# Policy Paper 49

# Economic Impact of Subsurface Drainage Technology

## *Institutional and Policy Imperatives for Upscaling*

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ICAR – NATIONAL INSTITUTE OF AGRICULTURAL ECONOMICS AND POLICY RESEARCH

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Kumar S, P S Birthal, S Kumar and R K Yadav. 2025. Economic Impact of Subsurface Drainage Technology: Institutional and Policy Imperatives for Upscaling. Policy Paper 49, ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi.

**Published**
February 2025

**Published by**
**Dr P S Birthal**
Director
ICAR-National Institute of Agricultural Economics and Policy Research (NIAP)
New Delhi-110012



Suresh Kumar, Satyendra Kumar, and RK Yadav are with ICAR-Central Soil Salinity Research Institute, Karnal, Haryana; and Pratap Singh Birthal is with ICAR-National Institute of Agricultural Economics and Policy Research, New Delhi. The views presented in this policy paper are those of the authors and do not necessarily represent the official position of the institutions they belong to.

**Printed at**
M/s Chandu Press, 469, Patparganj Industrial Estate, Delhi 110 092.

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# Preface

Sustaining livelihoods in fragile environments, characterized by land degradation amidst the increasing threat of climate change, is a significant challenge. Soil salinity and other forms of land degradation severely affect crop yield and food supply. Hence, both preventive and curative strategies are essential for managing salt-affected and waterlogged saline soils. To effectively promote such strategies, policymakers need robust evidence on their socio-economic impacts.

This study provides evidence of the economic impact of subsurface drainage technologies. In addition, it identifies constraints faced by farmers and project implementation agencies during the execution and operation of the subsurface drainage system. By highlighting these challenges, this study offers valuable insights into the practical difficulties in implementing strategies for reclamation of waterlogged saline soils.

The authors express their gratitude for the support received from various individuals, including Dr Rajni Jain, Dr Ankita Kandpal, Dr D S Bundela, and Dr Subhasis Mandal. The authors extend their sincere appreciation to Dr K Thimmappa, ICAR-Agricultural Technology Application Research Institute, Bengaluru, and Dr Ranjay K Singh, Division of Agricultural Extension, ICAR, New Delhi for their valuable comments and suggestions. The financial support provided by the ICAR-NIAP under the network project “Ecosystems, Agribusiness and Institutions” is gratefully acknowledged.

We hope that this study will be useful for policymakers and other stakeholders engaged in designing and implementing subsurface drainage systems. The recommendations presented in this study are likely to garner the necessary human, financial, and institutional support for reclaiming waterlogged saline soils.

Authors

# Executive Summary

Waterlogging and soil salinity often occur simultaneously and can significantly affect crop yields, farmers' livelihoods, and the national food security. In India, approximately 6.74 million hectares of land, predominantly concentrated in the northwest and coastal regions, is salt-affected. Severe salinity can reduce crop yields by up to 80%, and may render land unsuitable for cultivation. Soil salinity is expected to be exacerbated by several factors such as the increasing use of saline groundwater, inappropriate irrigation practices, and climate change.

Subsurface drainage (SSD), a community-based technology, is a promising solution for reclamation of waterlogged saline soils to restore their production potential. However, the adoption of SSD remains a significant challenge due to several socio-institutional and economic factors. Despite its potential to treat 2.95 million hectares of salinity-affected land, only 0.074 million hectares (2.57%) have been treated thus far. However, in Haryana and Maharashtra, the adoption rates of SSD are estimated to be higher, 16.65% and 6.34%, respectively.

*This study has evaluated the economic impact of SSD, focusing on the rice-wheat cropping system in Haryana, and sugarcane in Maharashtra. The key findings are as follows:*

***SSD significantly avoids yield loss:*** There are significant yield advantages associated with SSD, to the extent of 30.9% for wheat and 46.5% for paddy. However, the most dramatic advantage is observed for sugarcane (62.4%).

***Benefits of SSD extend beyond crop yield advantage:*** Besides avoiding yield loss, SSD offers numerous environmental benefits. It enhances cropping intensity, soil health, organic carbon content, and microbial activity and reduces soil electrical conductivity. The increased organic matter functions as a carbon sink, mitigating $CO_2$ emissions.

***Economic benefits of SSD are quite significant:*** An ex-post assessment of the economic benefits of SSD during the period 1998–2023 could generate a surplus of Rs 38,250 million from paddy, an average of Rs 1471 million per annum. The impact of SSD on wheat production was notable, with a total surplus of Rs 16,870 million or Rs 649 million per annum. When considering both the rice and wheat, the cumulative economic benefits from SSD are estimated as Rs 55,120 million, which is approximately Rs 2120 million per annum. The adoption of SSD in sugarcane has resulted in significant economic benefits of Rs 29,660 million during 2018-2023 or Rs 4943 million per annum. Depending on the improvements in the adoption rate, the benefits of SSD technology will increase in the future.

***Benefits of SSD are not restricted to farmers alone:*** By influencing production and prices of crops, implementation of SSD results in significant benefits for producers as well as consumers. The distribution of its benefits in the rice-wheat cropping system, is relatively balanced between producers and consumers. Nevertheless, in the case of sugarcane, its benefits are skewed towards producers.

***Progress in implementation of SSD has been slow:*** Despite significant economic benefits, adoption of SSD has been slow; thus far, only 2.57% of salinity-affected land has been treated. The primary constraints include insufficient machinery and equipment, inadequate funding for SSD projects, limited operational windows, low farmer awareness, and weak financing and institutional frameworks. Even in areas where SSD has been implemented, its performance has been suboptimal, owing to several factors, including overreliance on government support. This top-down approach results in low farmer participation in operation and maintenance of the SSD system. In addition, the problem of free riders and conflicting objectives of farmers complicate the successful application of this technology.

*Considering the likely increase in salt-affected areas in the future, there is an urgent need for a comprehensive approach to restore the productive potential of water-logged saline soils. The key issues that merit attention are as follows:*

***Dedicated budgetary support for SSD implementation***: Subsurface drainage technology requires substantial upfront capital investment. This includes the cost of specialized machinery, such as trenchers and pipe-laying equipments, as well as drainage pipes and filtration materials. Governments, recognizing its long-term benefits, may offer subsidies, grants, or low-interest loans to encourage its implementation. Financial institutions can play a crucial role in providing credit facilities. Public-private partnerships may also contribute to the financing of SSD projects, especially in regions where improved drainage is contemplated to result in substantial socioeconomic impacts.

***Address technical and logistical issues:*** The Implementation of SSD is affected by a shortage of specialized machinery, limited operational windows, and a lack of micro-level database on waterlogged saline soils. Improved planning is essential to maximize the use of limited operational windows. Furthermore, comprehensive soil mapping initiatives would provide the necessary micro-level data to inform more effective SSD designs and implementations.

***Regional targeting of SSD:*** Comprehensive regional assessments should be conducted to develop tailored subsurface drainage strategies that consider factors such as soil characteristics, topography, climate patterns, and water management infrastructure to ensure the most effective and sustainable drainage solutions. Collaborative efforts among government agencies, research institutions, and private sector can foster innovation and knowledge-sharing.

***Ensure community participation:*** In smallholder agriculture, implementation of SSD projects requires participation of farming communities. However, these often suffer from low community participation and free-riding problems. Thus, participatory approaches are crucial to better align the projects with community needs and priorities, foster a sense of ownership, and manage free rider problems.

***Manage conflicts:*** The diversity of crop choices and conflicting water needs of farmers comprise a complex set of challenges in implementation of SSD system. This calls for the development of cooperative approaches and for balanced water-management strategies to accommodate the varying requirements of different crops. The implementation of flexible drainage systems involving the use of controllable drainage structures or smart irrigation systems can be fine-tuned to satisfy the specific requirements of different crops at various growth stages. Additionally, promoting crop diversification aligning with drainage capabilities can help distribute water demands more evenly throughout the year and reduce the peak pressures on the system. Establishing water-user associations to manage shared resources can foster cooperation among farmers and provide a platform for collective decision-making.

***Capacity building:*** Enhancing the knowledge about the SSD system and the best practices in its installation and maintenance can significantly improve its adoption and effectiveness. Establishing demonstration sites, conducting regular training programs, and leveraging digital technologies for knowledge dissemination can play a significant role in this regard.

***Promote farmers' collectives:*** Subsurface drainage systems are technically implemented in an area with a physiographic setting with a common water outlet, spanning fields of multiple farmers, and necessitating substantial initial investment and coordination. Farmers' collectives, such as cooperatives and Farmer Producer Organizations (FPOs), can serve multiple purposes in SSD projects. First, they can function as unified entities to secure funding from various sources. Second, they can ensure an equitable distribution of benefits and costs among participating farmers, addressing potential concerns regarding uneven impacts across fields. In addition, farmer collectives can coordinate maintenance efforts to ensure the long-term sustainability of SSD systems.

***Enhancing synergy among related policies:*** The successful implementation of SSD projects requires integration with programs related to irrigation, soil conservation, crop diversification, and climate change adaptation. Enhancing coordination among various government departments, research institutions, and non-governmental organizations is essential to maximize the impact of SSD.

# 1 Introduction

Waterlogging and soil salinity often occur simultaneously, causing substantial losses in agricultural production and consequently affecting the livelihoods of farming communities (Barrett-Lennard 2003; Krauss et al. 2014; Martins et al. 2024; Shekhawat 2007). Globally, waterlogging affects over 1700 million hectares of land, resulting in an annual crop loss of US$74 billion (Kaur et al. 2020). As the population continues to increase, additional irrigation potential must be created to produce more food (Walia and Kaur 2023). However, the expansion of irrigation, if not managed judiciously, may exacerbate existing environmental concerns, including soil salinization (Singh 2018). Globally, approximately 45 million hectares of land are affected by irrigation-induced salinity (Ghassemi et al. 1995) and more than one-third of all irrigated lands suffers from salinization or waterlogging (Houk et al. 2006).

In India, salt-affected areas are estimated to be 6.74 million hectares, of which 3 million hectares are severely affected by waterlogging and salinity (2 million hectares in arid and semi-arid alluvial regions of northwest India and 1 million hectares in coastal and black cotton heavy or vertisol soils) (Singh and Lal 2018). The consequences of waterlogging and soil salinity can be severe, causing a decline in crop yields of up to 80% (Shabala 2011). In some cases, these conditions render the land unsuitable for cultivation (Singh and Lal 2018). The annual crop loss (wheat, rice, sugarcane, etc.) in India due to waterlogging is estimated over two million tons (Sultana et al. 2010). Waterlogging and salinity are expected to worsen because of the increasing use of saline or alkaline groundwater, inappropriate irrigation practices in canal command areas, and climate change (Sharma and Singh 2017; Mandal et al. 2019; Eswar et al. 2021). Projections suggest that the area affected by salinization may increase by 16.2 million hectares by 2050 (ICAR-CSSRI 2015).

Hence, there is an urgent need to restore salt-affected soils. One promising approach is the implementation of subsurface drainage (SSD) system (Datta and de Jong 2002; Raju et al. 2015). This involves the installation of a perforated pipe network at a desired soil depth to carry excess water present in the crop root zone. The SSD network maintains a water table below the root zone and creates a favourable environment for crop growth and restoration of land productivity. Soluble salts also move along with water through the SSD pipes.

Therefore, SSD improves physicochemical conditions of the rhizosphere ensuring sustainable crop growth. The SSD offers multiple benefits, including improved soil health, crop yield, and other ecosystem services. Moreover, the restoration of degraded lands with SSD aligns with the broader Land Degradation Neutrality target of restoring 26 million hectares of degraded land by 2030 (Singh and Tewari 2022).

Several studies have assessed the effects of SSD technology on crop yield, cropping intensity, and financial returns employing both before and after, and with and without approaches (Datta and de Jong 2002; Raju et al. 2015). Nonetheless, the results from most of these studies are restricted to the farm level, limiting the benefits to the individual or village level. However, these do not reflect broader socioeconomic and regional benefits. It is important to note that technology adoption shifts the supply curve, leading to changes in market dynamics or prices that affect the welfare of both producers and consumers.

Using the economic surplus approach, we evaluate the impact of SSD, considering the direct benefits for adopting farmers and indirect benefits for consumers. This allows for a comprehensive and accurate evaluation of the impact of SSD, enabling policymakers and stakeholders to make informed decisions regarding its implementation and upscaling. Specifically, this study addresses the following questions:

- What are the potential economic advantages associated with the implementation of subsurface drainage technology?
- What factors impede the implementation of subsurface drainage technology?
- What institutional and policy measures are necessary for the widespread adoption of this technology?

# 2

# Extent of Waterlogged Saline Soils

## 2.1 Estimates of waterlogged saline land at national level

The disruption of the equilibrium between groundwater depletion and replenishment is a significant factor contributing to waterlogging and salinity. This imbalance occurs due to seepage from canal irrigation networks and/or unsustainable irrigation management practices (i.e., excessive use of canal water). The absence of a natural or well-designed drainage network further exacerbates this problem as it fails to efficiently remove excess water from the soil (Temesgen 2018). These factors, combined with the poor-quality groundwater and inadequate irrigation management techniques, create conditions conducive to waterlogging and soil salinity (Datta and de Jong 2002).

During the nineteenth and early twentieth centuries, the problem of waterlogging and soil salinity in India was almost negligible because of the 'barrage-controlled' irrigation systems. These systems were designed to ensure even equity in the distribution of water across the vast areas especially for low rainfall regions such as Punjab and Haryana to minimize the adverse effects of droughts and famines (Datta and de Jong 1997). Historically, water levels were maintained at a safe depth prior to the advent of extensive irrigation. The need to achieve food self-sufficiency compelled a greater emphasis on irrigation development (GoI 1972a). Investment in irrigation and irrigated area increased considerably since 1950–51 (Narayanamoorthy 2022). Nonetheless, in the parts of Indo-Gangetic plains, the irrigation expansion has been accompanied by waterlogging (Berkoff 1990).

The Royal Commission on Agriculture, 1928, recognized the importance of integrating drainage systems into irrigation projects. However, this recommendation was overlooked despite subsequent recommendations from the Second Irrigation Commission (1972b) and the National Commission on Agriculture (1976). The neglect of drainage became particularly pronounced during the 'Green Revolution' period primarily because of fiscal constraints (Datta and de Jong 1997; Gopalakrishnan and Kulkarni 2007; Jayan and Sathyanathan 2010). Gupta (2002) highlighted that the non-integration of drainage in irrigation development had been a common practice to maintain a favourable benefit-cost ratio for irrigation projects. It was argued that drainage is not an immediate necessity at the beginning of irrigation projects and was can be addressed only after the negative consequences become apparent. This is exemplified by the formation of "*Mitti Bachao Samities*" (save the soil committees) in the Tawa command area (Gupta 2002). Additionally, drainage projects faced required significant upfront investment and collective approach (Roy and Singh 2024). The greater payback period and uncertain returns on investment in drainage systems further complicated the decision-making processes (Datta and de Jong 1997). Consequently, drainage has received considerably less attention in irrigation expansion initiatives (Satyanarayana and Boonstra 2007).

India faces significant challenges in terms of waterlogging and soil salinity. Waterlogging affects approximately 4.5 million hectares, nearly equally distributed between canal command and non-canal command areas (Bhattacharya and Michael 2003). Salt-affected soils, both saline and sodic, cover an even larger area of 6.73 million hectares.

**Table 2.1. Area under waterlogged and/or saline soils in India**

| Particular | Area (million hectares) | Reference |
|---|---|---|
| Waterlogged area (both irrigated and unirrigated) | 2.46 | GoI (1976) |
| Waterlogged area (both irrigated and unirrigated) | 4.84 | GoI (1972) |
| Waterlogged areas (canal command and outside of it) | 4.5 | Gopalakrishnan and Kulkarni (2007) |
| Waterlogging under irrigated commands | 2.46 | GoI (1991) |
| Waterlogged area | 3.3 | Bhattacharya (1992) |
| Waterlogged area | 3.95-16 | Bhattacharya and Michael (2003) |
| Waterlogging in irrigated commands<br>Salt-affected in irrigated commands | 1.72<br>1.03 | ISRO (2009) |
| Waterlogged-saline soils | 3.0 | Kamra et al. (2019) |
| Waterlogged soils | 5.0 | Dandekar and Chougule (2010) |
| Waterlogged soils | 5.5 | Jaglan and Qureshi (1996) |

Waterlogging and soil salinity may occur independently (for instance in parts of Maharashtra, Karnataka and Gujarat salinity arises by due to salts in irrigation water, particularly in the heavy texture soils) or in combination (e.g., parts of Haryana having shallow-saline groundwater). Nevertheless, there is a lack of accurate estimates for area affected by waterlogged saline soils. The estimates vary from 3.95 to 16 million hectares for waterlogged soils and 3.3 to 10.9 million hectares for saline soils (Bhattacharya and Michael 2003) (Table 2.1). Additionally, the spatial distribution of affected land is often not clearly defined in available data. Projections suggest an increase in salt-affected soils to 16.2 million hectares and 20 million hectares by 2025 and 2050, respectively (Singh and Lal 2014; ICAR-CSSRI 2015; Kamra et al. 2019).

## 2.2 State-wise estimates of area treated with subsurface drainage technology

This section examines the causes of waterlogging and salinity in the severely affected states. The section also focuses on identifying the factors responsible for waterlogging and salinity. The state-wise estimates of land treated with subsurface drainage technology and the potential area affected by waterlogging and salinity are presented in Table 2.2.

### 2.2.1 Haryana

Approximately 393,096 hectares in Haryana are affected by waterlogging and salinity of which 69,788 hectares are severely affected (water table depths of $<1.5$ meters) (GoH 2023). In the absence of appropriate reclamation measures, severely salt-affected soils may eventually become unsuitable for crop cultivation (Tripathi, 2011). To address these concerns, the Haryana Operational Pilot Project (HOPP) has implemented subsurface drainage systems in farmers' fields (Bundela et al. 2020).

The implementation of SSD system requires a comprehensive approach that encompasses the identification of problematic soils, field investigations, design and layout of drainage systems, and availability of funds. The selection of sites for SSD projects is primarily determined by two key factors: the presence of a surface drain for effluent disposal, and the willingness of farmers to establish farmers' drainage societies. These are supposed to be instrumental in the operation and maintenance of the drainage pumping units. Since its inception in 1996, approximately 11,629 hectares have been rehabilitated through SSD (GoH 2024). To further facilitate farmer participation, the HOPP has developed an online registration portal, which elicited interest from 4,821 farmers willing to reclaim 11,190 hectares in the future (GoH 2024).

### 2.2.2 Maharashtra and Gujarat

Estimates of areas affected by waterlogging and salinity in Maharashtra, depending on the source, vary significantly from 110000 to 426408 hectares (Dandekar and Chougule 2010; ISRO 2009). Soil salinity presents a complex environmental and agricultural challenge, particularly in Sangali district, owing to excessive irrigation, inadequate drainage, saline water, and arid climate. This issue is particularly pronounced in lift irrigation command areas, where black cotton soils are susceptible to both waterlogging and salinization (Gupta 2007a). The cultivation of water-intensive crops, notably sugarcane, in heavy, low-permeability soils in the Deccan Canal command area has significantly contributed to land degradation (Gupta 2007b).

Since the establishment of cooperative sugar factories in during the 1960s, farmers in southwestern districts such as Kolhapur, Pune, and Sangli have prioritized sugarcane cultivation. Over time, continuous cultivation and excessive water use has resulted in waterlogging and salinity. Consequently, sugarcane yield in Sangli district significantly decreased from 150 ton/ hectare in the 1970s to 50-60 ton/ hectare in the 2000s (Rathod et al. 2011). The Krishna River, the primary source of irrigation, has been extensively utilized through pump irrigation schemes (Gopalakrishnan and Kulkarni 2007). Addressing waterlogging and salinity issues in deep black vertisols is challenging (Kamra 2007). The adoption of SSD is hindered by its high costs and insufficient institutional support. Since 2006, public-private partnership has been promoted to implement SSD (Chinchmalatpure et al. 2020).

Waterlogging and salinity issues in Gujarat are complex and stem from both anthropogenic and natural causes. Seepage from unlined or damaged canals is a significant contributor, as water seepage from these irrigation systems and accumulates in nearby areas. This problem is exacerbated by an insufficient drainage. Groundwater overexploitation, often due to excessive pumping for irrigation, lowers the water table and results in saltwater intrusion in coastal areas. Overuse of irrigation, particularly in water-intensive crops, also leads to an increase in the water table and subsequent waterlogging (Singh et al. 2000). Low-lying areas are prone to waterlogging. In Gujarat, the estimates of affected soils vary from 265, 000 to 480,000 hectares (ISRO 2009; Dandekar and Chougule 2010).

### 2.2.3 Rajasthan

The Chambal irrigation project in Rajasthan, covering a command area of 385,000 hectares, successfully brought irrigation to 229,000 hectares. However, the implementation of irrigation projects in the 1960s caused salinity and waterlogging problems. By the 1970s, approximately 160,000 hectares was affected by waterlogging and 25,000 hectares by salinity. To address these problems, the Rajasthan Agricultural Drainage Research (RAJAD) project was launched in 1992 to implement the SSD system. The financial assessment of the RAJAD project revealed positive outcomes, with cost-benefit ratios ranging from 1.28 to 2.87, and internal rates of return ranging between 18% and 35% (RAJAD 2001). To ensure the sustainability of the project, Gopalakrishnan and Kulkarni (2007) suggested establishing water user associations (WUAs) for capacity building and training of farmers. Additionally, involvement of the private sector in SSD installation was encouraged, particularly in cases where farmers were willing to contribute financially.

*Indira Gandhi Nahar Pariyojana* (IGNP), one of the world's largest irrigation projects, aimed to transform desert land into agriculturally productive land. However, owing to various factors such as high seepage losses and the absence of natural drainage, approximately 208,000 hectares in the IGNP command area has been affected by waterlogging and salinity (Moharana et al. 2020; Chaudhari et al. 2024). The estimates of salt-affected areas in the state vary ranging from 8409 to 396,000 hectares (Tewari et al. 1997; Mandal and Sharma 2010; ISRO 2009; Dandekar and Chougule 2010; Moharana et al. 2020).

### 2.2.4 Karnataka

In Karnataka, the Tungabhadra Project (TBP) area led to waterlogging and soil salinity. Since late 1970s, the extent of waterlogging and soil salinization increased at a rate of 3000-6000 hectares per year (Manjunatha et al. 2004; Swarajyalakshmi et al. 2008). Within the command area, the groundwater table rose at a rate of 10 cm annually. Furthermore, the use of poor-quality groundwater for irrigation has resulted in soil salinization (Manjunatha et al. 2004). As part of land reclamation efforts, the main canal and its distributaries were lined and open or tile/pipe drains were installed to eliminate excess water from the surface or root zone. Additionally, desilting and deepening of natural brooks (locally referred to as *nalas*) and drains have been undertaken. The Command Area Development Authority (CADA) managed to reclaim 2500 hectares of salt-affected land by implementing subsurface tile drains (Manjunatha et al. 2004).

At the national level, the scale of the challenge remains immense, as only 2.57% of the total salt-affected area has been treated thus far. This underscores the importance of continued investment, research, and policy support for upscaling the SSD technology.

**Table 2.2. State-wise area treated with subsurface drainage technology and potential salt-affected area**

| State | Irrigation commands | Treated area (hectare) | Potential area for treatment |
|---|---|---|---|
| Haryana | Western Yamuna Canal, Bhakra Canal, Gurgaon and Agra Canal | 11,629 | Potential (1.5-3.0 m bgl): 323190 hectares; Critical (<1.5 m bgl): 69855 hectares (GoH 2023) |
| Rajasthan | Chambal, *Indira Gandhi Nahar Pariyojana* | 16,500 | 396000 hectares (Tewari et al. 1997); 22268 hectares (Mandal and Sharma 2010); 350000 hectares (Dandekar and Chougule 2010); 208000 hectares (Moharana et al. 2020) |
| Punjab | Sirhind Canal and Sirhind feeder canal | 4,050 | 85,000 hectares in Faridkot and Muktsar district (Shakya and Singh 2010); 1090000 hectares (Dandekar and Chougule 2010) |
| Maharashtra | Lift irrigation commands of the Krishna & Godavari rivers Neera canal command | 6,840 | 426408 hectares (ISRO 2009); 110000 hectares (Dandekar and Chougule 2010) |
| Karnataka | Upper Krishna, Tungabhadra Malprabha, Ghatprabha | 32,150 | 1,01,149 hectares (GoI 2013); 10,000 hectares (Dandekar and Chougule 2010) |
| Gujarat | Mahi-Kadana, Ukai-Kakrapar, | 1,300 | 2,65,000 hectares (ISRO 2009); 480000 hectares (Dandekar and Chougule 2010) |
| Andhra Pradesh and Telangana | Lower Krishna, Upper Godavari, Nagarjuna Sagar, Krishna Western Delta | 1,200 | 28267 hectares (ISRO 2009); 340000 hectares (Dandekar and Chougule 2010); 40,000 hectares (Satyanarayana and Boonstra 2007) |
| Madhya Pradesh | Barna, Tawa, Chambla, | 950 | 60000 hectares (Dandekar and Chougule 2010); |
| Kerala | Small projects in Kerala | 250 | 12330 hectares (ISRO 2009); 60,000 hectares (Dandekar and Chougule 2010) |
| National | Total | 74,869 | |

*Source: ICAR-CSSRI, Karnal.*

# 3 Cost of Installation of Subsurface Drainage System

## 3.1 Subsurface drainage technology

The main objective of SSD technology is to remove excess water and salts from the root zone, thereby improving the soil conditions for crop growth. This technology has been widely adopted in several countries including Egypt, the United States, Pakistan and India (Ritzema 2009; Kamra 2015; Tiwari and Goel 2017). In India, implementation of SSD was pioneered by ICAR-CSSRI towards the 1980s, initially in Haryana, and later in Rajasthan, Gujarat, Punjab, Andhra Pradesh, Karnataka, and Maharashtra (Kamra 2015; Tiwari and Goel 2017).

The design of an SSD system is determined by various factors such as rainfall, irrigation practices, hydrogeology, and soil texture. The depth of drain typically ranges from 1.5 to 2.0 m in alluvial plains and 0.9-1.2 m in vertisols, while the length of lateral drain may vary from 200 to 500 meters, with an optimal length of approximately 300 meters.

## 3.2 Cost of installation

The design and implementation of the SSD system requires careful consideration of various factors to ensure its optimal operational efficiency and cost effectiveness. Typically, a model operational SSD block of 40 hectares is considered as a reference. The spacing of lateral drains plays a crucial role in determining the cost of SSD installation. The major cost components include field surveys, preparation of detailed project reports, drainage materials (pipes and filters), structures (manholes), installation, dewatering, supervision, monitoring and evaluation, and farmer training.

The installation cost of SSD varies depending on soil texture. The installation cost is higher in heavy-textured soils (Table 3.1). Thus, installation cost between Maharashtra and Haryana can be attributed to variations in machinery type, soil characteristics, drain spacing, and drainage outlet conditions (Kamra and Sharma 2016). Among the various cost components, pipes and filters account for the largest share, 46.8% and 41.6% of the total cost in heavy- and medium-texture soils, respectively. The installation cost comprises 34% and 28.4% of the total for heavy and medium-texture soils, respectively.

**Table 3.1. Cost of installation of subsurface drainage system in heavy and medium texture soils (Rs per hectare)**

| Sr. No. | Component | Heavy texture soil (30 m drain spacing) | Medium texture soil (67 m drain spacing) |
|---|---|---|---|
| 1 | Detailed project report | 3599 (2.6) | 2993 (2.5) |
| 2 | Pipes and filters | 65713 (46.8) | 50724 (41.6) |
| 3 | Fittings | 3127 (2.2) | 2450 (2.0) |
| 4 | Structures | 3450 (2.5) | 11997 (9.9) |
| 5 | Installation cost | 47680 (34.0) | 34608 (28.4) |
| 6 | Dewatering cost | 0 (0.0) | 5356(4.4) |
| 7 | Supervision charges | 4199 (3.0) | 3492 (2.9) |
| 8 | Contingencies | 5999 (4.3) | 4989 (4.1) |
| 9 | Manpower | 3179 (2.3) | 2189 (1.8) |
| 10 | Monitoring and evaluation charges | 2399 (1.7) | 1996 (1.6) |
| 11 | Farmers' training | 1000 (0.7) | 1000 (0.8) |
| 12 | Total | 140345 (100) | 121794 (100) |

*Note: Figures in parentheses show the percentage of the total cost.*
*Source: Kumar et al. (2024).*

4

# Data and Methods

## 4.1 Study area and data

The semi-arid region of the Indo-Gangetic plains faces a significant challenge of waterlogging and soil salinity, which affect approximately 1.0 million hectares in Punjab, Haryana, Northwestern Rajasthan, and Western Uttar Pradesh (Kamra 2007). Approximately 393,096 hectares are affected in Haryana alone, of which 69,788 hectares are severely affected (GoH 2023). This causes substantial crop loss, sometimes as high as 80% (Shabala 2011), forcing farmers to abandon the cultivation on the affected lands. The situation is particularly challenging for resource-poor farmers who find themselves trapped in a "land degradation–poverty nexus" (Barbier and Hoachard 2018).

Subsurface drainage is a potential solution for restoring waterlogged saline lands; however, its implementation requires substantial resources and expertise, and community participation. Given these issues, initiatives to restore salt-affected soils are often funded by states. In Haryana, HOPP has played a leading role in promoting subsurface drainage and successfully rehabilitating over 11,039 hectares of waterlogged saline soils (Bundela et al. 2020).

The deep black vertisols in Maharashtra present a more significant challenge (Kamra 2007). The installation of subsurface drainage requires heavy machinery to work in heavy soils (Kumar et al. 2024). The combination of improper irrigation practices, low hydraulic conductivity of heavy soils, and dry climate has led to an increase in soil salinity. Sangali is one of the most severely affected districts by soil salinity (Padalkar et al. 2012). This problem is particularly acute in black cotton soils irrigated through lift irrigation projects (Gupta 2007a). Even areas not directly in the lift irrigation command have experienced salinization because of the mismanagement of irrigation water, especially in sugarcane cultivation. Sugarcane, a major crop in this region, is a significant contributor to land degradation in the Deccan Canal command area (Gupta 2007b). The implementation of SSD system in vertisols is affected by high cost and insufficient institutional support (Chinchmalatpure et al. 2020). However, since 2006, efforts have been made through public-private partnership to promote SSD.

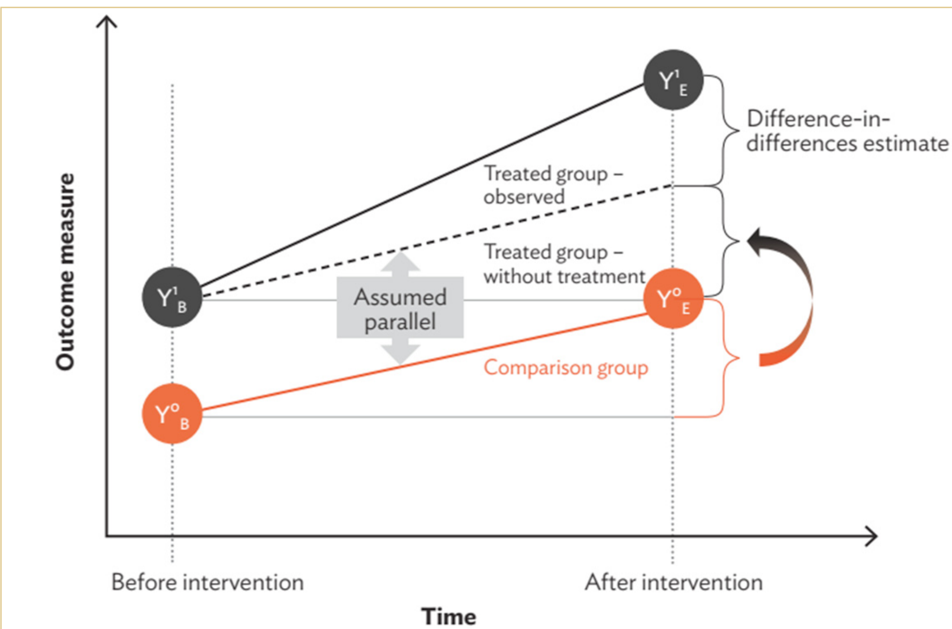
This study followed a multistage sampling approach. Three SSD sites were purposively selected in Haryana: Kanhi, Siwana Maal and Kathura in Rohtak, Jind, and Sonipat districts, respectively. Farmers were chosen from each site, comprising of 20 SSD adopters and 20 control farmers. Thus, a total of 120 farmers were selected. Similarly, a total of 80 farmers were chosen from two sites (Kasbe Digraj and Shirol in Sangali district) in Maharashtra. The investigation covered both pre- and post-SSD situations, and encompassed various aspects, including socio-economic factors, crop production, changes in crop management practices and inputs, and operational issues.

## 4.2 Methods of Estimation

### 4.2.1 Difference-in-difference approach

The Difference-in-Difference (DiD) is used to address selection bias in assessing the impact of any intervention. This quasi-experimental design compares the changes in outcomes over time between a group affected by a specific intervention (treatment group) and a group not affected by the intervention (control group). In the context of SSD, the treatment group consisted of farmers who adopted SSD, whereas the control group consisted of farmers who did not.

**Figure 4.1. Framework of difference-in-difference method**




*Source: White and Raitzer (2017).*

The DiD can be estimated as

$$\text{DiD estimate} = (Y_E^1 - Y_B^1) - (Y_E^o - Y_B^o) \qquad \dots (1)$$

Where, $Y_E^1$ is the value of the outcome of treated group after the implementation of SSD, $Y_B^1$ is the value of the outcome of treated group before the implementation of SSD, $Y_E^o$ is the value of the outcome of control group at the time after the implementation of SSD and $Y_B^o$ is the value of the outcome of control group at the time before the implementation of SSD. By analyzing the differences between treated and control groups before and after SSD implementation, as shown in Equation (1), we can isolate the effect of SSD from other temporal trends or extraneous factors that may influence the outcomes (Figure 4.1). The reliability of DiD estimates hinges on the critical assumption of common trends; that is, in the absence of treatment, both the treated and control groups would have experienced parallel trends in the outcome. If this assumption holds, any deviation from the parallel trend after the intervention can be attributed to SSD. However, in our case, the presence of only one period's pre-intervention observation precludes the execution of the parallel test, because it requires at least two pre-intervention periods for validity (Shikuku 2019). However, to overcome selection bias due to differences, if any, in pre-treatment observable variables, we used the predicted probability of link index (i.e., propensity score) to match the treated group with the control group (Shikuku 2019). Propensity Score Matching (PSM) can reduce selection bias due to confounding factors (Caliendo and Kopeinig 2008). The summary statistics indicate that treated and non-treated farmers are systematically different in some covariates, justifying the application of PSM-DiD (Table A1). In short, DiD in conjunction with PSM can effectively estimate the causal effect of a specific policy on concerned outcomes. Keeping these issues in mind, we employed PSM-DiD to examine to what extent SSD has affected crop yield. The matching methods are designed to estimate the average treatment effect on the treated (ATT), which is the average difference between the outcomes of the SSD-treated group and their counterfactual outcomes.

$$ATT = E\ (Y_i(1) - E\ Y_i(0) | D_i = 1) \qquad \dots (2)$$

Where, $D_i$ is a dummy variable indicating i[th] farmer's SSD status, and $Y_i$ is the outcome variable of i[th] farmer, as a function of $D_i$ The estimated Equation (3) is given below.

$$Y_{it} = \beta_0 + \beta_1 \text{SSD}_{it} + \beta_2 Post_t + \beta_3\ \text{SSD}_{it} * Post_t + \delta \sum X_{it} + \varepsilon_{it} \qquad \dots (3)$$

Where, subscript i denotes the farmer, t represents year, SSD is a dummy for implementation of subsurface drainage technology, Post is a dummy for the post-SSD treatment period, X represents the control variables, and ε is the stochastic disturbance term. The coefficient on $\mathrm{SSD}_{it} * Post_t$ suggests the effect of the SSD.

### 4.2.2 Economic surplus model

The implementation of SSD generates benefits for both farmers (direct) and consumers (indirect). Following Alston et al. (1995), we estimated the economic surplus and the direct and indirect benefits. ESM captures the SSD adoption-induced supply response (per unit cost reduction) through a K-shift parameter (Alston et al. 1995; Wossen et al. 2019).

$$K = \left(\frac{E(Y)}{\varepsilon_s} - \frac{E(C)}{1+E(Y)}\right)\delta A_t \qquad \dots (4)$$

Where, E(Y) is the expected proportionate yield change; $E(C)$ is the expected proportionate cost change; $\varepsilon_s$ is the elasticity of supply; $\delta$ is the probability that research will achieve the expected yield change (Alston et al. 1995), which is usually taken as 1; and $A_t$ is the adoption rate (Alston et al. 1995).

#### 4.2.2.1 Parameters for economic surplus model

#### Adoption rate

Understanding the determinants of technology adoption is essential for formulating effective strategies (Baerenklau and Knapp 2007). Empirical studies have indicated that the adoption trajectory of a new or improved technology typically follows a logistic or sigmoid pattern (Mansfield 1961). In numerous instances, natural resource management necessitates collective action and institutional support (Scherr 2000). For example, implementation of SSD in Haryana is predominantly coordinated by government agencies (Datta 2003; Grewal et al. 2021; Singh et al. 2022). Consequently, its adoption rate is influenced by the availability of resources, including machinery, materials, and technical personnel.

Moreover, the installation of SSD, which is costly and requires technical expertise, is a challenge for resource-poor farmers to implement on an individual or small scale. The installation of SSD system requires a minimum area of 100 ha, as per the HOPP guidelines. Because the movement of salts and water is a dynamic process in the subsoil zone, which sometimes connects even to the regional landscape, individual efforts may not be sufficient to manage waterlogged saline soils. Therefore, a community-based approach is essential. Hence, most irrigation and drainage projects in India are funded by central or state governments (Scheumann and Freisem 2002; Raju et al. 2015).

Thus, the implementation of SSD is determined by the availability of resources, such as machinery, materials, funding, and technical staff available to the implementing agency, and the level of participation of the community. Hence, the adoption trajectory is assumed to be linear and primarily influenced by the targets set by the implementing agency. Keeping these factors in view, based on the past trend (annual area treated under SSD), the future adoption rates were estimated.

### Estimation of cost change

The implementation of SSD leads to an increase in the cost of cultivation (E(C)) because of the cost associated with its installation and an increase in input usages.

$$E(C) = \Delta IC + ACI \qquad ...(5)$$

Where, $\Delta IC$ is the change in cost of cultivation due changes in input-usages, and $ACI$ is the annualized cost of SSD installation.

The cost of installation is the initial investment (IIC), which is annualized for five years.

$$ACI = \frac{IIC * r}{[1-(1+r)]^{-T}} \qquad ...(6)$$

Where, ACI is the annual investment, r (11.5%) is the interest rate, and T is the period in years.

$$\Delta IC = \sum_{i=1}^{n} \left( I^{i}_{before} - I^{i}_{after} \right) * P^{i}_{t} \qquad ...(7)$$

Where, $\Delta IC$ is the change in the cost of cultivation due to the change in input usage (seed, fertilizer, labour and farm machine etc.) due to SSD, and $I^{i}_{before}$ and $I^{i}_{after}$ are the quantities of the i$^{th}$ input per hectare, before and after installation of the SSD, respectively and $P^{i}_{t}$ is the prevailing price of the i$^{th}$ input.

### Estimation of yield change

SSD influences crop yield, which was estimated as

$$E(Y) = \frac{\left( Y^{i}_{after\ SSD} - Y^{i}_{before\ SSD} \right)}{Y^{i}_{before\ SSD}} \qquad ... (8)$$

$Y^{i}_{before\ SSD}$ and $Y^{i}_{after\ SSD}$ represent yield before and after installation of SSD, respectively.

Whether an economy is open to trade or not determines the effects of technology on producer and consumer surpluses. In a closed economy, prices will fall as a result of technological change, thereby increasing production, which will also change the consumer surplus (Kassie et al. 2018). Following Datta et al. (2004), for simplicity and to estimate the total social benefits of SSD, we use the closed-economy model to estimate the total economic surplus. Furthermore, we assume linear demand and supply curves. Following Alston et al. (1995), the incremental changes in producer surplus (ΔPS) and consumer surplus (ΔCS) in the closed-economy framework can be computed as

$$\Delta PS = P_0 Q_0 (K - Z)(1 + 0.5\varepsilon_d Z) \qquad \text{... (9)}$$

$$\Delta CS = Z P_0 Q_0 (1 + 0.5\varepsilon_d Z) \qquad \text{... (10)}$$

In Equation (9) and (10), $P_0$ is the pre-adoption of price of the crop in question, $Q_0$ is the pre-adoption level of its production, $\varepsilon_d$ is the price elasticity of its demand and $Z$ is the relative change/reduction in its price, which can be computed as

$$Z = \frac{K\varepsilon_s}{\varepsilon_s + \varepsilon_d} \qquad \text{... (11)}$$

Where, $\varepsilon_s$ and $\varepsilon_d$ are the absolute values of the price elasticity of the supply and demand, respectively. The total economic surplus can be computed as

$$\Delta TS = P_0 Q_0 K (1 + 0.5\varepsilon_d Z) \qquad \text{... (12)}$$

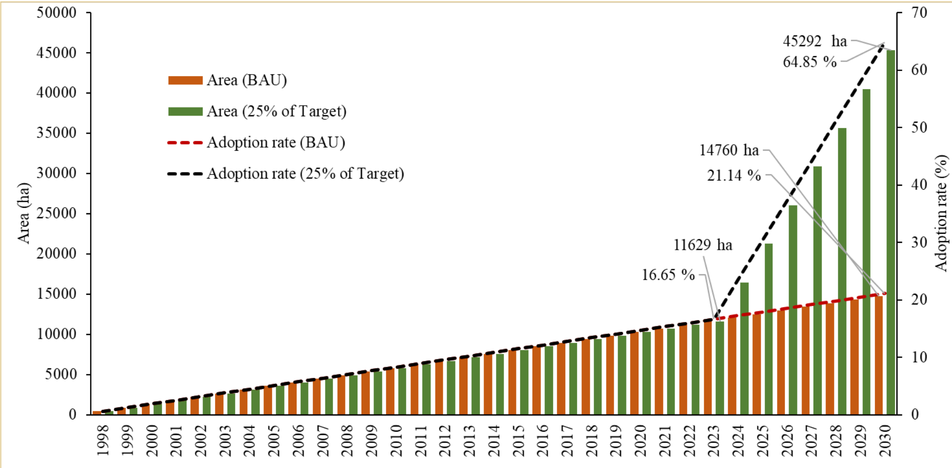
# 5 Economic and Environmental Impacts of Subsurface Drainage Technology

## 5.1 Economic impact of SSD in Haryana

### 5.1.1 Adoption

The pilot project for reclaiming waterlogged-saline soil in Sampla village in Rohtak district of Haryana initiated in 1980 was a milestone. This project, which focused on subsurface drainage (SSD) design for alluvial soils, laid the foundation for large-scale implementation of SSD. The success of this pilot project, in terms of increased yields of wheat and barley in the range of 2.5 to 4.9 and 2.1 to 4.2 ton per hectare, respectively from the almost barren lands (Gupta 2007a) motivated upscaling of SSD. HOPP has treated 11,629 hectares of waterlogged saline soils by 2023, representing 16.65% of the total waterlogged saline area in the state. Further, projections indicate that under the business-as-usual (BAU) scenario, approximately 14,760 hectares or 21.24% of the total affected area will be treated by 2030. However, the Integrated Water Resource Plan (IWRP) of Haryana for 2023-2026 has set a more ambitious target, aiming to bring an additional 52,709 hectares under drainage systems (GoH 2023). For *ex-ante* analysis, we assumed that approximately 25% of the targeted area, or 33,663 hectares, can be treated with SSD, given the current availability of the necessary machinery and manpower. This scenario has been termed as "25% of Target". Thus, by 2030, the cumulative area treated with SSD can reach approximately 45,292 hectares, representing 64.85% of the total area requiring SSD treatment (Figure 5.1). Based on these estimates, economic surplus was estimated for both BAU and '25% of Target' scenarios.

**Figure 5.1. Present and projected rate of adoption of subsurface drainage in Haryana**




### 5.1.2 Effect of subsurface drainage on crop yield and cost of cultivation

Wheat and paddy yield increased by 11.20 and 10.90 quintal per hectare (Table 5.1) or 30.9% and 46.5%, respectively, compared to the control (Table 5.2). Implementation of SSD reduced the soil salinity and water-table depth below the root-zone, and thereby improving over soil health and crop productivity.

**Table 5.1. Effect of subsurface drainage on crop yield (quintal per hectare)**

| Crop | ATT | Std. Error | t value | Pr(>\|t\|) |
|---|---|---|---|---|
| Wheat | 11.20*** | 0.99 | 11.32 | 0.001 |
| Rice | 10.90*** | 0.94 | 11.61 | 0.001 |

*Source: Authors' estimation based on primary survey.*

*Note: -Usually, it takes three years to stabilize the effect of the SSD; therefore, the post-SSD scenario shows the yields after 3rd year of SSD installation.*

**Table 5.2. Incremental change in crop yield due to subsurface drainage (quintal per hectare)**

| Particular | Control | Treated with SSD | Change (%) |
|---|---|---|---|
| Wheat | 36.30 | 47.50 | 30.9 |
| Paddy | 23.45 | 34.35 | 46.5 |

*Source: Authors' estimation based on primary survey.*

The implementation of SSD system significantly influences the cost of cultivation. For wheat, during the initial five years, total incremental cost, including the SSD installation cost, amounted to Rs 67,371 per hectare, representing a 51.9% increase over the control. The annualized investment cost for SSD installation is estimated at Rs 16,405 per hectare additional inputs at Rs 6,600 per hectare. However, it is noteworthy that from the six$^{th}$ year onwards, the incremental cost decreased substantially to 14.9% over the control (Table 5.3).

**Table 5.3. Incremental cost of production of wheat and rice after the installation of subsurface drainage (Rs per hectare)**

| Year | Control area | Increased Input cost with SSD | Annual investment cost | Treated area |
|---|---|---|---|---|
| | | Wheat | | |
| First 5 years | 44366 | 6600 | 16405 | 67371 (51.9%) |
| 6$^{th}$ year onwards | 44366 | 6600 | - | 50966 (14.9%) |
| | | Rice | | |
| First 5 years | 62415 | 5500 | 16405 | 84320 (35.1%) |
| 6$^{th}$ year onwards | 62415 | 5500 | | 67915 (8.8%) |

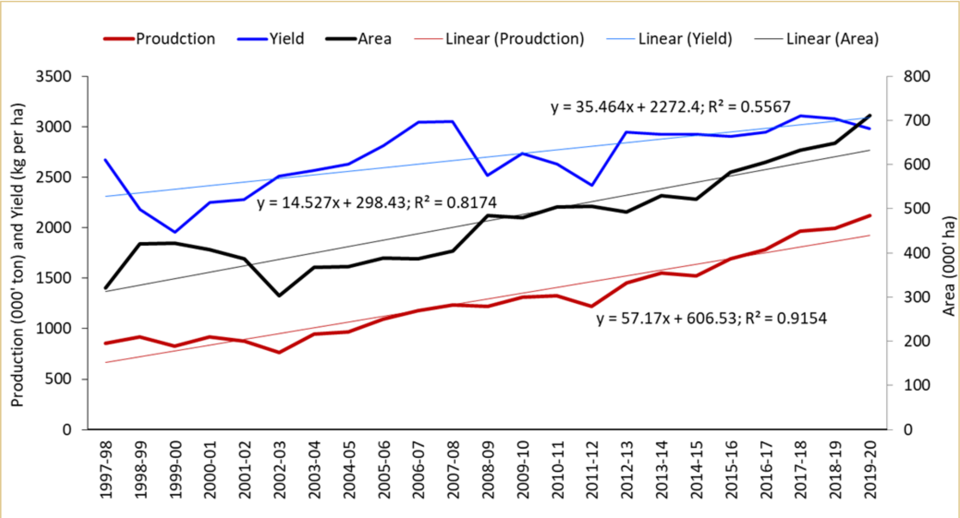
*Source: Authors' estimation based on primary survey; Note: Figures in parentheses are percent increase in costs over the control areas.*

A comparable change in the cost of cultivation was observed for rice, although the incremental cost was less than that for wheat. During the initial five-year period, the incremental cost of rice production with SSD implementation was 35.1% higher than that of the control farmers. However, from the sixth year onwards, the incremental cost decreased significantly to only 8.8% above the control (Table 5.3).

### 5.1.3 Performance of the rice and wheat in salt-affected soils

There are inherent difficulties in estimating precise rate of growth in crop production in waterlogged saline areas owing to the non-availability of data at such a micro-scale, as water-logged soils are often found in small patches and scattered. Therefore, district-level trends in the area and production were used to obtain insights into trends in wheat and paddy production. There was a significant increase in rice acreage, from 320 thousand in 1997-98 to 711 thousand hectares in 2019-20, implying an annual growth of 3.06%.

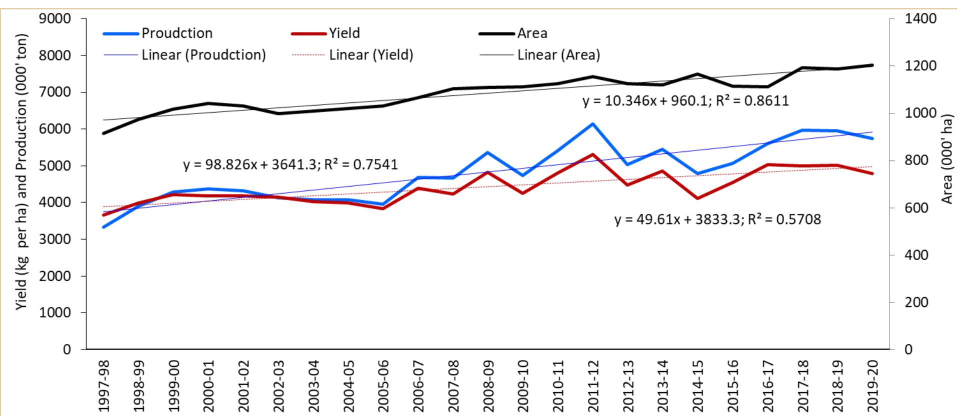
**Figure 5.2. Performance of the rice production in the waterlogged saline area in Haryana**




*Source: GoI (2020). Note: Charkhi Dadri, Fatehabad, Jhajjar, Jind, Panipat, Rohtak, Sirsa and Sonipat districts of Haryana represent the water-logged saline soils.*

However, the marginal increase in yield from 2627 kg per hectare to 2978 kg per hectare suggests that productivity improvements did not keep pace with area expansion. However, the yield remained below the state average (3332 kg per hectare), indicating the effect of salt-affected soils.

**Figure 5.3. Performance of the wheat production in the waterlogged saline area in Haryana**




*Source: GoI (2020).*

During this period, wheat production increased from 3339 thousand tons in 1997-98 to 5751 thousand tons at an annual rate of 2.10%. Area and yield increased by 0.97% and 1.13% per annum, respectively (Figure 5.3).

### 5.1.4 Estimated economic surplus

The economic surplus of rice due to the adoption of SSD was calculated using the parameters listed in Table 5.4. The values for $Q_0$ (base quantity) and $P_0$ (base price) were taken as 163.77 thousand tons (TE 1999-2000) and Rs 31980 per tons (TE 2022-24), respectively. The supply and demand elasticities were assumed to be 0.24 and -0.25, respectively (Kumar et al. 2011; Kumar and Mittal 2022). For wheat, the values for $Q_0$ and $P_0$ were 253.50 tons (TE 1999-2000) and Rs 20090 per ton (TE 2022-24), respectively (Table 5.5). Supply and demand elasticity were taken as 0.22 and -0.34, respectively (Kumar et al. 2011; Kumar and Mittal 2022).

**Table 5.4. Parameters of economic surplus model for rice crop in Haryana**

| Parameter | Description | Value | Source |
|---|---|---|---|
| $Q_0$ | Production quantity of domain areas ('000 ton) TE 1999-2000 | 163.77@ | GoI (1999-2000) |
| $P_0$ | Price (Rs /ton, TE2022-24) | 31980# | MSP for common paddy and Agmark net for basmati Rice (TE 2023-24) |
| $E(Y)$ | Yield change (%) | 46.35 | Focused Group Discussions (FGDs) and Primary survey |
| $E(Y)$ | Per hectare change in variable cost (%)<br>First 5 Years | 35.1 | FGDs, and Primary survey |
| | $6^{th}$ year onwards | 8.8 | FGDs, and Primary survey |
| $A_{max}$ | Maximum adoption rate (%)<br>business as usual 25% of the planned target | 21.14<br>64.85 | Expert opinions |
| $\varepsilon_s$ | Supply elasticity | 0.24 | Kumar and Mittal (2022) |
| $\varepsilon_d$ | Demand elasticity | -0.25 | Kumar et al. (2011) |
| EGR | Exogenous growth rate (%) | 4.48 | Authors' estimation |
| Prob. | Probability of success (%) | 80.0 | Expert opinions |

@ *Estimated based area under waterlogged saline soils.*

# *Weighted price for varieties grown (PB 1121, Basmati 1509 and PR varieties) in the SSD project areas.*

**Table 5.5. Parameters of economic surplus model for wheat crop in Haryana**

| Parameter | Description | Value | Source |
|---|---|---|---|
| $Q_0$ | Production quantity of domain areas ('000 ton in TE 1999-2000) | 253.50[@] | Authors' estimation based on GoI (1999-2000) |
| $P_0$ | Price (Rs/ton, TE2021-22) | 20090 | Farm Harvest Prices of Principal Crops in India (GoI 2024) |
| $E(Y)$ | Yield change (%) | 30.90 | Focused Group Discussions (FGDs) and Primary survey |
| $E(Y)$ | Per hectare change in variable cost (%)<br>*First 5 years*<br>*6th onwards* | <br>51.9<br>14.9 | FGDs, and Primary survey |
| $A_{max}$ | Maximum adoption rate (%) *business-as-usual*<br>*25% of thee planed target* | 21.14<br>64.85 | Expert opinions |
| $\varepsilon_s$ | Supply elasticity | 0.22 | Kumar and Mittal (2022) |
| $\varepsilon_d$ | Demand elasticity | -0.34 | Kumar et al. (2011) |
| EGR | Exogenous growth rate (%) | 2.1 | Authors' estimation |
| Prob. | Probability of success (%) | 80.0 | Expert opinions |

[@] *Estimated based area under waterlogged saline soils (69836 hectare) with base year yield of 36.3 q per hectare).*

The total economic surplus amounted to Rs 38250 million, and is almost equally distributed between producers (Rs 19510 million) and consumers (Rs 18730 million) (Table 5.6). For the extended period up to 2030, the producer surplus increases to Rs 37650 million and the consumer surplus to Rs 39220 million resulting in a total economic surplus of Rs 76870 million. Furthermore, we present an alternative scenario in which the economic surplus could potentially reach Rs 131440 million under the '25% of the Target'.

The nearly equal distribution of benefits between producers and consumers suggests that SSD has a balanced effect on the rice market. Producers benefit from increased yields, leading to higher profits. Simultaneously, consumers gain from potentially lower prices owing to an increase in supply. This balanced distribution of economic benefits indicates that SSD has not only improved agricultural efficiency but also contributed to broader economic welfare across the rice value chain.

For wheat crop, under the BAU scenario, the total surplus is estimated at Rs 16870 million, which is projected to rise to Rs 30020 million by 2030. However, the' 25% of the Target" scenario presents a more optimistic outlook. In this scenario, the economic surplus is expected to reach Rs 48030 million. Notably, consumers benefit more from implementation of SSD system.

The rice-wheat cropping system dominates Haryana agriculture. Under the BAU scenario, the total economic surplus from the implementation of SSD is estimated at Rs 5,5120 million for the period 1998-2023 and Rs 10,6890 million for the extended period 1998-2030. However, the '25% of the Target' scenario the economic surplus reaches Rs 17,9470 million.

**Table 5.6. Estimates of economic surplus from adoption of subsurface drainage in Haryana (Rs in million)**

| Particular | Business as usual (BAU) | | Adoption rate 25% of planned |
|---|---|---|---|
| | 1998-2023 | 1998-2030 | 1998-2030 |
| Rice | | | |
| Consumer surplus | 18730(49) | 37650(49) | 64380(49) |
| Producer surplus | 19510(51) | 39220(51) | 67060(51) |
| Total economic surplus | 38250(100) | 76870(100) | 131440(100) |
| Economic surplus per annum | 1471.2 | 2956.5 | 5055.4 |
| Wheat | | | |
| Consumer surplus | 6630(39) | 11790(39) | 18870(39) |
| Producer surplus | 10240(61) | 18220(61) | 29160(61) |
| Total economic surplus | 16870(100) | 30020(100) | 48030(100) |
| Economic surplus per annum | 648.8 | 1154.6 | 1847.3 |
| Rice-wheat system | | | |
| Consumer surplus | 25360(46) | 49440(46) | 83250(46) |
| Producer surplus | 29750(54) | 57440(54) | 96220(54) |
| Total economic surplus | 55120(100) | 106890(100) | 179470(100) |
| Economic surplus per annum | 2120.0 | 4111.2 | 6902.7 |

*Note: The figures in parentheses are the percent shares of consumer and producer surpluses in the total economic surplus.*

## 5.2 Economic impact of SSD in Maharashtra

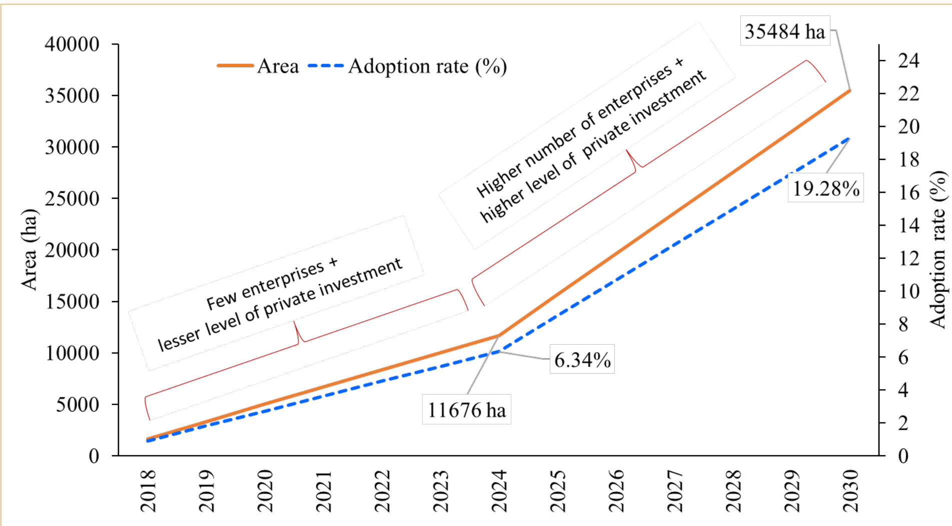
### 5.2.1 Adoption

The expansion of sugarcane in the southwestern region of Maharashtra has led to significant environmental challenge, primarily due to improper irrigation practices. These practices have resulted in widespread waterlogging and soil salinity, which significantly reducing sugarcane yield, 60-67% (Gupta et al. 2008; Rathod et al. 2011).

Although drainage projects have been implemented in irrigation command areas, the mismanagement of water in non-command lift irrigation schemes also has led to extensive waterlogging and salinity (Kaledhonkar and Kumar 2011).

In Sangli district, SSD is promoted by the state's Water Resources Department and Rex Polyextrusion Ltd. Despite the high initial costs and lack of institutional support (Chinchmalatpure et al. 2020), farmers are willingness to adopt SSD technology. Rex Poly Extrusion Ltd. installs SSD systems in farmers' fields, with farmers bearing full financial cost. Although precise data on SSD installations are limited, projections based on discussions with field functionaries, experts, and farmers indicate that by 2024, approximately 11,676 hectares has been treated (Figure 5.4).

**Figure 5.4. Present and projected adoption rate of subsurface drainage in Maharashtra**




*Source: Authors' estimation based on discussions with field functionaries and farmers of Maharashtra*

Though, data on waterlogged-saline soils are conflicting, Mandal et al. (2011) estimated the potentially treatable area at 1,84,089 hectares. To date, 11,676 hectares have been treated, representing 6.34% of the total potential area. The future outlook for SSD adoption appears optimistic, driven by two key factors: increasing numbers of farmer groups investing in technology, and a growing number of private firms entering into the SSD installation business. These trends suggest a potential acceleration in the adoption rates. The conservative estimate indicates that by 2030, approximately 35,484 hectares of land will be brought under SSD.

### 5.2.2 Effect of subsurface drainage on sugarcane yield and cost of cultivation

Installation of subsurface drainage led to an incremental sugarcane yield of 517.6 quintal per hectare, which was 62.4% over the control (Table 5.7 and 5.8). The economic impact of SSD is evaluated by considering the incremental costs associated with its adoption. For the first five years, the incremental cost is estimated at 52.2% above the baseline, while from the sixth year onwards, it decreases to 30.5% (Table 5.9).

**Table 5.7. Effect of subsurface drainage on sugarcane yield in Maharashtra (quintal per hectare)**

| Crop | ATT | Std. Error | t value | Pr(>\|t\|) |
|---|---|---|---|---|
| Sugarcane | 517.6*** | 19.2 | 270.2 | 0.001 |

*Source: Authors' estimation based on primary survey.*

**Table 5.8. Incremental change in crop yield due to subsurface drainage in Maharashtra**

| Particular | Pre-SSD (ton per hectare) | Post-SSD (ton per hectare) | Change (%) |
|---|---|---|---|
| Sugarcane | 82.88 | 134.64 | 62.4% |

*Source: Authors' estimation based on primary survey.*

**Table 5.9. Incremental cost of production of sugarcane after the installation of SSD in Maharashtra (Rs per hectare)**

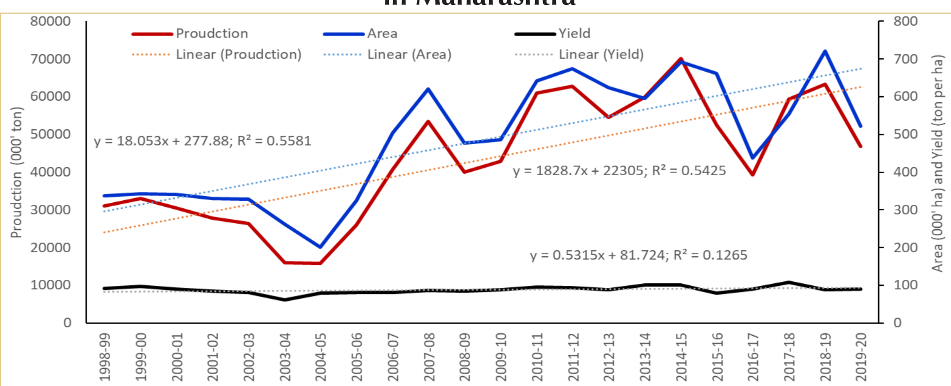
| Year | Control Area | Increased Input cost with SSD | Annual Investment cost | Treated area |
|---|---|---|---|---|
| First 5 years | 177750 | 54250 | 38480 | 270480 (52.2%) |
| 6th year onwards | 177750 | 54250 | - | 232000 (30.5%) |

*Source: Authors' estimation based on primary survey. Note: Figures in parentheses are percent increase in cost over the control areas.*

### 5.2.3 Performance of sugarcane in waterlogged-saline soils

The expansion of sugarcane cultivation in the salinity-affected areas from 1998-99 to 2019-20 was significant, increasing by 54% over two decades at an annual rate of 4.12% (Figure 5.5).

**Figure 5.5. Performance of sugarcane production waterlogged saline area in Maharashtra**




*Source: GoI (2020). Note: Pune, Sangali, Solapur, Ahmednagar, Nasik and Kolhapur districts of Maharashtra represent the water-logged saline soils.*

The production of sugarcane has increased at an annual rate of 4.77%, resulting in a nearly 1.5 times increase from 31,5,16 (TE-2000-01) to 56,4,79 thousand tons (TE2019-20). Despite the impressive growth in area, yield of sugarcane has not increased much, averaging approximately 90 tons per hectare. Salinity development in sugarcane growing regions is identified as a major contributing factor to this yield plateau.

### 5.2.4 Estimated economic surplus

Table 5.10 presents the key parameters used in estimation the economic surplus from the implementation of SSD in sugarcane. The baseline production quantity ($Q_0$) was taken as 15,261 thousand tons (TE 2107-18) and the current price ($P_0$) at Rs 2,726 per ton (TE2023-24). The supply and demand elasticities were assumed 0.122 and -0.340 (Kumar et al. 2011; Kumar and Mittal 2022). We assumed a success probability of 80% for SSD, recognizing the potential challenges associated with its operation and maintenance.

**Table 5.10. Parameters of economic surplus model for sugarcane crop**

| Parameter | Description | Value | Source |
|---|---|---|---|
| $Q_0$ | Production quantity of domain areas ('000 ton) T.E. 2017-18 | 15261 | GoI (1917-18) |
| $P_0$ | Price (Rs /ton, TE2021-22) | 2726 | Commission for Agricultural Costs and Prices, Government of India |
| $E(Y)$ | Yield change (%) | 62.4 | FGDs and Primary survey |
| $E(Y)$ | Per hectare change in variable cost (%) for the first 5 years<br>6th year onwards | 52.2%<br>30.8% | |
| $A_{max}$ | Maximum adoption rate (%) | 19.28 | Expert opinions |
| $\varepsilon_s$ | Supply elasticity | 0.1216 | Kumar and Mittal (2022) |
| $\varepsilon_d$ | Demand elasticity | -0.340 | Kumar et al. (2011) |
| EGR | Exogenous growth rate | 4.77% | Authors estimation |
| Prob. | Probability of success | 80.0% | Expert opinions |

[@] *Estimated based area under waterlogged saline soils.*

**Table 5.11. Estimate of economic surplus from adoption of subsurface drainage in Maharashtra (Rs in million)**

| Particular | 2018-2023 | 2018-2030 |
|---|---|---|
| Consumer surplus | 7810(26.3) | 34210(26.3) |
| Producer surplus | 21840(73.7) | 95650(73.7) |
| Total economic surplus | 29660(100) | 129860(100) |
| Economic surplus per annum | 4943.3 | 21643.3 |

*Note: The figures in parentheses are the percent shares of consumer and producer surpluses in the total economic surplus.*

The adoption of SSD resulted in significant economic benefits for both producers and consumers during the period–2018-2023. Consumers could harvest a surplus of Rs 7810 million, whereas producers benefited more with Rs 21840 million, resulting in a total economic surplus of Rs 29660 million (Table 5.11). During the extended period from 2018-2030, the projected benefits are significantly higher. The estimated consumers surplus is expected to reach Rs 34210 million, while the producers surplus is anticipated to increase to Rs 95650 million. Consequently, the total economic surplus by 2030 is projected to be approximately Rs 129860 million.

## 5.3 Environmental impact of SSD

The implementation of subsurface drainage systems has far-reaching implications beyond economic benefits, significantly addressing the challenges related to land degradation and food security. As the world's population continues to grow, the demand for agricultural land will also grow, leading to the expansion of irrigation and the associated risk of soil salinization. The United Nations Environment Programme (UNEP) identifies soil salinization as the primary cause of land degradation in irrigated areas, with an estimated 0.5–1.0 million hectares of irrigated land lost annually owing to waterlogging and salinity (FAO 1994). SSD is a promising solution, aligned with Land Degradation Neutrality (LDN) and Sustainable Development Goals (SDGs).

The environmental impact of SSD is observed through various indicators related to the LDN. Various studies (Table A2) have reported significant improvements in soil health and reductions in electrical conductivity (EC), ranging from 35% to 86% (Figure 5.6). The organic carbon content in the soil also increased by 0.15–0.22 percentage points in Maharashtra and 0.10–0.14 percentage points in Haryana (Figure 5.7). Furthermore, implementation of SSD led to substantial increases in cropping intensity ranging from 30.0 to 94.0% (Figure 5.8).

Improvements in these indicators demonstrate the potential of SSD to enhance ecosystem services, contribution to food security, and support to the achievement of SDGs such as Life on Land, No Poverty, and Zero Hunger (Mukhopadhyay et al. 2023a).

**Figure 5.6. Reduction in electric conductivity after installation of subsurface drainage**

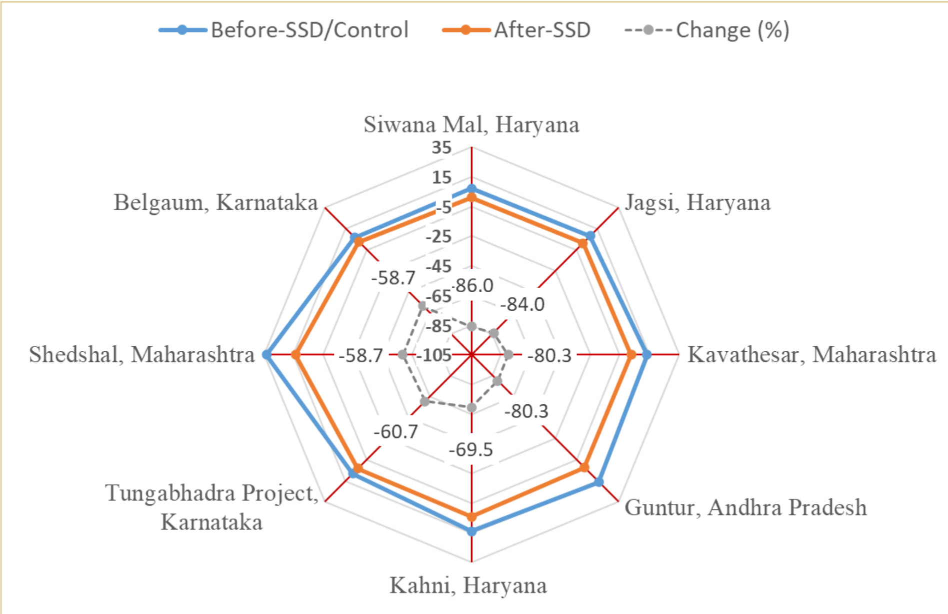



**Figure 5.7. Improvement in organic carbon (%) after installation of subsurface drainage**

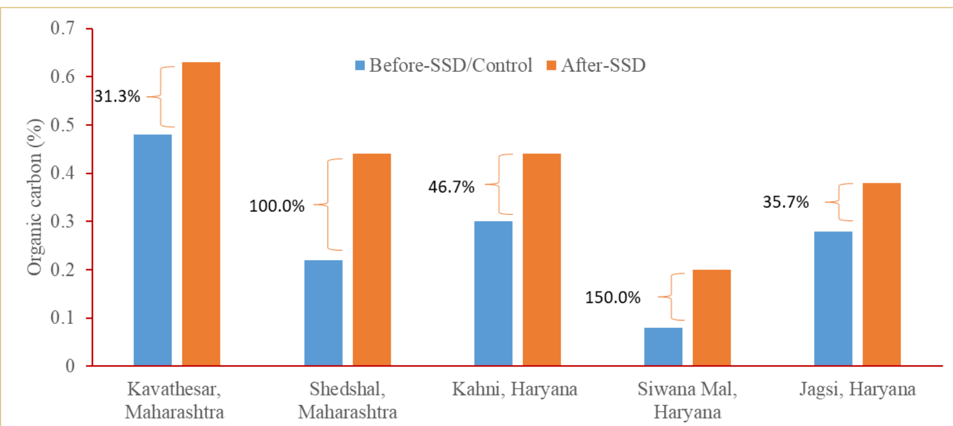
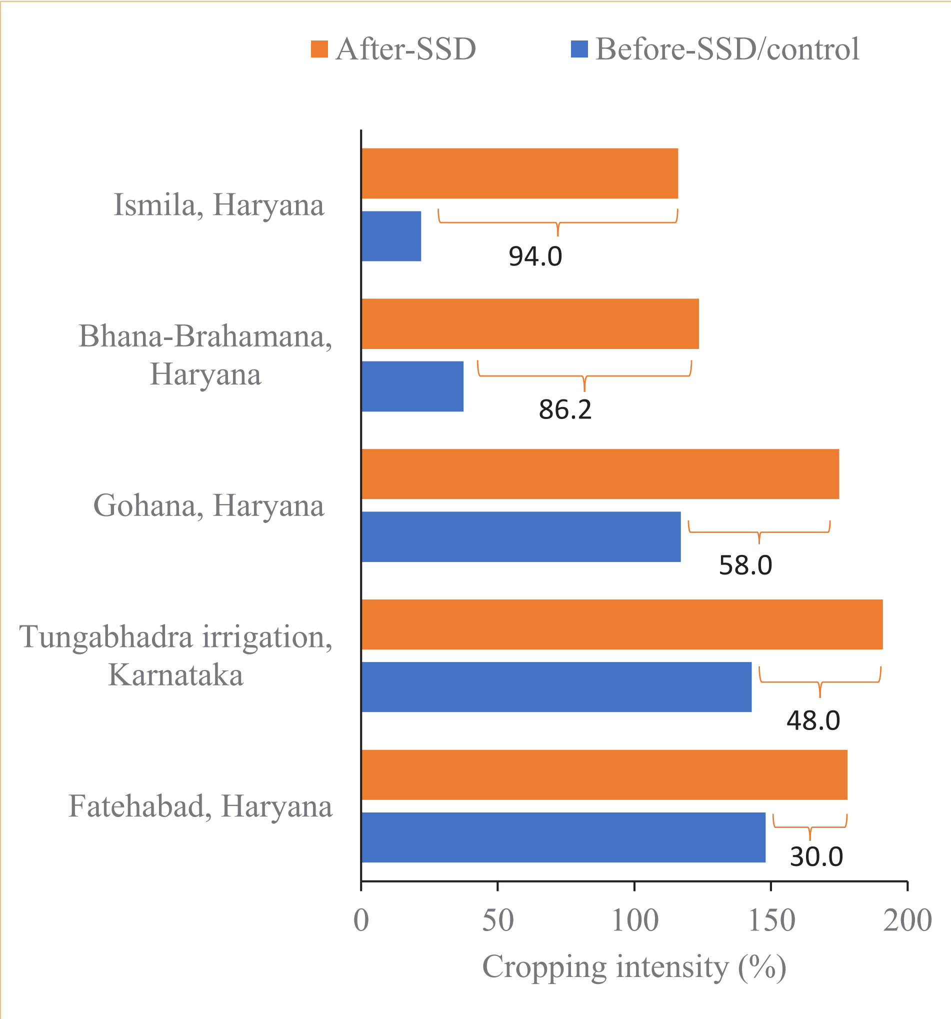


**Figure 5.8. Improvement in cropping intensity (%) after installation of subsurface drainage**



# 6 Constraints in Scaling-out of Subsurface Drainage

The success of SSD projects is influenced by a complex interplay of technological, social, and economic factors. These factors may include technological barriers such as limited access to appropriate machineries or inadequate knowledge of modern soil and water management techniques. Social aspects could involve resistance to change from traditional farming practices, lack of community engagement, or insufficient awareness of the benefits of SSD projects. Economic constraints might include financial limitations for farmers to adopt new technologies, inadequate market linkages for improved crop yields, and insufficient government support for SSD.

The constraints and issues identified in Haryana and Maharashtra, as presented in Figures 6.1 and 6.2, and highlight region-specific constraints that need to be addressed for the successful implementation of SSD initiatives.

**Figure 6.1 Constraints in scaling-out of subsurface drainage in Haryana**

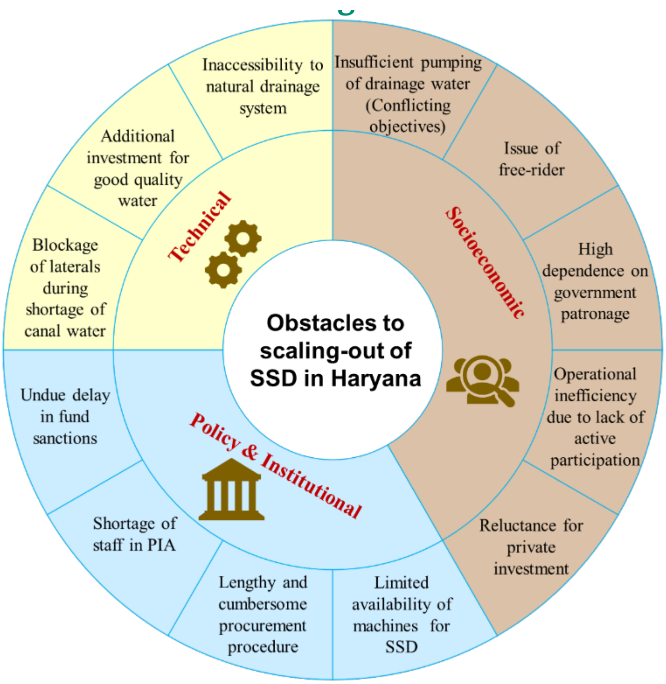
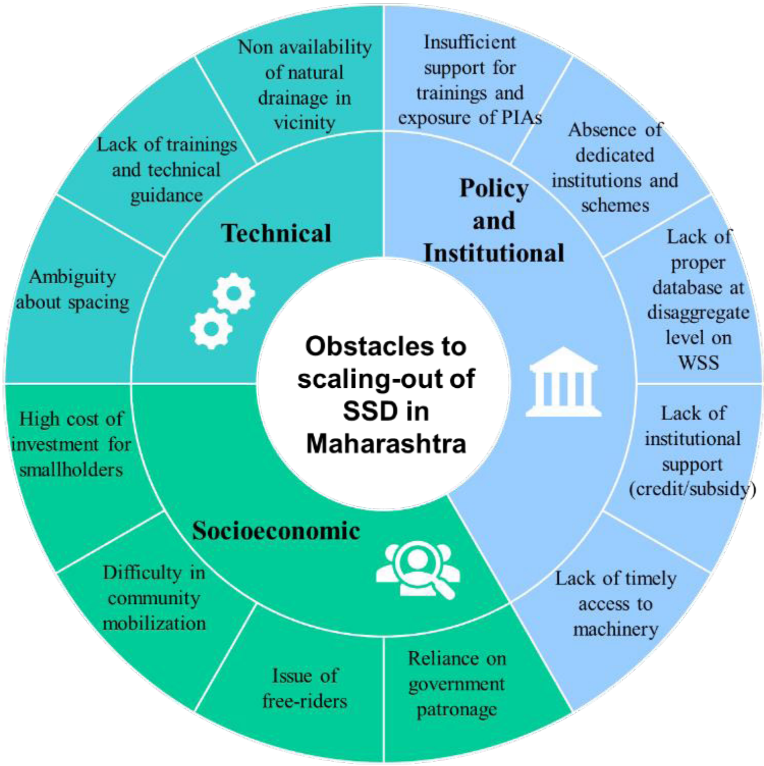


**Figure 6.2 Constraints in scaling-out of subsurface drainage in Maharashtra**




However, the factors identified for the poor implementation of SSD for the sake of simplicity are classified as those related to its scaling-up. SSD is an indivisible technology (Datta and Joshi 1993), and its scaling-up depends on institutional support. For better operational efficiency and cost-effectiveness, the indivisibility nature of SSD entails a certain minimum scale because it is neither technically feasible nor economically viable for an individual farmer to implement SSD in isolation. Furthermore, the implementation of SSD requires specialized technical skills, machineries, materials, and financial resources for project implementation. Therefore, institutional arrangements are essential to successful scaling-up. An example of institutional setup can be found in Haryana. In Haryana, the Operational Pilot Project (HOPP) was established in 1994 with technical support from the Netherlands. Considering the minimum operational scale requirement of SSD, the HOPP guidelines stipulate that a project size must encompass a minimum of 100 ha of land. Furthermore, for the successful execution of SSD projects also relies on the 'consent and cooperation' of all farmers of the project area, who are required to adhere to the cost-sharing norms established by the project implementation agency.

## 6.1 Constraint in out-scaling of SSD

The implementation of SSD has been progressing at a slow pace (Gupta 2002). This sluggish progress could be attributed to several factors.

**Lack of machinery and equipment:** There is a lack of specialized machineries, particularly trenchers, which are essential for SSD installation (Bhattacharya and Michael 2003). Extant trenchers are outdated and operate with diminished efficiency, which necessitates frequent maintenance. Moreover, delays in administrative and financial approvals for procuring essential materials such as pipes further impede the implementation process.

**Lack of dedicated funding and human resources:** SSD projects face severe constraints on human and financial resources. Understaffing at the Project Implementation Agency (PIA) level and delays in fund sanctions contribute to slow execution.

**Limited operational window:** The installation of SSD networks is constrained by the limited operational window. Field operations for SSD installation are only feasible for approximately 60-75 days in a year, typically between wheat harvest and the end of June. This narrow timeframe coupled with the aforementioned challenges significantly affects the pace of SSD implementation.

**Lack of micro-level data:** A significant challenge is the lack of microlevel data on water-logged saline soils. This makes it difficult to identify the problem areas accurately, thereby targeting the implementation of SSD.

**Lack of awareness:** The limited implementation of SSD results in a lack of awareness and interest among farmers, technicians and development agencies, which creates a cycle of slow adoption.

**Poor financing and institutional frameworks:** Except Haryana, in many states which are exposed to the waterlogging and salinity, lack dedicated schemes and departments to identify affected areas and implement SSD systems. Although some states utilize the "Reclamation of Problem Soils (RPS)" sub-scheme under RKVY to treat saline soils with SSD technology, the allocated funds are insufficient. The current cost norms, with an upper limit of Rs 60,000 per hectare (GoI 2016), are approximately half those required for the installation of SSD systems (Kumar et al. 2024).

## 6.2 Issues in post-SSD implementation

The effectiveness and efficiency of SSD projects are influenced by factors other than technical ones. Datta and Joshi (1993) identified several factors that limit project outcomes, including the level of beneficiary participation, free-rider problems, conflicting farmer objectives, village factionalism, reliance on government support, and the erosion of cooperative culture.

**Reliance on government support:** The implementation of SSD systems has shown varying degrees of success across different regions with a mix of public and private investment approaches. In states such as Gujarat, Andhra Pradesh, Karnataka, and Maharashtra, there have been isolated instances of private investments in SSD by farmers. These investments typically occur after farmers observe the benefits of government-implemented SSD projects in nearby areas, prompting them to adopt similar systems on their land. This pattern suggests that successful public initiatives are precursors to private-sector engagement. On the other hand, in Haryana, there is a notable absence of private investment in SSD systems, both at the individual and cluster levels. Farmers often postpone private investments and wait for their turn to avail the benefits of government schemes. This has led to the perception that managing waterlogged saline soils is the primary responsibility of public institutions.

In Maharashtra, cooperative societies play a crucial role in facilitating SSD implementation at the cluster level, by providing financial and technical support to farmers. This approach led to a more proactive adoption of SSD among farmers, with many financing the installation from their savings because of its proven benefits. The success of SSD in Maharashtra is further emphasized by the minimal operational costs once the system is installed, as drainage water is naturally discharged into open surface drains through gravity flow (Kamra and Sharma 2016). Gujarat saw success with a drainage-cum-irrigation system in the Ukai Kakrapar irrigation project area, where farmers have independently adopted the technology after witnessing its positive effects (Patel 2021).

**Top-down approach and low farmers' participation:** The implementation of SSD systems often faces challenges in operation and maintenance (O&M) because the top-down approach fails to consider site-specific conditions and farmer preferences (Grewal et al. 2021). This approach, typically adopted by government agencies, prioritizes technical aspects over institutional ones, leading to poor farmer engagement and subsequent system failures. The lack of farmer involvement in design and implementation contributes to their reluctance to maintain SSD systems properly, as noted by Ritzema (2009). To address these challenges, the importance of local institutions and participatory drainage management (PDM) have been crucial. Satyanarayana and Boonstra (2007) provided an example of a successful farmer-managed SSD in the Uppugunduru area of the Krishna Delta, where a cooperative society was established to oversee the O&M system.

**Problem of free-riders:** The problem of free-riding is a significant challenge for the implementation of collective projects. This issue arises when individuals benefit from a shared resource or service, without contributing to costs or maintenance. In the context of the Kahani SSD project (Haryana), farmers in the upper areas were reluctant to participate during the execution phase, as their plots had already yielded better results than the low-lying areas. These farmers may have anticipated that the hydrological connectivity of the region would naturally extend the benefits of the drainage system to them without requiring direct involvement or financial contribution. The farmers in the low-lying areas who bore the costs and actively participated in the SSD project found themselves inadvertently supporting those who did not contribute. A key concern during the reclamation process is the sequential removal of salt from upper areas, which then migrates to lower areas. This results in upper fields becoming productive sooner than those below, giving upper farmers the initial benefits of SSD while lower farmers lag behind. This disparity negatively affects the collective responsibility of pumping saline effluent, as upper farmers often hesitate to contribute to pumping costs once their plots are productive, leaving lower farmers to bear the burden. This can lead to inadequate pumping operations, undermining the SSD's effectiveness. Therefore, it is crucial to establish an institutional mechanism within SSD projects that incentivizes farmers who do not benefit in the early years.

**Conflicting objectives:** Conflicts among stakeholders due to diverse crop choices in drainage areas represent face challenge in water management. In the Gohana area of Haryana, rice farmers block lateral channels to preserve moisture in their paddy fields, whereas tail-end farmers struggle with insufficient moisture (Datta 2003b). Thus, a cooperative approach involving farmers is necessary for the reclamation of salinity-affected and waterlogged soils. This approach aims to balance the needs of different farmers and optimize water management for various crops while facilitating the reclamation process.

# 7 Institutional and Policy Imperatives

The upscaling of SSD remains a critical challenge. Despite the potential to treat 2.95 million hectares of affected land, only 0.074 million hectares (2.57%) have been treated so far. This low penetration is attributed to various factors, including lack of institutional support, dedicated schemes, and farmer participation. States such as Haryana and Maharashtra have slightly higher adoption rates at 16.65% and 6.34%, respectively.

Economic analyses demonstrate significant economic gains from the adoption of SSD for both producers and consumers. However, their realization is hindered by several key factors, including the absence of dedicated schemes for agricultural drainage, low beneficiary participation, free-rider problems, conflicting farmer objectives, village factionalism, overreliance on government support, and a declining culture of collective action and resource sharing.

The implementation of SSD systems in India faces significant challenges with far-reaching implications for agricultural productivity and soil health management. The slow adoption and poor implementation of SSD can be attributed to several interconnected factors, each presenting unique obstacles that require comprehensive solutions. The following are suggestions for accelerating the promotion of SSD.

**Funding:** The widespread adoption of SSD is hindered by insufficient funding and outdated cost norms. This calls for policy reforms in view of soil, water and socioeconomic resource endowments, and increased financial support to accelerate its adoption. Governments and financial institutions must collaborate to create a conducive environment for SSD implementation. This may involve revising existing policies, allocating dedicated funds for SSD projects, and updating cost norms to reflect the current economic realities.

**Technical and logistical facilitation:** The effective installation of SSD system is restricted by a shortage of specialized machineries, limited operational windows, and a lack of micro-level data on waterlogged saline soils. These challenges underscore the need for significant investment in equipment and technology, improved planning and scheduling of SSD installations, and comprehensive soil-mapping initiatives. Developing a national database of soil characteristics and drainage requirements can significantly enhance the precision and efficiency of SSD implementation.

**Social and organizational factors:** The success of SSD projects is often compromised by low farmer participation, free-rider problems, and conflicting objectives among stakeholders. In some states, erosion of collective culture, such as Haryana and Punjab, have raised issues of forming farmers' groups/society needed to collectively management of SSD (Datta 2000). These issues highlight the critical importance of community engagement and participatory approaches to project design and implementation. Engaging farmers from the initial stages of planning, providing education on the benefits of SSD, and fostering a sense of ownership among beneficiaries can significantly improve project outcomes. Additionally, establishing clear communication channels between farmers, implementing agencies, and other stakeholders can help align objectives and resolve conflicts.

**Regionally differentiated strategies:** The salinity issue may be sometimes a local reality, but has regional scale implications, particularly in managing the saline water and soils on the account of interconnected landscapes. Therefore, the planning needs to be done on regional-scale instead of one or two districts. Similarly, a single approach is not universally applicable. Therefore, there is a need for customized strategies that consider the local socioeconomic context, agricultural practices, and environmental conditions. Policymakers and implementing agencies should conduct comprehensive regional assessments to develop tailored SSD strategies that address specific local challenges and capitalize on existing strengths.

**Operation and maintenance:** The top-down approach in SSD implementation often leads to poor farmer engagement in O&M activities, resulting in system failures. This implies a pressing need for participatory drainage management approaches and the establishment of stronger local institutions to ensure long-term sustainability of SSD system. Empowering farmers with the knowledge and skills to maintain SSD system, coupled with the creation of local drainage management committees, can significantly improve the effectiveness of the system.

**Water Conflict management:** The diversity of crop choices and conflicting water needs among farmers in drainage areas creates complex challenges in water management (Datta et al. 2004). This calls for the development of cooperative approaches and balanced water-management strategies to accommodate the varying requirements of different crops. Implementing flexible drainage systems can be adjusted based on seasonal needs, promoting crop diversification that aligns with drainage capabilities, and establishing water-user associations to manage shared resources can help mitigate these conflicts.

**Capacity building and knowledge dissemination:** Enhancing the knowledge of SSD technologies, best practices in installation and maintenance, and the long-term benefits of proper drainage can significantly improve adoption rates and system effectiveness. Establishing demonstration sites, conducting regular training programs, and leveraging digital technologies for knowledge dissemination can play a vital role in this regard.

**Farmers' collectives:** Subsurface drainage system is implemented on an area-wide basis, spanning fields of multiple farmers and necessitating substantial initial investment and coordination. This approach requires collective action, as individual farmers may lack resources or incentives to independently undertake such extensive infrastructure improvements. By promoting farmers' collectives, such as cooperatives and Farmer Producer Organizations (FPOs), governments can facilitate the pooling of the resources required for successful SSD implementation. These collectives can serve multiple purposes in SSD projects. First, they can function as a unified entity to secure funding from various sources, including government grants, bank loans, or private investments, leveraging their collective bargaining power. Second, they can ensure an equitable distribution of benefits and costs among participating farmers, addressing potential concerns regarding uneven impacts across site landscape. In addition, farmer collectives can coordinate maintenance efforts to ensure the long-term sustainability of SSD systems.

**Policy coherence:** For addressing the issue of land degradation necessitates the development of a comprehensive policy and regulatory framework, the establishment of a central coordinating institution, and the fostering of interconnected institutional relationships (Mishra et al. 2024). Similarly, the successful implementation of SSD requires integration with broader agricultural and rural development policies. This includes aligning SSD initiatives with programmes related to irrigation, soil conservation, crop diversification, and climate change adaptation. Enhancing coordination among various government departments, research institutions, and non-governmental organizations is essential to create synergies and maximize the impact of SSD.

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# Appendix

## Table A1: Descriptive statistic of sample farmers

| Variable | Unit of Measurement | Maharashtra | | | Haryana | | |
|---|---|---|---|---|---|---|---|
| | | A | NA | Diff. | A | NA | Diff. |
| Age | Number of years | 49.9 (7.8) | 49.7 (8.3) | 0.20 | 47.7 (11.7) | 47.1 (10.8) | 0.60 |
| Education | Number of schooling years | 9.4 (3.0) | 8.6 (3.2) | 0.80 | 8.8 (4.7) | 7.2 (4.8) | 1.60* |
| Landholding | Size of land holding (hectare) | 3.5 (1.0) | 3.5 (1.0) | 0.0 | 1.3 (0.7) | 1.3 (0.7) | 0.00 |
| Family size | Number of family members | 7.2 (1.7) | 7.5 (2.3) | -0.30 | 5.8 (1.7) | 5.7 (1.8) | 0.10 |
| Off farm income | Takes one if farmer has any source of off-farm income; otherwise, zero | 25 (62.5) | 15 (37.5) | 10.00** | 38 (63.3) | 28 (46.7) | 10.00* |
| High salinity | Takes one if farmer perceive level of salinity high at his farm; otherwise, zero | 19 (47.5) | 16 (40.0) | 3.00 | 34 (56.7) | 25 (41.7) | 9.00 |
| Medium salinity | Takes one if farmer perceive level of salinity medium at his farm; otherwise, zero | 15 (37.5) | 8 (20.0) | 7.00 | 25 (41.7) | 17 (28.3) | 8.00 |
| Perceived benefits of SSD | Takes one if farmer perceive high level of benefits from SSD; otherwise, zero | 27 (67.5) | 12 (30.0) | 15.00* | 41 (68.3) | 25 (41.7) | 16.0*** |
| Member to cooperative | Takes one if farmer is member of cooperative society; otherwise, zero | 29 (72.5) | 13 (32.5) | 16.00*** | NA | | |

| Variable | Unit of Measurement | Maharashtra | | | Haryana | | |
|---|---|---|---|---|---|---|---|
| | | A | NA | Diff. | A | NA | Diff. |
| Area under sugarcane crop | Area under sugarcane crop (hectare) | 2.9 (1.1) | 2.4 (0.8) | 0.50** | NA | | |
| High prone to flood | Takes one if farmer state that his/her farm is high prone to flooding; otherwise, zero | 31 (77.5) | 15 (37.5) | 16.00*** | NA | | |
| Medium prone to flood | Takes one if farmer state that his/her farm is medium prone to flooding; otherwise, zero | 6 (15.0) | 20 (50.0) | -14.00*** | NA | | |
| Number of observations | | 40 | 40 | | 60 | 60 | |

Note: SSD: Subsurface drainage technology; A: Adopter; NA: Non-Adopter and Diff.: Difference; Figures in parentheses are standard deviation and per cent if the variables are continuous and categorical, respectively. *, **, *** show that difference is significant at 0,5 and % level of significance, respectively

## Table A2: Environmental impact of the subsurface drainage

| Before-SSD/ control | After-SSD | Change (%) | Site and State | References |
|---|---|---|---|---|
| **EC (Electric conductivity, $dSm^{-1}$)** | | | | |
| 13.27 | 2.61 | -80.3 | Kavathesar, Maharashtra | Mukhopadhyay et al. (2023a) |
| 33.21 | 13.72 | -58.7 | Shedshal, Maharashtra | Mukhopadhyay et al. (2023a) |
| 13.86 | 4.23 | -69.5 | Kahni, Haryana | Mukhopadhyay et al. (2023b) |
| 7.13 | 1.00 | -86.0 | Siwana Mal, Haryana | Mukhopadhyay et al. (2023b) |
| 8.17 | 1.31 | -84.0 | Jagsi, Haryana | Mukhopadhyay et al. (2023b) |
| 8.4 | 3.3 | -60.7 | Tungabhadra project, Karnataka | Manjunatha et al. (2004) |
| 16.2 | 2.66 | -80.3 | Guntur, Andhra Pradesh | Babu et al. (2010) |
| 6.6 | 2.52 | -58.7 | Belgaum, Karnataka | Raju et al. (2017) |
| 8.6 | 4.8 | -44.2 | Fatehabad, Haryana | Raju et al. (2015) |
| 7.1 | 4.6 | -35.2 | Gohana, Haryana a | Datta et al. (2004) |
| **Organic carbon (%)** | | | | |
| 0.48 | 0.63 | 0.15 | Kavathesar, Maharashtra | Mukhopadhyay et al. (2023a) |
| 0.22 | 0.44 | 0.22 | Shedshal, Maharashtra | Mukhopadhyay et al. (2023a) |
| 0.30 | 0.44 | 0.14 | Kahni, Haryana | Mukhopadhyay et al. (2023b) |
| 0.08 | 0.20 | 0.12 | Siwana Maal, Haryana | Mukhopadhyay et al. (2023b) |
| 0.28 | 0.38 | 0.10 | Jagsi, Haryana | Mukhopadhyay et al. (2023b) |
| **Carbon stock (Mg C per hectare)** | | | | |
| 17.72 | 25.83 | 45.8 | Kahni, Haryana | Mukhopadhyay et al. (2023b) |
| 5.15 | 12.18 | 136.5 | Siwana Mal, Haryana | Mukhopadhyay et al. (2023b) |
| 18.10 | 23.60 | 30.4 | Jagsi, Haryana | Mukhopadhyay et al. (2023b) |
| **Carbon sequestration potential (Mg C per hectare per year)** | | | | |
| - | 6.40 | | Shedshael, Maharashtra | Mukhopadhyay et al. (2023a) |
| - | 1.40 | | Kavathesar, Maharashtra | Mukhopadhyay et al. (2023a) |
| **Wheat productivity (kg per hectare)** | | | | |
| 3070 | 3610 | 17.6 | Gohana, Haryana | Datta et al. (2004) |
| 1290 | 4200 | 225.6 | Rohtak, Haryana | Mukhopadhyay et al. (2023b) |

| Before-SSD/ control | After-SSD | Change (%) | Site and State | References |
|---|---|---|---|---|
| 800 | 4200 | 425.0 | Jind, Haryana | Mukhopadhyay et al. (2023b) |
| 1110 | 1950 | 75.7 | Hissar, Haryana | Kaledhonkar et al. (2012) |
| 2980 | 3460 | 16.1 | Sonipat, Haryana | Tripathi (2010) |
| 1150 | 2440 | 112.2 | Sriganganagar, Rajasthan | Shekhawat (2007) |
| 2740 | 3410 | 24.5 | Fatehabad, Haryana | Raju et al. (2015) |
| **Rice productivity (kg per hectare)** | | | | |
| 520 | 3550 | 582.7 | Rohtak, Haryana | Mukhopadhyay et al. (2023b) |
| 700 | 4320 | 517.1 | Jind, Haryana | Mukhopadhyay et al. (2023b) |
| 3700 | 5600 | 51.4 | Konanki, Andhra Pradesh | Ritzema et al. (2008) |
| 4500 | 5500 | 22.2 | Uppugunduru, Andhra Pradesh | Ritzema et al. (2008) |
| 2730 | 4130 | 51.3 | Endakuduru, Andhra Pradesh | Satyanarayana and Boonstra (2007) |
| 1410 | 1740 | 23.4 | Sonepat, Haryana | Sharma and Gupta (2006) |
| 1420 | 2270 | 59.9 | Sriganganagar, Rajasthan | Shekhawat (2007) |
| **Sugarcane productivity (ton per hectare)** | | | | |
| 34 | 100 | 194.1 | Belgaum, Karnataka | Raju et al. (2017) |
| 78 | 115 | 47.4 | Segwa, Gujarat | Ritzema et al. (2008) |
| 37.44 | 98.00 | 161.8 | Surat, Gujarat | Chinchmalatpure et al. (2020) |
| **Cropping intensity (%)** | | | | |
| 37.5 | 123.7 | 86.2 | Bhana-Brahamana, Haryana | Datta et al. (2002) |
| 22 | 116 | 94.0 | Ismila, Haryana | Datta et al. (2002) |
| 143 | 191 | 48.0 | Tungabhadra irrigation project, Karnataka | Manjunatha et al. (2004) |
| 117 | 175 | 58.0 | Gohana, Haryana | Datta et al. (2004) |
| 148 | 178 | 30.0 | Fatehabad, Haryana | Raju et al. (2015) |
| **Water table depth (m)** | | | | |
| 0.55 | 0.75 | 36.4 | Fatehabad, Hayana | Raju et al. (2015) |
| 0.63 | 1.07 | 69.8 | Gohana, Haryana | Datta et al. (2004) |
| 0.30 | 1.00 | 233.3 | Lakhuwali, Rajasthan | Ritzema et al. (2008) |

*Note: In case of OC and cropping intensity, the changes are in percentage points.*

## Publications

**Policy Papers**

35. Singh, N. P., B. Anand, and S. Singh. 2020. *Impact of Climate Change on Agriculture in India: Assessment for Agro-Climatic Zone.*
36. Chand, S., P. Kishore, S. Kumar, and S.K. Srivastava. 2020. *Potential, Adoption and Impact of Micro Irrigation in Indian Agriculture.*
37. Subash, S.P., A. Jhajharia, and S. Pal. 2020. *Trade and Investment Policy for Overseas Acquisition of Fertilizers and Raw Materials: Role of the Government.*
38. Birthal, P.S., J. Hazrana, and R. Saxena. 2023. *Livestock Farmers' Information Needs, Search Behaviours, and Their Impact: Lessons for Extension Policy.*
39. Saxena, R., S.K. Srivastava, S.J. Balaji, A. Jhajhria, and M. A. Khan. 2023. *Changes in Indian Agriculture: Household-level Evidence.*
40. Nikam, V., H. Veesam, T.M. Kiran Kumara, and P. Chand. 2023. *Farmer Producer Organizations in India: Challenges and Prospects.*
41. Birthal, P.S., J. Hazrana, D. Roy, and K.J.S. Satyasai. 2024. *Can Finance Mitigate Climate Risks in Agriculture? Farm-level Evidence from India.*
42. Chand, P., T.M. Kiran Kumara, S. Pal, and K. Naik. 2024. *A Spatial Assessment of Sustainability in Indian Agriculture.*
43. Kishore, P., D. Roy, P.S. Birthal and S.K. Srivastava. 2024. *Regulation and Policy Response to Groundwater Preservation in India.*
44. Kandpal, A., P.S. Birthal and S. Mishra. 2024. *From Research to Impact: Payoffs to Investment in Agricultural Research and Extension in India.*
45. Sharma, P., M. Yeasin, R. K. Paul, D.C. Meena and M. E. Anwer. 2024. *Food Price Volatility in India.*
46. Srivastava, S.K., P. Kishore, P.S. Birthal and P.B. Shirsath. 2024. *Harnessing the Potential of Solar-Powered Micro-Irrigation for Sustainable Intensification of Agriculture.*
47. Saxena, R., P. S. Birthal, R. C. Agrawal, P. Sharma, S. J. Balaji, D. K. Pant, and N. Joshi. 2024. *From Local to Global: Opportunities to Accelerate Agriculture Exports from India.*
48. Kishore, P., P. S. Birthal, and S. K. Srivastava. 2025. *The Dilemma of Agricultural Price Policy Reforms: Balancing Food Security, Farmers' Interests, and Sustainability of Natural Resources.*

**Policy Brief**

45. Pal, S., R. Saxena, and S.J. Balaji. 2020. *Market and Innovation-led Agricultural Transformation.*
46. Roul, C., P. Chand, and S. Pal. 2020. *Developing Agricultural Sustainability Index for the Indo-Gangetic Plains of India.*
47. Birthal, P.S., J. Hazrana, D.S. Negi, and A. Mishra. 2022. *To Insure or Not to Insure: What Explains Low Uptake of Crop Insurance?*
48. Birthal, P.S. 2022. *Managing Climate Risks in Indian Agriculture: What do We Need to Know?*
49. Balaji, S.J., P. Sharma, P. Venkatesh, and K. Shreya. 2022. *Technology and Policy Options for Reducing India's Import Dependence on Edible Oils.*
50. Saxena, R., R.K. Paul, S.J. Balaji, and R. Kumar. 2022. *India's Agricultural Exports during the Covid-19 Pandemic.*
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