training for maintenance of these stations was performed twice by SEBA Hydrometrie during the project.

Figure 6.12: Installation and training at SEBA LogCom-2 at UAF test site. © FiW.

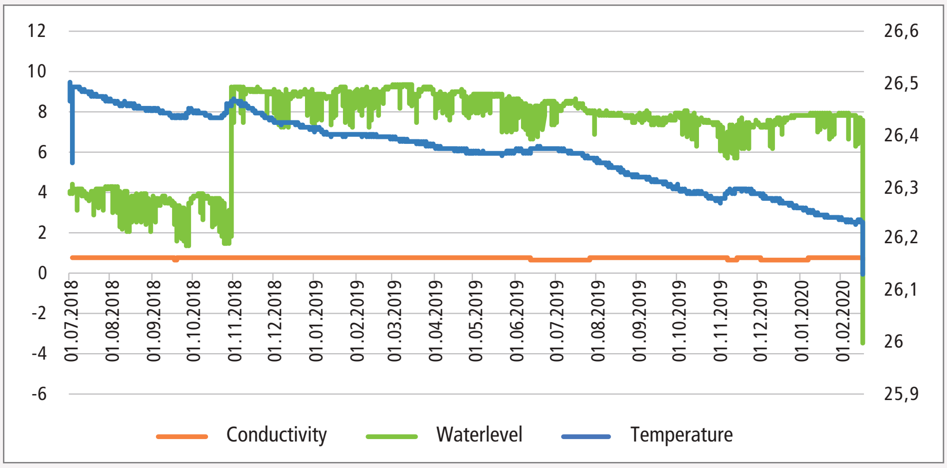
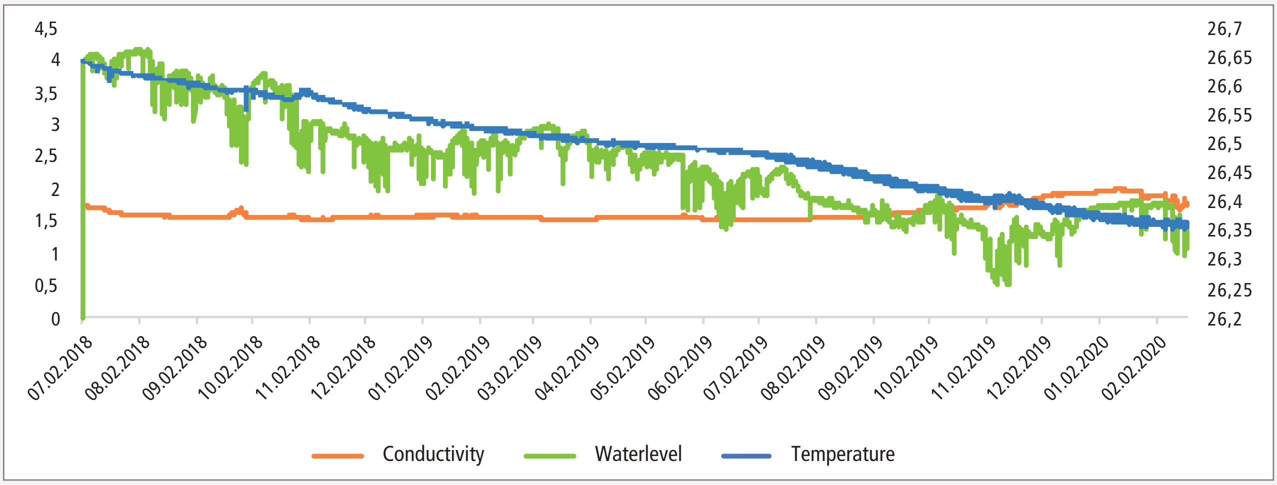


Figure 6.13: Graph with some key results of SEBA LogCom-2 at UAF test site (top) and multi-parameter-sensor MPS-K16 (bottom). © SEBA



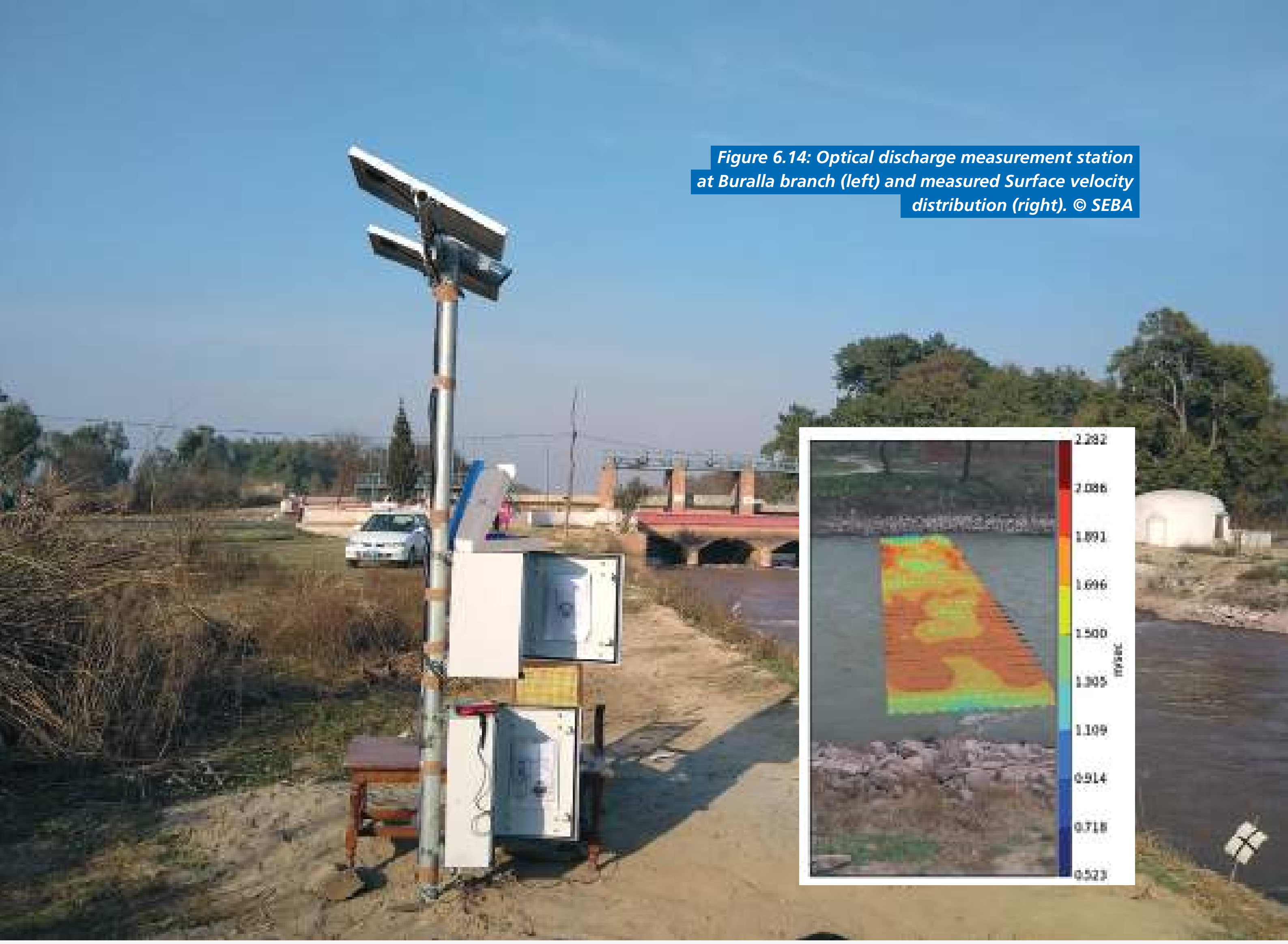


Figure 6.14: Optical discharge measurement station at Buralla branch (left) and measured Surface velocity distribution (right). © SEBA

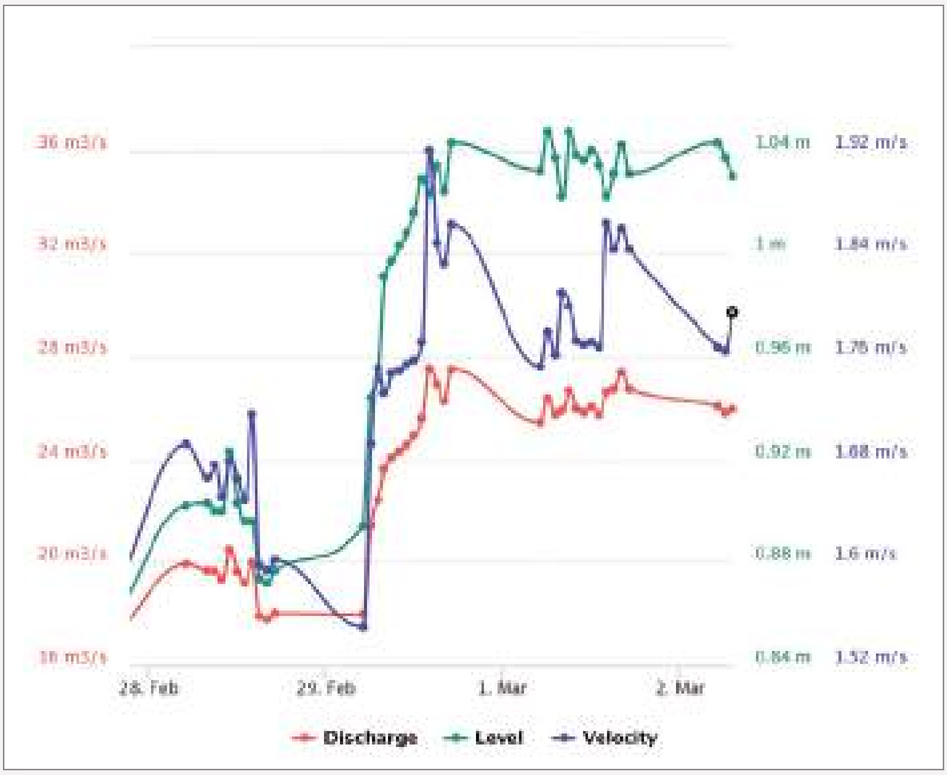


Figure 6.15: Discharge, water level and surface velocity at Buralla Branch canal. © SEBA

6.5.2 Discharge Monitoring of Irrigation Canals

SEBA Hydrometrie installed an optical system for the measurement of discharges at the head of the Buralla Branch irrigation canal to measure the water discharge available for irrigation (Figure 6.14). As the canal is regulated and was intermittently closed for maintenance, the measured values differ greatly, although they are in the same range of the average reported values by WAPDA (23.38 m^3/s), and the modelled average values used in the SWAT model (13.98 m^3/s). For the measurement period in March, the measured discharge was on average 19.4 m^3/s. The station also measured water level and surface velocity (Figure 6.15)

6.5.3 Pollutant Analysis and Regulatory Enforcement of Wastewater Effluent Standards

(F.-A. Weber, S. Balke)

In a dialogue with environmental authorities in Punjab, we conclude that authorities are currently hardly in a position to routinely measure and thus control existing textile effluent standards. This is due to a number of reason, including lack of laboratory equipment, lack of training of laboratory personal, and lack of regulatory enforcement. International brands and retailers are the key drivers increasingly mandating improvements of those textile manufacturers which produce for western markets.

To improve the technical capability and education at university level, the company LAR provided a Quick-COD-Analyzer und a photometer RIELE Photometer 680 to the Institute of Environmental Sciences and Engineering (IESE) at National University of Science and Technology, Islamabad. The Photometer has been utilizing by the students for the measurement of phosphate, sulfate, nitrite and nitrate. For the Quick COD Lab Analyzer initial problems with low air flow rate within the analyzer were resolved and calibration of the instruments is in process. Some impressions during calibration of the photometer and the Quick COD analyzer are shown in Figure 6.16.

The equipment is used to continue AnMBBR pilot-scale studies to demonstrate and optimize effluent treatment plant operation at different textile mills in Punjab.

Figure 6.16: Provided analytical instruments are used for wastewater analytics in use at NTU, Islamabad.

7 INTERNATIONAL COMPARISON: COTTON-TEXTILE INDUSTRY IN AEGEAN REGION, TURKEY

The water board WUA Söke (Aydın Province) is responsible for the irrigation of the cotton fields along the river Büyük Menderes south of Izmir, which are mostly cultivated as monoculture. During the joint Turkish-German research, field work and seminars, it became clear that WUA Söke is more strongly equipped with runoff measurements and internet-based online monitoring than the Pakistani counterparts, but equally struggles with water scarcity, water pollution and soil salinization. In the dry summer months, water is pumped from saline polluted drainage canals to irrigation supply to meet the high irrigation demand (Figure 7.1).

7.1 Study Area of the Water Use Association Söke in Menderes Basin

(B. Tischbein)

Contrasting potential evapotranspiration and rainfall based on long-term average values provides an entry point for comparing the conditions of cotton irrigation in Punjab and Söke. The climatic situation in Punjab (specifically: data from Faisalabad climate station) features in each month a potential evapotranspiration exceeding the rainfall (arid climate) with monsoon rainfall concentrated in July and August. The climate in Söke follows the Mediterranean type with precipitation in winter higher than the potential evapotranspiration (November till March) and a dry summer period with small amount of rain.

The net irrigation demand of cotton in Punjab and Söke is in a similar range (400 – 450 mm) with higher evapotranspiration in Punjab, yet a contribution by monsoon rainfall in the cotton growing season (April till October). Yet, there are differences with relevance to irrigation management, which are summarized in the following as they are helpful to explain differences in water productivity:

- Water supply for Söke is controlled by reservoirs and conveyed to the farms by a canal system equipped with sophisticated monitoring facilities and operated by automatic regulation.
- Irrigation water is applied in the WUA Söke by 3 or 4 irrigation events with rather high irrigation depth (whereas the Warabandi system in Punjab leads to much more irrigation events (7 – 15) with rather small amounts).
- Rainfall in the cotton growing season in Söke is small, factors influencing evapotranspiration are rather stable and therefore forecasts on irrigation demand are more reliable than in Punjab with monsoon rainfall and spatio-temporarily variable evapotranspiration.
- Cropping pattern in Söke is clearly dominated or even uniform by cotton, whereas the pattern in Punjab is much more diverse (although cotton accounts for biggest area share in Kharif).

The water application to the field is practiced in both schemes via surface irrigation methods (basin, border, furrow, raised-bed).

Figure 7.1: Cotton farming at WUA Söke. © FiW

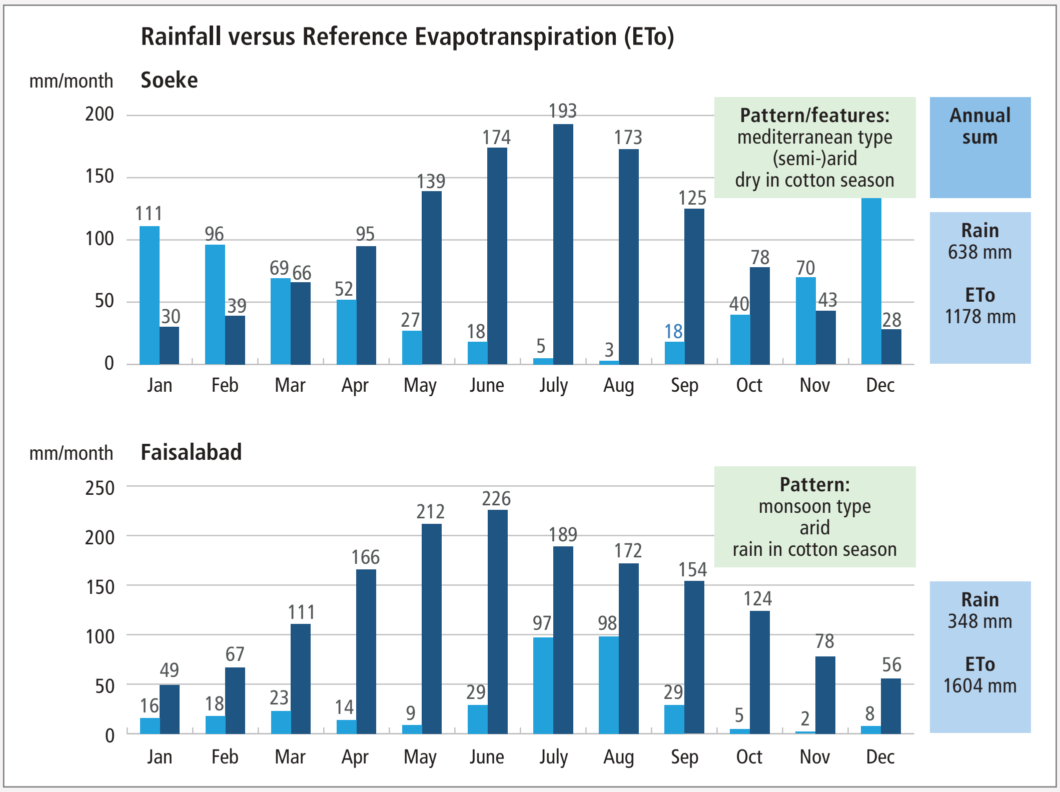


Figure 7.2: Comparison of rainfall and reference evapotranspiration (ETo) between cotton-farming area of Söke, Turkey and Faisalabad, Pakistan.

7.2 Satellite Remote Sensing (M1) of WUA Söke Study Area in Menderes Basin

(M. Usman, C. Conrad)

Remote sensing analyses were conducted for the study region in Söke, Turkey in order to make comparison of cotton crop productivity with LCC in Pakistan. Similar research objectives were achieved for the sack of comparison for the cropping year 2018.

Field campaign was run to collect ground-truth points for land-use land-cover classification and for cotton crop yield estimation. About 600 points of different land uses were collected and 80 farmers' fields were visited for the cotton yield data collection and analyses.

Derivation of field-based land use maps based on multi-temporal, high resolution optical and SAR systems based on Sentinel-1 and Sentinel-2 were generated. Both optical and SAR data were retrieved and processed during the period between May to October 2018. Optical data consist of NDVI, derived from reflectance, while SAR data consisted of VH, VV backscattering, and Kennaugh parameters were used. Sentinel data were processed in the SNAP tool followed by classification using machine learning in R-programming. Both Random Forest (RF) and Support Vector Machine (SVM) were used to map all major land use land cover classes in the region including cotton, marsh land, water, vegetables, urban, orchard, forest, barren and maize. Multiple data combinations and classification algorithms were tested to achieve best results for land use land cover mapping. Figure 7.3 shows the map of best results using SVM for all SAR and NDVI data.

The region is monoculture with the dominance of cotton crop, therefore mapping cotton using any data combination or algorithm is straightforward but mapping small classes is a hard task, particularly for maize and vegetables. The results also indicate that generally both the selection of the dataset and classification algorithms have strong influence on the classification. Under some cases, particularly for minor classes, with different classification algorithms and similar data usages, results are significantly different. Best classification results were achieved using

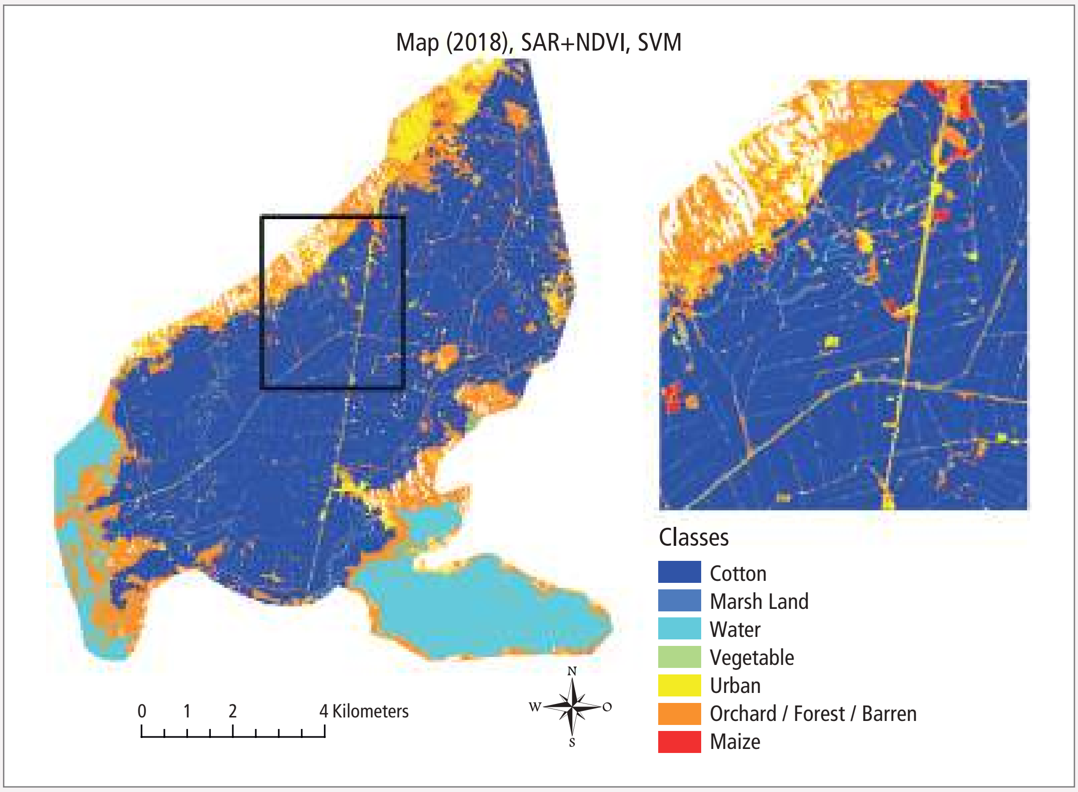


Figure 7.3: Land-use land-cover map of the Söke study area. © UW

SVM for all optical and SAR data, however, results with NDVI data under the use of both RF and SVM were also very good.

The next objective was to estimate the crop water consumption mainly for the cotton crop. Like LCC Pakistan, SEBAL algorithm for MODIS data was utilized. MODIS data were downloaded and preprocessed for the cropping year 2018 from April to October. Forty-three days out of 214 days were screened free of clouds and aerosols after performing the quality control. The SEBAL actual evapotranspiration results are also compared with results from Advective-Aridity (AA) and Penman-Monteith (PM) approaches, which can be seen in Figure 7.4. The relationship can be considered good considering that the AA method do not consider irrigation variations like SEBAL. Figure 7.4b shows that relatively higher ET can be seen in the regions on the eastern sides near to Menderes river and in the vicinity of ANA Tahliye canal. The areas in the south and southwest region show relatively lower ET. Further geo-spatial analysis of various variables would help in drawing matrices and would help finding reasons of heterogeneous water supply in the entire region.

Light use (LU) efficiency model as discussed earlier was used for the cotton crop yield estimation using MODIS and ECMWF data for cropping year 2018. The model was run for various values of light use efficiency (LUE) between 2 to 4.5 gC.M/J and best results were attained for 3.0 gC.M/J. The modeling results were compared with the yield data collected in the field campaign and can be seen for various simulations of LUE from the Figure 7.5.

Cotton yield was found lower in some of the upper eastern regions of Söke water user association (WUA) regions. Also, some patches of lower yield were found in the central and lower reaches of WUA. The lower yield in the lower reaches could be related to salinity issue there.

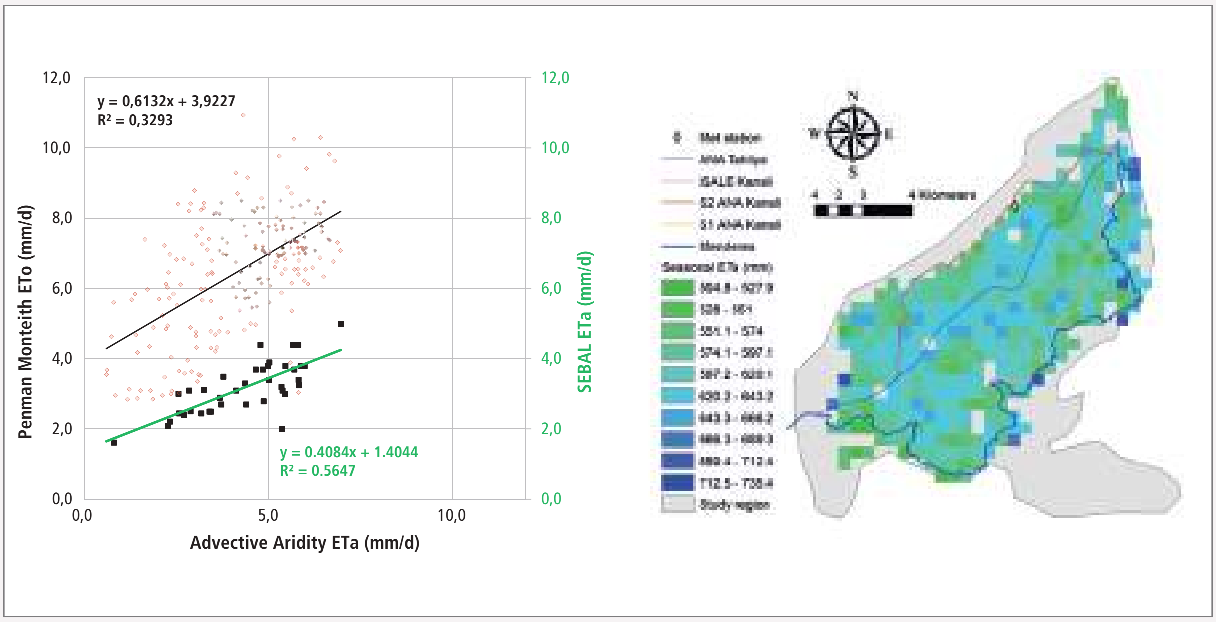


Figure 7.4: Comparison of SEBAL results with AA and PM for Söke, Turkey. © UW

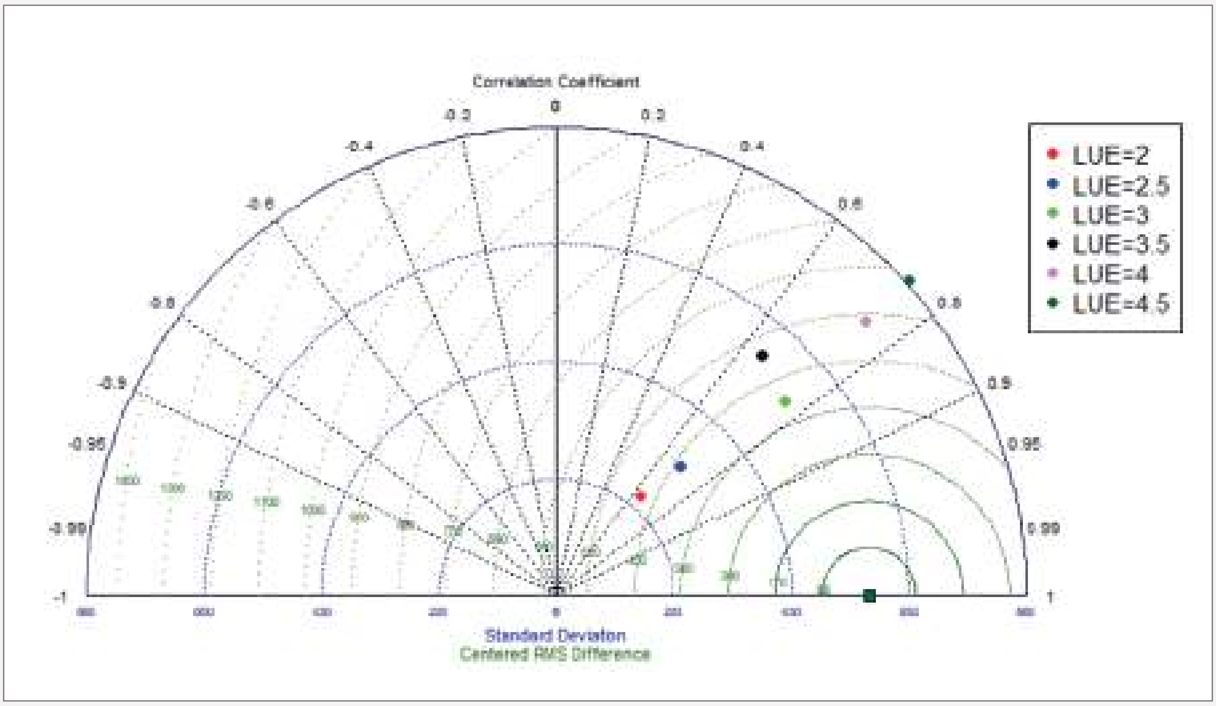


Figure 7.5: Taylor diagram for comparative statistics of yield results under various LUE values in Söke, Turkey. © UW

7.3 Irrigation Efficiency and Productivity (M2)

(B. Tischbein)

Focusing on the situation at WUA Söke and considering a comparison to Punjab this section contains: (i) a summary of major features relevant for (cotton) irrigation management at the two sites, (ii) estimation of irrigation efficiency in the WUA Söke based on the simulation of net irrigation demand versus the gross irrigation water input, and of gross water productivity related to cotton and (iii) summarizing potential reasons for the differences in cotton water productivity.

7.3.1 Estimating Irrigation Efficiency and Productivity for WUA Söke

In order to approach the irrigation efficiency for Söke, net irrigation demand is estimated and related to the water supplied to the WUA. This approach leads to the technical overall irrigation efficiency of the WUA.

The FAO AquaCrop model was used to establish a field water balance for cotton under average meteorological conditions in Söke, loamy soil and cotton growing season from mid-April to October and to derive an irrigation schedule (Figure 7.6).

The simulations show, that 3 irrigation events summing up to a seasonal net irrigation amount of 408 mm lead to a yield of 4.52 ton per ha. As this yield is rather close to the raw cotton yield level of around 5.00 ton per ha achieved in the WUA and 3 irrigation events coincide with the current practice, we consider a sum of 408 mm as a plausible number representing net irrigation demand in Söke (the gap between actual evapotranspiration minus rainfall versus net irrigation demand is covered by storage depletion in the root zone with initial filling realized by winter rain).

Based on information gained in the discussion at meetings and field visits in Söke, the gross water input directed to the WUA amounts to 650 mm. Utilizing the above estimated net irrigation amount enables to estimate the technical overall scheme irrigation efficiency in the range of 60 to 65 %.

The water productivity of cotton in the WUA Söke reaches a high level of 0.77 kg raw cotton per m³ gross irrigation water input. When going for a comparison with water productivity for cotton irrigation in Punjab, two issues should be taken into consideration: cotton irrigation in Punjab is in a deficit situation (water stress due to undersupply), and the Punjab system is partly based on reusing water from irrigation losses (as the losses from irrigation recharge groundwater, which is pumped back into the irrigation cycle). Yet, monitoring of water input and yield in the area of the Mungi Distributary in Punjab lead to a gross water productivity in the range of 0.2–0.3 kg raw cotton per m³ gross water input for surface irrigation methods (reaching to 0.4 in case of raised-bed technique). As based on remote sensing and therefore covering larger areas, the numbers on water productivity in Sections 7.2 and 7.4 are more stable estimations.

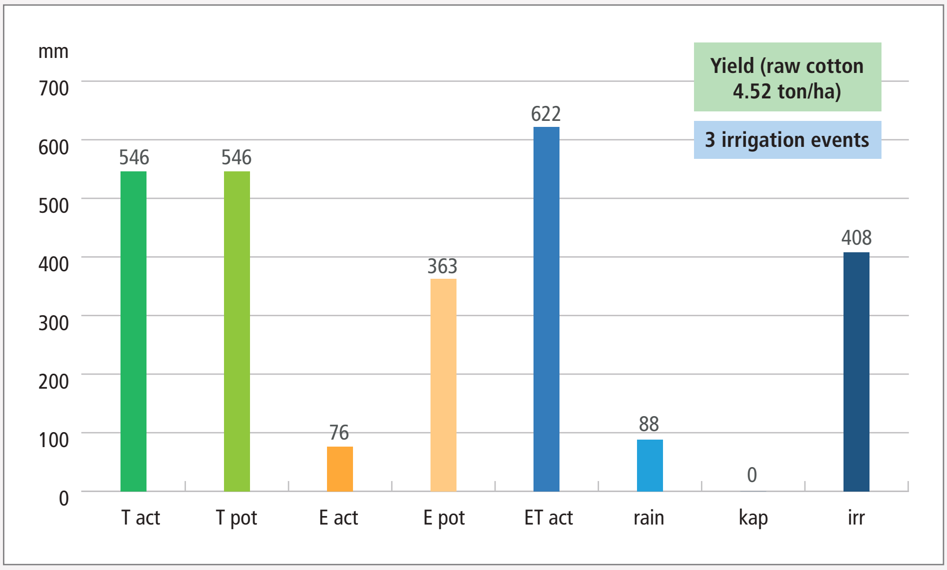


Figure 7.6: Field water balance and irrigation schedule for cotton under the conditions in the WUA Söke (actual and potential transpiration, actual and potential evaporation, evapotranspiration, rain, capillary rise, irrigation).

7.3.2 Discussing Reasons for the Yield Difference between Punjab and Söke Situations

Reasons for the large difference between yield levels in Punjab and Söke were discussed in a meeting with experts from Pakistan and Turkey during their visit in Aachen in December 2019. The reasons can be grouped into two categories:

(A) Irrigation/ water management system:

- low irrigation losses in the Söke canal network due to a high level of monitoring and automatization of the hydraulic system
- application of irrigation water in Söke by 3 to 4 events is advantageously utilizing the storage capacity of the soil and reducing evaporation losses (compared to a practice applying the water in many events with small irrigation depths (as in the Warabandi-guided Punjab system) in tendency rising non-productive evaporation and leading to comparatively higher losses due to non-uniform distribution of water in the field)
- the reservoir-based system in the Menderes river scheme including WUA Söke enables to control water provision towards a better match between time-depending supply-demand relations in periods of peak-demand (avoiding crop water stress) as well as in periods with low demand (saving water in reservoirs)
- monsoon rainfall – highly variable over space and time – and strong fluctuations in evapotranspiration in Punjab compared to rather stable meteorological conditions in Söke create a more complex situation for water management in terms of flexible reaction to changing environments. Furthermore, the uniform cropping pattern in Söke dominated by cotton eases water management compared to a situation with diversified cropping (as in Punjab), which features higher variability of water demand challenging the water management.

(B) Agricultural system:

- Reasons going beyond the irrigation water management refer to factors influencing the yield. Advantages at Söke in terms of available seed quality, plant management and mechanization sum up to a strong impact towards enabling higher yields.
- Water-related factors and features of the agricultural system interplay in a way that the agricultural system favours higher yield in Söke and more efficient irrigation lowers the gross water input – these trends cumulate in a strong effect on the water productivity (relation between yield and gross water input).
- The irrigation system in the WUA Söke performs at a very high level (in terms of efficiency and productivity). When seeking for options for further improvement, the irrigation at farm and field level could be an entry point (whereas the network is rather at a maximum level in terms of infrastructure and operation). Potential options could consist in (i) advancing the surface irrigation methods and their handling (optimizing application discharge; raised-bed), and (ii) further adapting irrigation schedules to site-specific conditions (e.g. soil), time-depending factors (rainfall) and eventually controlled deficit irrigation in case of non-avoidable undersupply (expected as an impact by climate change). The AquaCrop model is a tool to support working out these options.

7.4 International Comparison of Crop Water Productivity

(M. Usman, C. Conrad)

We compared the crop water productivity (CWP) results of two Pakistan and Turkey. The comparison is based on the common methodologies adopted for the remote sensing data processing and analysis as presented earlier. As can be seen from the Figure 7.7, the study area in Turkey had achieved highest crop water productivity (CWP) ranging mainly between 0.3 to 0.4 kg/m³, whereas Pakistan ranging between 0.04 to 0.23 kg/m³. For Pakistan, the lower CWP is mainly associated to lower yields (I.e. 400–1200 kg/ha lint cotton), about 2.5 times lower than Turkey (2000–2400 kg/ha). Despite highest CWP is achieved for Turkey, there is still a room for further improvement through introduction of on-farm water management. In the case of the other two countries, particularly for Pakistan, major improvements are possible through maximizing crop yields.

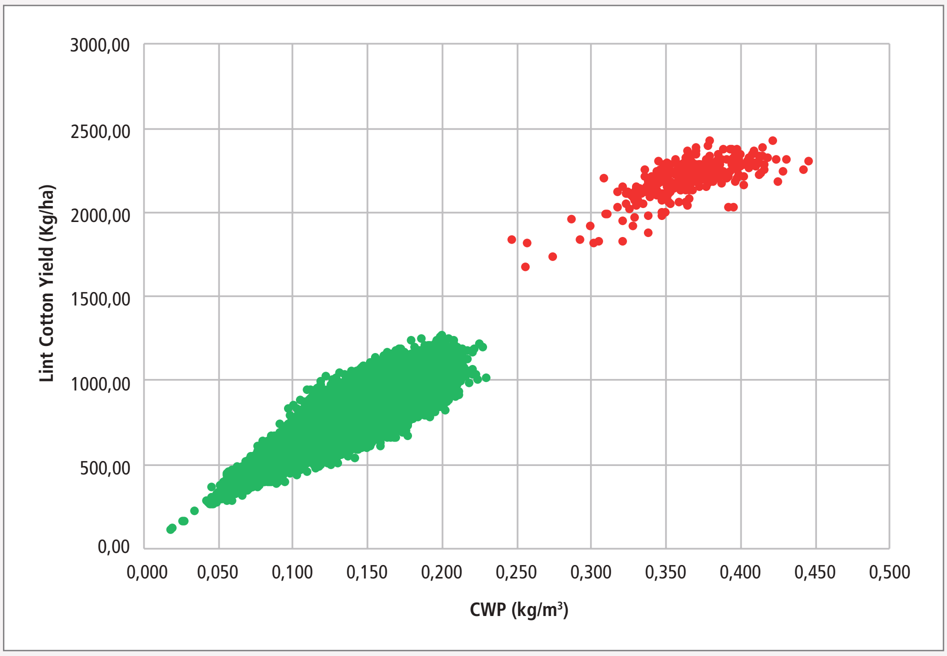


Figure 7.7: International comparison: Results from satellite remote sensing in Rechna Doab, Pakistan (N=44,633) and WUA Söke, Turkey (N=346). Yield in lint cotton. © UW

7.5 Institutional Framework of Water Use in Söke in comparison to Punjab (M5)

(J. Schultze, N. Zimmermann, M. Oelmann)

The physical, socio-economic and technical features of both irrigations are fundamentally different thus, a transfer of the proposed solutions for Punjab, Pakistan to the cotton areas of the Menderes Basin is not reasonable. In a nutshell, it can be said that both the institutions as well as the technological know-how of cotton cultivation are much more advanced and functional in the Menderes River Basin.

During our field study, we visited the WUA Söke, which has about 2,800 to 3,000 members and a total area of about 340 km². The association has a staff of 29 permanent and 22 non-permanent employees. The manager and former president of the WUA Söke is well-respected among farmers as well as among the irrigation agency that he consults with on a regular basis.

What may be learned for Pakistan is that it is generally advisable for farmers to manage themselves but there are two major fundamental preconditions to do this successfully. First of all, responsibilities and jurisdictions between the WUA and the irrigation agency must be clear and a mutual cooperation must be ensured. Secondly, a monitoring system must be in place that provides every farmer with reliable information on water availability.

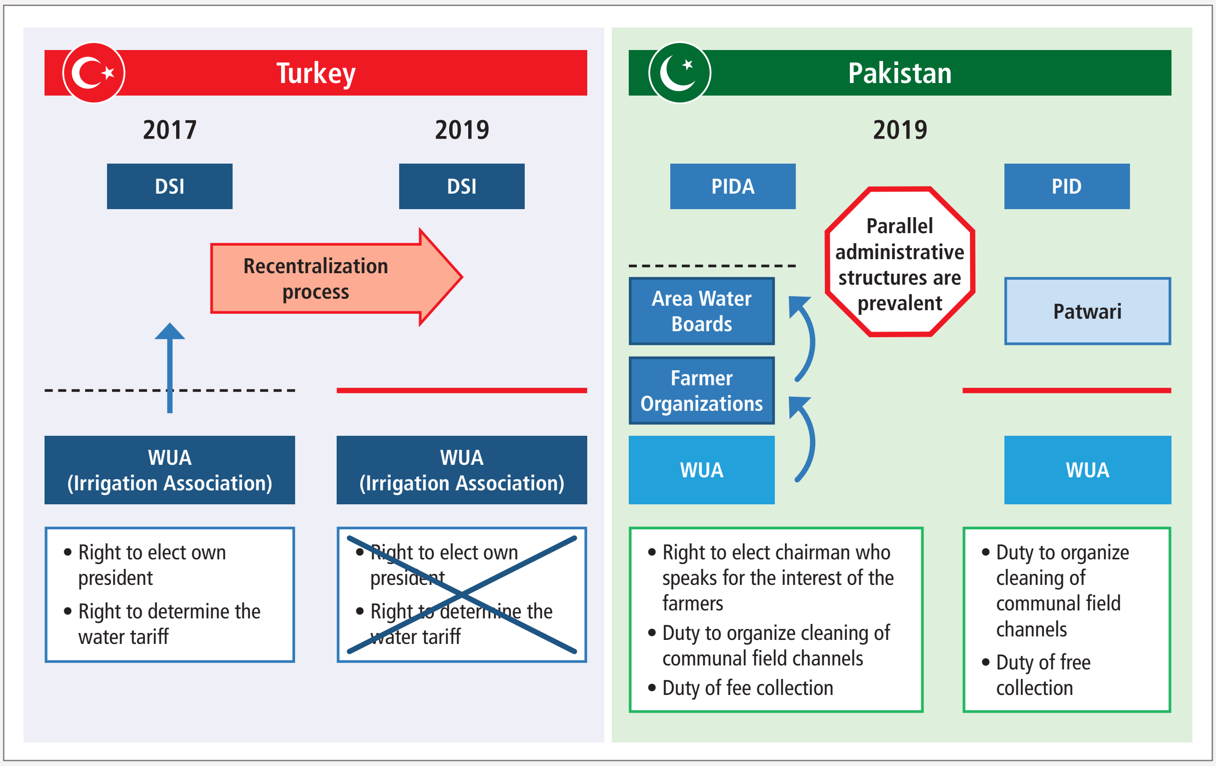


Figure 7.8: Institutional comparison of organisational set up in the irrigation sector between Turkey and Pakistan. © HRW

8 WATER FOOTPRINT: CALCULATION AND OPTIONS FOR IMPROVEMENT

The water footprint was calculated based on the inventory analysis in chapter 4. The results include green, blue, and grey volumetric water footprint, water scarcity footprint (WSF) for the irrigation subdivisions in the study area and impacts on human health due to water pollution. Furthermore, the water footprint reduction potential was determined for the following optimization strategies:

- advanced irrigation and flexible irrigation scheduling
- organic farming
- canal lining
- water-efficient machinery in textile processing
- treatment of the textile wastewater
- application of advanced dyestuff in textile processing.

8.1 Volumetric Water Footprint on Provincial Level

(N. Mikosch, M. Berger)

Within the InoCottonGROW project, the volumetric water footprint was calculated for the water consumption (green and blue water footprint) and water pollution (grey water footprint) during the cotton and textile production. The region-specific results are calculated for Punjab and Aydin in the Aegais Region and then compared to country-average values for Pakistan and Turkey, respectively. In the following, the results are presented for one ton of ready-made textiles. The conversion factors for the raw cotton and cotton lint are based on the product and value fraction according to Mekonnen and Hoekstra (2011) (Table 8.1).

Table 8.1: Conversion factors for raw cotton and cotton lint (Mekonnen and Hoekstra, 2011).

Conversion	Raw Cotton to Cotton Lint	Cotton Lint to Final Textile
Product Fraction	0.35	0.95
Value Fraction	0.79	0.99

The green water footprint includes the soil moisture that originates from precipitation and which is consumed by the cotton plants. The green water footprint reaches around 2500 L/kg in Punjab, which is slightly lower than the result for Pakistan (2200 L/kg). This can be explained by higher precipitation rates in Punjab compared to the country average. In Aydin, the green water footprint account for only around 1200 L/kg, which is slightly higher than the country-average for Turkey (1100 L/kg). The reason for the low green water consumption is low precipitation during the cotton growing period. In both Pakistan and Turkey, the green water footprint is significantly lower compared to the green WF of cotton from top-10 cotton producing countries (6700 L/kg). The reason is that these are countries with higher precipitation rates in the cropping season, as India, China, Brazil and Burkina, where most crop water demand is fulfilled by rainwater. During the textile production, no green water is consumed.

In both Pakistan and Turkey, irrigation is applied throughout the cotton cultivation time to fulfil the cotton water demand. Consumption of the irrigation water from the surface and groundwater bodies is accounted as the blue water footprint. The blue WF reaches 4650 L/kg in Punjab and almost 5300 L/kg in Pakistan. These results are slightly lower than the blue water footprint of the cotton grown in Turkey, where it ranges from 5400 to 5700 L/kg (Mekonnen and Hoekstra, 2011). The reason for this is very low precipitation throughout the whole cotton growing period in Turkey and therefore high irrigation demand, while in Pakistan, some of the crop's water demand is covered through the precipitation during the monsoon season (July–August). The blue water footprint of the textile production reaches 27 L/kg and is considered as not site-specific (i.e. water consumption depends on the applied technology, but not on the local climate conditions). The low blue water consumption can be explained by the fact that most water withdrawn for the textile processing is release back in the environment.

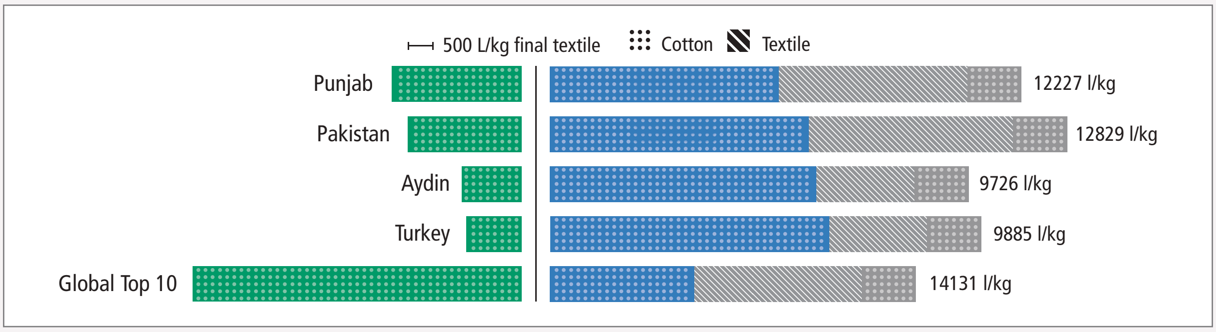


Figure 8.1: Green, blue and grey water footprint of 1 kg of textiles.

The grey water footprint is a measure for the water pollution and is calculated as the amount of water needed to dilute the contamination to a water quality threshold (Hoekstra *et al.*, 2011). The grey WF for the cotton cultivation is calculated based on the leaching rates of the nitrogen applied on the fields with the fertilizers. The nitrates threshold of 50 mg/l is set for the calculation. Grey water footprint reaches around 4100 and 3800 L/kg in Pakistan and Punjab, respectively, which is almost double as high as the results for Tukey. The grey water footprint of the textile production was calculated based on the wastewater quality analysis of the wastewater generated in textile producing companies in Lahore and Faisalabad. The calculation is based on the foundational thresholds of the ZDHC (Zero Discharge of Hazardous Chemicals (ZDHC Foundation, 2016) – an international wastewater guidance for the textile industry. The grey water footprint of the textile processing step reaches 1108 L/kg with BOD5 being the most penalizing pollutant.

8.2 High-Resolution Water Scarcity Footprint

(N. Mikosch, M. Berger)

Region-specific water scarcity factors as well as water consumption and water scarcity footprint (WSF) of cotton were calculated for 17 irrigation subdivisions in Punjab based on the data provided by the hydrologic model SWAT and hydraulic model FEFLOW (see Figure 3.3 for the data flow). Water scarcity was calculated with the monthly resolution using the model WAVE+ (Berger *et al.*, 2014, 2018) and expressed by means of the Water Deprivation Index *(WDI)*. The latter demonstrates the potential to deprive other users of using freshwater when water is consumed by an activity (e.g. crop irrigation) in a certain region and month.

Water scarcity significantly varies in the study area throughout the year with the average maximum WDIs of 1.0 and minimum of 0.1 $m^3_{deprived}/m^3_{consumed}$, which is determined by the climate conditions (e.g. monsoon in July and August) and cropping patterns that affect irrigation requirement. The scarcity level varies also between different irrigation subdivisions. The annual median WDI for the whole study area (17 irrigation subdivisions) is 0.97 $m^3_{deprived}/m^3_{consumed}$. Similar scarcity levels are reached in the irrigation subdivisions located in the south of the region. In the north, median annual water scarcity amounts to 0.75 $m^3_{deprived}/m^3_{consumed}$. Lower water scarcity rates in the north are determined by larger amounts of water delivered by the canal system and higher precipitation rates. Furthermore, water consumption is on average 50 % lower in the northern regions than in the south, mainly due to less arid climate conditions (Figure 8.2).

The average WSF of cotton grown in the study area amounts to 2,333 $m^3_{deprived}$ per ton and varies from 1,476 $m^3_{deprived}$ in the irrigation subdivision Mohlan located in the northeast of the study area to 2,483 $m^3_{deprived}$ in the southern irrigation subdivision Bhagat (Table 8.2). These results are on average about 40 % higher than the WSF calculated by means of the scarcity factors with the lower resolution on the country level (Mikosch *et al.*, 2020). For the country level 1,661 $m^3_{deprived}$ was calculated.

Further reading:

Mikosch N., Becker R., Schelter L., Berger M., Usman M., Finkbeiner M. (2019): High resolution water scarcity analysis for cotton cultivation areas in Punjab, Pakistan. Ecological Indicators 109 (2020) 105852. https://doi.org/10.1016/j.ecolind.2019.105852.

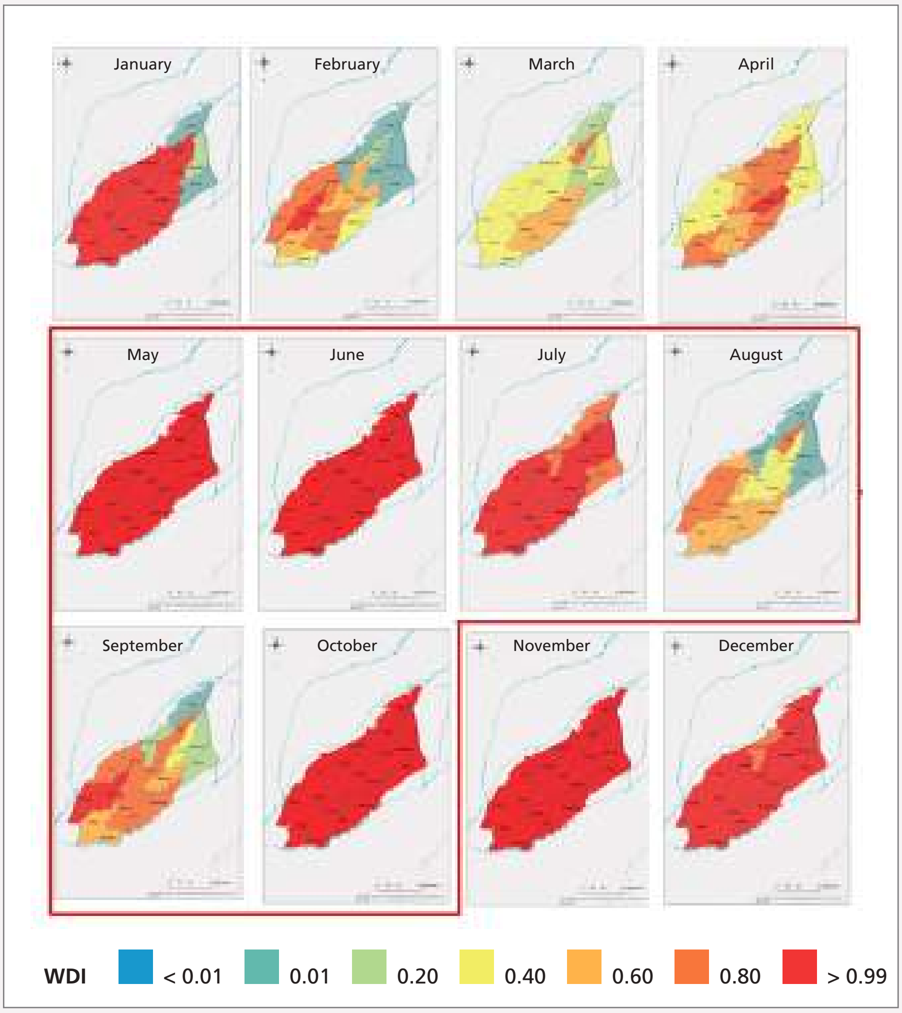


Figure 8.2: Water scarcity calculated as WDIs for the irrigation subdivisions [$m^3_{deprived}/m^3_{consumed}$]. Cotton growing season is highlighted with the red frame (Mikosch et al., 2020). © TUB

Table 8.2: Water scarcity footprint of cotton grown in the study area calculated with the factors for region-specific water scarcity factors for the irrigation sub-divisions.

Irrigation subdivision	Water scarcity footprint [$m^3_{deprived}$ per ton]
Mohlan	1476
Tandilanwala	2116
Buchiana	2193
Tarkhani	2409
Kanya	2460
Sultanpur	2460
Bhagat	2483
Production weighted average	**2333**

8.3 Impact assessment of Advance Irrigation and Irrigation Scheduling

(N. Mikosch, M. Berger)

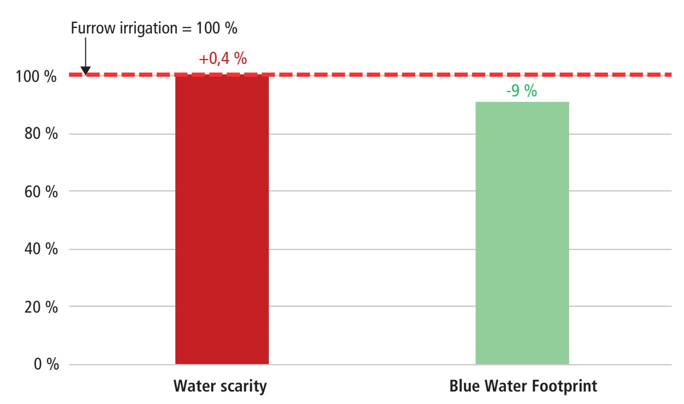
Drip irrigation allows supplying small amounts of irrigation water to the plants' roots and therefore avoiding unproductive leaching and evaporation. However, drip irrigation is only slightly reducing the water footprint (Text Box 13).

- Drip irrigation significantly reduces water use per hectare and per ton of cotton (by 23 % and 30 %, respectively). This is achieved by increasing the irrigation efficiency from 64 % for furrow irrigation to 83 % for the drip irrigation.
- Water consumption per hectare increases by 0.4 %. The reason is increased yield and therefore more cotton plants consume water.
- Water consumption per ton cotton is reduced by almost 9 %. This is achieved, because increased of yield per hectare (+10 %) is higher than increase of water consumption per hectare (+0.4 %) (Figure 8.3).
- Positive effect on the water footprint of cotton, but a negative effect on water balance in the region: water scarcity increases due to increasing water consumption per hectare.

Text Box 13:

Why does drip irrigation not significantly reduce the water footprint compared to furrow irrigation?

In furrow irrigation, flooding of the fields in the Warabandi system results in an open water column on the soil surface with high evaporation rates just every 7 or 14 days, while the top soil dries up in between. At the same time, over 30 % of applied water percolates into the groundwater and is not taken up by the plants (irrigation efficiency of around 60 – 70 %). In drip irrigation, water is added in small amounts on the regular basis and the top soil is kept moist continuously over the cultivation period potentially resulting in higher unproductive losses due to evaporation from the soil. The percolation rate is low, since almost all water amount is taken up by the plants (irrigation efficiency over 80 %). Nevertheless, although drip irrigation significantly reduces water use (amount of water applied on the field), it has a low effect on the water footprint (reduction of around 9 %). The reason for this is that the amount of water consumption (transpiration by the plants and evaporation from the soil surface) remains on the same level and the reduction of the percolated water is not accounted in the water footprint, since water remains available in the groundwater compartment.



	Yield (t/ha)	Efficiency	Productivity (kg raw cotton/m³ gross irrigation)	Gross irrigation, m³/ha
Furrow full irrigation	2.95	64 %	0.48	6137
Drip irragation	3.25	84 %	0.68	4750

Figure 8.3: Effect of the drip irrigation on the water use and consumption per hectare and per ton of cotton (all values related to furrow irrigation). Green colour indicates a positive and red colour a negative effect.

8.4 Impact Assessment of Organic Farming

(N. Mikosch, M. Berger)

The evaluation of organic farming (organic cotton) and cotton produced according to the requirements of BCI (Better Cotton Initiative) (Better Cotton Initiative, 2018, 2019) is conducted based on literature review of the studies carried out in Pakistan and the requirements for the organic production (Terörde, 2018; Nitzsche, 2019).

- BCI cotton reduces blue water consumption and therefore the blue water footprint of cotton by 0.4 %. According to the BCI requirements, farmers has to evaluate and manage water availability for the irrigation, but there are no specific requirements (for example, drip irrigation). The studies for organic cotton demonstrate controversial results for water consumption. We assumed the positive effect of the water management strategies applied in organic production to reduce blue WF same as by the BCI production.
- BCI cotton reduces the input of fertilizers by around 22 %, since BCI production requires conducting an evaluation of the fertilization needs and fertilizers management. Therefore, the nitrogen leaching decreases (a linear correlation to the fertilizers input is assumed), which reduces the Grey WF. Same reduction is assumed for the organic production due to fertilizers' management and organic fertilization.
- The BCI production requires pesticides' management, therefore, less pesticides are applied for BCI cotton and the toxicity impacts are reduced by 29 %. Since organic production completely prohibits application of pesticides, toxicity impacts are reduced by 100 % (Figure 8.4).

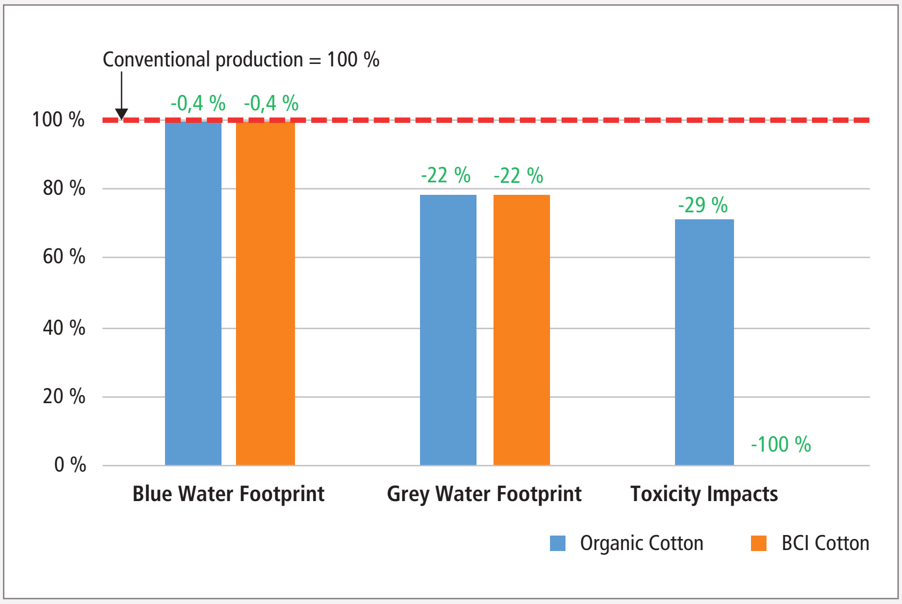


Figure 8.4: Effect of the organic and BCI production on the blue water footprint, grey water footprint and toxicity impacts of cotton.

8.5 Impact Assessment of Canal Lining on Water Scarcity

(L. Schelter, H. Schüttrumpf)

Lining of canals means to cover the canal bed with slabs, usually made of concrete and sealing the grouts using bitumen or concrete. This practice is wildly discussed in literature and called the "most cost-effective method of augmenting water supply in irrigation systems" (Chatha *et al.* 2014) by some while others conclude that "lining does not demonstrate significant improvements in tail end conditions or overall hydraulic performance" (Murray-Rust & Vander Velde 1994) or more recently that "lining of canals cannot effectively save water" (Arshad *et al.* 2009).

The effect of lining is generally assessed using the simple inflow-outflow method. In this method the discharge of a canal is measured at a specific inflow point and again at a specific out-flow point located in the same canal downstream at a specified distance. The difference of discharge between the two points gives the amount of water that is lost in between and can be normalized using the known distance of the two points.

The mean overall losses from different studies have been summarized and show that on average 4.75% of initial discharge are lost per 100 m for 34 investigated canals. The six investigated lined channels only lost 1.44 % of initial discharge per 100 m (Figure 8.5). This means that lined channels loose roughly one third of what unlined channels would lose. In other words, the lining decreases the leakage rate by roughly 70 %. However, certain assumptions are necessary for these results to hold, namely the lifetime of the lining and the percent of canals that will be lined. In a follow-up study Moshabbir recommended that "lining of any watercourse is viable up to 55 % which may decrease water losses up to 81 %" (Moshabbir *et al.* 2018). His results suggest decreasing returns for increasing lining in terms of economic viability given the costs of lining and providing water supply. The lifetime of the lining is another important issue as lining deteriorates over time and often leakage rates reach levels as high or even higher than before lining if proper maintenance is neglected (Arshad 2004; Arshad *et al.* 2009). Desilting is proposed as another option for improving hydraulic performance that is significantly less costly compared to lining (Murray-Rust & Vander Velde 1994).

Regarding the impact assessment of canal lining on water scarcity, however, these uncertainties and conflicting recommendations are of minor concern, since the lining does not have any effect on water scarcity assessment. The method considers total water availability and does not discriminate between surface water or groundwater. Therefore, percolation of canal water into the aquifer is not lost water but just a transfer into another storage compartment. Consequently, lining or a lack thereof does not affect the water footprint. The necessary underlying assumption is that farmers will extract the same amount of water from irrigation canals as they would from groundwater, depending on which source is more readily available.

Nonetheless, there are effects of the lining in practice. For example, the distribution of water is altered as more water reaches the tail end of the canal. The pumping by farmers can also be reduced by lining the canals as more surface water is available reducing the need for groundwater. This leads to a reduction of CO_2 emissions because less diesel is burned in the generators for groundwater pumping.

Figure 8.5: Visualization of mean losses in percent of initial discharge per 100 m from unlined (left) and lined channels (right).

8.6 Impact Assessment of Water-Efficient Machinery in Textile Processing

(F.-A. Weber)

We demonstrated that a water-use reduction of up to almost 20 % is feasible in reactive black shade dyeing by installing water efficient textile machinery. Introducing advanced dyestuff can further reduce water use up to 40% under certain conditions but Pakistani companies are rarely in a position to pay higher prices despite water and energy savings. We find process-integrated measures to often go along with energy savings, but little WF reduction.

8.7 Impact Assessment of Wastewater treatment on Human Health

(N. Mikosch, M. Berger)

Human health impacts resulting from water pollution in textile production was calculated according to the cause-effect chains presented in Figure 5.4. It is based on the toxicity effects of chemicals discharged with the wastewater from the textile processing including heavy metals, dyestuff residues, and auxiliary substances. The impacts are calculated for the untreated water discharged into surface body and wastewater treated according to the ZDHC standard, foundational thresholds (ZDHC Foundation, 2016). Heavy metal concentration in the discharged water is based on the inventory analysis conducted in InoCottonGROW and literature data for Pakistan (Manzoor *et al.*, 2006; Bhardwaj *et al.*, 2014). The dyestuff input is set to 15 kg/ton textiles and the fixation rate is set to 70 % (Schönberger and Schäfer, 2003). The calculation was conducted for five dyes, for which toxicity factors are available. Out of these dyes, two are prohibited by Global Textile Organic Standard (GOTS) due to their high toxicity (GOTS gGmbH, 2017). The concentrations of the auxiliary substances were based on their maximum solubility, since no literature data is available.

As an illustrative example, the calculation was done for the chemicals considered as hazardous included in the manufacturing restricted substances list (MRSL) (ZDHC Foundation, 2016). The results are calculated in Disability Adjusted Life Years (DALYs). High impacts of the untreated wastewater, MRSL substances dominate.

Table 8.3: Chemicals' concentrations in the wastewater applied for the calculation of toxicity impacts on human health.

Recipe for Textile Processing		ZDHC not implemented		ZDHC Foundational	
		Effluent conc. (arbitratry) [µg/L]	**Total Human Toxicity**	**Effluent conc.** (Foundational) [µg/L]	**Total Human Toxicity**
Dye	**Dyestuff:** 15 kg dye / t cotton fixation 70 %	Direct blue 6 1.04E+05	**0.16 DAILYs** per ton lint cotton	Direct blue 15 1.04E+05	**0.00064 DAILYs** per ton lint cotton
MSRL substances	**Chlorophenols**	8.0E+05		0.5	
	Dyes – Azo	5.0E+05		0.1	
	Flame Retardants	8.0E+03		5.0	
	Glycols	1.0E+09		50.0	
	Halogenated Solvents	8.6E+06		1.0	
	VOC	1.2E+07		1.0	

9 TOWARDS ACHIEVING THE UN-SDGS: SCENARIO ANALYSES

9.1 Scenario Definition

(K. Wencki, C. Strehl)

Within the InoCottonGROW project different technically, economically and institutionally feasible ways of increasing the efficiency and productivity of water use along the entire cotton-textile value chain in Pakistan have been examined from a technical and hydrological perspective. In order to facilitate practical implementation of the measures proposed, individual measures were summarized in six different scenarios (Table 9.1), considering major changes in irrigation and wastewater treatment technologies, large-scale infrastructural measures, and organizational provisions. The different policy scenarios are compared to a baseline scenario to investigate how implementation could contribute to achieving selected UN-Sustainable Development Goal targets in Pakistan. The baseline scenario is considering climate change only. Population growth and land-use change projections are not yet included.

Table 9.1: Overview of policy scenarios.

No.	Title	Storyline
1	**Making the most of the current system**	In the first scenario, basically everything remains as in the baseline scenario: there are no changes in the legal situation, no technological or infrastructural upheavals, nor any changes in irrigation supply. But all processes are optimized to the last drop. Incentivized by funding and other public support mechanisms, all cotton farmers strive to maximize water-use efficiency in cotton production on a field level and all textile companies reduce their water usage in exhaust dyeing to a technical, economical, and institutional feasible level. Using less and/or alternative dyes enables companies to realize further energy savings.
2	**Many pennies make a dollar**	Still based on the assumptions that there are no changes in the legal situation and no technological or infrastructural upheavals, technological changes are implemented only on a small scale. But as we all know: Many pennies make a dollar! Therefore, farmers are further incentivized to maximize water-use efficiency in cotton production on a field level via technological and management changes (e.g., decentral short-time storage, improved irrigation practices). Textile companies make their contribution by reducing water usage in exhaust dyeing to a technical, economical, and institutional feasible level. Using less and/or alternative dyes means less environmental impact and, at the same time, enables the companies to realize cost and energy savings. However, due to the fact that government is paying much more attention to water quality issues now, all medium and large textile processing companies are forced to reinvest some of the saved money to install functioning effluent treatment plants.
3	**Think big**	"Small scale" is outdated. Government intervenes more strongly and introduces countermeasures against water scarcity by itself. Therefore, large-scale infrastructure projects in water supply and sewage disposal (e.g., lining of main canals and sewers or installation of wastewater treatment plants at central drains) are realized mostly with government funding. Textile companies still try to reduce their water and dyes usage in exhaust dyeing to a technical, economical, and institutional feasible level in order to realize cost and energy savings.
4	**Regional water shifting**	Following the slogan „more water to the tail", major changes in the institutional setup occur while the technical infrastructure remains unaffected. Cotton farmers use controlled deficit irrigation and an adjusted water distribution among the residents lead to an optimum water utilization for all parties.
5	**Regionalcrop shifting**	Farmers are incentivized to modify their cropping patterns and use water more efficiently in order to serve the common good. Food crops are promoted so that less fruits, vegetables, grains and rice have to be purchased from abroad.
6	**Quality instead of quantity**	Being more aware of the environmental effects of their buying behaviour, consumers demand for more organic cotton products. This means reducing pesticides use to a minimum and using water-efficient irrigation methods in the first place. Cotton farmers in Punjab recognize this market development timely and adapt their cultivation practices. In order to reduce the harmful environmental impacts of textile processing, all medium and large textile companies install functioning effluent treatment plants. If the technical requirements are not met, companies have to fear severe penalties for non-compliance.

9.2 Qualitative Scenario Assessment

(K. Wencki, C. Strehl)

In a first step, all six scenarios were assessed qualitatively in accordance with an assessment approach established by the International Council for Science (ICSU, 2017) in order to identify and assess the strength of interlinkages between selected UN SDGs. This methodology, based on a seven-point scale was adapted to evaluate the effects of the proposed scenarios on SDGs achievement on a target level. As measures and scenarios were initially selected with the aim to reduce the water footprint of the global cotton-textile industry, SDG assessment was limited to interactions with UN SDGs concerning zero hunger (#2), clean water and sanitation (#6), affordable and clean energy (#7), industry, innovation and infrastructure (#9), responsible consumption and production (#12), life below water (#14), and life on land (#15). According to this methodological approach, each scenario was evaluated based on expert judgment indication whether the scenario has a positive or negative impact on or is affected by the respective SDG in any kind of way. According to the ICSU approach a grade was given on a scale of -3 to +3, with +3 meaning that the scenario has a strong ("indivisible") positive effect on this SDG and -3 meaning that the scenario is has a strong ("cancelling") negative effect on the scenario. The results of this qualitative impact assessment are presented in Table 9.2. Here, also the so called type of influence of the respective SDG target is indicated. "Influence on" means, that the implementation of the respective scenario has an influence on the linked SDG. "Influence by" means, that the implementation of the scenario itself is (positively or negatively) influenced by a greater achievement of the SDG.

Table 9.2: Results of the qualitative impact assessment of six policy scenarios to reduce the water footprint of the global cotton-textile industry in Pakistan. Presentation of SDG targets is limited to targets which are assumed to be influenced by any scenario or having an influence on any scenario. Legend of scores: +3 = "indivisible"; +2 = "reinforcing"; +1 = "enabling"; 0 = "consistent"; -1 = "constraining"; -2 = "counter-acting"; -3 = "cancelling").

SDG Targets	Type of influence	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2.1	on	+1	+1	+2	+2	+3	+2
2.2	on	+1	+1	+2	0	+1	+1
2.3	on/by	+1	+1	+2	+2	+2	+1
2.4	on/by	+2	+1	+1	+2	+2	+2
2.a	on/by	+1	+2	+1	+2	+1	+1
6.1	on	+1	+2	+2	+2	+1	+2
6.2	by	0	0	0	+1	+2	0
6.3	on/by	+2	+3	+3	0	-1/+3	+3
6.4	on/by	+3	+2	+2	+3	+1	+2
6.5	by	0	0	0	+1	+1	+1
6.6	on/by	+2	+2	+1/-1	-1	+1	+2
6.a	by	+1	+1	+1	+1	+1	+1
6.b	on/by	+2	+1	0	+1	+1	+1
7.1	on/by	0	+1	-1/+2	0	0	-1/+2
7.2	on	0	0	+1	0	0	+1
7.3	on	+1	+1	+3/+1	+3	+3	+3/+1
7.a	by	+1	+1	+1	0	0	+1
9.1	by	+2	+1	0	0	+1	+1
9.2	on/by	+1	+1	+2	0	+1	+1
9.3	on/by	+1	+1	+1	0	+1	+1
9.4	on/by	+2	+3	+2	0	+1	+2
9.5	on/by	+1	+1	+1	+1	+1	+1
9.a	on/by	+1	+1	+2	+1	+1	+1
9.b	by	0	0	0	+1	0	0
9.c	by	+1	0	0	0	+1	0

SDG Targets	Type of influence	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
12.1	on/by	+2	+2	+1	+1	+1	+2
12.2	on/by	+2	+3	+1	+1	+2	+2
12.4	on/by	+2	+2	+2	0	+1	+3
12.5	on/by	+2	+3	+2	0	+1	+2
12.6	on/by	0	+1	+2	0	0	+1
12.7	by	+1	0	0	0	+1	0
12.8	by	+1	+1	+1	0	0	+1
12.a	on/by	0	+2	+1	+2	+3	+2
12.c	on/by	0	+1	+1	-2	0	0
14.1	on	+1	+2	+2	0	-1	+1
14.2	on	+1	+2	+1	0	-1	+1
14.3	on	+1	0	0	0	0	0
15.1	on/by	+1	+2	+2	+2	-1	+2
15.3	on	+1	+1	+1	0	+1	+1
15.5	on	+1	+2	+1	0	0	+1
15.9	on	0	0	0	+1	0	0
15.a	by	+1	+2	+1	+1	+1	+1

Based on the results of this qualitative assessment we concluded that all management and technology based solutions proposed could have highly positive effects on the achievement of several SDG targets. As all scenarios were designed with special focus on water footprint reduction, highest impacts might occur with regards to water quality (#6.3) and water-use efficiency (#6.4). Nevertheless, side benefits to the achievement of other SDG targets become visible, such as food security (#2.1), energy efficiency (#7.3), upgrade of infrastructure (#9.4), sustainable management of natural resources, chemicals and wastes (#12.2 & 12.4), and waste reduction (#12.5). Negative effects might concern the protection and restoration of water-related ecosystem (#6.6), if water is regionally shifted, and marine ecosystems (#15.1 – 3) in case of adjusted crop cultivation. However, it must be considered that each scenario is linked to individual challenges for implementation. Only if those are met, positive effects highlighted by the assessment approach might occur.

For example, all measures proposed in scenario 3 would need funding by credit loans since rising water fees will probably only be accepted by farmers if water services are significantly improved (Oelmann *et al.*, 2018). One exemplary measure to achieve scenario 3 could be to rearrange the Warabandi schedule from a seven to a tenday irrigation schedule. Studies show that famers can irrigate their fields more efficiently by irrigating with fewer but longer irrigation turns (Chapter 6.1).

With regard to scenario 4 it is important to note that in the past there had already been many attempts to reform the irrigation system in Punjab but they were all futile to bring about substantial institutional changes. Most prominently, the PIDA Reform of 1997 tried to restructure the irrigation sector but has never been upscaled beyond the five pilot project areas in Punjab (Mekonnen *et al.* 2015). The main motivation for this reform was to lower the costs of the Irrigation Department that had only be sustained through government subsidies by empowerment of farmers to carry out maintenance, allocation of water rights, monitoring and sanctioning, as well as water fee collection themselves (Qureshi, 2014). The reform followed the right objectives but did not have enough political support to be implemented sufficiently. It sought an immediate radical transformation of the water sector by dissolving the powerful Irrigation Departments and to replace them with financially independent organizations that included farmers at the highest level. But Pakistani government underestimated the strong grip of power those agencies hold (Javaid and Falk, 2015) and overestimated the capacity of smaller farmers to emancipate themselves from the well-established patronage system that is dominated by the large landowners and the local feudal elite (Bell *et al.* 2015). Learning from the past, to launch another reform a powerful nationwide coalition would be needed to have the political weight to bring about the necessary institutional changes into the irrigation sector. Additionally, new reform attempts might be more successful following a step-by-step approach. A first step could be the rehabilitation of the canal infrastructure and the build-up of appropriate farmers' organizations. However, a better dialogue between all involved actors including the Irrigation Department as well as a stronger commitment by the provincial and national government would be essential to make sure that all actors do comply with the outlined reform process. The implementation of this reform process should be jointly monitored and evaluated by all stakeholders involved. Furthermore, it needs to be clear from the very beginning that this is a long process, which requires institutional learning of all actors involved along with persistence. Besides this organizational challenges, there are also economic conditions challenging the achievement of scenario 4. For example, establishing a reliable and functioning monitoring system would be required to introduce incentives for farmers to conserve water. Moreover, as it can be seen when studying successful irrigation reforms in other countries, a diligent monitoring is an essential precondition to establish a transparent a coherent water right system.

9.3 Quantitative Scenario Assessment

(K. Wencki, C. Strehl)

Chapter 9.2 outlined a qualitative assessment approach, relating water management changes in Punjab and their effects on achieving high level goals like the SDGs. The comprehensive quantification chain from regional water management changes, in a regional setting as conducted within InoCottonGROW towards its effect on highly aggregated SDGs is a complex challenge, calling for extensive modelling. Therefore, the subsequent chapters outline two different approaches as developed along the project: The first one is based on comprehensive hydrological simulations of proxy-indicators on a regional level that are upscaled to a national scale, while the other one is based on the water footprint concept, taking the respective mid-points and end-points of the assessment as a starting point.

9.3.1 From Hydrological Modelling to UN-SDGs

Top-down-bottom-up framework for hydrological data processing

As summarized in Figure 3.3 different water management key variables/indicators are quantified through hydrological modelling within InoCottonGROW, e.g.:

- Amount of irrigation water applied [mm/season]
- Groundwater recharge [mm/season]

These variables/indicators can be used to quantify the regional effects of water management scenarios in reference to the initial situation. Figure 9.1 illustrates a way of linking national SDG indicators and regional scale hydrological modelling.

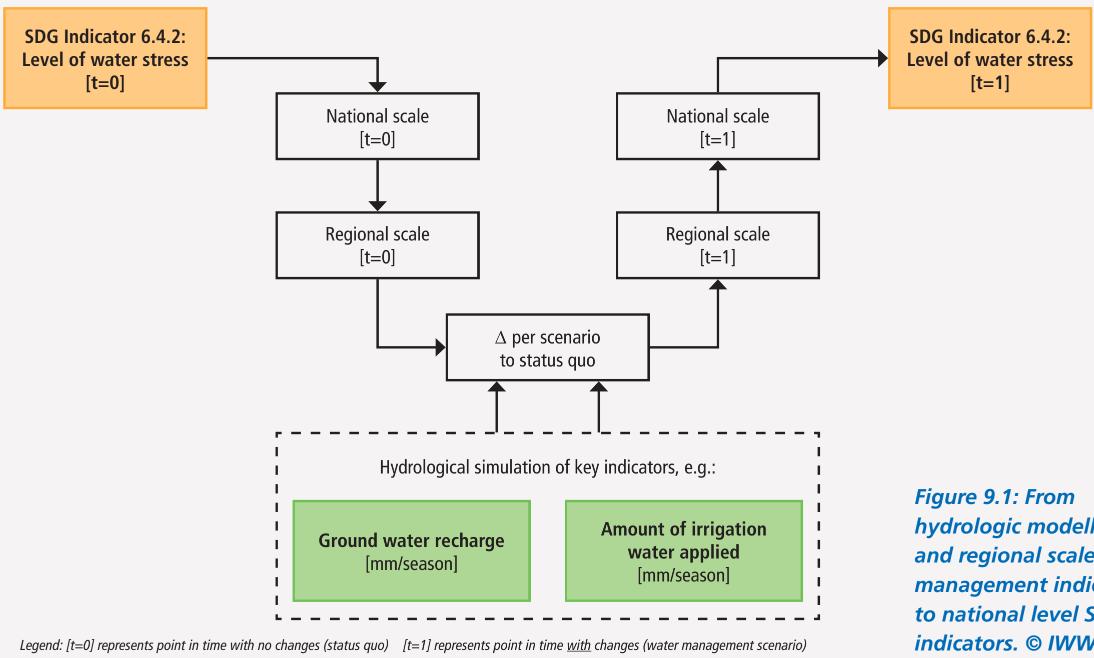


Figure 9.1: From hydrologic modelling and regional scale water management indicators to national level SDG indicators. © IWW-MH

This example is based on SDG indicator 6.4.2 “level of water stress: freshwater withdrawal as a proportion of available freshwater” (UN STAT, 2019). According to UN-IAEG the indicator is defined:

$$\textit{SDG Indicator 6.4.2} = \textit{Level of water Stress (\%)} = \frac{TWW}{(TRWR - EFR)} * 100$$

with TWW: total freshwater withdrawal
TRWR: total renewable freshwater resources
EFR: environmental flow requirements

TWW, TRWR and EFR are per definition values on a national scale, representing a point-in-time of the complex and dynamic water cycle across several catchment scales. In contrast, hydrological modelling and accurate quantifications of regional water management changes needs to be based on the smallest scale possible to deliver reliable data adequate for decision-making. This poses a challenge for assessing the effectiveness of regional scale changes in water management based on their effect on national level SDGs. This challenge is illustrated in Figure 9.1, also proposing a framework for calculations. To quantify the effectiveness of a management scenario, influencing the regional hydrology in Punjab in relation to the cotton and textile industry, a top-down data processing followed by a bottom-up data processing is needed.

Top-down data processing

- Calculation of SDG indicator 6.4.2: level of water stress for a point in time with no (regional) water management changes in status quo [t=0]
- Downscaling of national quantitative data from SDG indicator 6.4.2 (TWW, RWR, EFR) to regional scale (Punjab) from status quo [t=0]
- Analysis and processing of linkages with regional hydrological water management models

Bottom-up data processing

- Calculation of the differences in key hydrological indicators in status quo [t=0] to a simulated management scenario [t=1] (Δ per scenario to status quo)
- Upscaling
- Recalculation of the indicator 6.4.2, level of water stress for the point in time with changes of the (regional) water management [t=1]
- Analysis of absolute and relative difference in SDG indicator 6.4.2 for t=0 to t=1 and conclusion of the effectiveness and relevance of regional water management changes to achieve SDG 6.4

Figure 9.1 points out the relation of regional scale hydrologic key indicators to high-level water management related SDG indicators. In this example, the regional scale hydrological indicators relate to the national scale SDG indicator 6.4.2 as follows:

- Regional scale indicator “Groundwater recharge” → influence on national scale variable “total renewable freshwater resources” (TRWR)
- Regional scale indicator “Amount of irrigation water applied” → influence on national scale variable “total freshwater withdrawal” (TWW)

9.3.2 From Water Footprint Assessment to UN-SDGs

Although the water footprint concept was developed long before UN-SDGs were adopted, the underlying approaches of both concepts are very well in line. Thus, the advanced water footprint concept that was developed and applied within InoCottonGROW can help to showcase the implicit effects on water-related as well as other SDGs. This can be illustrated best based on the cause-effects chains defined in Figure 9.2 to Figure 9.4.

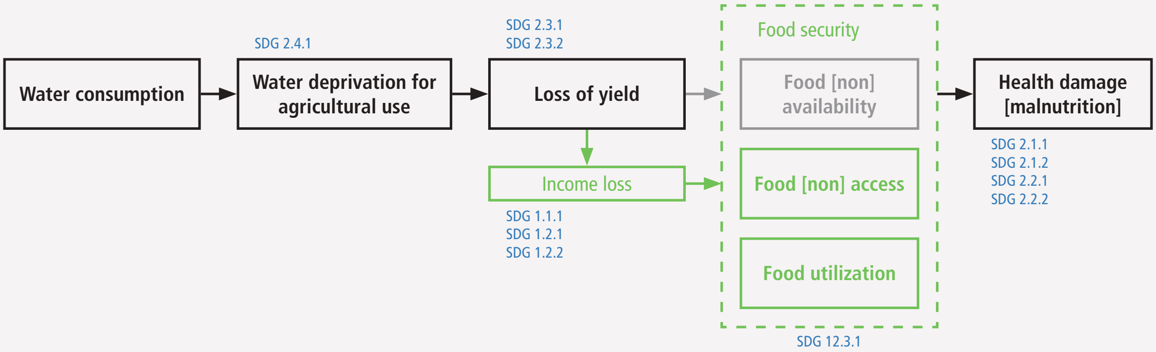


Figure 9.2: Existing (black) and proposed (green) cause-effect chains for human health impacts associated with malnutrition due to the water consumption and its linkages to UN-SDGs (compare to Figure 5.3). © IWW-MH

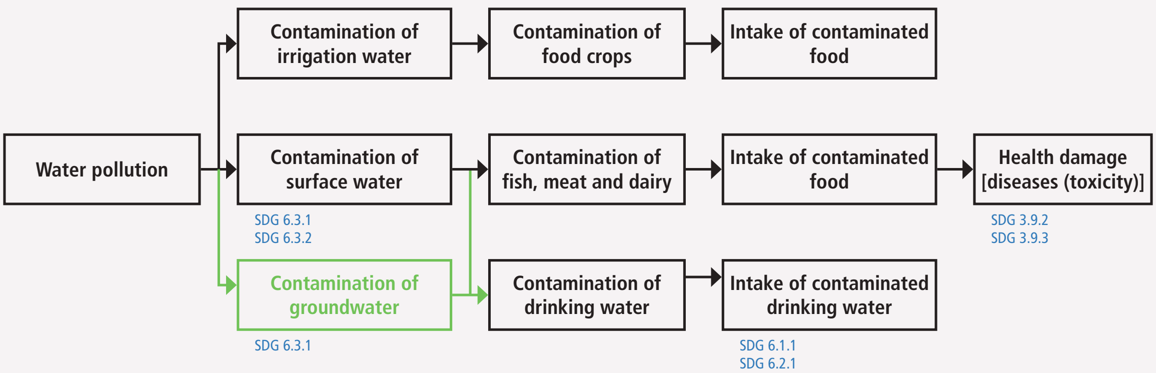


Figure 9.3: Existing (black) and proposed (green) cause-effect chains for the human health impacts associated with toxicity diseases due to the water pollution and its linkages to UN-SDGs (compare to Figure 5.4). © IWW-MH

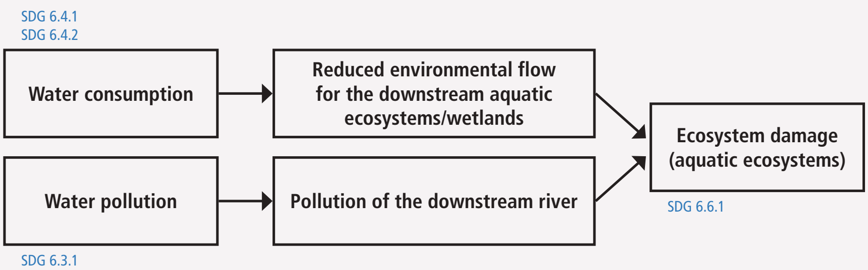


Figure 9.4: Cause-effect chains for the ecosystem damage and its linkages to UN-SDGs (compare to Figure 5.5). © IWW-MH

The cause-effects chains are modelled within the water footprint concept to reflect the connection between water consumption and pollution and the areas of protection (AoPs) human health, natural environment and resources. The mid-point result "water scarcity" as well as the end-point results for the AoPs human health and ecosystems could be furthermore used to showcase the implicit effects on water-related as well as other corresponding UN-SDGs via proxy indicators. For example, the indicator DALY (disability adjusted life years) captured by WHO could be used as a proxy indicator for measuring the potential for reducing health damage (malnutrition) as a result of water deprivation and can therefore be used as a proxy for the UN-SDG #2 "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" and its corresponding targets and indicators.

However, as the direct connection of the mid- and end-point WF results to the SDG indicators was not part of this project, implications of the different scenarios (see chapter 9.1) on SDG achievement could not be calculated exactly using the water footprint tool but it has been used to verify the assumed impacts on SDG (see chapter 9.2) achievement on a qualitative basis. The causality links between water footprint and SDG assessment are exemplified based on the assessment of scenario 2 and 6 below.

Water Footprint Assessment and SDG implications of Scenario 2

According to the water footprint assessment, the measures described under scenario 2 "Many Pennies make a dollar" will lead to an increased irrigation efficiency (less litres consumed per kg cotton) and higher local water scarcity (measured as WDI) at the same time. The main reason for this is a decrease of the water consumption per kg of cotton and an increase in water consumption per area due to higher yields obtained through a more efficient water application. With regard to SDG 2 this is more likely to have positive effects because malnutrition (SDG target 2.2) can be decreased if increased irrigation efficiency is accompanied with increased yields. At the same time grey water footprint reduction caused by wastewater treatment installed in the textile production can substantially decrease toxicity impacts. Impacts on local ecosystems (SDG indicator 6.6.1) are ambivalent since water deprivation will increase and toxicity impacts are likely to decrease.

Table 9.3: Effects of scenario 2 ("Many pennies make a dollar") on the water footprint and SDGs.

	Intervention	WF	Secondary Effects (relevant for SDG assessment)
COTTON	Promotion of flexible irrigation scheduling within Warabandi system	↘	reduced soil evaporation
COTTON	Promotion of drip irrigation techniques	↗	higher application efficiency, reduced groundwater recharge
COTTON	Increased dissemination of storage systems	↘	indirect effects by supporting measures above
TEXTILE	Promotion of water-efficient machinery in textile processing	→	reducing water usage (groundwater pumping), additionally energy and time savings
TEXTILE	Promotion of advanced dyestuff and process chemicals	↓↑	reduce in groundwater pumping, additionally energy and time savings, increased COD concentration without WWT
WASTE WATER	Installation and operation of effluent WWTPs in all large- and medium-size textile finishing plants	↓	increased energy consumption, reduced emission concentrations to ZDHC foundational

Water Footprint Assessment and SDG implications of Scenario 6

According to the water footprint assessment, the production of organic cotton and effluent treatment in the textile production, described under scenario 6 "Quality instead of quantity", has little effect on water consumption and no increase or even a decrease in yield is expected, since pesticides are not applied and fertilization is reduced. At the same time, water consumption might be reduced, since water management and applying water-use efficiency measures are required for the certification. Overall, this means that water scarcity remains on the same level, and the blue and green water consumption as well as the water scarcity footprint will stay the same or slightly increase or decrease depending on the yield and water management applied on the fields. However, looking at the qualitative SDG assessment, there are various other benefits linked to this scenario affecting almost all SDGs considered in a positive way (Table 9.4).

Table 9.4: Effects of scenario 6 ("Quality instead of quantity") on the water footprint and SDGs.

	Intervention	WF	Secondary Effects (relevant for SDG assessment)
COTTON	Increased share of organic cotton production on a regional scale	→	reducing pesticides use, efficient irrigation technologies
WASTE WATER	Installation and operation of effluent WWTPs in all large- and medium-size textile finishing plants	↓	increased energy consumption, reduced emission concentrations to ZDHC foundational

9.4 Potential Policy Interventions in the Irrigation System in Punjab

(J. Schultze, N. Zimmermann, M. Oelmann)

The scenario analysis served two different purposes (i) to find out which measures and policies will be best suited to implement the UN SDGs, and (ii) to evaluate its political feasibility. Both questions deal with very different aspects; nevertheless, in order to have a reasonable ranking for decision-makers it makes sense to juxtapose them. Yet, is has to be made clear that the final ranking as well as the scenario and feasibility assessments themselves only represent well-founded opinions of the authors which can be disputed.

Unsurprisingly, our SDG and feasibility assessments came to fundamentally different results. While there is no clear favourite scenario in terms of which is best suited to achieve the SDGs since the differences among them are only marginal, there are strong variations between the scenarios in terms of their feasibility. For example, contrary to the SDG assessment there is a clear preferred feasibility scenario, while we considered other scenarios not feasible at all. We argue that the most likely scenario for a feasible implementation is scenario three. The reasoning of this evaluation is rather simple and straightforward. Since institutions and public administrations lack strength and the reform of the institutional framework is a tiresome and long-term effort (Briscoe *et al.* 2005), large investments in infrastructure will have from our point of view the most immediate effect. At the same time, all private efforts that merely rely on private incentives are currently unlikely to produce any significant improvements since the regulatory and legal system is both inadequate and too weak to create an enabling environment. Nonetheless, investing in infrastructure such as lining canals and building a comprehensive sewage system for textile companies is not a stand-alone solution (Meinzen-Dick, 2007). To operate them sustainably, investments in the institutional framework are indispensable (Huppert, 2000). Another feasible policy option has been introduced in scenario 4a: more water to the tail. This scenario explicitly considers the dominant head-tail allocation problem by introducing a compensation mechanism. This compensation mechanism essentially would give farmers with privileged access to surface water in the head reaches of the canal system financial incentives to voluntarily give up of some of their surface water so that there is more water available for farmers at the tail. However, to implement this would require a strong political mandate and a reliable monitoring system to track in real time the water that flows through the canals (Shah *et al.*, 2016).

Another aspect that is important to consider for any reasonable policy recommendation is the rather complex relationship between the different SDGs within the specific context of cotton farming and textile industry. Since the different goals and targets are not necessarily complementing each other but at times are also constraining one another any reasonable policy recommendation needs to put that into consideration. The question of political costs is in particular relevant when the implementation of a policy objective compromises another policy goal. In effect, this always translates into a zero-sum game situation between those two objectives (Olson, 2009). For example, if the policy objective is to leave more water for the Indus delta in South of Pakistan to protect this fragile eco-system this objective will also reduce the amount of water available for farmers. In terms of SDGs we can look at this dilemma as a trade-off between SDG 1: no poverty and SDG 15: life on land.

In this context, it is important to point out that ultimately this prioritization of SDG goals and targets is above all a political and not a scientific decision. At the end of the day, decision-makers must carefully weigh which trade-offs between SDGs are acceptable and what is the relationship between the expected outcomes and the political costs involved for certain policy choices. The National SDGs Framework prioritized UN-SDG 6, among SDG 2 "No Hunger", SDG 3 "Good Health and Well Being", SDG 4 "Quality Education", SDG 7 "Affordable and clean energy", SDG 8 "Decent work and Economic Growth" and SDG 17 "Peace and Justice" to be achieved in the short run (Government of Pakistan, 2017). In a Voluntary National Review the first Local Government Summit on the UN Sustainable Development Goals (SDGs) identified water among education, employment, energy, and peace and governance as major issues to address (Government of Pakistan, 2019).

10 OUTREACH

Workshops and capacity development together with Pakistani partners, including farmers' organizations, textile companies, universities, authorities and ministries, are intended to facilitate implementation of the measures investigated. By creating video documentaries, developing an online water footprint tool and a water footprint based textile label, the project aims at raising awareness of internationally operating brands & retailers as well as German consumers for sustainably produced textiles.

10.1 Documentary Video

(F. Nawrath)

The 11-min documentary video produced within InoCottonGROW (Nawrath *et al.* 2020) is available online: https://youtu.be/dEBe-B36JJQ.

This documentary video gives an insight into the journey of our garments and the people producing it – starting at the cotton fields in the heartlands of Punjab, Pakistan, to the garment factories in the outskirts of the vibrant Punjabi cities, ending up in department stores in the hand of consumers in Germany. We wanted to transport perspectives and let the voices be heart of those people directly impacted by the Punjabi water crisis.

The research project addresses different factors in depth along the cotton production value chain. Communicating and translating these findings to a general audience without oversimplification is a balancing act. It was day-to-day planning and iterating the next days's filming and interviews in Punjab. Documentary filmmaking involves a level of scripting but also an element of serendipity: to be at the right place at the right time.

Water scarcity is a sensitive topic in Pakistan – nobody can deny it – but making a clear statement on camera about things having to change demands a form of accountability that persons interviewed seem to avoid. Meeting the environmental lawyer Ahmad Rafah Alam, it was refreshing to get blunt statements addressing the big picture both from a Pakistani as well as an international point of view.

Another key moment during filmmaking was witnessing the first ignition of biogas produced in the pilot wastewater treatment plant at a garment factory. This moment marks the transformation of wastewater being seen not as waste but as a resource to produce energy, both in the eyes of workers and management present as well as for the audience of the film.

A great deal of support was given by our project partners in Pakistan who helped with deep knowledge, assisted us in giving interviews and organized stays, transportation and introducing us to their country.

10.2 Workshop in Germany on Integrated Water Resource Management

(B. Grün)

In cooperation with the WETI-Project of GIZ, a group of Pakistani decision makers was invited by the Lippeverband for a knowledge exchange workshop on Integrated Water Resource Management (IWRM), which is still fragmented in Punjab. Impressions of this and other training measures conducted within the course of InoCottonGROW are shown in Figure 10.1.

This workshop took place on May 5, 2018 at the central wastewater treatment plant of the Emschergenossenschaft in Dinslaken. Bjoern Gruen (LV) presented the concept and measures of integrated river basin management and duties / benefits of a German water management association. Mr. Gruen also introduced the "Future Cities Adaptation Compass" – a tool, which allows for easy estimation of the consequences of climate change for a region and adaptation measures. In the knowledge exchange and discussion, the Pakistani partners asked question on financing, organizational structure of a German water board and technical questions on wastewater treatment itself. Detailed answers were by Stefan Stegemann (EG) during a site visit of the plant.

Figure 10.1: Workshops and training measures with Pakistani colleagues. © FiW

CONFERENCE PROGRAM

Monday 02.12.		
Arrival of all 5+2 delegates at DUS, Transfer from Airport to Aachen (100km, 2 hours, MiniVan)		16:20h
Leonardo Hotel Krefelder Str. 221 52070 Aachen **Hotel Benelux** Franzstraße 21-23 52064 Aachen	**Meeting in hotel lobby** Go for dinner (nearby Italian restaurant L'Osteria, Gut-Dämme-Straße 1)	19:30h
Tuesday 03.12.		
Breakfast in Hotel		
Pick-up at Hotel		08:15h
FiW e.V., Aachen InoCottonGROW Roadmap Workshop *Dr. Frank-Andreas Weber (FiW) and InoCottonGROW Roadmap Team* • Introduction • Presentation FiW e.V. • Presentation of Pakistani and Turkish partners • Discussion of InoCottonGROW results and recommendations https://www.fiw.rwth-aachen.de https://www.inocottongrow.net		09:30h
Lunch buffet (halal) at FiW **Cont´d FiW e.V., Aachen InoCottonGROW Roadmap Workshop** *Dr. Frank-Andreas Weber (FiW)*		12:30h
RWTH Aachen Institute of Hydraulic Engineering and Water Resources Management (RWTH-IWW) *Prof. Holger Schüttrumpf, Lennart Schelter* http://www.iww.rwth-aachen.de		17:00h
Leonardo Hotel Krefelder Str. 221 52070 Aachen	**Dinner in Old City Christmas Market**	evening
Wednesday 04.12.		
Breakfast in Hotel		
Transfer from Aachen to Bonn (100km, 2 hours)		07:30h
Campus Klein-Altendorf, Wormersdorf near Bonn *Dr. Bernhard Tischbein (Center for Development Research ZEF)* • Visit of agricultural campus at University of Bonn https://www.cka.uni-bonn.de https://www.zef.de		10:00h
Fingerfood at Campus Klein-Altendorf		
Transfer from Bonn to Dinslaken (150km, 2 hours)		12:00h
Emschergenossenschaft und Lippeverband (EGLV) Kläranlage Emscher-Mündung Turmstraße 44a, 46539 Dinslaken *Mr. Björn Marcus Grün (EGLV)* • Centralized wastewater treatment plant KLEM • Cleaning of polluted central drain before discharge in river • Integrated Water Resources Management and renaturalization in the Ruhr area https://www.eglv.de/en		14:00h
Travel from Dinslaken to Halle (450km, 6 hours)		16:30h
Dinner along the way Herkules Terrassen Schloßpark 26 34131 Kassel		
Hotel TRYP by Wyndham Hotel Neustädter Passage 5 06122 Halle/Saale		23:00h
Thursday 05.12.		
Breakfast in Hotel		
University of Halle *Prof. Dr. Christopher Conrad, Prof. Dr. Wolfgang Gossel, Dr. Muhammad Usman* • Excursions and field visits (coal mining, dismantling chemical industry, groundwater contamination, and renaturation), • Site Visit: Former coal mining and chemical complex in Bitterfeld https://www.geo.uni-halle.de/		08:30h - 15:00h
Lunch (Halal)		
Prof. Christopher Conrad, Dr. Gerhard Schmidt, Dr. Muhammad Usman (Marktplatz • Halle Excursion (Geology, Salt, and Water) • Shopping & Christmas market		15.00h - 18.00h
Hotel TRYP by Wyndham Hotel Neustädter Passage 5 06122 Halle/Saale **Dinner in Halle City Center** Hallesche Spezialitätenbrauerei Kühler Brunnen Große Nikolaistr. 2 06108 Halle/Saale		
Friday 06.12.		
Breakfast in Hotel		
Transfer from Halle to Frankfurt (400km, 5 hours)		07:30h
Friday Prayer DITIB Ayasofya Camii Stockstädter Straße 5 Biebesheim am Rhein		13:30h
Wasserverband Hessisches Ried, Biebesheim near Frankfurt *Michael Polotzek (WHR)* • Managed Aquifer Recharge for Irrigation and Drinking Water Purposes https://www.whr-infiltration.de/		14:00h
Transfer to Frankfurt (50km, 1 hour) Check-in Hotel **Closing of Roadmap Workshop // Debriefing**		
MEININGER Hotel Frankfurt/Main Messe Europa-Allee 64 60327 Frankfurt	**Dinner**	
Saturday 07.12.		
Breakfast in Hotel Shopping and Sightseeing in Frankfurt		
Transfer to Airport (50km, 1 hour)		11:30h
Departure FRA		15:00h

Looking forward to welcoming you at the Conference.

ABOUT THE ROADMAP WORKSHOP

In the three-year R&D project "Innovative impulses reducing the water footprint of the global cotton-textile industry towards the UN Sustainable Development Goals (InoCottonGROW)" funded by the German Ministry of Education and Research (BMBF), 14 German research and industry partners work in collaboration with 13 Pakistani and 2 Turkish institutions to study approaches to increase water efficiency and productivity along the entire cotton-textile value chain. We have applied a range of different methodologies and conducted demonstration projects on cotton irrigation and scheduling, as well as water efficiency and wastewater treatment in textile industry. As the project is going to end in spring 2020, the goal of this roadmap workshop is to discuss results, outreach and possible recommendations of the InoCottonGROW project with renown scientists and practitioners from Pakistan and Turkey, visit best-practice examples in Germany and plan ahead for further collaboration.

For more information on the project, please visit https://www.inocottongrow.net

CONTACT

Dr. Frank-Andreas Weber (FiW e.V.)
weber@fiw.rwth-aachen.de
+49 173 7848918

Wolfram Schröder (FiW e.V.)
w.schroeder@fiw.rwth-aachen.de
+49 162 4456381

Fabian Nawrath (FiW e.V.)
nawrath@fiw.rwth-aachen.de
+49 152 29517888

Tuba Yesilyurt
+49 178 2714018

Dr. Mohammad Usman (UW)
usmanigw@gmail.com
+49 176 29006069

Prof. Dr. Christopher Conrad (University of Halle)
christopher.conrad@geo.uni-halle.de

SPONSORED BY THE Federal Ministry of Education and Research

InoCotton GROW

InoCottonGROW Roadmap Workshop

December 2nd to 7th, 2019

Funded by the German Ministry of Education and Research (BMBF)

Organized by Research Institute for Water and Waste Management at RWTH Aachen (FiW) e.V.

Figure 10.2: Programme of the InoCottonGROW Roadmap Workshop in Germany. © FiW

Furthermore, a Roadmap Workshop took place from 02.12. – 07.12.2019 as a further training and excursion programme with Turkish and Pakistani project partners of the InoCottonGROW network (Figure 10.2). Within the framework of this multi-day event, a joint workshop was held by the Lippeverband on December 4th, 2019 at the central wastewater treatment plant of the Emschergenossenschaft. The main topics of this workshop were the treatment of polluted wastewater, fee charging and sanction options as well as integrated water resource management and the renaturation of the water system in the Emscher region.

The event was concluded by a tour of the large-scale sewage treatment plant with explanations of each treatment step. For most participants it was the first time to visit a wastewater treatment plant that is operated 24/7. Furthermore, the roadmap workshop included further visits to partners and research institutions of the InoCottonGROW network as well as a water association with drinking water production.

Two major differences between Pakistan and Germany are how measures are financed and who is responsibility for IWRM. In Germany using tap water results in paying for wastewater treatment as well. In Pakistan this is not the case, since many households have private wells for domestic water supply. Measuring the amount of water disposed to a sewer system is difficult. During the discussion two options for billing were favored: Flat charges depending on the size of the household or shifting the supply to measured tap water. Due to increasing contamination of the local groundwater aquifer in the urban areas the last option might be necessary for quality reasons.

In Pakistan, the water management responsibilities are distributed over different institutions. Working more closely together is an in important factor. An example for such a cooperation could be the EU Water Framework Directive (Directive 2000/60/EC) in the field of water policy.

For Lippeverband one interesting new field was to learn from Pakistani partners about their research activities in wastewater treatment by wetlands. In Germany, wetlands could be options for treating polluted water in rural areas, which have no access to public sewer systems.

10.3 Online Water Footprint Tool

(N. Mikosch, M. Berger)

The free accessible web-based water footprint tool contains the database and impact assessment model developed in the InoCottonGROW project. It provides information on the water use and pollution intensity of cotton and textile production (dyed fabric and yarn) on a global and national (country averages) level as well as on a local level (Punjabi irrigation sub-divisions). For both cotton and textile production, the users can set relevant parameters (such as irrigation technology for cotton cultivation or wastewater quality parameters in textile production) and reduction options (see chapter 6).

The origin of the cotton and supplied amount has to be provided by the user. Other parameters can be entered if data is available. Otherwise, default values are applied (TU Berlin, 2020).

Input parameters for the cotton cultivation:

- Share of cotton under drip irrigation [%]
- Share of cotton under deficit irrigation [%]
- Certification [BCI/organic cotton/no]
- Share of certified cotton [%]
- Nitrogen input (fertilizers) [kg/ha]
- Pesticides input [kg/ha]

Input parameters for the textile production:

- Water use [m³/ton]
- Wastewater discharge [m³/ton]
- Compliance with ZDHC (Zero Discharge of Hazardous Chemicals) thresholds [yes/no]
- Dyestuff input [kg/ton textile]
- Dyestuff (5 dyestuffs are available)
- Dyestuff fixation rate [%]
- General wastewater quality parameters
- Heavy metals
- MRSL (Manufacturing Restricted Substances List) substances

By modifying these parameters, the user can calculate the effect on the water footprint. Several alternative scenarios can be combined and analysed simultaneously, which allows for comparison and development of optimization strategies. Provided default values allow to use the tool even by incomplete or non-available primary data. The figure below demonstrate the user interface and the results for the conventional and 100 % organic cotton grown in Pakistan (Figure 10.3). Other examples are textiles produced in Turkey without and with wastewater treatment according to ZDHC foundational standard. The tools are available on the following web-page: http://wf-tools.see.tu-berlin.de/wf-tools/inoCotton/#/.

Text Box 14:

What is the water footprint of washing my cloths in Germany?

Recent studies estimate that on average textile products are washed 72 times during their entire use phase before they are disposed by the consumer (Cotton Incorporated, 2012). This results in 8,830 litres water used per kg textile product for the laundry and equals to the total water use associated with the textile production including both cotton cultivation and textile manufacturing steps (8,604 litres/kg garment calculated in the InoCottonGROW project). However, despite the high usage, most water is discharged directly after the washing, while only around 10 % of water is effectively consumed (mainly via evaporation) and therefore contributes to the product's water footprint. For this reason, the WF of the textile use phase amounts to only 997 litres/kg, which corresponds to one-fifth of the WF of the textile production. Finally, assuming that the textile is worn in Germany, the water scarcity footprint (WSF) attributed to the textile use phase amounts to only 4 % of the WSF associated with the textile production, which is explained by low water scarcity in Germany compared to Pakistan.

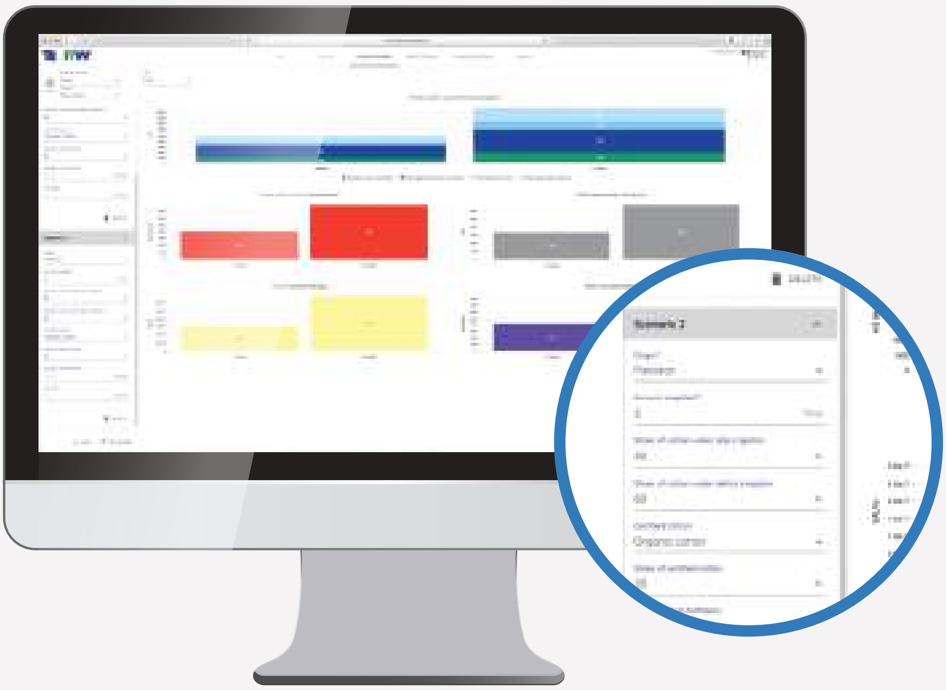


Figure 10.3: Water Footprint Tool: user interface and calculation results for the conventional and 100 % organic cotton grown in Pakistan (TU Berlin, 2020).


100% COTTON
DO NOT BLEACH
95
MADE IN PAKISTAN

10.4 Water Footprint in Textile Labelling

(N. Mikosch, O. Heß)

Disclaimer: The selection of labels discussed in this report does not apply any recommendation or criticism with any of the labels mentioned. The authors declare that they have no connection or financial interests with any of the labels whatsoever.

The consumers' awareness of environmental issues associated with the textile production is increasing and therefore also the wiliness to buy certified textiles. Fairtrade-labelled textiles sold in Germany increased from 2,6 million pieces sold in 2012 to 14,0 million pieces in 2018 (source: TransFair).

Currently over 100 different labels can be identified on the web-portals as Siegelklarheit, Eco-label-index and Label-online. Most labels determine criteria for the first two life cycle stages of the textile products – raw material production (cotton cultivation) and textile processing, while the use phase and disposal are usually not addressed.

Table 10.1: Overview of some ecolabels (Diekel, 2019).

Name	Considered life cycle stages					Short description	Founded in
	raw material	textile processing	distribution	use phase	EoL		
Organic cotton	x					"Certified organic cotton is produced in accord with specific country-level or international organic agricultural standards, integrating ecological processes, maintaining local biodiversity, and avoiding the use of toxic and persistent synthetic pesticides and fertilizers as well as genetically modified seeds" (Textile Exchange, 2016).	1990s
Better Cotton Initiative (BCI)	x					The BCI is "a global approach that provides a solution for the mainstream cotton industry, including both smallholders and large scale farmers" (Better Cotton Initiative, 2020).	2009
Cotton made in Africa (CmiA)	x					The label promotes sustainable cotton growing and farming approaches to enable African cotton farmers to improve their living conditions on their own, referring to ecological, social, and economic aspects.	2005
bluesign®	x	x				With special focus on the used chemicals, bluesign™ offers a standard for suppliers, manufacturers, and top-brands to reduce their textile footprint.	2000
Global Recycled Standard (GRS)	x	x				Observing the full supply chain, the standard focuses on traceability, environmental principles, social requirements, and labelling. It tracks and verifies recycled input material from input to the final product.	2008
Blue Angel Textiles	x	x	x			The Blue Angel label sets requirements for environmentally friendly product design. The Blue Angel Textiles represents a subcategory of the Blue Angel Label.	1978
Global Organic Textile Standard (GOTS)	x	x	x			The self-declared leading textile standard considers social and environmental criteria in the processing of organic fibres throughout the entire textile supply chain.	2005 agreement on the first version and implementation scheme.
Cradle to Cradle Certified™	x	x			x	Based on the Cradle to Cradle framework, the certificate consists of basic, silver, gold, and platinum levels for safer, more sustainable products made for the circular economy. The label certifies different product categories one of which is textiles.	2005 by McDonough Braungart Design Chemistry and donated to the Cradle to Cradle Products Innovation Institute in 2010.

While none of the analysed ecolabels includes the WF as a requirement, all of them address WF related environmental aspects that are subject to the certification, for example, raising irrigation efficiency in the cotton cultivation (contributes to blue WF) or wastewater treatment (contributes to grey WF). The latter can be grouped in three general categories: water use, chemicals and wastewater. While water use influences the blue and green WF and the WSF, chemical use and wastewater discharge contribute to the grey WF as well as cause toxicity impacts on ecosystems and human health. As demonstrated in chapter 8.4, certified cotton production (organic farming and BCI) can lower the WF, for example, the toxicity impacts can be reduced by up to 100%.

Within the InoCottonGROW project, we developed a WF label for the textile products, which aims at addressing the water use related issues in the textile value chain. A direct WF label (comparing green, blue, grey WF and the WSF) was considered as potentially misleading, since it would always favour water-rich countries (i.e. with less irrigation requirement for the cotton cultivation and low water scarcity) instead of addressing the application of innovative and/or water saving technologies. For example, even if applying only drip irrigation, the WSF of cotton produced in Pakistan will still amount to 3,758 litres deprived/kg, which is more than 10-times higher than the WSF of the cotton produced in China under the conventional flood irrigation (314 litres deprived/kg) (TU Berlin, 2020). Relying the decision-making upon such metrics could lead to a short-term boycott of water-intensive products, which may have devastating economic and social consequences in the cotton growing areas.

For this reason, the WF label concept developed in the InoCottonGROW project follows the concept of the EU energy efficiency label and therefore addresses the efficiency level of individual production aspects in the cotton cultivation and textile production. The latter are derived from the existing textile labels and initiatives (Table 10.1). The label addresses two life cycle steps – cotton cultivation and textile wet processing, since these steps can be directly influenced by the producers and/or suppliers. Both water pollution and consumption aspects are being evaluated, e.g. water use, fertilizers and pesticides use, wastewater treatment and chemicals management. The efficiency is measured by means of the point scale from 0 to 3 as following:

- 0: conventional production / no efficiency measures
- 1: raised efficiency (e.g. reduced fertilizers use or monitoring of the water use)
- 3: high efficiency (e.g. avoiding the use of pesticides, wastewater treatment according to national standards).

For two aspects, an additional efficiency rate (5 points) is adopted, which reflects very high/maximum efficiency: advanced water use in the cotton cultivation (e.g., soil moisture monitoring / drip irrigation / rain-fed cultivation) and advanced wastewater treatment in the textile processing (e.g., according to the ZDHC foundational (or higher) thresholds).

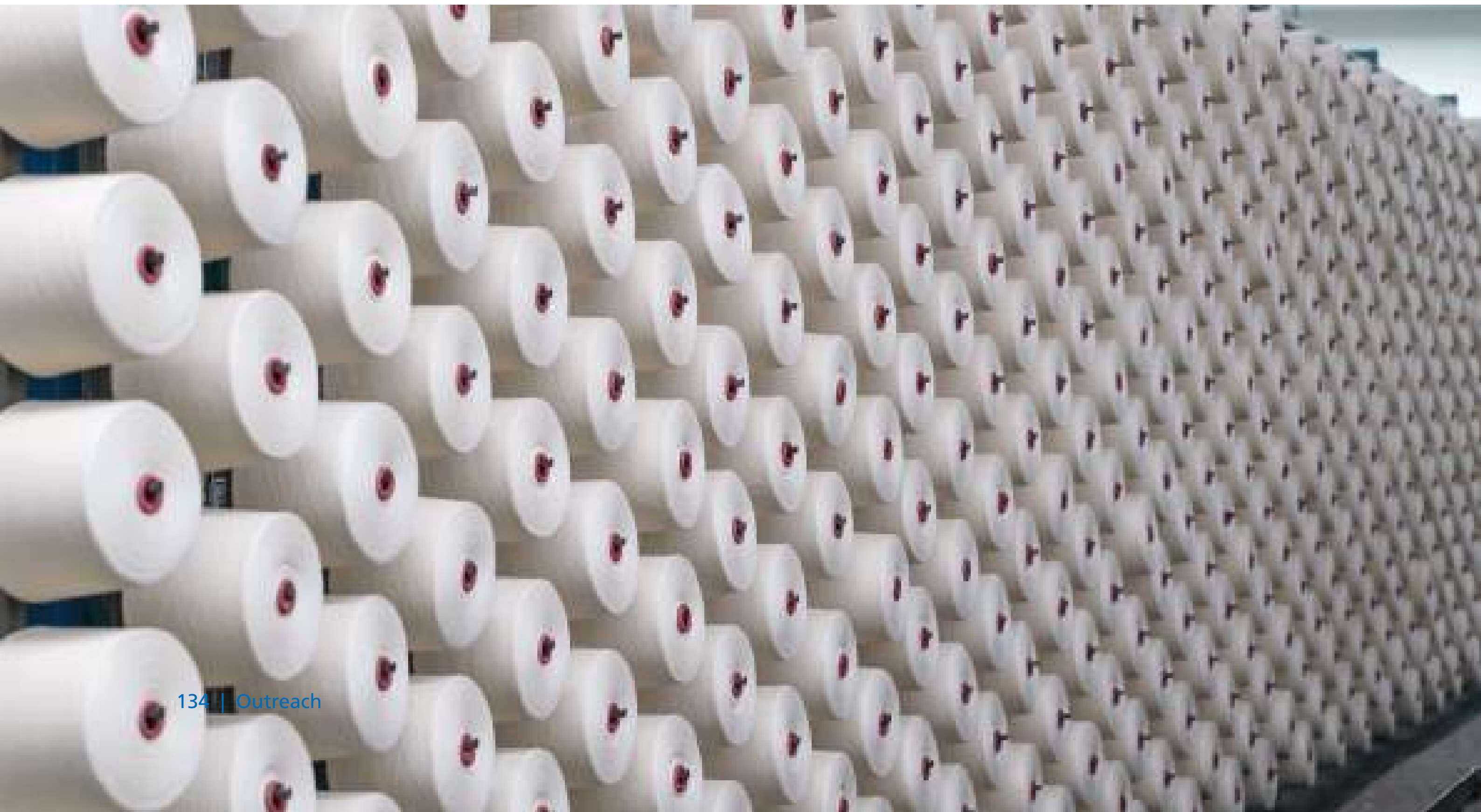


Table 10.2: Efficiency grade and rating of the Water Footprint related production aspects for cotton and textile.

Life Cycle stage	Criteria	Efficiency grade	Rating	Contribution to the WF
Cotton cultivation: Conventional cotton	Fertilizer use and management	Conventional use	0	Grey WF
		Reducing the use of the fertilisers	1	
		Restricting the use of fertilisers	3	
	Plant protection products (e.g. pesticides, herbicides) use and management	Conventional use	0	Grey WF Toxicity
		IPM (Integrated Pest Management) Reducing /restricting the use of plant protection products	1	
		Avoiding the use of plant protection products	3	
	Water use	Conventional	0	Green and blue WF WSF
		Monitoring of the water use	1	
		Raising efficiency of the water use	3	
		Advanced water use, e.g. through soil moisture monitoring / drip irrigation / only rain-fed	5	
	Water stewardship	Includes a stakeholder-inclusive process that involves site- and catchment-based actions	1	
Cotton cultivation Organic cotton	Organic cotton	Includes all aspects of the fertilization, application of the plant protection products and water use required for the organic production	12	Green and blue WF WSF Grey WF Toxicity
	Water use	Advanced water use, e.g. through soil moisture monitoring / drip irrigation / only rain-fed	2	WSF
	Water stewardship	Includes a stakeholder-inclusive process that involves site- and catchment-based actions	1	
Textile production	Water use	No measures for water saving/monitoring	0	Green and blue WF WSF
		Water use monitoring / raising water use efficiency / water management on a production site level	1	
	Chemicals use	No restrictions	0	Grey WF Toxicity
		Some toxic substances are restricted	1	
		ZDHC Manufacturing Restricted Substances List (MRSL) is adopted	3	
	Wastewater	No requirements	0	Grey WF Toxicity
		All wastewater is treated according to the national standards	3	
		All wastewater is treated according to the foundational ZDHC or similar thresholds or higher	5	
	Water stewardship	Includes a stakeholder-inclusive process that involves site- and catchment-based actions	1	WSF

Performing water stewardship is rated with an additional point in both cotton cultivation and textile processing steps, since the measures adopted within the water stewardship initiative can reduce the impacts of the water use, reduce water scarcity in the river basin and therefore reduce the WSF. Water use in textile processing is rated only on the scale from 0 to 1, since it has a low impact on the WF. The cotton cultivation phase includes two alternative scenarios: 1) conventional and 2) organic cotton. All criteria are evaluated by the proposed WF label are shown in Table 10.2.

Based on the proposed rating, five efficiency levels from A+ to D were defined. For each level, certain amount of points (according to Table 10.2) have to be reached. Furthermore, some absolute requirements are defined for fulfilling the levels A+ (very high), A (high) and B (good) (Table 10.3). A possible graphical display of the label is shown Figure 10.4.

Table 10.3: Proposed labelling scheme.

Result	Efficiency level	Points	Description	Absolute requirement
A+	very high	>=20	Best technologies are applied to all WF related aspects in both life cycle stages. Highest wastewater treatment efficiency.	Wastewater treatment is rated with 5 points
A	high	13–19	Efficient technologies are applied to most WF related aspects in both life cycle stages. Good wastewater treatment efficiency.	Wastewater treatment is rated with at least 3 points
B	good	7–12	Efficiency is raised for some WF related aspects in both life cycle stages. Good wastewater treatment efficiency.	Wastewater treatment is rated with at least 3 points At least two aspects of cotton cultivation are addressed
C	low	3–6	Efficiency is raised for some WF related aspects in both or only one life cycle stage.	–
D	Very low	<3	Few or none of the WF related aspects are addressed.	–

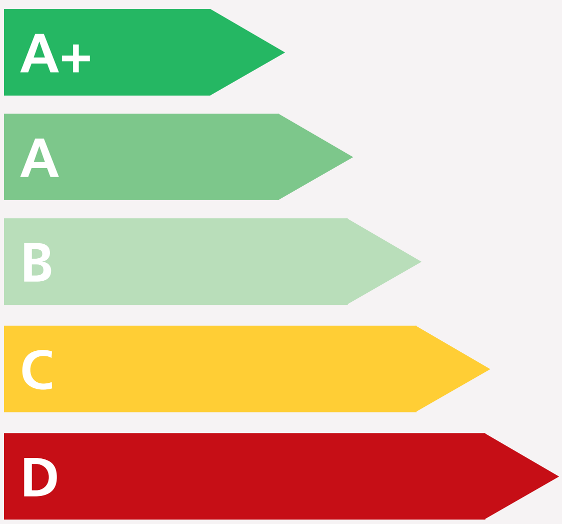


Figure 10.4: Water Footprint in textile labelling: proposed efficiency label.

Table 10.4 presents possible results for the following theoretical scenarios:

- Scenario 1: organic cotton and ZDHC wastewater treatment
- Scenario 2: certified textile (e.g. Blue Angel, GOTS), water stewardship in the cotton cultivation phase
- Scenario 3: textile made out of BCI cotton, wastewater treatment according to national thresholds
- Scenario 4: Organic cotton and water stewardship, none of the aspects addressed in the textile production
- Scenario 5: some measures in both cotton cultivation and textile production are implemented

Table 10.4: Exemplary scenarios and the resulting labelling.

Life cycle stage	Criteria	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Cotton cultivation (conventional)	Fertilizers use	–	–	3	–	1
	Plant protection products use	–	–	3	–	1
	Water use	–	–	5	–	1
	Water stewardship	–	–	1	–	0
Cotton cultivation (organic)	Organic cotton	12	12	–	12	–
	Water use	0	–	–	0	–
	Water stewardship	0	1	–	1	–
Textile production	Water use	1	1	0	0	1
	Chemicals use	3	3	0	0	0
	Wastewater	5	3	3	0	3
	Water stewardship	0	0	0	0	0
Results	**TOTAL points**	**21**	**20**	**15**	**13**	**7**
	Efficiency level	**A+**	**A**	**B**	**C**	**B**
	Comment		Despite 20 points, level A, because only 3 points are achieved in the wastewater treatment		Despite 13 points, only level C is achieved, because the wastewater is not treated	

10.5 Approaching Brands & Retailers

(O. Heß, B. Mahltig)

In order to raise awareness in the textile industry we contacted clothing companies (Brands & Retailers) based in Germany with a global supply chain. All offer cotton T-shirts on the German market. Their decisions where and how textiles are produced are based on individual requirements and German laws. Twelve companies have been contacted. Three of them were visited at the company headquarters (KIK, ESPRIT, Armedangels) presenting results of InoCottonGROW. It was concluded in the discussion that the aspect of water consumption or WF will for sure play an important role in the near future within the supply chain but it is too early to integrate in business strategies now. The following brands have currently not responded to the contact: Tschibo, Zero, Sanetta, Cinque, Review, C&A, Wunderwerk, Tigha. One cancellation was due to a lack of interest (Street One – CBR Group). Possible explanations for the weak interest might be the high competitive pressure on the clothing market. Many companies struggle against changing consumer behaviour in fast fashion. Additionally, further steps are difficult to implement at the moment due to the lack of human resources. The first step of companies towards a more sustainable production leads to collaborations with existing eco labels to meet demand for more sustainable textiles. The sustainable fashion fair Neonyt in January 2020 in Berlin with more than 210 sustainable fashion brands from 22 countries gathered more sustainable fashion brands than ever before and doubled the number of trade visitors compared to January 2019.

11 OVERALL CONCLUSIONS AND POLICY RECOMMENDATIONS

(F.-A. Weber)

Key finding of InoCottonGROW were discussed among Pakistani, Turkish, and German Researchers in a roadmap workshop organized by FiW inviting two Pakistani and three Turkish representatives to Germany in December 2019 and a policy seminar organized by WWF Pakistan in Lahore in February 2020. In the joint discussion, great progress was made in agreeing on common policy recommendations, that area summarized in the following.

11.1 Recommendations on Cotton Irrigation and Irrigation Scheduling

Key findings

1. LCC is an undersupplied system.
2. Groundwater is storage: Canal lining is not the ultimate solution. Quality aspects first.
3. Minimize unproductive losses (i.e. evaporation): Irrigation technology and scheduling is key.
4. Increasingly variable environment expected in future: Flexibility within Warabandi – start at farm-level.
5. Low cotton yield only partly due to water stress.
6. Climate Change impacts: Heat stress will dominate.
7. Good water governance is key: Also groundwater needs governance.

Policy Recommendations

- Farmer education is cornerstone.
- Small ponds at the farm level can increase flexibility, should be implemented bottom-up.
- High-quality, resistant seed are important.
- Crop shifting is an easy option to adapt to expected water supply and soil conditions.
- Floodplains help with diverting flood waters and recharging groundwater.
- Rain water harvesting for recharging groundwater should be promoted.
- Pricing of surface and groundwater is an important instrument for management, but increases crop cost.
- Storage for early Kharif needed:
  - Storage at farm level is a prerequisite for efficient irrigation because it is light and frequent, which requires adequate availability of irrigation water.
  - Similarly storage at outlet level or upstream or in water reservoirs need to be promoted.
  - Canals may be kept flowing during flood season, which may require sediment entrap strategies to minimize sediment loading in canal system.
  - Flood water can be stored either at farm level or may be stored in the aquifer by managed aquifer recharge (MAR).
- Adaptation to climate change needed:
  - Climate change causes more frequent occurrence of extreme events in the form of very high temperature peaks in summer, very low temperature in winter, very high intensity / amount rainfall.
  - Management practices to increase availability of adequate soil moisture in the root zone using drip irrigation or bed-furrow can help crop survive during peak weather conditions.
  - As learnt from farmer during field visit, early sowing of cotton can help adapt to climate change because of getting more time to mature prior to peak temperature.

Figure 11.1: Discussing policy options during the roadmap workshop in December 2019. © FIW

11.2 Textile Production and Effluent Treatment

Key findings

1. Installation of functioning effluent treatment is key for reducing grey water footprint in Punjab.
2. Low-hanging fruits do exist: positive amortization of investments in process- and product-integrated measures.
3. Process-integrated measures often go along with energy savings, but little effect on water footprint.
4. Maintenance and training for operation personnel is key.

Which policy options are feasible?

- Capacity building for the operational personnel on operation and maintenance in regional centres across the country.
- Common effluent treatment plants to be built and operated at textile clusters by the Government, wherever possible.
- Support textile industry for national standard and ZDHC compliance (chemical management and effluent treatment).

Policy Recommendations

- Treatment plants first, training accordingly.
- Trainings need to be short, practical and frequent.
- Cleaner production can reduce treatment need.
- Pricing companies according to pollution.
- Waste is a challenge and opportunity, infrastructure needed.
- Platform for exchange on existing best practices between industry and academia.
- Regulations are in place, implementation is lacking.
- Improvement needs time, start early.
- Doable, cheap wastewater treatment is to be promoted.

11.3 Capacity Development and Knowledge Management in the Field of Water Use and Management in the Textile Finishing Industry

(H. Krist)

To assure the use and further development of the research results of the InoCottonGROW project, a systematic strategy to put the results and findings into added value is necessary.

The operating knowledge management comprises the interconnectedness between knowledge, action and competence. The awareness about which knowledge and capabilities are needed to improve the competitiveness is important to develop structures and processes to make an enterprise fit for a knowledge-based competition.

Challenges

- In many cases, producers have a substantive knowledge gap on sustainable environmental and chemical management. Especially the knowledge and experiences of up to date wastewater treatment, solid waste management, and water & energy efficiency measures are insufficient.
- The assistance provided by leading brands to strengthen the capacities in the producing companies is often limited to awareness campaigning and one-day trainings, which can be barely sufficient for a substantial change process. For most brands, capacity development activities is limited to piloting and large scale rollout is rare.
- There is a lack of competent local service providers for trainings and implementation.

Solutions

- Harmonize existing training modules based on a jointly agreed standard, publication of best available techniques and good practices to set benchmarks.
- Add wastewater treatment and waste water sludge management to the chemical management toolkit.
- Explore and evaluate the experiences of the ongoing capacity development projects to make use of the lessons learnt.
- Develop and / or make use of e-learning concepts, webinars and other forms of innovative knowledge exchange (like an informed choice matrix), seek for university cooperation.

The following four levels of capacity development interventions are key:

Enabling Environment

The enabling environment represents the broad context within which development processes take place. Sound policies, high levels of commitment, effective coordination, and a stable economic environment are important contributors to an enabling environment which can greatly increase prospects for success.

Attempts to effect change at the enabling environment level generally take a considerable length of time given the nature of the issues being addressed policies, structures, attitudes, values etc. While not all capacity development initiatives will seek to effect change in the enabling environment, they will need to be sensitive to factors at this level which may have an impact (positive or negative) on initiatives which are focused primarily on the sectoral, organizational, or individual level.

Sector / Network Level

This reflects an increasing awareness of the importance of coherent sector policies, strategies and programming frameworks, as well as effective coordination within and across sectors. Capacity development initiatives at this level may focus on policy reform, improvements in service delivery, or increased coordination among institutional actors.

Organisational Level

Capacity development interventions at this level will usually seek to promote synergies among organizations and may be designed to contribute to change at the sectoral or enabling environment level, e.g. more effective integration of activities within the sector, and the promotion of new policies based on the innovative practices of individual organizations or networks.

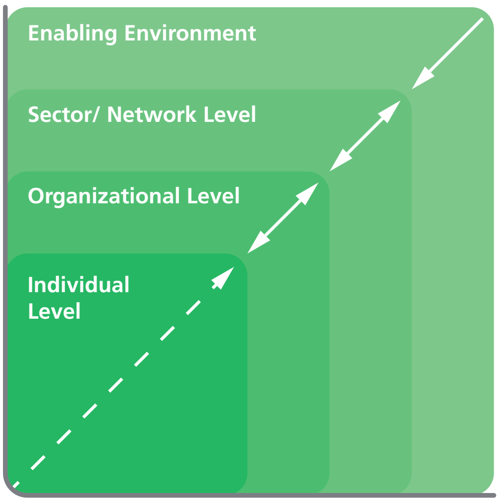


Figure 11.2: Capacity Development: Conceptual Framework (CIDA, 2000).

Individual Level

The individual capacities of concerned operational staff, operational managers as well CEOs has to be strengthened through appropriate trainings and exchange of experiences. A network of national and regional master- and factory trainers should be promoted by Training-of-Trainers measures.

The diagonal axis in the framework (Figure 11.2) highlights the importance of the links among the various capacity dimensions and the importance of thinking in multi-dimensional terms ('zooming in and out' to use the UNDP language). This helps development planners and practitioners to assess opportunities and constraints at various levels, their potential impact on one another, and to determine the most appropriate level(s) or type(s) of intervention. Interventions, for example, may 'zoom in' on a particular level (e.g. support for an organizational change process) or alternately seek to address a development issue(s) across several levels.

WWF has taken the initiative in ILES (https://www.wwfpak.org/our_work_/water_/iles/) with the International Labour Organization (ILO). Recently, GIZ has launched new projects to further support the textile industry in Pakistan and elsewhere:

- FABRIC: Promoting Sustainability in the Textile and Garment Industry in Asia (https://www.giz.de/en/downloads/giz2019_en_FABRIC_Asia_Factsheet.pdf.pdf)
- LSP: Labour Standards Programme (https://gender-works.giz.de/competitions2020/pakistan-inspiring-change-women-in-action-in-the-textile-garment-industry-of-punjab/)

These projects should be actively encouraged to use and disseminate the results generated in InoCottonGROW.

However, based on the in-depth analysis conducted within InoCottonGROW it is obvious that far more ambitious approaches are needed to set the global framework for sustainable cotton-textile production. The role of consumers is critical since national authorities are currently hardly in a position to enforce existing standards in many Asian textile producing countries.

12 PUBLICATIONS OF InoCottonGROW

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2021

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Baumann C. (2017): Kooperation mit Schwellenländern – am Beispiel der Textilindustrie in Pakistan. Vortrag auf dem VIU-Verbandstag, 20.11.17, Berlin.

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Heß O., Korger M., Mahltig B., Weber F.-A, Freericks H. (2020): Reactive Dyeing of Cotton: Reducing the Water Use by Implementation and Application of Efficient and Advanced Dyeing Chemicals and Technologies. Poster presented at Poster Talk 07, 35th International Cotton Conference Bremen – The hybrid edition 2021, Mar. 17-18, 2021, Bremen, Germany. https://cotton-conference-bremen.de/talque/lecture-list/

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Nawrath F., Baumann C., Weber F.-A. (2017): InoCottonGROW – Water Footprint of the Cotton-Textile Industry in Pakistan, 1 min-Trailer available on YouTube, https://youtu.be/X2Oyj_dGZgA

Doctoral Theses

Becker R. (2021): Modeling climate change impacts on agricultural water demand and productivity. Doctoral thesis, Department of Applied Geosciences, TU Darmstadt (Supervisor: Prof. Dr. Christoph Schüth).

Master Theses

2020

Hossain Chowdhury, A. (2020): Overview on textile dyeing process uses in a company in Gazipur, Bangladesh. Master thesis at Hochschule Niederrhein, University of Applied Sciences, Textile and Clothing Technology, Moenchengladbach, Germany (Mentor Prof. Dr. Boris Mahltig).

Hossain A (2020): Comparison of batch-dyeing and spin-dyeing process. Master thesis at Hochschule Niederrhein, University of Applied Sciences, Textile and Clothing Technology, Moenchengladbach, Germany (Mentor Prof. Dr. Boris Mahltig).

Hossain A. (2020): View on water processes in dyeing of cotton fabrics. Master thesis at Hochschule Niederrhein, University of Applied Sciences, Textile and Clothing Technology, Moenchengladbach, Germany (Mentor Prof. Dr. Boris Mahltig).

Islam A. (2020): Ecological aspect of textile printing. Master thesis at Hochschule Niederrhein, University of Applied Sciences, Textile and Clothing Technology, Moenchengladbach, Germany (Mentor Prof. Dr. Boris Mahltig).

Islam N. (2020): Waste water management and safety issues in textile production in Bangladesh. Master thesis at Hochschule Niederrhein, University of Applied Sciences, Textile and Clothing Technology, Moenchengladbach, Germany (Mentor Prof. Dr. Boris Mahltig).

Muhammad Humayun Naseem Awan (2020): Investigating water productivity for cotton fields at Mungi Distributary area. Master Thesis at University of Agriculture Faisalabad, Pakistan (supervisor: Prof. Dr. Allah Bakhsh).

Muhammad Zaman Khan (2020): Evaluation of cotton water productivity under drip irrigation. Master Thesis at University of Agriculture Faisalabad, Pakistan (supervisor: Prof. Dr. Allah Bakhsh)

2019

Ansar Hayat (2019): Performance evaluation of drip irrigation system for cotton fields. Master Thesis at University of Agriculture Faisalabad, Pakistan (supervisor: Prof. Dr. Allah Bakhsh).

Muhammad Akmal Fareed (2019): Evaluation of irrigation efficiency at cotton fields in Mungi Distributary area. Master Thesis at University of Agriculture Faisalabad, Pakistan (supervisor: Prof. Dr. Allah Bakhsh).

Muhammad Nauman Shafiq (2019): Simulating cotton yield using AquaCrop model for Mungi Distributary area. Master Thesis at University of Agriculture Faisalabad, Pakistan (supervisor: Prof. Dr. Allah Bakhsh).

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Baumann C. (2018): Anaerobic Digestion of Desizing Wastewater in Pakistan. Master thesis, Chair of Environmental Engineering, RWTH Aachen University (Mentor: Frank-Andreas Weber, Supervisor: Prof. Dr. Johannes Pinnekamp, Dr. Regina Haußmann).

Diponker K. (2018): Water Management of Textile Industries in Bangladesh. Master thesis at Hochschule Niederrhein, University of Applied Sciences, Textile and Clothing Technology, Moenchengladbach, Germany (Mentor Prof. Dr. Boris Mahltig).

Bachelor Theses

More than 10 Bachelor Theses were supervised within InoCottonGROW.

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Reducing the Water Footprint of the Global Cotton-Textile Industry towards the UN Sustainable Development Goals