Pathways to Water Security: Exploring the Impacts of Irrigation Investments in Madhya Pradesh, India

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"Knowledge that sees in all things a single, imperishable being, undivided among the divided – this kind of knowledge is sattvic."

The Bhagavad Gita

Abstract

Agriculture-dependent societies invest in irrigation infrastructure to enhance water security for agricultural production and improve farmers' livelihoods in the face of hydroclimatic risks. While these investments have historically contributed to food security and economic growth, we have an incomplete understanding of their distributional impacts. We lack evidence of the dynamic outcomes of investments in irrigated agriculture in specific contexts with respect to uncertain hydrological cycles, policy impacts, and socio-economic poverty. This thesis addresses this gap by exploring how investments in irrigation infrastructure influence agricultural, poverty, and behavioural outcomes. To do so, it uses a ten-year World Bank funded programme to modernise irrigation infrastructure in the Indian state of Madhya Pradesh (MP) as a case study.

The thesis builds upon prior work analysing the relation between infrastructure, water security, and the economy. In particular, it relates to the literature on: (1) the association between hydrological variability, rehabilitated irrigation infrastructure, and crop yields; (2) the distributional impacts of irrigation and links to poverty alleviation through well-being; and (3) the role of infrastructure and financial incentives in driving the irrigation choices of farmers. The overarching research question of the thesis is: do investments to modernise and rehabilitate irrigation infrastructure enhance outcomes related to agricultural water security in Madhya Pradesh? To answer this question, the thesis explores the impact of improved infrastructure by examining changes in crop yields, farmer well-being, and irrigation practices by taking into account contextual factors related to hydrological variability, crop price and subsidy policies, socio-economic characteristics of farmers, and social dynamics among farming communities. The thesis utilises a mixed methods approach combining analysis of rainfall anomalies at the district-scale supported by a cross-sectional survey of 918 farmers and consultations with stakeholders from government, donor, and farming communities.

The results advance knowledge of the multiscale and multidimensional consequences of irrigation infrastructure investments with implications for water security. The thesis highlights that in the context of Madhya Pradesh: a) there is a positive correlation between infrastructure and crop yields in average rainfall areas and little to no effect of rehabilitation on yields in low or high rainfall areas after accounting for district-scale hydroclimatic variability; b) national food security policies such as the Minimum Support Price for cereal crops are strongly correlated with crop yields more so than hydrological factors; c) access to modernised surface irrigation is positively correlated with improvements in farmers' well-being, with evidence of higher gains among poorest segments of farming communities and where rainfall is low; d) in areas with improved irrigation canals there is reduced probability that farmers will use sprinkler or drip systems and instead prefer to flood irrigate; and, e) social networks strongly influence the irrigation practices of farmers.

While findings remain contextual to the study area and the factors examined, the thesis concludes that a process-driven approach to irrigation investments in the state, focused on improving water supply based on rehabilitation of ageing canals, cannot adequately account for the risks associated with sub-basin hydrological variability and the consequential impacts on crop yields. The thesis calls for further analysis on whether integration of contextual factors related to district-scale rainfall variability data; knowledge of how policies and social norms shape farmer crop and irrigation choices, and well-being responses among different farmers into the design and appraisal of future infrastructure investments may enhance multiscale water security benefits to smallholders in the face of increasing climatic risks to agriculture in India.

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List of Acronyms

ABM	Agent-Based Model
ADB	Asian Development Bank
AC	Acres
BPL	Below Poverty Line
CCA	Culturable Command Area
CMO	Context Mechanism Outcome
CUREC	University of Oxford Central University Research Ethics Committee
GDP	Gross Domestic Product
GHWMs	Global Hydrology and Water Resources Models
GPM	Global Precipitation Measurement
GWP	Global Water Partnership
GoMP	Government of Madhya Pradesh
GRACE	Gravity Recovery and Climate Experiment
GSDP	Gross State Domestic Product
Ha	Hectares
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
MM	Millimetres
MP	Madhya Pradesh
MPWSRP	Madhya Pradesh Water Sector Restructuring Project
NABARD	National Bank for Agriculture and Rural Development
NIA	Net Irrigated Area
NSDP	Net State Domestic Product
NSSO	National Sample Survey Organization
NVDA	Narmada Valley Development Authority
OBC	Other Backwards Caste
OECD	Organisation for Co-operation and Development
O&M	Operation & Maintenance
PICU	Project Implementation Coordination Unit

PIM	Participatory Irrigation Management
PMKSY	Pradhan Mantri Krishi Sinchayee Yojana
QCA	Qualitative Comparative Analysis
RBI	Reserve Bank of India
RCT	Randomised Control Trial
SC	Scheduled Caste
SD	Standard Deviation
ST	Scheduled Tribe
ToC	Theories of Change
TRMM	Tropical Rainfall Measuring Mission
UN	United Nations
WASP	Weighted Anomaly of Standardized Precipitation
WALMI	Water and Land Management Institute
WRD	Water Resources Department
WUA	Water Users Association
WUE	Water Use Efficiency

For the farmers of Madhya Pradesh

1. INTRODUCTION

"It is looking at things for a long time that ripens you and gives you a deeper meaning."

Vincent Van Gogh

1.1 Defining and achieving water security in agriculture: the role of irrigation infrastructure

Global agriculture systems are under pressure to increase food production to feed growing populations while simultaneously facing increasing climatic and hydrological shocks. Due to increasing competition for water from thirsty cities, and threats related to changing hydrological cycles, agricultural production in many regions is facing multiple challenges that are likely to negatively affect local, regional, and global food supplies, food security, economic growth, and ecological health of water bodies (Hall et al., 2014; OECD 2017, Garrick et al., 2019). While irrigated agriculture is responsible for more than 90% of all consumptive water use in water-scarce regions; globally, irrigated agriculture accounts for an estimated 70% of all freshwater withdrawals (Richter et al., 2017). Thus, agricultural production simultaneously contributes to and is at the greatest risk from water stress, as climate change is decreasing the reliability of available water supplies in many parts of the world (Postel et al., 1996; Greenland et al., 1997; Vorosmarty et al., 2000; Barker and Molle, 2004; Bakker 2012; FAO 2017; Du Plessis 2019; Campanhola and Pandey, 2019; Garrick et al., 2020). This is particularly relevant for low-income countries with high dependence on agriculture (more than 20% of the Gross Domestic Product (GDP) from agriculture) (Grey and Sadoff, 2007; Sadoff et al., 2015).

In the face of these complex and multifaceted challenges, the concept of *water security* has emerged as a prominent objective, framing policy goals and actions to address the full spectrum of water-related hazards to society in the agricultural sector, as well as in the environment, urban, health, and energy domains (Sadoff et al., 2020). Conceptualisations of water security span a diverse range of approaches that have evolved from an initial focus on the minimum quantity of water available for a given purpose to broader considerations of water access, quality, risk, health, ecological, and governance concerns (Jepson et al., 2017; Wutich et al., 2017). As water security is multidimensional, arising from the challenge of balancing human and environmental water needs, it has been interpreted in different ways by different institutions and scholars (Scott et al., 2019; Sivapalan et al., 2014; Srinivasan et al., 2017). As a result, there is no single globally

accepted definition of water security; there are several, which range from broad to narrow, as well as, theoretical to normative interpretations (Bakker 2012; Cook and Bakker, 2012).

One of the prominent conceptualisations of water security is by UN-Water, the United Nations (UN) body coordinating the work of UN agencies working on water and sanitation, which states that water security is:

> "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human wellbeing, and socio-economic development, for ensuring protection against waterborne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability." (UN Water, 2013).

This definition implies that water security can be achieved when society "protects" or safeguards the source of water to enable "*sustainable*" supply of an "*adequate*" amount of water. The premise that is inferred in this framing, is that once the right quantity of water supply is available, at the right quality, that supply will sustain livelihoods, ensure well-being, enable economic and social development, protect water bodies from environmental and ecological degradation as well as enhance resilience against water-related disasters contributing to peace and stability of political systems[1]. The trigger for the wide-ranging benefits implicit in this definition is access for humans to an adequate quantity and quality of water, which enables the purported benefits to be obtained. The central role of access to water supply as a means to achieve water security is also mirrored in the often quoted definition by the Global Water Partnership (GWP), which defines water security as follows:

> "Water security, at any level from the household to the global, means that every person has access to enough safe water at affordable cost to lead a clean, healthy,

[1] Although the scalar and temporal complexities of water supply are emphasised here with respect to access to water for food production, it is also important to take note of the notion of water as a source of conflict(s) at diverse geographical and political scales, which is alluded to in this definition of water security by UN-Water, "*in a climate of peace and political stability*". This concept has been emphasised by Mollinga et al., (2008), who states that "*water resources management practices will equally continue to generate a large number of conflicts and other contestations*…" (p.17); for additional work on water security and conflict, often referred to as 'hydropolitics' (see Waterbury 1979, Ohlsson 1995; Wolf 1999, Dinar 2002, among others).

> and productive life, while ensuring that the natural environment is protected and enhanced"(GWP 2000a).

Although both of these definitions highlight a slightly nuanced set of benefits, they rest on the assumption that once the 'productive' force of water is harnessed (namely through adequate supply and access to quality water) and the 'destructive' risks minimised, water security is achieved (Grey and Sadoff, 2007).

In the context of agriculture, it is investments in surface irrigation infrastructure that emerges from the scholarship as one of the prominent pathways for achieving water security. Canal irrigation networks are considered the means through which adequate access to water supply is ensured for farmers, minimising hydrological risks for food production and are thus considered "*important constitutive elements of water security*" (Siddiqui et al., 2018, p.44) for agriculture-dependent nations (Chambers 1988; Cook and Bakker, 2012; Swamee and Chahar, 2015). This understanding of the role of infrastructure as an enabler for water security in the agriculture sector is supported by the work of Lankford (2013, p.256) who argues that:

> "water security seeks, and is consequent to, the sharing of water surpluses and deficits between different users mediated by the designed architecture of water infrastructure deployed to address the spatial, temporal, and scalar complexities of demand and supply… these intertwined effects (of water insecurity) are mediated by the types of infrastructure selected for different sectors (e.g., irrigation)" (Lankford, 2013, Chapter 16, p.256).

The notion that water security in the agriculture sector can be achieved by means of irrigation infrastructure, among other interventions, has been supported by multiple scholars (Jacoby 2002; van de Walle and Cratty, 2002; Hussain and Hanjra, 2004; Smith 2004; Lipton 2005; Van Den Berg and Ruben, 2006; Del Carpio et., al 2011), who argue that the infrastructure can harness the productive capacity of water and reduce risks from water-related shocks for agriculture-dependent societies. This can lead to benefits such as (a) protection against hydrological variability while ensuring continued growth through improvements in crop production (Balooni et al., 2016; Dadson et al., 2017; Gulati et al., 2017); (b) enhanced farm productivity and reduced poverty for farmers as the infrastructure

then contributes to improved farm incomes (Bhattarai et al., 2003; Porter et al., 2014); and (c) with improved access to surface irrigation contributing to increased farm incomes this reduces the transaction costs for farmers to access seasonal finance, enabling them to improve their farming techniques (as argued by Ishikawa 1967; Hussain and Hanjra, 2004; IWMI 2006; Bourguignon and Pleskovic, 2007; Narayanamoorthy 2009b; Rosegrant et al., 2009; Gleick et al., 2011). Ishikawa (1967) concluded that in parts of Asia, specifically in India,

> "despite its changing phases, irrigation was invariably conceived in these plans [he refers to the Indian government five-year planning cycles, RS] as the major contributing input to the increase in agricultural production" (p.116).

Although it is believed that improving irrigation system performance by rehabilitating and modernising aging infrastructure can be a critical production factor that can help lift the hydrological constraints on agricultural productivity (Merrey 2008; UNESCO-IHE 2009; Ostrom et al., 2011; Gunawardana et al., 2013; Suhardiman et al., 2015; Petit 2016; Wichelns 2017), on the other hand, it is also well documented in the literature, that there are many confounding factors that can negatively influence the promised benefits of water security and the productivity effects of irrigation investments. For instance, Ishikawa (1967) illustrated that, "*even though irrigation ratios are similar between two areas, the productivity effects of irrigation are quite different because of the difference of the technical qualities of irrigation facilities in the two areas*" (p.90). As a result, it is well established that managing water systems, particularly in the context of surface irrigation, is an inherently complex process with multiple adaptive processes occurring at multiple scales and dimensions within specific locations (Tomich et al., 2019; Grafton et al., 2019). However, empirical analysis that quantifies outcomes (at multiple scales - farm, basin, sub-national, national) and (along multiple dimensions - hydrological, agricultural, social, behavioural) from investments in irrigation infrastructure *after implementation* are scarce and incomplete in the scholarly literature (Pritchett & Woolcock, 2004). This leads to a further line of enquiry, do improved irrigation systems generate the promised benefits from enhanced agricultural water security in specific settings?

The remainder of this chapter is organised as follows. In the next sections, I frame the background and rationale for this research by: (a) identifying evidence gaps related to the distributional impacts of irrigation infrastructure investments, (b) highlighting the relevance of studying these issues in the contextual setting of India and the state of Madhya Pradesh as well as clarifying my position and background with respect to this study, and (c) introducing the thesis research question, objectives, and the justification for exploring outcomes of irrigation investments related to hydrological, agricultural, socio-economic, and behavioural aspects. To close this chapter, I briefly introduce the three core empirical chapters and outline the thesis format.

1.2 Contextual evidence gaps of outcomes from investments in irrigated agriculture

While emerging debates and discussions around the concepts of water security are advancing, policy interventions in irrigation infrastructure across many agriculture-dependent economies continue to be based on the notion that if and when canal systems are modernised or improved they will ensure adequate supply and access to water for food production (De Loë and Bjornlund, 2008). Since the early 2000s, international financing in the rural irrigation and agriculture water management sector, spearheaded by the World Bank, other international donors, and UN agencies has focused on upgrading physical irrigation infrastructure (FAO 2018). Investments have been channelled towards surface systems that are degraded past designed performance standards due to poor operation and maintenance (Ward et al., 2006; ADB 2017). However, despite the significant amount of national and global investments made by donors and governments on improving surface irrigation systems, evidence of whether water security benefits from modernised and rehabilitated irrigation infrastructure have been realised, *ex post*, at a sub-national scale and along multiple dimensions is still patchy. The rationale for this is due to several factors.

First, although a number of scholars are exploring how to measure the outcomes of water security (e.g., van Beek & Arriens, 2014; Garfin et al., 2016; Gain et al., 2016; Hoekstra et al., 2018; Jensen & Wu, 2018), only a few have shown how that can be applied to the interconnected outcomes of improved irrigation infrastructure (Gober and Wheater, 2014; Siddiqui et al., 2018) across diverse segments of a farming population and at diverse

spatial and temporal scales within a specific setting. This highlights a knowledge gap on how investments in irrigation infrastructure affect outcomes related to water security within specific contexts. "*We know that successful investments are path-dependent, e.g., that context matters. But we do not know, for different basins and development paths, what are the critical balance and sequencing of investments in institutions, infrastructure, and information*" (Hall et al., 2014, p. 430). In supporting the validity of this argument, Sadoff et al., (2020, p.10) state that "*knowledge of the type and sequences of investments that are more appropriate for different contexts is limited, as each pathway for water security will be context dependent*". The stated lack of '*context dependent'* knowledge signifies a potential blind spot among scholars, policymakers, and donors alike into the *types* of investments that are better suited for specific locations to enhance the intended 'productive' benefits of water for food production. Thus, further analysis is needed on whether interventions to enhance water security through irrigation infrastructure modernisation are leading to the intended impacts in specific settings.

Second, researchers that have pointed out the shortcomings of the prevailing paradigms on water security highlight issues of scale and the lack of distributional understanding around the complexities of national and sub-national investments in water-related infrastructure (Cook and Bakker, 2012; Klumper et al., 2017). However, most of this literature focuses on global and regional trends and is largely silent on outcomes at a sub-national or household-scale in the context of canal irrigation (Turral et al., 2010; Sadoff et al., 2015, Dadson et al., 2017; Damania et al., 2017). Lankford (2013) points out that "*water insecurity results not only from a lack of infrastructure to face water-related impacts of climate change (Jowitt, 2009), but also from how infrastructure is put together to serve increasingly interconnected users and sources*." (Lankford 2013, Chapter 16, pg. 256-257). As water-related risks tend to principally impact poor households, particularly in agriculture-dependent regions, it is critical to quantify risks and understand household-level responses to improved irrigation infrastructure in order to obtain a more granular and distributional picture of the effectiveness of irrigation infrastructure investments (Baker 2000; Hope et al., 2012).

Third, outcome indicators related to the efficacy of interventions to enhance water security by means of upgraded surface irrigation infrastructure such as: a) rainfall variability and growth (Brown and Lall, 2006, Brown et al., 2011; Khan et al., 2017; Thatte 2017), b) irrigation and poverty (Smith 2004), and c) how irrigation infrastructure catalyses improvements in farming practices are typically dealt with independently in the literature (Carey and Zilberman, 2002; Olen et al., 2016). Work by Sivapalan et al., (2012) and others argue that understanding water security as a function of access to adequate water supplied is insufficient and thus promote a transdisciplinary understanding of water security grounded in the growing field of socio-hydrology (Sivapalan et al., 2014), in which "*human and natural components of coupled water systems interact to produce emergent properties*" (Scott et al., 2019). They claim that effective management of water over long periods of time requires an understanding of the "*coevolving dynamics and feedbacks inherent in coupled human-water systems*" (Sivapalan et al., 2017, p. 13). This implies that pursuing water security requires understanding the dynamic feedbacks and interactions between the natural ecological characteristics of water, with regard to drought, flooding, river diversion, and unbalanced distribution of water resources (Norman et al., 2010), the socioeconomic features related to poverty-related benefits as well as the behavioural components including understanding the consequences on water management and farming practices (from the perspective of water users) to avoid excessive water consumption leading to water shortage and water pollution (Bakker, 2012; Cai et al., 2020).

However, with respect to canal irrigation, various disciplines tend to focus studies of the impact of irrigation systems by exploring impact indicators and using methodological approaches related to their field of expertise, as Mollinga (2019, p.790) points out, "*in terms of disciplinary communities, geographical, historical, anthropological, sociological, policy science, legal, and political economy interests and approaches are quite distinct*". As a consequence, distinct disciplines may examine the impacts of irrigation infrastructure from diverse perspectives such as: a) hydrological dimensions (natural scientists analyse hydrological parameters to optimise the supply of canal water), b) infrastructure variables (irrigation engineers may focus on canal system design to maximise agricultural efficiency and cost recovery for operation and maintenance

costs), or c) sociological dimensions (social scientists, economists, sociologists, anthropologists, political ecologists focus on agricultural productivity, demand-side allocation, equity, income poverty, water use efficiency, water governance, corruption and political economy of canal infrastructure, among other factors) (Wade 1982, 1985; Suhardiman and Mollinga, 2016; Kurian 2017, among others). Thus, it can be difficult to compare findings across distinct disciplinary approaches at diverse scales, time periods, and factors of analysis to develop a multidimensional and multidisciplinary picture of the dynamic, distributional impacts of canal irrigation infrastructure investments in a particular geographical setting (Balasubramanya and Stifel, 2020). Siddiqui et al., (2018) state that in the case of irrigation systems, there is a need for scholars to undertake interdisciplinary analytical studies on the outcomes of investments in canal infrastructure across space and time within a specific context along multiple dimensions involved in achieving water security in irrigated agriculture. In their recent work, Pahl-Wostl et al., (2020) cite that "*despite the obvious importance of policy implementation, systematic comparative analyses on the effectiveness of (water) policy implementation in particular at the operational level are largely lacking*" (p.25). This presents an evidence gap between the dominant theoretical and applied approaches for *how* to improve water security in the agriculture sector, *what occurs* in specific locations *after* the implementation of infrastructure-related investments in irrigation, and whether these interventions *lead to* the benefits expected from enhanced water security from an interdisciplinary perspective.

Although this Chapter has presented broader definitions of water security, which encompass different water use sectors (e.g., drinking, energy, environment, among others) and address national and global water resources management concerns, this thesis concentrates on exploring the role of irrigation infrastructure in enabling water security for the agriculture sector and its related benefits in the context of India. Thus, the starting point for this thesis departs from the definitional understanding that the "*deployment*" of irrigation infrastructure to ensure "*adequate supply*" to harness the productive capacity of water is one of the main levers for achieving water security for food production within an agriculture-dependent economy such as India. Studying the outcomes of irrigation investments in India is highly relevant as agriculture in India accounts for 90% of

freshwater use (Dhawan 2017) and the country has a long tradition of state-level public expenditure on improving canal irrigation across multiple states (Ishikawa 1967; Wade 1988; Mollinga 2003). Therefore, the research conducted in this thesis is concerned with exploring a set of interdisciplinary outcomes, along multiple scales, after investments in canal modernisation and rehabilitation are completed within the contextual setting of an Indian state.

1.3 A timely opportunity to understand the effectiveness of irrigation infrastructure in India

In India, over the course of the past decade, water sector reforms within the framework of Integrated Water Resources Management (IWRM)[2], led predominantly by the World Bank, were mirrored across multiple states including Madhya Pradesh. State governments embarked on a series of modernisation and irrigation sector reforms focusing on infrastructure, but also other reforms in governance, legislative, and on-farm water use efficiency programmes to varying degrees of success (Burton et al., 2011). Underlying the design of most investment programmes within Indian states laid the conventional wisdom that investments to upgrade and modernise ageing irrigation infrastructure (based on the performance standards of the physical systems) would improve the resilience of agricultural production systems to climate-induced hydrological variability and uncertainty (World Bank 2010; FAO 2018).

With funding from the World Bank, the Indian state of Madhya Pradesh embarked on a large-scale water sector reform and irrigation infrastructure investment programme. The Madhya Pradesh government initiated the Madhya Pradesh Water Sector Restructuring Project (MPWSRP) in 2005, a programme focused on rehabilitating and modernising surface irrigation systems across multiple river basins in the state to deliver timely and effective irrigation services to farmers across the state (World Bank 2005). The project aimed to improve the productivity of water for sustainable growth, and poverty reduction across 31 districts in six (Chambal, Sindh, Betwa, Ken, Tons, and Wainganga)

[2] IWRM is defined as a "*process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*" (GWP 2000b).

out of the ten river basins in the state. MPWSRP focused on a) rehabilitating and modernising its surface irrigation networks; b) reforming its Water Resources Department; c) creating farmer-led Water User Associations; and d) investing in improved river basin modelling and information systems for enhanced decision-making (World Bank 2005).

From 2010 to 2014, I worked closely with the Government of Madhya Pradesh (GoMP), on behalf of the World Bank, in supporting the Madhya Pradesh Water Resources Department (WRD) implementation of the MPWSRP. In 2015, the Madhya Pradesh government completed the MPWSRP and the World Bank signed-off that the project was completed with success. Madhya Pradesh saw its State Gross Domestic Production increase significantly, agricultural growth in Madhya Pradesh, which had registered negative growth in 2000-01, 02-03, 04-05 and 07-08, rose close to 20% in 2011-12 and above 20% in 2012-13 (Sapre 2014). Donor reports and government assessments attributed this state-wide growth to crop yield improvements from the MPWSRP investment strategy for improving irrigation system performance, which they reported led to an increase in net irrigated area from 6.9 million ha in 2009-10 to 8.6 million ha in 2012-13 (ADB 2018). In addition, this specific approach to enhancing water security mainly through infrastructure rehabilitation consisting of repairing deficient infrastructure to restore it to its original design capacity, along with other interventions to create WUAs and reform irrigation departments, was replicated by the World Bank in other states in India (e.g., Karnataka, Rajasthan, Uttar Pradesh) concurrently as the MPWSRP was implemented (FAO 2018).

As Madhya Pradesh prioritised investments to modernise and rehabilitate irrigation infrastructure seeking to reduce risks from water-related shocks and generate returns to the state's economy through improvements in agricultural production, the end of the project presented me with an important research opportunity. The MPWSRP presented a case study in the convergence of theory and practice of an infrastructure-related intervention to achieve water security for the agriculture sector. Thus, the motivation for the research undertaken for this doctorate was borne out of this timely opportunity. Consequently, the research design and approach presented in the subsequent chapters has evolved from my direct involvement, as a practitioner, in implementing the MPWSRP in partnership with the Government of Madhya Pradesh.

Chapter 1

Prior to presenting the main research question and objectives of the thesis, I would like to reflect on my positionality as a practitioner-researcher, how it influenced, enabled, and potentially biased the perspectives adopted in this research, facilitating its legibility to a specific readership. As I was formerly employed by the World Bank in India, I came into this research study with about ten years of site specific contextual knowledge from a practitioner's perspective on water sector reform in India, aware of and embedded in the political dynamics of this setting, accustomed to interacting and negotiating with Indian bureaucrats, engineers, economists, farmers, and politicians. Consequently, my background as a former practitioner is tightly associated with why I developed this study from a normative perspective with specific transdisciplinary objectives to examine specific outcomes and produce research outputs, which may potentially respond to the needs and challenges of policymakers and practitioners working on irrigation sector reforms for promoting water security and agricultural growth in India. Although this unique vantage point afforded me with privileged insights and information that shaped my choices for the research design, objectives of the study, and outcome indicators; my stance as a former practitioner may also potentially bias my perspectives of the role of irrigation infrastructure in the agriculture sector in India, towards a more normative position. As a result, I opted to design and share the research outputs of this work in "partnership" with a core set of actors (e.g. World Bank irrigation specialists, senior policy advisors in the Indian government, Indian civil servants and engineers in the Madhya Pradesh Water Resources Department, and the farmers themselves) who I formally worked with and worked for, as it was important for me that the insights of this thesis are meaningful for the academic community as well as are translatable to policy makers and staff at the World Bank.

My past relationships with these actors also granted me unique access to data and thus influenced me to ground the study in the context of the state. My position with respect to these key actors, and the contextual insights I had prior to the start of this research, thus explicitly shaped some of the methodological choices and the outcomes examined that are inherent to the research design. As such, this thesis focuses on exploring a set of interdisciplinary outcomes related to the agricultural, socio-economic poverty, and behavioural consequences of canal irrigation reform in Madhya Pradesh at various scales

of analysis, ensuring that the outputs can contribute to the scholarship in this field as well as remain relevant for the practitioner community associated with the case study.

1.4 Thesis question, research objectives, and format

The central focus of this thesis is to provide an analytical basis for understanding how improvements in canal infrastructure influence distributional outcomes across space and time in the context of rural Madhya Pradesh. Building on this, the overarching research question is: *do investments to modernise and rehabilitate irrigation infrastructure enhance outcomes related to agricultural water security in Madhya Pradesh?*

In order to respond to the research question, and to address the evidence gaps highlighted in this Chapter with respect to limited contextual knowledge of the distributional impacts from rehabilitated and modernised canal irrigation infrastructure at the sub-national scale in India, I chose to ground the analysis on a set of interdisciplinary indicators spanning hydrological, economic, and social domains. With this approach, I aim to provide a more nuanced and multidimensional picture of the potential outcomes after canal irrigation systems are upgraded within an Indian state. Although, the research undertaken in this thesis certainly does not exhaust the multiplicity of contextual and interdisciplinary factors associated with canal irrigation in India (see Chapter 3 for a discussion of these limitations), I focused on exploring impacts from upgraded irrigation systems in Madhya Pradesh along the following aspects: (1) how irrigation infrastructure influences agricultural outcomes by examining changes in crop yields in surface irrigated areas by accounting for the variability in rainfall patterns at a sub-basin scale over time; (2) analysing whether contextual, non-infrastructure (e.g. national crop price policies in India) factors influence yield outcomes; (3) how irrigation effects multidimensional indicators of poverty among smallholder farmers by focusing on well-being rather than income poverty as well as understanding the distributional impacts by examining differential responses among diverse segments of a farming population; and, (4) whether improved surface infrastructure and the availability of technology subsidies influence farmer irrigation practices, to partially understand how canal irrigation interventions influence the behaviours of smallholders with respect to their farming techniques.

The core research question is addressed through the following three research objectives, each of which illustrates a justification for why these specific outcome indicators were selected for analysis within the three empirical chapters in the thesis (Chapters 4-6):

a) to determine whether investments in irrigation infrastructure modernisation lead to higher crop yields and buffer yields from fluctuations in rainfall at the district-level (Chapter 4)

To test the basic assumption that improved canal irrigation can contribute to enhanced crop growth by protecting crops against hydrological variability (Bhattarai et al., 2003; Porter et al., 2014) in Madhya Pradesh, I explore the hypothesis that rehabilitating irrigation systems in specific districts and river basins in Madhya Pradesh results in increased crop yields and protects crop yields against rainfall variability for three key cereal crops. However, as detailed in Chapter 2 Literature Review, instead of using aggregated national or state-level annual rainfall data to examine whether crop yields respond positively to investments in irrigation infrastructure, I focus on incorporating data at a more granular, sub-basin or district-scale in Madhya Pradesh. To my knowledge, studies that explore post-investment impacts on crop yields by incorporating data on sub-basin (district-scale) rainfall patterns to analyse the differential influence of the infrastructure on yields over a period of ten years, across multiple districts in India are rare in the literature. In addition, to obtain a more nuanced contextual understanding of potential non-infrastructure factors driving crop yields in Madhya Pradesh, I also investigate whether yield outcomes are influenced by national policy factors such as the Minimum Support Price for crops. This chapter illustrates that rainfall patterns are highly variable from district to district, within a river basin, and from year to year within Madhya Pradesh. Furthermore, findings from the survey analysis suggest that irrigation modernisation investments are positively correlated with improved crop yields in average rainfall districts but are not significantly correlated with yields in districts with deficient or above average rainfall compared to control districts with no investments.

b) to examine whether modernised irrigation infrastructure influences the subjective well-being of smallholder farmers (Chapter 5).

Considering that 90% of farms worldwide are less than two hectares in size and sustain most of the world's poorest people (McIntyre et al., 2009), it is important to understand the role of irrigation infrastructure in reducing poverty for smallholder farmers. Although, multiple studies have focused on understanding the effects of irrigation on farm incomes (Huang et al., 2005; Dillon 2011; Achempong et al., 2018), less attention has been paid to the effect of modernised infrastructure on farmer well-being (Jana et al., 2018; Passarelli et al., 2018). To determine the relationship between improved irrigation infrastructure and multidimensional outcomes of poverty, Chapter 5 builds on the hydrological and agricultural (e.g., crop yield) outcomes presented in Chapter 4 to examine the relationship between rehabilitated irrigation infrastructure and farmer well-being. Farmer survey data are modelled to explore changes in well-being among farmers in districts and households where canals were rehabilitated in comparison to districts with no investments based on primary data from a large-scale survey of farmers across multiple river basins. Socio-economic poverty indicators for households are interacted with infrastructure investments to understand well-being responses among households that are more vulnerable and economically disadvantaged, providing a more nuanced, distributional understanding of how improved canal systems influence socio-economic poverty outcomes. Results suggest that access to rehabilitated irrigation canals has a positive relationship with well-being improvements among a sample of farmers in Madhya Pradesh.

c) to understand how the combination of modernised irrigation systems and financial subsidies for irrigation technologies influence the irrigation practices of farmers in Madhya Pradesh (Chapter 6).

By 2050, the total quantity of freshwater supply available is expected to be less than the projected water demanded for irrigation in major food-producing countries if current production methods continue unchecked (Grafton et al., 2017; Grafton et al., 2019). As

water scarcity challenges grow in countries with large populations of farmers, which are simultaneously facing increasing risks of climate change, researchers are focusing on demand management as an approach to reduce agricultural water use (or to improve water conservation) (Balasubramanya and Stifel, 2020). These studies argue that reducing overuse of surface and groundwater will require changes in water use behaviour among users (Balasubramanya and Stifel, 2020). On the other hand, studies have also shown the role of irrigation infrastructure in contributing to improvements or changes in farming techniques of farmers in Asian countries (Ishikawa 1967). However, the influence of investments to enhance water security by upgrading canal infrastructure on farmer water use practices are still poorly understood (O'Keeffe et al., 2016). Specifically, more contextual knowledge is needed about the behavioural responses of farmers to improved canal systems and whether infrastructure interventions influence their preferences for making farm-level investments in irrigation technologies (e.g., sprinkler and drip systems) with implications for rates of agriculture water use among surface irrigated farms (Jiménez et al., 2014). While there is recognition in the literature that adopting irrigation technologies (e.g., sprinkler or drip systems) are necessary for reducing water use in agriculture, there are ongoing debates about whether the use of these technologies may lead to increased water use (Dinar and Zilberman 1991; Massarutto, 2002; Srinivasan et al., 2017; Perez-Blanco et al., 2020).

In the case of India, researchers have argued that in order to adequately examine the impacts of irrigation interventions in the agriculture sector, generating information on the behaviours of water users, as well as on the water resource itself, is essential as the factors influencing irrigation practices on a local level are much less understood (O'Keeffe et al., 2016). This is reinforced by a study by Cai et al., (2020) in China, which concludes that one of the main factors affecting water security in irrigated systems are the proportionate change in agriculture water use behaviours among farmers as the choice of irrigation methods (e.g., the number of farmers practicing flood irrigation) is indeed an important indicator of relative farm-scale water use or "agricultural water use" (among other relevant indicators). In terms of non-infrastructure factors, experts cite limitations of price-based policies as an appropriate tool for water use demand-management in irrigated

systems (Molle and Berkoff, 2006). However, there is limited evidence of whether the combination of public irrigation investments to improve canal systems, subsidy policies to incentivise farmers to use sprinkler or drip technologies, which are prevalent in many Indian states, catalyses a behavioural response among farmers with respect to their irrigation practices.

To address this gap around the behavioural implications of canal irrigation investments, Chapter 6 explores whether infrastructure investments and subsidies for technology adoption influence farmer irrigation practices. The chapter uses a combination of primary household data on self-reported irrigation methods of survey respondents and qualitative interviews with a sub-set of farmers to understand the influence of infrastructure and financial subsidies in driving their choices around irrigation technology use in the study area. The Chapter demonstrates that once irrigation canals are rehabilitated, there is a reduction in the probability that farmers will choose to use sprinkler or drip technologies. Instead, most farmers prefer flood irrigation methods in areas where MPWSRP improved irrigation canals compared to farmers in areas where canals were not upgraded. Of the small percentage of farmers who are investing in sprinkler or drip systems, most are in areas where MPWSRP did not upgrade canals. However, some 'adopting farmers' are located on farms where canal systems were improved, indicating that irrigation technologies are not necessarily alternatives to improved surface water supply. Next, the majority of adopting farmers are from poor and vulnerable groups with limited access to surface irrigation and higher water scarcity, suggesting that socio-economic factors may not always pose a barrier to farmers from adopting in times of water stress. Finally, all adopting farmers provide evidence of learning about the benefits of sprinklers and drip systems from within their social networks, illustrating the potential role of social incentives to drive changes in farmer irrigation practices. These insights reveal that improved surface canals can effect relative changes with respect to the agricultural water use choices of farmers which contributes to an enhanced understanding of how interventions to improve irrigation systems influence the farming techniques of a sample of smallholders in Madhya Pradesh.

In this thesis, I contend that understanding the dynamic outcomes of modernised irrigation canals requires analysis of operational outcomes in practice along multiple factors related to hydrological, agricultural, socio-economic, and behavioural dimensions. The thesis, therefore, seeks to complement the crop productivity, farm wage, canal system performance indicators that have been used in impact evaluations in the literature (Plusquellec et al., 1990; Del Carpio et al., 2011) by introducing a preliminary exploration of a selection of interdisciplinary outcomes stemming from infrastructure interventions in India. Limiting the complex range of potential outcomes that can emerge from irrigation infrastructure investments at multiple scales to focus on agricultural, poverty, and behavioural aspects is an obvious simplification, but the findings draw attention to the need for multidisciplinary and context-specific studies on the consequences of efforts to achieve water security through modernised irrigation infrastructure in India.

The thesis contains seven chapters, a consolidated bibliography, and appendices. After the introduction, a review of the literature (Chapter 2) discusses the theoretical gaps in the literature providing a detailed rationale for exploring canal irrigation outcomes along the agricultural, socio-economic poverty, and behavioural dimensions analysed within the three empirical chapters. The Chapter also provides a detailed discussion on different types of methodological approaches for evaluating programs and interpreting causality, their strengths and weaknesses, as well as the rationale for the methodological choices made in the thesis to conduct the analysis. Following a review of the literature gaps and analysis of different methodological approaches, Chapter 2 presents a general, analytical framework that conceptually illustrates how the examination is conducted in the diverse settings of multiple river basins and districts of Madhya Pradesh. Chapter 2 also presents each of the three sub-research questions explored within the three empirical chapters underpinning the overall research question. Chapter 3 introduces the area of study in Madhya Pradesh and provides an overview of the methodologies applied for data collection and analysis, including consideration of the limitations of this research. Chapters 4-6 present each of the three empirical chapters, which go into depth into one of the three objectives of the thesis, by addressing each of the sub-research questions that aim to resolve the overall question.

The three empirical chapters are presented as submitted/published journal papers in Chapters 4-6.

The thesis takes the form of the "paper route", whereby the substantive empirical chapters are academic papers provided as published in or submitted to, peer-reviewed journals[3]. The authorship declaration and detailed co-author agreements for each of the papers can be found in Appendix 1.

Published

Sinha, R., Gilmont, M., Hope, R., & Dadson, S. (2018). Understanding the effectiveness of investments in irrigation system modernization: Evidence from Madhya Pradesh, India. *International Journal of Water Resources Development*, *35*(5), 1-24. doi: https://10.1080/07900627.2018.1480357.

Submitted

Sinha, R., Dadson, S., & Hope, R. (2020). Does irrigation infrastructure influence the well-being of smallholder farmers? Empirical evidence from Madhya Pradesh, India. Submitted to *Special Issue of ICID Journal Irrigation and Drainage - Achieving Climate Resilience through Improved Irrigation Water Management from Farm to Basin Scale*.

Sinha, R. & Hope, R. (2020). Do modernized canals influence irrigation technology choices? Evidence from smallholders in Madhya Pradesh, India. Submitted to *Water Economics and Policy*.

The text, figures, and tables in each empirical chapter (4-6) are the same as published or presented in the submitted version to the journal with exceptions in formatting as highlighted at the start of each chapter. The references to figures and citations have been standardised to provide a coherent format throughout the thesis. Supplementary tables that refer to the respective papers are summarised at the end of each of the three chapters. All references are presented as a consolidated bibliography at the end of the thesis.

[3] The majority of the primary household and secondary data collection for the first two papers was conducted during my MPhil thesis research (2014-16). Initial versions of Chapters 4 and 5 were presented as the core empirical chapters of my MPhil thesis (Submitted in September 2016). However, the papers have undergone substantive methodological and empirical revisions and build on the initial research findings of the MPhil.

Supplementary information to support the methods of the chapters is included as appendices at the end of the thesis. In Chapter 7, the thesis concludes with a discussion of the implications for established scholarship stemming from the empirical results of each of the chapters. After reflecting on the limitations of the work, I discuss avenues for further research by suggesting opportunities for utilising diverse evaluation methods which can build upon the conclusions stemming from the analysis in the thesis.

2. Review of the Literature

"Canal irrigation is shrouded in mists of misinformation."

Robert Chambers

2.1 Understanding the role of irrigation infrastructure in enabling water security and growth

It has been argued that the fate of empires such as the Chinese, Mesopotamian, Egyptian, and Mayan, were distinctly intertwined with their ability to build large-scale irrigation systems and flood control works (Wittfogel 1957). These '*hydraulic societies'* "*covered more territory, lasted for more years, and shaped more lives than any other stratified agrarian society*" (Wittfogel 1957, p.414). Constructing irrigation systems allowed them to acquire food surpluses, release labour for other cultural (or warfare) activities, catalyse improvements in farming leading to further increases in food supply and to rising populations (Barker and Molle, 2004; Molle et al., 2009). On the other hand, Steward et al. (1995) argue that the growth of societies has been constrained by their inability to access adequate quantities of water. Historical records indicate that the Mohenjo-Daro and Harappa civilizations (3000 – 1500 BC) collapsed when shifts in the course of the Indus River ensued floods that destroyed their sophisticated irrigation systems, leading to their decline (Alam et al., 2007). Thus, it was the act of controlling water on a large scale, namely by constructing infrastructure for food production, power, and other purposes that have been associated with the formation and demise of many early civilizations (Barker and Molle, 2004).

To date, countries channel public investments in irrigation infrastructure with the aim of ensuring adequate and timely water supply for food production. This approach is reflected in the widely cited understanding of water security promoted by Grey and Sadoff (2007) and Sadoff et al., (2015), who are argue that investments in "*policies and infrastructure"* are necessary for enhancing water security, as the infrastructure (along with other investments) enables water to be delivered at specific times, places, prices, to be allocated between alternative uses, which protects societies from water-related hazards, leading to a profound impact on *"economic growth, inclusiveness, and the structure of economies*" (Sadoff et al., 2015, p.39). Across India, where irrigation is considered to play a major role in agricultural growth, investment in rehabilitation and modernisation of canal irrigation infrastructure has been one of the key pillars of the Government of India's

policies to reduce variability in water availability for agriculture (Planning Commission 2012).

Despite attempts to diversify India's economy, agriculture remains an intrinsic and fundamental component of India's growth, society, and culture (Singh and Chhetri, 2016). Agricultural productivity in India is heavily influenced by climatological patterns of rainfall variability. In parts of India, 50 percent of the precipitation falls in just 15 days, and over 90 percent of river flows are concentrated in four months of the year (Briscoe & Malik, 2006). Rainfall variability, therefore, is one of the major factors limiting agricultural productivity in India (Haileslassie et al., 2016). Empirical investigations of the impact of climate change conclude that agricultural productivity in India is climate sensitive, and the fluctuations in temperatures and rainfall patterns adversely affect crop productivity, and thus pose substantial risks to food security (Kar & Kar, 2008; Ranuzzi & Srivastava, 2012; Singh, 2012; Praveen and Sharma 2020). Thus, canal irrigation represents a large percentage of recurrent public expenditures for development of the agricultural sector (Small and Svendsen, 1990; Bourguignon and Pleskovic, 2007), playing a critical role in improving water security and reducing rural poverty (Balooni et al., 2016).

India's irrigation sector is one of the largest in the world and the irrigated area has increased from 20.9 million hectares (ha) in 1950-51 to 78.4 million ha in 2002-2003 (Narayanamoorthy 2011). Within the broad category of types of irrigation, there has been a major shift with canal irrigation accounting for about 42% of the net irrigated area (NIA) whereas tank and groundwater accounted for about 18 and 29% respectively during the fifties and sixties (Narayanamoorthy 2011). This changed in 2002–2003 where groundwater alone accounted for about 62% of NIA, and surface irrigation sources such as canals and tanks together accounted for only about 33% (Narayanamoorthy 2011). Subsequently, multiple states in India, financed by donor-led programmes, have made large-scale investments to modernise and rehabilitate their surface irrigation systems to keep pace with growing demands for food amidst an ever-increasing population (Burton et al., 2011). By the end of the 11th Five-Year Plan (2007-2012), the extent of potential created of large-scale major and medium canal irrigation was officially reported by the

Government of India as 47.41 million hectares (ha) with 35.01 million ha utilised and groundwater irrigation area at 41.82 million ha (Planning Commission, Government of India 2013, 183; Mollinga 2016). With increasing emphasis by the Indian government to modernise canal irrigation networks to provide adequate water supplies for food production during variable or deficient rainfall (Swamee and Chahar, 2015), this raises the critical question of whether the policy of investing in canal irrigation systems has indeed led to enhanced water security and its related benefits for Indian farmers?

Multiple research studies (e.g. Michel 1972; Small and Svendsen, 1990; Postel 1992, Hille and Vlek, 2005; Khan et al., 2006; Mollinga 2016; Mollinga and Veldwisch, 2016) have explored the dynamic impacts of irrigation performance and endeavoured to generate evidence of the consequences of irrigation infrastructure investments in Asia and specifically in India. Robert Chambers (1988) sought to focus efforts on demystifying canal irrigation infrastructure in South Asia, identifying the core gaps that undermine its performance. Chambers focused on aspects of surface irrigation infrastructure such as a) main system management, including the scheduling and delivery of water and communications around delivery; b) canal irrigation at night – management of canal systems jointly by farmers and government officials; c) professional conditions and incentives for irrigation managers; and d) methods for diagnostic analysis to identify cost-effective actions for improvement of the systems (Chambers 1988). His findings challenged how canal irrigation systems are diagnosed and tested for performance. He produced one of the most comprehensive records on how to improve irrigation system performance and to enhance their poverty alleviation benefits.

The works of Wade (1988a, b) and Chambers (1988), triggered a rich body of literature on evaluations of irrigation system performance (Perry 1995) and consequences for agricultural water and land productivity (Shah and Singh 2002), hinging around the roles of infrastructure (Ostrom et al., 2011), institutions (Turral et al., 2010), governance and socio-political dynamics (Suhardiman and Mollinga, 2017) in determining outcomes for water security (Garrick and Hall, 2014). However, scholars argue that the evidence surrounding the dynamic impacts of investments in canal irrigation is still incomplete (Pahl-Wostl, 2007a; Giordano 2013). Giordano et al. (2019) based on their analysis of the

methodological developments in the literature in the context of understanding the outcomes of interventions in irrigation systems, conclude that "*whether irrigation systems contribute to broader development objectives, depends on a number of complex and interrelated factors, and requires more detailed analysis in those specific settings*" (Giordano et al., 2019, p.18). In advancing understanding of the role of rehabilitated and modernised canal irrigation in enhancing water security and its related benefits to the agriculture sector, this thesis focuses on exploring the dynamic outcomes stemming from infrastructure investments in the Madhya Pradesh Water Sector Restructuring Project in the state of Madhya Pradesh.

In order to build the rationale from the literature on *how* this study conducts the analysis and *why* it analyses specific outcomes, this chapter does the following: a) it provides the rationale for exploring agricultural outcomes by analysing literature on the relationship between spatial and temporal hydroclimatic variability, investments in irrigated infrastructure, and impacts on crop yields and growth (Thakkar 1999; Mosse 2006; Hope 2007; Gilmont et al., 2018), leading me to enquire whether investments in irrigation infrastructure modernisation buffer crop yields from fluctuations in rainfall at a district scale; b) it highlights the role of irrigation infrastructure and the hydrological drivers that influence rural poverty alleviation (Hussain and Hanjra 2004) in the context of smallholder farmers in India by raising questions about how well-being (Ed Diener (1994) and colleagues) is influenced by irrigation infrastructure, thus building the rationale for examining socio-economic outcomes; c) it seeks to understand behavioural outcomes by examining how the combination of modernised irrigation systems and financial subsidies catalyse changes in farming practices with respect to the irrigation methods of farmers in Madhya Pradesh. To do so it delves into the literature on the incentive mechanisms influencing water use behaviours of farmers in the irrigation sector including price, technology, and policy levers (Chris Perry et al., (2009), Francois Molle (2008), Quentin Grafton (2018), and others). Relevant research on social learning factors among agricultural communities are considered in order to understand how contextual factors related to social dynamics among farming communities influence the irrigation practices of farmers; and, d) this chapter reviews different methodological approaches for evaluating

the impacts of programs and policies, discusses divergent interpretations of causality and presents their strengths and weaknesses, reflecting on the methodological approach chosen for this thesis in relation to the central research question, aims, and objectives of this study (Hussain and Hanjra 2004; Pawson and Tilley 1997; Pawson 2008; Marx, Rihoux, and Ragin 2014; Thornton et al., 2017 and others).

2.2 Spatial and temporal variability, infrastructure, and crop yields

It is well-established that investments in water-related infrastructure are critical to protecting nations against hydrological variability while ensuring continued growth, particularly for developing countries facing water-related shocks to the agriculture sector. However, there is limited evidence of the effectiveness of rehabilitated irrigation infrastructure to protect crop yields when changes in hydrological patterns are examined at diverse spatial and temporal scales. This section provides an overview of the broad discussion from the literature on the relationship between rainfall variability, investments in modernisation of irrigation infrastructure, and impacts on crop yields.

2.2.1 Hydrological variability, climate uncertainty, and economic growth

The link between economic growth and hydroclimatic variability in the context of climate change has been firmly established, particularly in low-income countries. Brown et al. (2013) conclude that precipitation is closely linked with whether countries grow successfully or not. Their results suggest that a 1% increase in drought area is associated with a 2.8% reduction in economic growth per year (Brown et al., 2013). A 1% increase in flood-impacted area is associated with a 1.8% reduction in economic growth in that year, with possible important lagged effects (Brown et al., 2013). Multiple studies have attempted to use global and national datasets to understand the link between climate-induced hydrological variability and impacts on economies that are dependent on agriculture production (Rockström et al., 1998; Brown and Lall, 2006; Brown, Meeks, Hunu and Yu., 2011; Brown, Meeks, Ghile and Hunu, 2013). With respect to countries with high dependence on agriculture, work by Thornton et al. (2014) shows that there is a close relationship between annual rainfall variability and changes in national gross

domestic product and agricultural gross domestic product. Thornton et al. (2014) show the importance of understanding rainfall variability at the national-level by examining interannual rainfall variability as a 12-month Weighted Anomaly of Standardized Precipitation (WASP) within three countries in sub-Saharan Africa. They determine that hydrological variability has substantial impacts on biological systems and on the smallholders, communities, and countries which depend on agriculture.

For the South Asian context, these findings are supported by the work of Thurlow et al., (2011) who develop a dynamic economy-wide model of Bangladesh to estimate economic damages from historical climate variability and future anthropogenic climate change. Using a combination of historical yield variability and 10 climate projections, they determine that future anthropogenic climate change damages are estimated to reduce national rice production in Bangladesh by about 9 percent and most of these losses are attributed in the analysis to flooding damage and climate variability (Thurlow et al., 2011). Dai et al. (2011) show that rainfall variability can have substantial effects on agricultural growth at the national level as precipitation may become more intense but less frequent (e.g., longer dry spells). They claim that this has the potential to increase flash floods and runoff, and as a result increase soil erosion, diminish soil moisture and increase the risk of agricultural drought as well as increasing the potential for crop losses due to flooding (Dai, 2011). Singh et al., (2014) conduct a comprehensive statistical analysis of precipitation observations (1951–2011) across the South Asian sub-continent, revealing statistically significant decreases in peak-season precipitation over the region, which coincided with significant increases in daily-scale precipitation variability. Their analysis reveals changes in the atmospheric conditions towards more intense wet periods of rainfall and more frequent but less intense dry periods illustrating substantial variability within the monsoon season (Singh et al., 2014). Singh et al., (2014) argue that these fluctuations can cause extreme wet and dry regional conditions that adversely impact agricultural yields, water resources, infrastructure systems, and societies across the region. Similar trends are reported in studies that examine the dynamics of rainfall and agricultural growth in India.

As India receives 85% of its annual rainfall during the South Asian summer monsoon season, the monsoon is particularly important for the agricultural sector. Research on the effects of hydroclimatic fluctuations has shown a direct impact on agriculture productivity in India. Studies have shown that long periods of deficient monsoons during July to August substantially reduce yields of Kharif (monsoon) crops if the dry spells occur at the same time as soil preparation, transplanting, or the critical crop growth period (Annamalai and Slingo, 2001; Turner and Annamalai, 2012). Others have shown that the occurrence of severe monsoon droughts can adversely affect the Rabi (winter) crops, cause livestock mortality and damage natural ecosystems in India (Sivakumar and Stefanski, 2011). Roxy et al., (2017) conduct a trend analysis of daily precipitation variability in India, which indicates increasing fluctuations in precipitation closely connected to intense surges of moisture transport covering all of central India. The results of their correlation analysis suggest a strong positive correlation with the westerly moisture transport from the Arabian Sea along with a consistent decrease in the precipitation and humidity levels suggesting a rise in the daily variability (variability on daily timescales) and confirming its role in intensifying the precipitation events across central India (Roxy et al., 2017). Through their work and the work of others, these findings highlight the importance of understanding observed fluctuations in monsoon seasons with relevance for water resources management, agriculture productivity, disaster preparedness, and infrastructure planning.

The scale of the global, South Asian, and to some extent national-level (India) empirical literature illustrating the diverse set of risks from hydrological and climate-related variability to the agriculture sector is evident. However, the literature on localised spatial hydrological variability at the sub-national or even sub-basin scale is limited within India. It is well documented in the literature that "*precipitation is a highly variable non-continuous process in space and time*" (Schleiss et al., 2011, p. 1), that can be characterised by long dry periods which can transition to shorter precipitation events with complex spatial and temporal structures. Thus, it is important to analyse hydrological variability and its influence on agricultural growth at diverse spatial scales in India. Ghosh et al., (2009) find that if analysis of the Indian summer monsoon rainfall trends in terms of amount and frequency is conducted at a more granular spatial resolution (1° latitude × 1° longitude),

the results contradict studies that conduct trend analysis over a larger region (10° latitude × 12° longitude). Their results reveal significant spatial diversity in rainfall occurrence patterns for different parts of India, unlike previous studies that claim a more homogenous increase in precipitation of daily rainfall due to climate change across multiple regions of India (Goswami et al., 2006; Ghosh et al., 2009).

The nature of the spatial diversity in the interannual and intra-annual monsoon patterns in India raises the question of whether yields irrigated from modernised irrigation systems are sensitive to this hydrological variability when examined at diverse scales. This leads to the formulation of the first sub-research question analysed in Chapter 4, which is, to what degree does rainfall heterogeneity dominate when hydrological data is examined at a district-scale over a ten-year period across multiple river basins in Madhya Pradesh? This query leads me to incorporate data on district-scale rainfall over ten years into the analytical framework guiding the examination of agricultural outcomes (e.g., changes in crop yields) stemming from MPWSRP investments to rehabilitate and modernise irrigation canals in the state (Figure 1).

2.2.2 Investments in irrigation infrastructure as a buffer to hydrological variability

Most of the literature advancing recommendations for agriculture-dependent economies suggest that water-related infrastructure investments can de-couple national economic growth from hydroclimatic variability. To illustrate that investments in infrastructure (as well as institutions, among other interventions) are key to enabling a nation to address the multifaceted challenges of water stress, Dadson et al. (2017) developed a growth model. The model relates country wealth to investment in both protective and productive water-related assets. Their findings illustrate how each country starts with a level of wealth and that wealth is ultimately diminished by hydrological-related losses. The losses depend on exposure (wealth) and risk, where risk can be managed by investing in water-related assets. Their model illustrates how some countries need more investment to reduce their risk to a tolerable level and the more critical the needs for water security within a nation, the more will need to be invested. The investment will level off as water security is achieved (Dadson

et al., 2017). Therefore, Dadson et al., (2017) conclude that investment in water-related assets has two roles: it generates returns to the economy, and it reduces losses. Investing in the development, management, and operation of water-related infrastructure and assets can act to insulate a country from adverse water-related risks. Developing and maintaining critical assets and institutions reduces the risk that a country's efforts to grow in other sectors of the economy will be damaged by water-related drags on productivity thereby enhancing its water security (Grey et al., 2013; Hall et al., 2014; Dadson et al., 2017). These findings are complemented by the previous work of Brown and Lall (2006) who illustrated that interannual and intra-annual rainfall variability are significant variables that have been overlooked in analyses of the economic development of nations and promote specific solutions to address this variability. They endorse investment in water infrastructure (irrigation systems, dams, groundwater wells) and policy (water rights, trading, efficiency incentives), which they claim provide countries with increased resilience to rainfall variability to enhance economic development as well as mitigate against risks expected from the impacts of climate change (Brown and Lall, 2006).

In the context of India, a study by Gilmont et al., (2018) examines the relationship between rainfall variability and economic growth across 15 Indian states from 1961-2012. The study provides evidence that some states with expanded irrigation area and other structural transformations, which occurred during the Indian Green Revolution in the 1960s are associated with a transition from a statistically significant relationship between rainfall and economic growth to a non-significant relationship (Gilmont et al., 2018). Although the study concludes that irrigation expansion (mainly through groundwater irrigation) contributes to a 'decayed correlation' between rainfall and economic growth in four out of the 15 Indian states analysed, evidence of the role of surface irrigation infrastructure in contributing to the decoupling of rainfall and economic growth versus other structural measures of the Green Revolution within these states is limited. The authors cite limitations of the available data, presenting a constraint to identifying rainfall-infrastructure-growth relationships within individual states in India. They emphasise the need to explore the mechanisms and possible delinking of the relationship between rainfall and growth because

of irrigation infrastructure investments within the specific context of individual Indian states (Gilmont et al., 2018).

Although, there is uncertainty in the ability of global and regional climate and hydrological models to estimate expected changes in rainfall and temperature in the future at granular spatial scales, existing literature either ignores, downplays, or cites limitations due to lack of data on localised spatial and temporal rainfall variability at a sub-national or sub-basin scales and the related effects on agricultural growth in India (Gilmont et al., 2018), with a few exceptions (Roxy et al., 2017). In fact, the literature calls for robust analysis in weather and climate variability over short temporal and high spatial scales to support decision-making (Ramirez-Villegas et al., 2013). The Food and Agriculture Organization of the United Nations (FAO 2018) has cited the need for the development of irrigation and drainage systems that will adopt new design criteria that build on historical hydrological records and can take into consideration the projected impacts of climate change.

Sullivan et al., (2002) state that "*the water environment is naturally heterogeneous, with the physical availability of water varying even over very short distances*". This brings to attention the question of scale and dimension. It is important to understand water availability for food production in the context of rural India from diverse hydrological scales (global, national, basin, and sub-basin) in terms of precipitation as well as administrative scales (national, state, and district) and how the two intersect with improved irrigation infrastructure to influence the benefits of water security with respect to crop yields. This brief review has illustrated the importance of the impact of hydroclimatic variability, with a focus on present and future climate risks, on agricultural outputs and economic growth in India. It has also demonstrated some of the received knowledge from the literature that argues that irrigation infrastructure, along with other policy interventions can protect against this variability. Reviewing the literature, however, there is little evidence on the role of rehabilitated and modernised irrigation infrastructure in mitigating the effects of hydrological variability on agricultural outcomes (e.g. crop yields) *after* investments are completed at diverse scales of analysis (e.g. sub-basin or sub-state), among

different segments of a population (distributional effects), and in the context of multiple interventions (e.g. infrastructure and non-infrastructure policies) in India. For instance, the Government of India provides non-infrastructure related economic and social benefits to farmers for livelihoods and food security support. Across all states in India, the government sets a minimum price for specific crop commodities, for which there is guaranteed purchase from the government called the Minimum Support Price (MSP) policy. This policy aims to protect farmers against crop price shocks and guarantee food security (Gouel, Gautam, & Martin, 2016).

Despite the plethora of existing literature in this space, there is need for further evidence within the Indian context on: (i) how interannual and intra-annual rainfall patterns change or differ when examined at diverse spatial and temporal scales (e.g., sub-state and sub-basin)?, and (ii) whether improvements in surface irrigated infrastructure play a role in protecting crop yields from this variability within an Indian state? These queries are crucial to advance understanding of the dynamic outcomes from investments to enhance water security in rural India by means of irrigation infrastructure. They are also necessary for nuancing existing literature, which tends to evaluate the performance of canal infrastructure investments by examining a relatively limited set of indicators (e.g., most studies tend to focus on the performance of canal irrigation based on system design, water distribution, irrigation efficiency, cropping intensity, and engineering performance measures). Thus, in order to explore whether interventions to enhance water security by upgrading irrigation systems improve agricultural outcomes in Madhya Pradesh, it warrants inclusion of multi-scale and dynamic factors related to sub-basin hydroclimatic variability, Indian crop price policies, and their influence on crop yields into the analytical framework to better understand the complex relationship between infrastructure, rainfall, crop price policies, and crop outputs. This empirical investigation is conducted in Chapter 4. In light of exploring outcomes from an interdisciplinary perspective, the exploration of crop yields, crop policies, and sub-basin hydroclimatic variability is coupled with an examination of the socio-economic conditions of smallholder farmers following investments in surface infrastructure in Madhya Pradesh.

2.3 Poverty, well-being, and infrastructure

Although, the primary goal of governments and donors to make investments in upgrading irrigation infrastructure in India is the alleviation of poverty and the promotion of agricultural growth, the distributional implications from investments and whether they succeed in addressing the multidimensional nature of poverty (e.g., beyond income) of farming communities is not well understood. This then raises the question; beyond crop yields and income, how do improved canal irrigation systems contribute to the wellbeing of diverse groups of smallholder farmers?

2.3.1 Irrigation investments and poverty linkages

One of the first studies which highlighted the importance of physical water infrastructure to the needs of human populations was undertaken by Falkenmark and Lindh (1974), followed by others who took their approach further (Brouwer & Falkenmark, 1989; Falkenmark & Suprapto, 1992; Gleick, 1997a,b; Postel, 1990, 1992; Raskin, Gleick, Kirshen, Pontius, & Strezepek, 1997; Seckler et al., 1998). Much of the literature that assesses the impacts of irrigation on poverty alleviation utilises the following approaches: a) systematic empirical research measuring changes in income-related variables with experimental and quasi-experimental methods using primary or secondary data and information, focusing on specific locations; b) general papers based on common perceptions and logic; and, c) appraisals, evaluations, and assessments of projects, mostly undertaken by donor agencies who invest in infrastructure programs (Datt and Ravallion 1997; Rosegrant et al. 1998; Barker et al. 2004; Hussain and Hanjra 2004; Huang et al. 2005). These studies tend to use econometric approaches to conduct empirical analysis either "before and after" and/or "with and without" to establish the "*irrigation-poverty nexus*" by measuring changes in farm incomes.

In the early 2000s, Hussain and Hanjra (2004) conducted a detailed empirical investigation of the poverty related impacts of irrigation infrastructure and found that irrigation is a negative determinant of poverty. They argue that incidence, depth, and severity of poverty are lower in irrigated compared to rain-fed dependent farms (Hussain

and Hanjra, 2004). They state that poverty headcount ranges from 18 to 53% in irrigated and 21–66% in rain-fed farms, with poverty incidence 20–30% less in irrigated settings (Hussain and Hanjra, 2004). Other researchers have contributed with multiple studies evaluating the impacts of access to small-scale irrigation on farmer household income and poverty status. Gebregziabher et al. (2009) found that in Ethiopia, irrigating households have about 50% higher average income than non-irrigating households. A study by Dillon (2011) finds that households in Northern Mali with access to surface irrigation increased their household consumption by 27-30%. Results of a study by Jin et al. (2012) confirms that irrigation has a strong impact on land productivity, however, they find that productivity impacts tend to vary by the type of irrigation as well as the quality of irrigation.

Within the literature on South Asia, Borgomeo et al., (2017) apply a dynamical system modelling approach to analyse the interactions between multiple water-related hazards (soil salinity and periodic flooding), agriculture-based incomes and interventions and maintenance of water infrastructure in embanked areas in coastal Bangladesh. Their analysis illustrates how water-related hazards can substantially impact opportunities for economic and human development, leading to a water-poverty trap (Borgomeo et al., 2017). They conclude that interventions in water security, in the form of improved reliability, maintenance, and operation of water infrastructure are critical to enabling coastal communities to emerge from a poverty trap induced by water-related disasters (Borgomeo et al., 2017). In the context of India, Datt and Ravallion (1998) using Indian state-level time-series data for the period 1957–91, demonstrate that states with higher initial investments in physical and human infrastructure have performed better in promoting growth and alleviating poverty than poorly endowed states. They note that differences in trend rates of poverty reduction (measured as a squared poverty gap) are attributed to different growth rates of yield per acre, an indicator for technological progress in agriculture, and different initial conditions. Overall, they determine that higher initial irrigation intensity, higher initial literacy, and lower initial infant mortality rates all contributed to higher long-term rates of poverty reduction (Datt and Ravallion, 1998). However, not all researchers agree on the positive benefits of irrigation investments.

Some argue that irrigation does not always provide the claimed poverty reduction benefits to farmers. These differing viewpoints on poverty-related outcomes from irrigation stem partly from the scale at which impacts are examined and partly from the distributional impacts of irrigation, where some benefit and others do not. For instance, Clement et al. (2011) find that interventions aimed at increasing water productivity (e.g., investment in irrigation infrastructure) does not necessarily benefit the poorest members of rural communities – rather these might favour better-off farmers who have access to a wider range of capital and have the additional resources to make changes in their farming system and practices. A report by the International Water Management Institute (IWMI) points out that for irrigation investments to be geared towards poverty reduction, investments cannot only be focused on the number of hectares developed, length of canal infrastructure rehabilitated, irrigation intensity increased, but must also consider how households or farmers are benefited from these investments (Hussain 2005).

2.3.2 Non-income and distributional impacts of irrigation – incorporating multidimensional factors of poverty

Literature that advances the notion that "irrigation is a negative determinant of poverty", which has been presented thus far focuses largely on income-related indicators for poverty linked to cropping intensity, crop productivity, labour productivity, and wage benefits for farmers. However, truly understanding the impact of irrigation investments on poverty reduction for farmers also depends on how poverty is defined and measured. A significant body of research has advanced the understanding of multidimensional drivers of poverty, which state that poverty is not just defined by income and employment-related indicators. Specifically, factors related to well-being that assess beyond monetary indicators are also considered important measures of understanding household and individual poverty.

There is a long history of literature that has studied the role of subjective well-being. Diener (1994) cites and refers to previous literature that begins to clarify and articulate what well-being means. Veenhoven (1984, p.22) defines subjective well-being as "*the degree to which an individual judge the overall quality of her or his life as a whole - subjective well-being is how well the person likes the life he or she leads*" (Diener 1994).

Andrews and Withey (1976, p.18) state that subjective well-being is "*both a cognitive evaluation and some degree of positive or negative feelings, e.g., affect*". Veenhoven (1984) asserts that individuals use two components in evaluating their lives: *their effects and their thoughts*. Diener (1994) then cites Campbell, Converse, and Rodgers (1976, p.8), who define satisfaction, the cognitive component, as "*the perceived discrepancy between aspiration and achievement, ranging from the perception of that to deprivation. Satisfaction implies a judgmental or cognitive experience while happiness suggests an experience of feeling or affect*". This literature highlights the rationale for subjective well-being measures and points out the importance of distinguishing between income and well-being effects in order to understand the multiple dimensions of poverty.

Research in the field of water studies recognizes the limitations of purely economic or income-based welfare indicators when evaluating the socio-economic and distributional impacts of policy interventions in water-related infrastructure (Dasgupta and Maler, 2001; Lokshin and Ravallion, 2005; Lokshin et al., 2006, Carletto and Zezza, 2006). Scholars argue that in some cases subjective well-being analysis can complement existing measures on income and provide information on socio-economic factors that may affect a households' perception of their personal welfare. This approach can be particularly useful when measuring well-being responses of farming households to improved irrigation systems. However, commodity determinants of subjective well-being currently do not incorporate the responses of individuals to irrigation infrastructure investments (Dasgupta, 1993; Dasgupta, 2001; Dasgupta and Maler, 2001).

For the most part, current and past literature does not explore the well-being implications for individual farmers who are exposed to improved irrigated infrastructure for the poorest households in India. In other words, there is limited evidence on how infrastructure (once available) influences different components of poverty for different segments of a farming population (e.g., households from different caste groups and with diverse asset ownership profiles). This presents an opportunity to advance the existing scholarship on irrigation and the consequential benefits of infrastructure-related investments in water security with respect to socio-economic outcomes by incorporating

factors related to non-income poverty into an analysis of the changes in farming households before/after and with/without modernised surface irrigation infrastructure in the contextual setting of Madhya Pradesh. This discussion demonstrates that exploring the relationship between well-being and infrastructure availability in irrigated agriculture is a valid area of enquiry that can further complement existing literature which examines the role of infrastructure by measuring poverty through income, employment, and headcount ratios in agriculture-dependent economies. This is reinforced by the findings of Borgomeo et al. (2017, p.23) who suggest that appraisals of investments in water security should "*go beyond marginal approaches, which only quantify the direct impacts on specific sectors, to account for the non-marginal effects that improvements in water security might have on growth and development dynamics at multiple, nested scales and for different actors of society*".

Thus, investigating the role of irrigation infrastructure in reducing poverty from the perspective of well-being is an interesting dimension that is relatively underexplored in the literature and warrants inclusion of subjective well-being of individual farmers as a socio-economic outcome indicator into the analytical framework (Figure 1). This approach can, therefore, enhance the understanding of how interventions to improve agricultural water security through modernised irrigation infrastructure influence multidimensional poverty dynamics for different groups of farmers in MP. This leads me to explore the research question whether irrigated infrastructure influences the well-being dynamics of farming households in diverse rainfall settings with varying socio-economic vulnerability characteristics in Madhya Pradesh?

Hussain and Hanjra (2004) note, however, that studies documenting concrete linkages between irrigation and poverty are rare, and more so, in the case of studies documenting indirect linkages between irrigation and poverty. To address this gap and contribute to the established knowledge exploring irrigation infrastructure and income poverty, an investigation of the well-being responses among farming households exposed to modernised irrigation systems compared to households with no exposure to investments is carried out in Chapter 5. This investigation advances the arguments for recognising the coupled human-water dynamics of water security (Sivapalan et al., 2017) and conducting

analyses at diverse hydrological, administrative, household, and individual scales along multidisciplinary factors (e.g., hydrological, agricultural, and socio-economic) that were presented in the Introduction in Chapter 1. Household-level and individual-scale analysis can complement the work at the district-scale in Chapter 4, by examining the distributional impacts of canal irrigation among a diverse population of farmers across multiple districts and river basins in Madhya Pradesh. The exploration of changes in well-being among farming households in Madhya Pradesh leads us to a related theme that is also underexplored in the literature – the dynamic relationship between improved irrigation infrastructure, financial incentives, and changes in the farming techniques of smallholders with respect to their irrigation methods and on-farm technology choices.

2.4 Understanding behavioural outcomes of irrigation infrastructure and policy incentives

In the context of understanding the multidimensional effects of improved irrigation infrastructure, the review, thus far, has presented some of the established assumptions in the literature: that modernised irrigation infrastructure has the potential to alleviate hydrological stress for farmers leading to enhanced crop productivity resulting in improved income for farming households due to the availability of an adequate quantity of surface water in a timely manner. However, as crop yields improve, and income poverty reduces for farmers, a further set of questions emerge. Does the infrastructure influence improvements in farming practices, specifically with respect to cropping choices and irrigation practices? Does the combination of policy instruments such as irrigation technology subsidies along with the infrastructure drive changes in farmer water use behaviours? This section provides the rationale from the literature for the empirical investigation carried out in Chapter 6.

2.4.1 Surface irrigation, policy instruments, and improvements in farming practices

An established body of literature has argued that there is a link between the availability of surface irrigation, poverty reduction, and improvements in farming techniques (Ishikawa 1967; Barker and Molle, 2004; Stein et al., 2013; Cai et al., 2020). Hussain and Hanjra (2004, p.4) argued that "*access to reliable irrigation water can enable farmers to adopt*

new technologies and intensify cultivation, leading to increased productivity, overall higher production, and greater returns from farming". They find that the anti-poverty impacts of irrigation can be intensified by creating conditions or enabling environments (through policy interventions) that could incentivise more efficient irrigation practices by users themselves. These include: a) equitable access to land; b) integrated water resource management; c) access to and adequacy of good quality surface and groundwater; d) use of modern irrigation technology; e) shift to high-value market-oriented production; and f) opportunities for the sale of farm outputs at low transaction costs (Hussain and Hanjra, 2004). "*Despite that, the poor and landless benefit, in both absolute and relative terms, from irrigation investments. Recent advances in irrigation technologies, such as micro-irrigation systems, have strong anti-poverty potential*" (Hussain and Hanjra, 2004, p.1). In other words, the assumption implicit in this literature is that one of the indirect effects of enhancing water security through improved supply of surface irrigation is better income, which enables farmers to improve their farming practices. Other literature supports the inverse of this claim; that it is the *lack of* infrastructure, among other interventions, in developing countries that is causing 'inefficient use' (and over abstraction) of water, thus further exacerbating water stress in agriculture for smallholder farmers (Campanhola and Pandey, 2019).

A second recurrent theme in the literature is the role of diverse governance and policy instruments including irrigation technology subsidies, crop price gurantees, credit support, among others, that incentivise changes in farmer crop choices and irrigation practices. For instance, in order to incentivise more 'efficient' on-farm crop water use, national and state governments in India have introduced financial subsidy policies to reduce the cost of purchasing micro-irrigation equipment (e.g. sprinklers, drip, and other technologies) for farmers (Malik et al., 2018). Other examples of governance and policy support from the Indian government include providing farmers a Kisan Credit Card (the ability to purchase farm machinery and other inputs on credit) and a Below Poverty Line ration card. Although several studies in the literature have examined the efficacy of these governance and policy instruments in achieving food security and rural poverty alleviation in India (Aditya et al., 2017), they tend to exclude the joint relationship between improved

surface irrigation, access to financial subsidies, and the impact on farmer irrigation practices. Other studies focus on singular factors with respect to the impact of subsidy policies for irrigation technologies, such as changes in rates of adoption. For instance, Malik et al., (2018) find that despite the reported economic advantages and the concerted support of the government, donors, and NGOs to subsidise the upfront costs for farmers, the area under micro-irrigation in India is significantly lower in proportion to its potential. Although policies to rehabiliate irrigation infrastructure in India are often implemented simultanesouly with financial subsidies for technology adoption, there is limited knowledge in the literature on whether attempts to enhance water security through infrastructure measures, concurrently with financial incentives, effect the irigation choices of farmers with respect to their rates of technolody adoption.

Some authors argue that addressing water scarcity requires going beyond ensuring the "physical availability of water", implying that there is a behavioural dimension contributing to exacerbated water stress (Giordano et al., 2019). Knox et al., (2012) argue that the pathway to achieve efficient irrigation water use requires systematic optimisation of soil and water management practices and the adoption of irrigation equipment by farmers. Other claim that changes in farmer irrigation choices in turn lead to improvements in water use efficiency, thereby reducing on-farm water abstraction in the agricultural sector (Namara et al., 2007). Although there is an ongoing debate in the literature on the true 'water saving potential' of drip and sprinkler technologies (Perry et al., 2017; Pérez-Blanco et al., 2020), it is largely silent in terms of exploring whether farmer choices for adopting irrigation technologies are influenced by modernised canal irrigation systems, when subsidies are available, in the context of specific Indian states. This leads me to focus the study of outcomes stemming from measures to improve water security through canal systems in Madhya Pradesh on behavioural outcomes, specifically exploring changes in farming techniques by examining the irrigation practices of smallholders with respect to their technology adoption choices.

2.4.2 Factors driving irrigation technology choices on surface irrigated farms

Many studies have attempted to understand the factors driving technology adoption and collective behaviour among irrigated communities in surface irrigated areas in India. This literature focuses on constraints related to land size, financial, and socio-economic factors, as well as institutional and governance concerns (Sivanappan 1994; Narayanamoorthy 2003; Namara et al., 2007; Marenya and Barrett, 2007; Narayanamoorthy 2009; Suresh et al., 2018). These studies claim that adoption depends on the biophysical and institutional context as well as the specific type of irrigation technology (e.g. sprinkler or drip) and agronomic practices applied by farmers and how they are managed (Seckler 1999; Molden, Sakthivadivel, & Keller, 2001; Molden et al., 2007; Kendy, Molden, Steenhuis, & Liu, 2003; Kijne 2003; Ward & Pulido-Velazquez, 2008; Dagnino & Ward, 2012; Pfeiffer & Lin, 2014; Fishman, Devineni, & Raman, 2015). As a result, there is an implicit assumption in the literature that sprinklers and drip systems are alternatives or substitutes to surface irrigation (Darouich et al., 2014). The literature also tends to focus on price incentives for enhancing water use efficiency through technology adoption in irrigated systems (Grafton et al., 2018). Extensive work by Francois Molle, however, has shown that price-based regulation of water demand by farmers in large-scale public surface irrigation schemes has largely failed to reduce water demand (Molle and Berkoff, 2006; Molle and Berkoff, 2007; Molle et al., 2008). As investments in on-farm irrigation technologies are primarily the choice of farmers themselves, the importance of learning from the behaviour of other farmers within the farming community and whether this influences farmers to invest in irrigation technologies has been largely overlooked beyond the focus on financial incentives (Ghanem 2011; FAO 2014; Aerni 2015).

Social learning is defined as processes of "*collective learning, reflexive practice, and action*" (Keen et al., 2005; Rist et al., 2007; Pahl-wostl et al., 2007b). Pande and Savenije (2016), argue for the need to view smallholder systems from a "socio-hydrological" perspective where humans and their environments are inherently "coupled systems" that are dynamic and bidirectional, constantly learning from one another. Thus, social dynamics surrounding the technology choices of farmers is particularly important in the context of irrigation technology adoption, as the Indian government has widely

promoted investments in micro-irrigation technologies, mainly through subsidies for drip and sprinkler systems (Verma 2004; Schuck, Frasier, Webb, Ellingson, & Umberger, 2005; Kumar et al., 2013; Venot et al., 2014). Despite national policies to provide farmers with subsidies for purchasing micro-irrigation equipment, however, low adoption rates continue to be an unresolved challenge facing policymakers across India (Narayanamoorthy 2004; Balooni et al., 2016). As of 2012, only 12.2 percent of the potential drip irrigation area and 7.8 percent of the potential sprinkler area had been realised, with many variations across different Indian states (Palanisami 2012). However, existing literature on irrigation technology adoption constraints in the context of India does not explore the influence of social learning in influencing the irrigation practices of farmers as surface infrastructure is improved and financial incentives are available.

Next, the important role of collective institutions and governance instruments has been cited in the literature as a means to incentivise "*water use efficiency*" among water users in irrigated settings (Leroy & Arts, 2006). These individual choices leading to collective interactions between humans and nature was what Elinor Ostrom argued necessitated the design of irrigation institutions to prevent a "*tragedy of the commons*" (Ostrom 1990, 1992, 1993, 1999). This gave rise to much of the existing literature on understanding and studying collective behaviour with respect to infrastructure (canal) performance (Bardhan 1993; Meinzen-Dick et al., 1997; Gulati et al., 2005). Multiple studies have explored the role of community institutions by evaluating whether WUAs are performing "well" in the context of improved operation, management, and financial recovery of irrigated infrastructure (Singh 1983; Coward 1985; Coward and Uphoff, 1986; Lowdermilk 1986; Uphoff 1986; Hunt 1989; Mollinga 2000).

Others have explored the social and cultural dynamics of irrigated communities with respect to the construction of irrigation systems. For instance, Horst (1996) examined farmer responses to the Indonesian government's investments to modernise Balinese "subak" irrigation structures in the 1970s. Horst (1996) highlights that reforms carried out on the division structures reflected the "broader cultural, political and economic logic of Indonesian irrigation society" which influence irrigation management just as much as the technical engineering design elements of the structures. Such examples are cited by

Mollinga and Veldwisch (2016, p.224) who analyse the social construction of South Indian canal irrigation systems to determine that "*the economic, political and cultural 'context' of irrigation system design and construction acts as a 'selection environment', and thus shapes the system characteristics of the irrigation systems*". Although there is a vast body of existing literature that examines the social dynamics between irrigation infrastructure and the power relations, political, and institutional factors that influence irrigated communities, analysis of changes in the farming techniques of individual farmer members within a collective irrigation institution (e.g., a WUA) as a result of surface irrigation infrastructure is largely overlooked in the institutional governance literature. Evidence is also limited on how individual farmer irrigation practices are influenced by the behaviour of other farmers in their social network as canal systems are modernised and financial subsidies are available.

These gaps in the established knowledge in the studies of irrigation infrastruture, technology subsidy policies, and social factors driving individual farmers to adopt irrigation technologies in India leads me to my next query. Do farmers with access to rehabilitated systems and access to subsidies change their irrigation practices (particularly with respect to using sprinkler or drip systems) compared to farmers in command areas where systems are not modernised in Madhya Pradesh? This question warrants incorporating contextual factors related to subsidy policies and testing whether farmer technology choices are influenced by the social dynamics in their villages in diverse rainfall settings into the analytical framework (see Figure 1). Furthermore, in order to complement the existing body of literature examining collective behaviour of irrigation communities, in this thesis, I shift focus away from community behaviour to analyse how modernised and rehabilitated irrigation infrastructure influences changes in *individual* farmer irrigation practices. Thus, this opens an area of analysis that is underexplored in the literature about whether improvements in irrigated infrastructure, the availability of subsidy policies for technology adoption and the social dynamics among farmers influences individual choices around irrigation methods. This gap is addressed in the empirical analysis in Chapter 6.

In Chapter 6, I build on this line of enquiry by analysing behavioural outcomes by exploring farmers' irrigation practices (e.g. whether they choose flood irrigation methods

or sprinkler or drip irrigation in command areas with and without rehabilitated canals). In addition, I also analyse whether social networks and social learning among farmers contributes to the individual technology choices of farmers? Thus far, this review has addressed and discussed some of the established literature in the field of water security and irrigation studies, in order to provide the rationale for the themes and variables of interest examined in the thesis (Figure 1). I now turn to review the literature on the recognised methods for how to evaluate and attribute impacts stemming from policy and program interventions in the development sector with a focus on providing justification for the methods selected for the analysis conducted in the thesis.

2.5 Diverse methodological approaches for assessing and evaluating program interventions

In the literature that focuses on identifying the outcomes of development interventions, terms such as 'impact assessment' are often used interchangeably with 'impact evaluation', which are defined as the welfare changes from a given intervention on individuals, households, and institutions by determining whether those changes are attributable to the project, programme, or policy intervention (Baker 2000; World Bank 2002a). These types of impact assessments are undertaken to gather information on the likely economic and environmental impacts, determine how the flow of costs and benefits are distributed across the affected populations, and understand any social impacts (Shiferaw et al., 2005). Such evaluations are often carried out *ex ante*, evaluating the impact of current and future interventions, or *ex post*, evaluating the impact of past interventions (Shiferaw et al., 2005). However, conventional economic impact assessments are only one of the multiple methodological approaches in the field of social sciences for assessing complex outcomes of policy and program interventions. Out of the numerous methodological techniques for determining impact from program interventions available to social scientists, this section focuses on reviewing three relevant evaluation methodologies including: a) experimental design methods, b) Qualitative Comparative Analysis, and c) realist evaluation methods. This section also discusses how these different approaches interpret causal linkages from program interventions and presents their relative strengths and weaknesses. I conclude this section with a reflection on the methodological approach chosen in this thesis.

2.5.1 Characterisations of diverse methodological approaches and their interpretations of causality

2.5.1.1 Experimental design methods

Experimental evaluations or experimental design approaches are based on systematic empirical research measuring impacts from program or policy interventions with rigorous methods using primary or secondary data and information, focusing on specific locations. At the core of this evaluation approach is to estimate the "counterfactual", or to determine what would have happened had the intervention never taken place (Shiferaw et al., 2005). This is at the heart of this evaluation approach, which starts from a concern about the reliable identification of program effects in the face of complex and multiple channels of causality (Banerjee and Duflo, 2009). An important aspect of experimental approaches is to understand how interventions affect the beneficiaries or affected populations and to identify whether any outcomes and improvements are a direct result of the intervention.

Pawson (2008) describes experimental design approaches as a "successionist" mode of causal explanation, where successionists locate and identify vital causal agents as 'variables' or 'treatments'. This approach to evaluation seeks to observe the association between such variables by means of surveys or experimental trials. As Pawson states, "*explanation is a matter of distinguishing between associations that are real or direct (as opposed to spurious and indirect) and of providing an estimate of the size and significance of the observed causal influence(s)*." (Pawson, 2008, p. 1). Empirical research studies differ in terms of geographic coverage, scale of analyses, and approach adopted in measuring impacts (Hussain and Hanjra, 2004). The scale of analyses can range from household to village, region, national to international levels. The approaches adopted in various studies can be classified into three major categories: a) ''before and after'' comparisons; b) ''with and without'' comparisons; and c) ''more and less'' comparisons using econometric methods applied in all three categories (Hussain and Hanjra, 2004).

Typically, three types of quantitative methods can be used to identify an appropriate counterfactual including estimation methods, which are a) randomised experimental

design, b) non-randomised quasi-experimental methods, and c) non-experimental designs (Heckman and Robb, 1985; Heckman and Smith, 1995). In the experimental design approach, groups are selected randomly from the same population as the programme participants, while the control group is randomly assigned among those who do not receive the programme (Banerjee and Duflo, 2009). The control group must closely resemble the treatment group, with the only difference between the two being the presence of the programme intervention in the treatment group (Shiferaw et al., 2005). In order to measure the impact of an intervention, experimental approaches focus on controlling for other confounding factors to narrow down to specific outcomes that can be attributed only to the intervention itself, thereby estimating the counterfactual. Thus, the intervention impact can be estimated by the mean difference between the treatment and control groups. Quasi-experimental designs such as matching, reflexive comparison, double difference methods, and non-experimental designs, such as instrumental variables methods, can be used when it is not possible to construct treatment and comparison groups through experimental design.

Matching involves identifying non-programme participants comparable in essential characteristics to programme participants to be matched based on common characteristics that are believed to influence programme outcomes (Steiner and Cook, 2013). The propensity score matching approach that is based on the predicted probability of participation given observed characteristics is commonly used for matching. The reflexive comparison method compares programme participants before and after the programme. The double difference method compares both programme participants and nonparticipants before and after the programme (Khandker et al., 2010). Instrumental variables consist of using ‘instruments’ that matter to participation but not to outcomes given participation, allowing identification of exogenous variation in outcomes attributable to the programme, while recognising that its placement may not be random but purposive (Heckman 1997). Instrumental variables are first used to predict programme participation; then the programme impact is estimated using predicted values from the first equation (Baker, 2000).

The main benefit of experimental design methodology is the simplicity in interpreting the results – intervention impact can be estimated by the mean difference between the treatment and control groups (Shiferaw et al., 2005). This is of consequence in communicating results in a transdisciplinary context. However, while experimental and non-experimental design techniques are well established approaches to estimating intervention impacts with a substantial body of literature associated with them, there are several limitations. Experimental design suffers from both challenges related to determining attribution and selection bias in impact analysis, as well as conceptual and methodological challenges that arise when the techniques are applied to water resources management and related sectors.

Firstly, randomisation as a technique suffers from several difficulties which can prevent its use for establishing a valid counterfactual including ethical issues, political acceptability, cascading economy-wide effects that make randomisation unfeasible, and technical infeasibility of establishing the treatment and control groups, as well as time and cost issues (Shiferaw et al., 2005). When such obstacles prevent evaluators from constructing treatment and control groups, non-randomised quasi-experimental and non-experimental designs are preferred. Second, non-randomised designs face challenges related to selection bias, which occurs when pre-existing conditions skew outcomes in a way that is not truly attributable to the programme intervention. If challenges with selection bias are not addressed, this may lead to inaccurate results with erroneous inferences and conclusions about the impacts of the intervention (Friedlander and Robins, 1995, Shiferaw et al., 2005). Quasi-experimental and non-experimental designs use statistical methods to minimise bias due to non-random data to enable comparison of programme participants and non-participants while controlling for the process of selection (Greene, 1997; Baker, 2000). Third, as Pawson (2008) points out experimentalists employ a “successionist” approach to causation (e.g., context held constant through randomisation), thus contextual factors are conceptualised as confounding variables, which are included as “control” variables and excluded from the analytical understanding of outcomes. Instead, outcomes are collected from those exposed or not exposed to the intervention. Where these outcomes achieve the desired change in a statistically systematic fashion, the intervention can be

imputed to be causally related to its outcomes (Blamey and Mackenzie, 2007). As impact assessments in the water resources and related environmental sectors need to address important challenges of attribution, measurement, spatial and temporal scales, and multidimensional outcomes, this poses unique difficulties to identify causal impacts attributable to the intervention (Nelson and Maredia, 1999).

A measure to address these concerns, especially related to impact evaluations in the water and natural resources related programs, is to couple quantitative approaches that allow statistical tests for causality and isolation of programme effects from other confounding influences with qualitative methods. While quantitative methods enable scholars to answer impact assessment questions about 'what' and 'how much', qualitative methods are preferred for exploring questions of 'how' and 'why'. A mix of quantitative and qualitative approaches helps the evaluator find explanations for the results obtained in the quantitative analysis as well as an explanation of the processes and relationships that yielded such outcomes. While quantitative approaches focus on statistical tests for causality and isolation of programme effects from other confounding influences, qualitative methods allow for more in-depth study of selected issues enabling the evaluator to seek explanations for the results obtained in the quantitative analysis (Shiferaw et al., 2005). Qualitative research (e.g., in-depth interviews and field observation) may provide an understanding of the "causal process," or the detailed sequential "mechanisms" by which certain outcomes were obtained (Hesse-Biber and Johnson 2015). One example of a qualitative method is Theories of Change (ToC).

A theory of change provides a detailed narrative description of an impact pathway (the logical causal chain from input to impact) and how changes are anticipated to happen, based on assumptions made by the people who are undertaking the work (Thornton et al., 2017). ToC approaches, built on theoretical underpinnings, revolve around clear articulation of the linkages between inputs and outcomes, and the assumptions that accompany these linkages, with the aim of improving evaluation and program performance (Funnell and Rogers, 2011). ToCs focus on establishing a link between the strategies and the desired outcomes to enable robust measurement and evaluation, using a 'results chain'

to capture the causal linkage between an intervention and desired impacts through a series of expected intermediate results (Margoulis et al., 2013; Garrick et al., 2020). Thus, a Theory of Change methodological approach enables the specification of counterfactuals to compare the results of different interventions with the likely trajectories and outcomes under business-as-usual scenarios (Rana and Miller, 2019). When qualitative approaches are used in conjunction with quantitative approaches, referred by some scholars as 'mixed methods' (Baker, 2000), such combinations can enhance the validity and reliability of impact evaluations (Bamberger, 2000). As a result, experimental evaluation research has increasingly come to incorporate a 'multimethod perspective'—which entails combining a variety of methods that more robustly evaluate programs in terms of process and outcomes and varieties of methods both within and between qualitative and quantitative methods (Hesse-Biber and Johnson 2015). Cook et al. (2008) note the use of different methods in combination have utility for answering a variety of different questions in evaluation research.

2.5.1.2 Qualitative Comparative Analysis

A methodological technique that seeks to combine both qualitative and quantitative methods during a study's analysis phase is qualitative comparative analysis (QCA). QCA seeks causation via several combined attributes that together bring about an outcome, focusing on attributes rather than variables (Pawson 2008). This analytic technique was first introduced by Charles Ragin (1987, 2000, 2004, 2009) with clarifications by other scholars (Bennett 2004; Byrne 2009; Fielding & Warnes, 2009; Rihoux & Lobe, 2009).

QCA focuses on the assembly of both variable-based and case-based configurations as part of the same analysis and is an umbrella term for a variety of types, including 'crisp set QCA' (csQCA) where conditions have binary values (Befani et al., 2007; Befani 2013; Blackman et al., 2013; Holvoet and Dewachter 2013; Ledermann 2012), 'multi-value QCA' (mvQCA) where conditions have discrete values (cf. e.g. Balthasar 2006; Sager and Andereggen, 2012) and 'fuzzy-set' QCA (fsQCA) where conditions can have any value between 0 and 1. A typical QCA methodological approach includes the following steps (as stated in Gerrits and Verweij, 2016):

> **Step 1**: First, the researcher should decide about the type of QCA. The three available main types – csQCA, mvQCA and fsQCA;
>
> **Step 2**: Structure the qualitative data into a data matrix;
>
> **Step 3**: Convert the data matrix into a truth table. The truth table lists all the logically possible combinations of conditions (excluding the outcome) and sorts the cases accordingly; and,
>
> **Step 4**: Development of the minimized solution formula in order to derive the persistent patterns across cases. Solution formula is of little value without a (qualitative) interpretation of the results.

Two measures guide the interpretation of QCAs: consistency and coverage (Ragin 2006). QCA has been used in evaluation literature to comparatively study any number of cases, ranging from eight (Befani 2013) up to thirty (Holvoet and Dewachter, 2013), aiming at the identification of causal patterns that explain the occurrence of specified outcomes in cases. These causal patterns are configurations of conditions, or interacting elements, that

are expected to contribute to the occurrence (or non-occurrence) of the outcome of interest (e.g., to determine the effects of a certain intervention) (Gerrits and Verweij 2016).

Pawson (2008) classifies QCA methods as falling into the category of 'configurationist' He states that configurationists "*begin with a number of 'cases' of a particular family of social phenomenon, which have some similarities and some differences. They locate causal powers in the 'combination' of attributes of these cases, with a grouping of attributes leading to one outcome and a further grouping linked to another. The goal of research is to unravel the key configurational clusters of properties underpinning the cases and which thus are able to explain variations in outcomes across the family*" (Pawson, 2008, p. 1). The key distinction between configurationists, utilising QCA methods, or what is known as 'case-oriented research' and 'successionists' utilising 'variable-oriented' or experimental research is based on the ultimate goals of the research (Ragin, 1987, 2000; Gerring, 2005, 2012; Rihoux, 2008; Rihoux and Ragin, 2009). Case-oriented strategies focus on making sense of a relatively small number of cases, selected because they are substantively or theoretically significant in some way (Eckstein, 1975), while variable-oriented or successionist strategies "*are centrally concerned with the problem of assessing the relationship between aspects of cases across a large number of generic 'observations', usually with the goal of inferring general patterns that hold for a population*" (Marx et al., 2014, p. 129).

QCA emerged as an alternative to statistical or quantitative, experimental approaches offering what Gerrits and Verweij (2016) refer to as a "*more holistic, important and valuable alternative to approaches that try to isolate the effect of conditions (e.g., interventions or contextual characteristics) on outcomes*". One of the main benefits of QCA is that it accounts for the real-world complexity during the comparative stage and as such aids learning through evaluation (Sanderson 2000). This is a major advantage of QCA as it permits multiple conjunctural causations; it recognizes that certain outcomes are driven by simultaneous occurrence of certain factors) (Srinivasan et al., 2012). QCA examines data differently than regression-based statistical analysis as it does not aim to determine the net effect of various independent variables on a single dependent variable

across all cases (Ragin and Rihoux, 2004). However, QCA approaches are not without their own set of drawbacks, as QCA aims to establish some degree of generalisation of conclusions in the face of complexity it does not attempt to establish correlation or causality at all.

Causality in the context of QCA methods is assumed to be established within the case studies. The Boolean algorithm sorts the cases to find common causal pathways (Srinivasan et al., 2012). As Pawson (2008) points out, this type of analytical approach means that there are no enduring empirical generalisations as all emphasis is placed on limited explanatory ingredients, attribute-based explanations are inherently "*incomplete and incompletable*". QCA can be eternally iterative. It is always possible to delve further into the sequences and configurations depicted in the models by adding more attributes and continuously consider alternative measures. In his critique of both experimental and QCA methods, Pawson (2008) states that "*dealing with complexity in the form of introducing variable X_{123} or attribute A_{234} is self-defeating. All other coefficients and estimates change with each such iteration. There are no enduring empirical generalisations*." (p.23). Realist evaluation methods offer a partial remedy to the issues with experimental and QCA methods as they adopt a generative approach to attribution, focused on a cumulative and iterative process of theory building, testing, and refinement in relation to specific programme subcomponents.

2.5.1.3 Realist Evaluation Methods

Critical realist evaluation emerged to address some of the perceived challenges that successionists and configurationists face in disentangling complex causal mechanisms underpinning program interventions. Realist evaluation methods or 'generative' social research focuses on causal explanation as represented by a tie or link between a set of variables, as context is key to understanding the interplay between programmes (interventions) and outcomes (effects) (Pawson 2008, Blamey and Mackenzie 2007). Pawson (2008) classifies realist evaluation as 'generativist', defined as:

> "*Generativism is designed to utilise mechanisms and contexts to explain outcome patterns and so provides the most complete approach to causal explanation.*

> *Because explanation trades in peoples' choices and societal constraint., it calls on the full repertoire of social research to provide supportive empirical data. As with the other methods, it struggles with complexity. But because theory carries the explanation, its component causal mechanisms and contexts have a measure of abstraction allowing them to be recycled and empirical inquiry to cumulate*" (Pawson, 2008, p.39).

Realist evaluation methods derive their roots from a historical tradition of causal ontology, called 'realism' or 'critical realism' and focus particularly on the policy and programme evaluation space, pioneered by Pawson and Tilley (1997), and others. The realist ontological paradigm focuses on theory-driven investigation hinging on the central question, "*what are the causes*?". Building on this query, realist evaluation methods strive to understand the roots of a particular outcome pattern to drive the understanding of causality. While experimental or quasi-experimental designs focus on questions related to '*what difference did the intervention make?*', generativist, or realist evaluation methods, argue that this is an incomplete picture of the causal mechanisms contributing to a particular impact and thus focus on questions such as, '*what are the root causes of the observed changes*?' to corroborate causal claims generated by successionist or constructivist approaches.

These approaches emerged in the 1990s in response to some of the perceived flaws of successionist methods, which appear to reduce the presence of context in experimental research design. Thus, realist evaluators consider context as instrumental in shedding light on the circumstances and reasons "why" an intervention works or not. One of the main benefits of realist evaluation approaches is that it aims to constantly refine learning about which mechanisms are triggered in which circumstances for which individuals. In this manner, realist approaches to reviewing evidence focuses on developing a greater understanding of context, mechanism, and outcome configurations (Pawson 2002a, 2002b, 2006). Therefore, although traditional experimental methods can statistically determine whether a complex set of program interventions achieved their aims or not, realists argue that they do so by "*establishing black box associations*" between interventions and

outcomes (Howe, 2011, p. 169) as results provide little guidance on how and why the interventions worked or how they functioned differently across contexts (Pawson, 2006).

Thus, in order to determine causality, realist evaluation methods focus rigorously on an understanding of context, using some of the following steps: a) understand the nature of the programme, aims, contexts of operation, determine theories of what works versus what does not, b) relate various contexts of programme to multiple mechanisms which produce outcomes, c) conduct outcome inquiry with respect to different theories, and d) explore how Context, Mechanism, Outcome (CMO) play out in a programme = develop tentative theory of what works for whom in what circumstance (Pawson and Tilley, 1997). In short, the central driving focus of realist evaluation is to uncover "*the hidden mechanisms that influence the underlying processes (the black box) and assuming the existence of meso-regularities (middle-range theories) in the world's phenomena*", thereby proposing an alternative to both the successionist and configurationist approaches to evaluation (Hesse-Biber et al., 2015, Chapter 27, p.444).

Concerns emerge, however, to what extent realist evaluation methods can truly break the 'black box' of causal pathways associated with development interventions, particularly in the water sector. As factors and contexts are continuously changing and evolving, it remains to be seen whether any type of CMO configurations determined by realist evaluators can truly come to a "complete" picture of causality that is enduring without endlessly considering more and more contextual factors. This is particularly relevant for dynamic water resources systems in the agriculture sector or wider water resources management interventions. A review of the literature applying realist evaluation techniques reveals that these methods have rarely been tried or tested against evaluations of water sector interventions, and only recently have been suggested as a methodological approach for evaluating canal irrigation 'problemsheds' in South India by Mollinga (2020).

In the water sector, specifically with respect to canal irrigation, Mollinga (2020) argues, with good reason, that context in a given watershed which may trigger an outcome, cannot be ignored. Thus, it is the potential contextual conditions and their various

configurations and related factors that have a role in determining the outcomes of interventions in canal irrigation (Mollinga 2020). He states that "*the scope of the validity of a particular (set of) mechanism(s) depends on the stability of the conditions of possibility of that mechanism. When these are stable over time, we have an enduring mechanism; when these are stable across space, we have a globally valid mechanism; and when the conditions of possibility are stable over time and space we have something that may appear to have universal validity*" (Mollinga, 2020, p. 16). However, the problematic aspect of water resources and specifically irrigation infrastructure, which realist evaluation appears to be silent about, is how do you demonstrate, even while considering contextual mechanisms, when and which conditions are stable over time and space with respect to outcomes related to canal irrigation interventions? Realist evaluation techniques do not appear to be able to demonstrate 'any enduring mechanisms' that are stable across time and space in the water sector, at least not in the published literature I have encountered thus far. In other words, to what degree of confidence do realist evaluations provide evidence that one 'generative causal pathway' is stable versus another alternative causal theory? In this sense, the 'black box of causality' does not appear to be fully uncovered.

Next, questions emerge as to the validity and efficacy of the realist evaluators approach in the selection of "*certain contextual elements (supporters), or others (interrupters, derailers, or off-setters)*" as Mollinga (2020, p. 16) references the process of identifying contextual factors with the goal of dividing the context into these categories for the specific purpose of "*unraveling the black box of causality by specifying how exactly, in causal terms, contexts shapes a given process*" (p. 16). This approach is problematic as the decision upon which contextual factors acts as "supporting conditions" and which are "interrupting" appear to be based on subjective decisions (perhaps by the researcher or evaluator or based on subjective responses from a set of stakeholders), and who gets to decide which contextual factors matter as there appear to be no valid quantitative criteria based on a statistically determined degree of confidence to illuminate which contextual factors are more important than others and which fall into which categories. Next, to avoid arriving at reductionist solutions or generalisations, realists argue that context matters but then context is itself reduced into binary categories or 'contextual black boxes' (supporting

versus interrupting categories) and is assumed that the context of complex village and river basin dynamics of agricultural settings in India, would neatly fall into one of these "roles" as argued in the generative causal process (see Figure 5 in Mollinga, 2020, p. 15). This raises the concern how do we know when this contextual map of categories is ever truly complete and stable (unchanging) for a specific agricultural context?

Realist evaluative approaches also place less emphasis on gaining stakeholder consensus on articulated theories or evaluation priorities (Barnes et al., 2003, Sullivan et al., 2002). Developing a robust evidence base for realist evaluation requires evidence on how intervention activities, contextual factors, and intermediate and longer-term outcomes interact as part of complex systems. In other words, in order to gather evidence in the form of theories to understand "*what works for whom in what circumstances and in what respects*" (Pawson, 2006, p. 74), the time horizon of such an evaluation may not be suitable with the timeline of a program cycle or near the close of a program intervention. Critics of realist evaluation point to the tendency of realist evaluators to generate a whole range of hypotheses from qualitative case studies that cannot be tested with the available empirical evidence. "*It is undoubtedly desirable to test theories about causal mechanisms underlying the effect of an intervention on an outcome. The main problem is that numerous hypotheses can be formulated, and it is difficult to collect adequate data to test many of them*." (Farrington, 2003, p.66). Thus, realist evaluation methods may not be suited to certain types of evaluations where specific project outcomes are assessed, *ex post,* or within a short timeframe of the intervention itself.

Additionally, concerns have been raised that this approach may be very time-consuming and the findings may not justify the resources required to generate them (Sheldon, 2005). Although realist evaluation methods are an approach that can deliver more detailed and substantive programme learning, it also appears to be less suited to measurement at multiple levels (individual, group, organization and community) as processes face practical and conceptual difficulties once theories are developed. Similar to challenges with realist evaluation methods, ToCs suffer from a need for agreement on the theories articulated, and the specificity required to determine whether they are plausible,

doable, and testable requires an iterative process, which can be time-consuming and incompatible with the programme evaluation life cycle (Mackenzie and Blamey, 2005).

Thus, in order to derive meaningful observations from highly complex, multi-site interventions with multifaceted and multiscale outcomes from a specific programme (e.g., MPWSRP), the use of statistical, variable-based regression analytical techniques remains important and valid as a method. This technique enables researchers to explore specific outcomes at multiple scales within a certain contextual setting where infrastructure interventions are made.

2.5.2 Rationale for methodological approach chosen for thesis

First, in reflecting on an appropriate methodological technique for answering the core research question underpinning this thesis, *do investments to modernise and rehabilitate irrigation infrastructure enhance outcomes related to agricultural water security in Madhya Pradesh?* I note that few studies using QCA or critical realist perspectives to my knowledge have attempted to identify causal mechanisms in the water sector with respect to canal irrigation interventions (exceptions being recent work by Mollinga 2020 and Mollinga and Gondhalekar, 2014). Thus, the field of study associated with applying realist evaluation methods to identify causal mechanisms for water security that can be attributable to irrigation infrastructure is still underdeveloped. A majority of publications or empirical studies using realist evaluation methods address social issues related to crime prevention and housing (Laycock 1985; Foster and Hope, 1993), improvements in breastfeeding rates (Hoddinott et al., 2010), health research and practice (Jagosh et al., 2012), and initial application of realist evaluation approaches to the role of value chains in improving poverty for farmers (Ton et al., 2011), among many others. I would emphasize here that realist evaluation methods are not generally known or acknowledged as recognized methodological techniques by practitioners in the field of irrigation and water security studies.

On the other hand, there is an established body of literature on the use of correlation-based analysis to examine the impact of irrigation infrastructure on poverty and growth. Briefly, a few examples include studies such as Lipton et al. (2002) who conduct an extensive review of empirical studies on the direct and indirect impacts of irrigation on outputs, employment, prices, health, the environment, resource allocations, and its equity and poverty implications at micro- and macro-levels. Jayaraman and Lanjouw (1999) carry out a review of 35 longitudinal village-level studies from Andhra Pradesh, Bihar, Gujarat, Karnataka, Kerala, Maharashtra, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh, and West Bengal in India. Kishore (2002) conduct empirical studies on the socioeconomic impacts of canal irrigation in India. These examples along with multiple other studies primarily use experimental, quasi- and non-experimental econometric methods to provide empirical evidence of the role of irrigation in enhancing crop intensification and productivity, generating employment, promoting growth, and enhancing and sustaining rural livelihoods (Hussain and Hanjra, 2004). As the thesis was focussed on analysis of the role of irrigation infrastructure, successionist or experimental methods with a substantial methodological literature is preferred as an initial first step for the core research questions of this thesis. It is also important to recognise that this thesis is one of the first attempts to understand, at multiple scales, the dynamic effects of investments in modernised and rehabilitated irrigation infrastructure on a combination of interdisciplinary outcomes in the context of rural Madhya Pradesh within a single study.

Second, as the thesis focused on exploring "*what difference did the modernised infrastructure make*?" to a set of established outcomes derived from infrastructure investments to improve water security by comparing changes within a sample population *with* and *without* as well as *before* and *after* (based on recall of the past due to the absence of baseline data) at multiple scales (district, farm, individual) across multiple sites (6 river basins, 30+ districts, and over 900 farmers) within a relatively short timeframe after the MPWSRP program of investment closed, in 2015, experimental methods were better suited to this type of study. Thus, a quasi-experimental, reflexive comparison approach using statistical, econometric methods was more appropriate to the research questions central to this doctoral study. Next, the study began in 2015, *ex post*, after the MPWSRP program

had already been designed, implemented, and evaluated for effectiveness by the World Bank and the Government of Madhya Pradesh. The timeline of the MPWSRP program closure, which coincided with the start of this doctoral research project as well as the relatively short timelines associated with the lifecycle of a doctoral thesis deemed experimental methods as a preferred option at this stage of analysis over theory-based, critical realist evaluation methods or QCA methods.

Third, prior to the start of this doctoral project, the Madhya Pradesh government and the World Bank completed monitoring and evaluation reports of MPWSRP outcomes related to physical infrastructure characteristics of the systems that were upgraded including analysis of irrigation potential achieved, status of the canal system after the program concluded, changes in canal conveyance in a sub-set of irrigation systems upgraded by the MPWSRP (World Bank 2015). Data collected for these evaluation reports, however, was insufficient to carry out a study of the impacts of the MPWSRP infrastructure investments with respect to the multifaceted and multidisciplinary outcomes that are explored in this thesis. Data that is limited to contextual factors related to physical infrastructure and strictly sampled from the areas of intervention alone are not sufficient to conduct robust statistical econometric tests of the effects of the intervention on diverse developmental outcomes. Researchers have shown that data that does not assess variations in outcomes relative to different contextual factors, that does not capture the interaction between water-related and non-water related contextual factors, that does not assess the moderating effects of factors such as intervention setting or characteristics of interveners on participants as well as non-participants (e.g., race/ethnicity, literacy level, and related observable socio-economic characteristics) are insufficient to capture the interaction of interventions within the dynamics of complex systems (Rueda et al., 2006; Hawe et al., 2009).

Thus, the initial availability of data related to impact assessment criteria used to evaluate MPWSRP investments in infrastructure, at the outset of the research project coupled with the timeline of the start of the research project (at the closure of the MPWSRP), rendered a choice of QCA or realist evaluation research design unfeasible.

However, in order to conduct an empirical investigation of the role of infrastructure with respect to multifaceted water security outcomes using quasi-experimental designs, required a large dataset of observations to be constructed grounded in the "complex" context in which the investments were made. This dataset did not exist at the inception of this doctoral research project. To address the research question in this thesis required large-scale primary and secondary data collection focused on gathering spatial and temporal data on the contextual factors of the study area and target population at multiple scales. This included constructing a dataset of secondary data from intervention and non-intervention areas on sub-basin rainfall patterns (daily rainfall data across multiple districts and river basins over a period of ten years), infrastructure (data on the 228 irrigation systems upgraded by the MPWSRP as well as non-upgraded irrigation systems managed by the government across multiple river basins and districts), agricultural productivity (crop yield data for multiple crops across multiple districts over a period of ten years), policy instruments (MSP crop prices for multiple crops over a period of ten years), and primary household data (socio-economic information on hundreds of farming households across multiple districts in intervention and non-intervention areas), and individual characteristics of farmers (self-reported data on well-being, irrigation choices and cropping practices), among other characteristics.

Recognising the limitations of purely quantitative variable-based regression analysis, additional qualitative data collection of a small sub-set of the population of farmers was also included to understand the "*why*" and "*how*" queries underpinning the observed changes in farmer irrigation practices in the third empirical chapter. The large comparative dataset of primary and secondary observations of multiple variables across multiple scales and time periods constructed in this thesis lays the groundwork for further iterative understanding of context-mechanism-outcome configurations (for Realist Evaluation approaches) and opens the door for advancing the methods and applications of the data taken in this thesis towards the development of causal theories in further research. Thus, normative theories stemming from the outputs of empirical investigations can improve significantly when more causal theory is generated, and thus can benefit from

coupled and iterative evaluative approaches that further test causal assumptions building on experimental methods (see Chapter 7 for a discussion on this).

Fourth, the choice of experimental methods for the analysis conducted in the thesis is grounded in normative and transdisciplinary motivations. The aim for undertaking the research was explicitly focused on producing research outputs that can be easily translated, communicated, disseminated, and understood by the core set of actors or decision-makers associated with the case study in Madhya Pradesh, which inadvertently influenced the choice of methodological approach. My personal perspective in understanding the audience to which the outputs of the research results are targeted lent themselves to experimental methods mixing quantitative and qualitative techniques that are common to the field of development economics, well known to World Bank practitioners as well as technical counterparts in the Indian government. As Shiferaw et al., (2005) note, ex post, empirical studies attempt to understand the pathway through which observed impacts have occurred and why interventions fail or succeed in attaining stated objectives. Thus, analytical studies grounded in empirical methods can present insights for policy decisions as to whether planned irrigation infrastructure programme interventions should be discontinued, modified, improved or sustained in the future. In order to achieve this aim, the choice of methods, which are "translatable" as well as familiar to a core set of practitioners explicitly interested in the outputs, is important.

As Claudia Pahl-Wostl (2020) argues, "*science can provide expert knowledge for evidence-based decision making and can facilitate processes of negotiation and learning. Scientific research should develop diagnostic approaches that allow teasing out which kind of lessons learned can be transferred and which kind of influence must be attributed to social, political, economic or environmental contexts*." (p.408). Even though teasing out "*expert knowledge for evidence-based decision making*" is important, it is not automatic and guaranteed that public sector decision makers and practitioners in the water sector will extract meaningful lessons and act upon the evidence generated by scientists and scholars. I argue that in order to influence policy actors and practitioners to make 'evidence-based' choices, it is necessary but not sufficient to generate knowledge based on sound

methodological approaches grounded in a particular scholarship. Equally and if not more critically, is the *translation* of that evidence (including the methodological approaches of how researchers arrive at the evidence) into a language that is legible and meaningful to decision makers, grounded in the terms and methods that they are familiar with. Such translation is necessary for scientific evidence to be absorbed and acted upon, and thus may require specific methodological approaches, which are familiar to decision-makers who are ultimately responsible for taking decisions stemming from the outputs of the research.

Because of this transdisciplinary condition, I selected research methods that could be easily understood by the actors I was aiming to provide insights to and ultimately influence. Thus, research design choices that can be perceived as normative, or overtly biased towards a specific school of thought (e.g., experimental methods) are in fact critical to facilitating active processes of "learning" that is required to provide evidence-based insights to future researchers, as well as to practitioners, policy decision-makers, and donors. These are some of the steps I took to facilitate new insights and knowledge about the relationship between a large-scale program in Madhya Pradesh to enhance water security by rehabilitating and modernising irrigation infrastructure and its consequential effects by exploring diverse interdisciplinary outcomes at diverse scales.

2.6 General analytical framework

Thus far, this chapter has presented a broad review of the literature considering the themes of infrastructure and hydroclimatic risk and its consequential outcomes for growth in developing countries; the potential of infrastructure to reduce household poverty in agriculture-dependent rural economies from the lens of well-being; the role of infrastructure, policy instruments and subsidies, as well as social dynamics in influencing the irrigation practices and technology choices of farming communities; and, diverse methodological techniques, their interpretations of causality, their strengths and weaknesses as well as the rationale for the optimal methodological choice for the thesis.

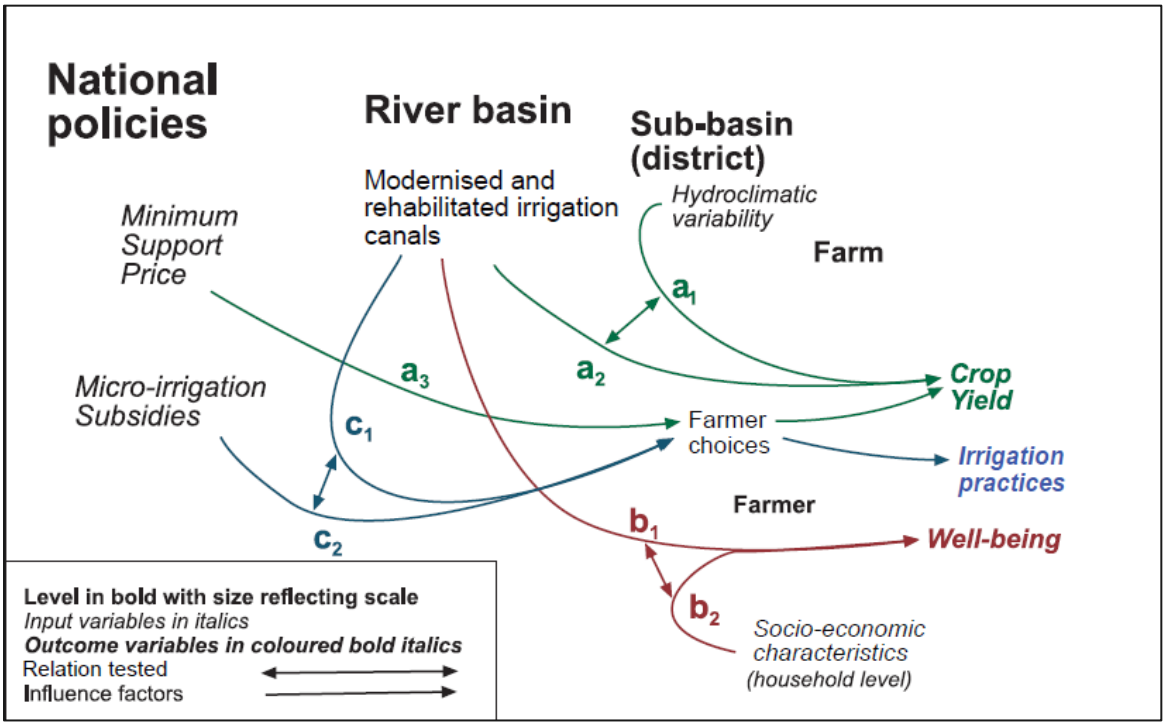
Building upon these themes, the main goal of this thesis is to explore the role of irrigation infrastructure in influencing a set of multidisciplinary development outcomes at the individual, farm, district, and river basin scales in Madhya Pradesh. To this end, gaps in the literature with respect to understanding dynamic water security outcomes in the context of agriculture have been explored. Discussions around contextual factors related to hydro-climatic variability, policy instruments such as crop prices, financial subsidies for technology adoption, and the social dynamics of farmer irrigation practices, among other factors with respect to canal irrigation have been mentioned. This review has also provided rationale for why direct and indirect benefits derived from interventions to enhance water security by means of canal irrigation are explored from the perspective of crop yields, subjective well-being, and irrigation practices in this thesis within the context of rural India.

Advancing from the review of the literature and the gaps identified, an analytical framework that guides the overall investigation in the thesis is presented (Figure 1). The analytical framework is a graphical, conceptual map that summarises how the examination of the role of modernised and rehabilitated infrastructure in influencing specific outcomes is conducted. The empirical tests are conducted at multiple scales of analysis using quasi-experimental methods framed by corresponding research questions in Chapters 4-6 in the context of the Madhya Pradesh Water Sector Restructuring Project. Although this thesis does not comprehensively cover all of the potential contextual factors associated with irrigation and agriculture production in rural India, it begins to lay the building blocks for such an exploration by analysing whether water security outcomes are influenced by contextual factors related to hydrological, policy, socio-economic, and behavioural dimensions at diverse spatial scales of analysis (national, river basin, district, farm, and individual). Figure 1 reveals how these factors are incorporated into the empirical analyses conducted in Chapters 4-6.

In Chapter 4 of the thesis, the relationship between hydroclimatic variability (sub-basin scale) and rehabilitated irrigation infrastructure (river basin scale) is tested by exploring the impacts on crop yields (district scale). In this analysis, additional policy factors (at a national scale in India) are also incorporated by testing the relationship with

crop price policies and crop yields. This set of tests are depicted as a_1, a_2, and a_3 (Figure 1). In Chapter 5, the relationship between rehabilitated irrigation infrastructure (at the river basin scale) and the socio-economic vulnerability characteristics of farmers (at the household scale) is tested by examining farmer responses to well-being depicted as b_1 and b_2 in the analytical framework (Figure 1). In Chapter 6, the relationship between rehabilitated irrigation infrastructure (river basin scale) and financial subsidy policies (state and national scale) are tested by exploring changes in farmer irrigation practices with respect to irrigation technology choices (individual scale) depicted as c_1 and c_2 (Figure 1). Additional qualitative analysis is also conducted in Chapter 6 to understand how social dynamics among farming communities influence farmer choices for using sprinkler or drip irrigation technologies. In a nation as diverse and complex as India, the impacts of surface irrigated infrastructure will be influenced by multiple interrelated hydrological, agricultural, institutional, governance, cultural and social systems at diverse scales. This study has taken an initial step to generating evidence of these multiple factors of influence by examining a limited set of outcomes stemming from efforts to enhance agricultural water security within an Indian state using quasi-experimental methods.

Figure 1. Analytical framework of water security outcomes



Building on the literature gaps discussed above, three research questions are identified, addressed in each of the three empirical chapters.

Research question 1 (Chapter 4): *Do investments in irrigation infrastructure modernisation lead to higher crop yields and buffer yields from fluctuations in rainfall at the district-level compared to districts without investments?*

Gap: Studies that investigate the effectiveness of irrigation investments in developing countries largely do not explore the influence of sub-basin hydrological variability and the resulting impact on crop yields after investments are made to modernise irrigation infrastructure. Thus, there is limited evidence on how hydrological patterns vary spatially and temporally at a sub-basin scale and whether the availability of surface water through improved canal infrastructure reduces the risks of this variability on crop yields at a sub-basin (or district-scale). Also, little is known about how related, non-infrastructure

policy interventions such as national-level food security policies influence outcomes for crop yields.

Contribution: Chapter 4 contributes to the literature by investigating the outcomes of irrigation infrastructure investments by exploring the relationships between variables $a_{1,}$ $a_{2,}$ and a_3 in Figure 1. Chapter 4 tests the hypothesis that investments to modernise irrigation infrastructure lead to higher crop yields and buffer yields from fluctuations in rainfall at the district-level in Madhya Pradesh. The chapter contributes to the gaps in the wider literature by conducting an empirical analysis comparing crop yields from districts with investments in irrigation rehabilitation to yields from districts with no investments, while accounting for inter- and intra-annual district-level monsoon anomalies. The chapter also examines the influence of national policies for guaranteed crop price factors on yields over a period of ten years in Madhya Pradesh. This additional factor of analysis is included in order to test the influence of national-level policies on infrastructure outcomes with respect to crop yields. The secondary dataset of multiple observations that is built for the investigation carried out in Chapter 4, consisting of data on crop yields of three cereal crops, rainfall patterns, crop prices over a decadal period across multiple districts in MP represents one of the unique contributions of this chapter.

Research question 2 (Chapter 5): *Does modernised irrigation infrastructure influence the well-being of smallholder farmers in Madhya Pradesh?*

Gap: The importance of multidimensional indicators for poverty such as well-being measures is well established in the literature. However, there is no clear understanding of how rural farmers perceive improvements in irrigation investments on their well-being. Much of the literature in the Indian context does not explore the relationship between improved surface irrigation systems and household responses to well-being. Instead, studies on the impact of irrigation infrastructure modernisation in India focus on the change in the amount of irrigated area serviced by the canals and the consequential impact on income and employment among farmers.

Contribution: Chapter 5 provides insights into whether farming households with access to modernised irrigation systems experience changes in their subjective well-being compared to farmers who do not have access to irrigation investments. The chapter focuses on examining the relationships between the variables outlined in the analytical framework under b_1 and b_2 (Figure 1). The study employs a unique dataset built from more than 700 farmer interviews across Madhya Pradesh as well as analysis of decadal inter- and intra-annual rainfall patterns across districts which received investments as well as districts with no investments. This dataset represents an important opportunity to understand if there is a relationship between modernised irrigation infrastructure and gains in subjective well-being for smallholder farmers in rural Madhya Pradesh. The survey data is used to build a logistic regression model with a dichotomous dependent variable representing subjective well-being controlling for exogenous variables such as district-specific rainfall patterns, district fixed effects, socio-economic indicators, and irrigation practices of farming households in control and treatment areas. The chapter provides critical insight into the distributional implications of irrigated infrastructure on perceived well-being among farmers.

Research question 3 (Chapter 6): *How do investments in irrigation infrastructure and technology subsidy policies influence farmer irrigation practices?*

Gap: Much of the literature that examines how public investments in irrigation efficiency influence the water use behaviours of farmers fail to explore the effects of multiple policy actions (e.g., improved irrigation infrastructure and financial subsidies for technology adoption) on farmer irrigation practices. Understanding whether farmers' change their irrigation practices with respect to preferences for sprinkler or drip adoption in the context of India after canals are rehabilitated has significance for the debates surrounding whether investments in canal irrigation improve farming practices and whether irrigation technologies are substitutes to surface water. Little is understood about how farmers change their behaviour with respect to irrigation practices after surface systems are modernised and subsidies for technology adoption are available. This reinforces the need to understand outcomes of infrastructure investments at the spatial scale

of the farm field and from the perspective of individual irrigation choices or water use behaviours of farmers. Few studies in India have investigated how infrastructure modernisation at a system level and national and state financial subsidy programmes influence the irrigation practices of farmers.

Contribution: Chapter 6 contributes to the gaps in the literature by exploring how the availability of modernised infrastructure and subsidies for technology adoption influences the irrigation practices of smallholders in surface irrigated farms in Madhya Pradesh. The empirical tests carried out in this Chapter are depicted as *c1* and *c2* in Figure 1. The study employs a mixed methods approach combining logistic regression analysis of household survey data of 918 farmers with qualitative semi-structured interviews with a small sub-set of farmers from the larger sample. The quantitative results reveal that there is a reduction in the probability that farmers will adopt drip or sprinkler technologies once irrigation systems are rehabilitated. Qualitative results from the semi-structured interviews of farmers adopting drip or sprinkler irrigation suggest that: (1) open, gravity canals do not restrict drip and sprinkler adoption and therefore are not necessarily alternative or substitute irrigation options, (2) socio-economically vulnerable farmers are more likely to adopt these technologies when faced with water scarcity, and (3) learning about the benefits of the technologies through their own social networks appears to be a positive incentive for adoption as smallholders struggle to access government subsidies. The chapter offers critical insights that contribute to the broader literature on the potential of social networks to incentivise changes in irrigation practices, which can complement understanding of how supply-side infrastructure investments and financial incentive policies influence the farming techniques of smallholders facing climatic risks to food production across India.

3. Methodology

"And whereas Sense and Memory are but knowledge of Fact, which is a thing past, and irrevocable; *Science* is the knowledge of Consequences, and dependence of one fact upon another."

Thomas Hobbes

Chapter 3

3.1 Introduction

In this chapter, I outline the research context as well as the methods applied in each of the papers that comprise this doctoral research study. The thesis draws on an interdisciplinary mixed methods approach to achieve the overall aim and address the three research objectives as laid out in Chapter 1, section 1.4 on *Thesis question, research objectives, and format*. The research methods combine quantitative, quasi-experimental statistical regression analyses of household survey data, consultations and interviews with senior government officials in the Madhya Pradesh government, World Bank staff, and farmers, as well as secondary data collection of interannual and intra-annual district-level rainfall values, district-level crop yield data for three cereal crops, MPWSRP irrigation investment data, and crop price data over a ten-year time period.

To coordinate and design the data collection and survey processes, I spent time in Bhopal (the capital of Madhya Pradesh) and in rural districts where surveys were conducted with farming households on and off between 2015 - 2018. Prior to data collection, approvals were obtained from the Government of Madhya Pradesh Water Resources Department and Oxford University's Central University Research Ethics Committee (CUREC). The background of the research process, the design of the research methodology, and the utilisation of a mixed methods approach expand the quantitative and qualitative evidence base and deepen understanding of whether and how rehabilitated and modernised irrigation infrastructure investments across multiple districts of Madhya Pradesh influence specific outcomes. I close this chapter by outlining the limitations of the research.

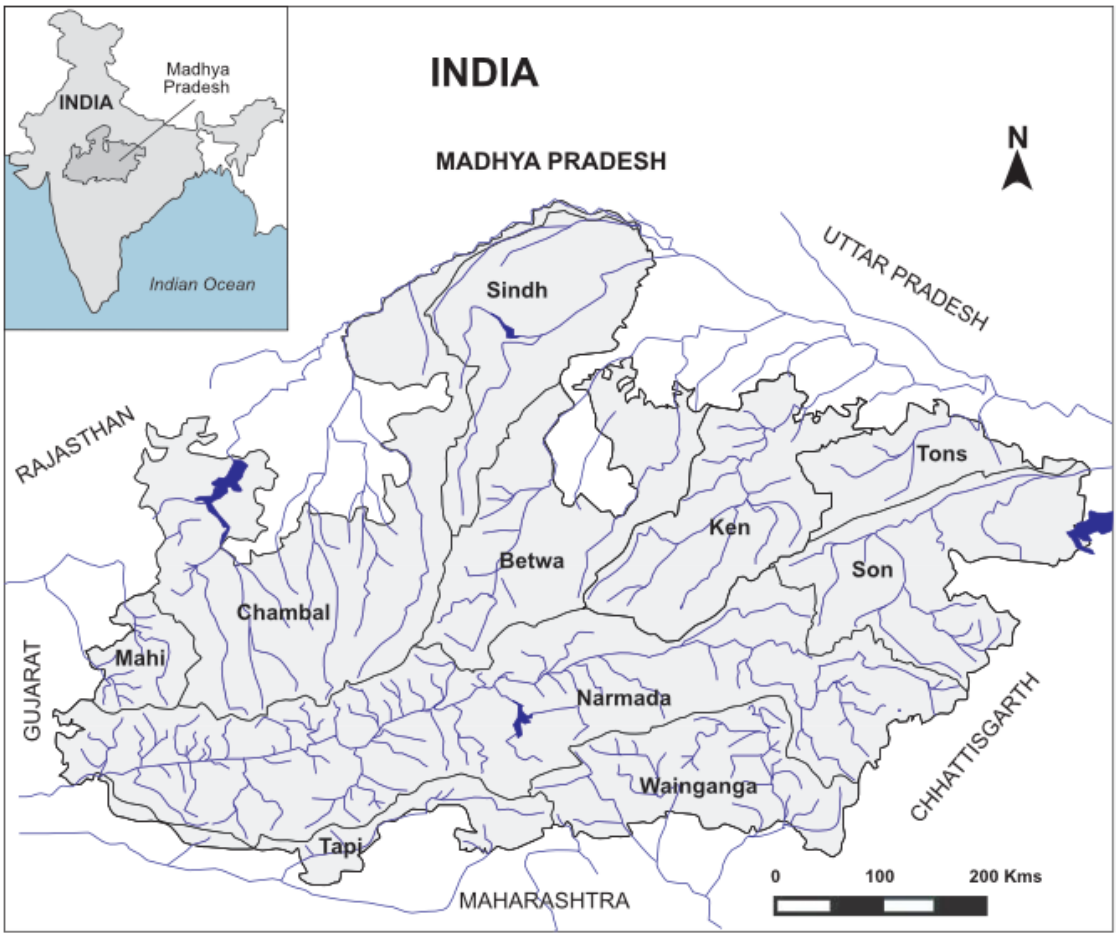
3.2 Study area and data collection

3.2.1 Background on Madhya Pradesh

The Indian state of Madhya Pradesh is situated in the centre of India. The topography of MP is mostly plains from north to the south separated by upland areas. The state is endowed with rich natural resources including several river basins, the second-highest production of mineral resources in India, and forest areas, which cover 30.7% of the state. MP has ten

river systems (Mahi, Chambal, Sindh, Betwa, Ken, Tons, Son, Narmada, Wainganga, and Tapi) (Figure 2). All except the Sindh river basin are part of transboundary (inter-state) river systems. The Sindh and Tons sub-basin systems are a part of the Yamuna river basin. The Sindh River joins the Yamuna in the Indian state of Uttar Pradesh. Chambal, Betwa, Sindh and Tons are tributaries of the Yamuna, which is part of the Ganga Basin. Tons and Son are tributaries of the Ganga. These rivers flow north originating from the central plateau of MP. Wainganaga is a tributary of the Godavari flowing southeast to the Bay of Bengal. The Narmada, Mahi, and Tapi are west flowing river systems terminating in the Arabian Sea.

Figure 2. Map of the River Basins of Madhya Pradesh[4]



MP has five regions with 52,143 villages, 23,044 panchayats (village councils) and 323 development blocks in 51 districts. The state has a great deal of diversity with areas ranging from less than 50 metres above mean sea level to more than 1200 metres. There are 10 agro-climatic zones and five main crop zones in the state (De et al., 2001)[5]. The state has five physiographic regions: a) Northern low-lying plains; b) Malwa and Vindhya plateau; c) Narmada valley; d) Satpura stretch; and e) Bastar plateau (De et al., 2001). The

[4] Map designed by Giraldo, C. (2019) based on the Environmental Atlas of Madhya Pradesh, Map No. 23 Surface Water Quality by the M.P. Pollution Control Board. Water Resources of Madhya Pradesh: Major projects, Water Resources Department, Government of Madhya Pradesh, January 2006.

[5] The agro-climatic zones are Bastar Plateau Zone, Kymore Plateau and Satpura Hill Zone, Vindhya Plateau Zone, Central Narmada Valley Zone, Grid Zone, Bundelkhand Zone, Satpura Plateau Zone, Malwa Plateau Zone, Nimar Valley Zone and Jhabua Hill Zone (De et al., 2001).

Human Development Index of Madhya Pradesh has consistently ranked the state among the bottom four in India (Planning Commission, 2011). More than one-third of the population is categorised as "socially and economically disadvantaged" consisting of Scheduled Tribes (ST) (20%) and Scheduled Castes (SC) (15%). This figure is one of the highest in India (Government of Madhya Pradesh, 2011). The economy of Madhya Pradesh is predominantly agrarian with agriculture, animal husbandry, and fisheries making up the primary sectors in the state. Growth of the agriculture sector in MP has shown large-scale fluctuation with growth rates ranging from -2.4% in 2007–08 to 11.2% in 2010–11 (Sapre 2014). During this period, per capita income rose by an average of 4% (Government of Madhya Pradesh, 2011). Although the contribution of agriculture in the state's Gross State Domestic Product (GSDP) has gradually declined from about 60% in 1961 down to 20.5% in 2010–11, the percentage of labour employed in the sector continues to be over 70% (Sapre 2014; Gilmont et al., 2018). Thus, growth in the agriculture sector is critical for the socio-economic welfare of the population engaged in farming and related activities.

The net sown area in MP is 15.07 million ha with a total irrigated area of 6.72 million ha. The total irrigable area is the net sown area less than the area that is not available for irrigation. As of March 2014, the state had created irrigation potential of 3.15 million ha through the development of surface water projects such as dams, irrigation canals, and diversion channels (Enarth et al., 2016)[6]. Out of the Net Irrigated Area in the state, 68% of the irrigation is received from wells and tube wells, indicating a high dependence on groundwater sources. About 2.1 million ha of cropland is irrigated using surface water sources at an average gross cropping intensity of about 80% (Enarth et al., 2016). As of 2006, small and marginal landholdings constituted over 67% of the total land holdings in the state (Enarth et al., 2016). Between 2000 and 2006, the average landholding size reduced from 2.22 ha to 2.02 ha. As stated in the Madhya Pradesh 2011 state plan, about 59% of the gross cropped area was under food crops and the remaining 41% area was under non-food crops. During 2009-10, the gross cropped area under wheat was 23% and 7.4%

[6] Irrigation potential is the area which can potentially be irrigated depending on the physical resources 'soil' and 'water', combined with the irrigation water requirements as determined by the cropping patterns and climate. However, environmental and socioeconomic constraints also have to be taken into consideration in order to guarantee a sustainable use of the available physical resources (*Source*: FAO).

was under paddy (Government of Madhya Pradesh, 2011). Wheat and rice contribute about 50.5% of the total food grain production in the state. Pulses collectively contribute about 27% of the total food grain production. Among non-food crops, oilseeds production is dominated by soybean in MP (Government of Madhya Pradesh, 2011). A study by Sapre (2014) empirically analyses whether agricultural growth performance in MP determines the overall growth trajectory of the state economy. The results indicate that over a period of three decades fluctuations in agricultural growth coincides with fluctuations in GSDP growth with considerable impact on the state's growth performance (Sapre 2014).

Annual rainfall in Madhya Pradesh ranges from 800 millimetres (mm) to 1,600 mm from west to east, occurring mainly during the monsoon (June to September) (Government of Madhya Pradesh, 2011). Historical analysis of rainfall variability indicates that the summer monsoon (June to September) in central India has changed significantly between 1950 and 2000 (Sushant 2013). The frequency of days with heavy rainfall (100 mm/day) increased from 45 to 65 days per year, while the frequency of extreme rainfall events (150 mm/day) has doubled from 9 to 18 days per year during this period (Sushant 2013). In contrast, the frequency of days with moderate rainfall (e.g., between 5 and 100 mm/day) has decreased. An increased frequency of extreme events and erratic rainfall along with a decline in the number of moderate rainfall days indicates that MP is facing high levels of hydroclimatic variability. Overall, 40% of the total sown (cropped) area in the state is served by surface water and 60% of the cropped area in the state is irrigated by groundwater. Therefore, erratic and uneven distribution of the monsoon is one of the main constraints in accelerating and sustaining the growth of the agriculture sector.

Gilmont et al. (2018) find that from 1961 to 2012, there is a sustained statistically significant relationship between rainfall and economic growth in Madhya Pradesh. To determine this trend, they calculate the percentage deviation of rainfall from the 1961-2011 average values and regressed this against annual economic growth rates for the same period. The paper finds that this relationship persists even after the separation of Chhattisgarh from Madhya Pradesh in 2000 (Gilmont et al., 2018). The states' sensitivity to drought also persists despite significant growth in the irrigated area in the state until

2007 (Gilmont et al., 2018). Overall, Gilmont et al. (2018) conclude that the agricultural dominant economy of MP remains coupled to rainfall fluctuations until 2012. The work of Gilmont et al. (2018) has built upon earlier work by Singh (1997) who found that Madhya Pradesh faces high water insecurity in the form of droughts and floods with strong linkages between state-wide economic growth and variability in its monsoons. In the agricultural sector, Shankar (2005) reviews four decades of agricultural development in the state. He finds that the lack of regional or location-specific policies and unsustainable irrigation practices led to a near-stagnation of agricultural development in early 2000, thereby leading to the technological and economic deterioration of many regions in the state.

Over the past decade, the state government in Madhya Pradesh prioritised a renewed approach to overcome variations in agricultural growth and promoted water-related infrastructure investments in the state (Sapre 2014). A number of major, medium and minor irrigation schemes were developed through large-scale investments under successive five-year plans. Prior to the start of the World Bank funded MPWSRP, most of the state's irrigation schemes were old (many over 20 years and some older than 50 years) and required substantial investments to modernise the systems, to improve the productivity of the land, and to enhance water management efficiency for crop productivity. The MP Water Resources Department holds the main responsibility for irrigation development in the state. It is responsible for estimation, planning, maintaining, and comprehensive utilisation of surface and groundwater resources. Based on this context, the GoMP WRD was the lead public sector agency to obtain financial support from the World Bank for implementing a ten-year programme of modernisation and rehabilitation of irrigation systems that began in 2005 and closed in 2015. The Madhya Pradesh Water Sector Restructuring Project financed infrastructure investments in rehabilitation and modernisation on a hydrological basin-scale in six out of the ten river basins in the state (Chambal, Sindh, Betwa, Ken, Tons, and Wainganga) (Figure 2). Irrigation investments comprised of engineering repair works on dams and embankments including a) resolving seepage and drainage issues, b) improving boundary stones, and c) repairing sluice and radial gates on the infrastructure.

The primary justification for selecting six out of the ten basins was to take all major river basins north of the Narmada basin. The Narmada basin is a transboundary basin and thus could not be part of the project due to World Bank lending regulations (World Bank 2005). There are seven river basins north of the Narmada (Figure 2). The Mahi river basin was determined to be too small for integration into the project due to the lack of large-scale irrigation systems. Within the six intervention basins, investments were targeted to engineering needs; systems that were built before 1986, and those that exceeded a certain degradation threshold of designed performance, were selected for rehabilitation (World Bank 2005). The methodological approach for this thesis, therefore, focused on data collection within the six river basins of intervention which include a total of 31 districts. The data collection and analysis concentrates on the 31 districts that fall within the six selected river basins and excludes river basins where no MPWSRP investments were made. Districts in India are local administrative units that form the tier of local government just below the state.

3.2.2 Secondary data collection

The data collection strategy is divided into two parts. The first part is the collection of secondary data as a basis to conduct the empirical and qualitative analysis within the three chapters to achieve the research objectives. Secondary data collection focused on aspects such as a) compiling daily rainfall data for 12 months from 2005-2014 for all rain gauge stations in each of the 31 districts of study; b) collecting annual crop yield data from all 31 districts for three staple crops (wheat, rice, and gram) from 2005-2014; c) compiling annual crop price data for wheat, rice, and gram from 2005-2014 as per the Minimum Support Price (MSP) in Madhya Pradesh for each crop; and, d) collecting data on the 228 MPWSRP irrigation investments within 21 districts (out of the 31) where systems were rehabilitated as well as data on irrigation systems within ten districts that did not receive MPWSRP investment across the six river basins. Each empirical chapter includes a detailed description of the data collection and methodological specifications for the analysis conducted. A summary of the methodological approaches for the secondary data collection is described in more detail below as well as a brief overview of how this links with specific elements of the analytical framework (Figure 1).

3.2.2.1 Rainfall data analysis

In order to answer the first research question, *do investments in irrigation infrastructure modernisation lead to higher crop yields and buffer yields from fluctuations in rainfall at the district-level compared to districts without investments?* in Chapter 4, the first step of the methodological approach was to collect rainfall data for all rain gauge stations across all 31 districts from 2005-2014. Monthly rainfall data from 2005-2014 for all districts was obtained from the Government of Madhya Pradesh Water Resources Department officials. Data was provided for all districts for each month (January – December) for the years 2005-2014. At the time of data collection (in 2015) 2015 rainfall data had not been compiled by the Department. For each district, daily rainfall values in millimetres were available for each of the rain gauge stations within the district. It is important to note that the data obtained were actual observed values for rainfall collected by the WRD rather than satellite data. Based on raw values for each day, monthly averages were calculated for each district by summing data from all rain gauge stations and then aggregated for annual values for each year. The district of Katni, however, did not have any monthly rainfall values for 2014, as these were not available with the Department. Once the data was compiled, the interannual and intra-annual analysis was carried out for both the monsoon period (June – September) and the winter period (January – May and October – December).

Interannual variation in the monsoon cycle is determined by the relative contribution of multiple external and internal air-sea interactions and oscillations, with heavy or less rainfall traditionally resulting in floods or droughts (Ratna et al., 2011; Neena et al., 2011). To analyse interannual rainfall variability in MP, I classified the 31 districts into three rainfall zones: **low rainfall**, **average rainfall,** and **high rainfall**. First, this was to determine if there is significant temporal diversity in the interannual long-term rainfall averages among the districts over the ten-year study period. Second, districts were characterised into rainfall zones to compare differences in their temporal long-term averages within districts that received investment from the MPWSRP (**Rehab**) and districts that received no investment from the MPWSRP (**No Rehab**). Thus, I analysed how many

of the districts among the 31 tend to have low, average, or high rainfall and divided the 31 districts into Rehab versus No Rehab investment categories. Once the monthly average for each year (2005-2014) for each district was calculated, I then calculated the ten-year (long-term) average for that district. The last step was to classify each district according to its corresponding rainfall zone. To classify each district into the three zones, the following formula was applied:

Average rainfall: In order to determine if a district falls into the average rainfall zone, I compared each individual districts' 10-year average rainfall value relative to the average of the 10-year (long-term average) rainfall value of all 31 districts combined. For example, for the Rajgarh district, which is in the **Rehab** investment category, the rainfall zone classification was determined by comparing the 10-year average rainfall value of Rajgarh of 1019 mm/year against the total 10-year long-term temporal average value of all 31 districts, which is 942 mm. As Rajgarh's 10-year average value is within 10% of the 942 mm value of the 10-year average of all districts, it is classified as having *average* rainfall. The boundary classification for the district-specific long-term average rainfall is determined to be between 869 –1062 mm, thus Rajgarh falls into the average rainfall zone.

Low rainfall: This classification was determined in the same way as average rainfall, except the criteria to fall into low rainfall is when the district has a 10-year long-term average rainfall value that is less than 10% of the 942 mm (10-year average of all the districts). For instance, Dhar is a **Rehab** district that falls into the *low* rainfall zone, as the 10-year average rainfall value for Dhar is 860 mm. The boundary classification for low rainfall is less than 869 mm.

High rainfall: The criterion for high rainfall is when the district has a 10-year average rainfall that is 10% higher relative to the 942 mm (10-year long-term average value of all 31 districts). For instance, Bhopal is a **Rehab** district that falls into the *high* rainfall zone, as the 10-year average of Bhopal is 1119 mm. The boundary classification for high rainfall is districts with average values greater than 1062 mm.

A summary table of the classification of each district into the three rainfall zones, observed average rainfall values for all 31 districts, the number of rainfall gauge stations in each district, their corresponding irrigation investment categories, and the district agro-climatic and crop zones are provided in Tables 2 and 3 in Chapter 4. The interannual analysis indicated that a) there is heterogeneity in the interannual temporal long-term average values from one district to another and relative to the total 31-district long-term average value; and, b) not all districts received the same degree of investment within each of the Rehab districts and not all districts fell into the same rainfall zone categorisation. Comparing long-term rainfall averages across multiple districts within a river basin and across multiple basins within Madhya Pradesh is a relatively complex exercise. The method used for interannual rainfall analysis transformed a continuous variable (data on daily rainfall patterns for ten years) for each of the rain gauge stations in the districts into a categorical variable (classification of districts into 1 of 3 rainfall zones). This method represents some limitations as it reduces the granularity of the daily rainfall data collected across multiple rainfall gauge stations in each district. However, this classification approach allowed me to simultaneously compare political (or spatial) boundaries (district to district), hydrological variability (temporal interannual long-term variability of each district) and changes in total irrigated area (MPWSRP investment districts vs. no-investment districts). This approach enabled a comparison matrix to be built across multiple layers of spatial, temporal, and investment data.

Building on the interannual rainfall analysis, I also examined intra-annual rainfall variability among the 31 districts of study, which was a necessary step to determine whether investments to modernise irrigation infrastructure buffer crop yields from fluctuations in rainfall at a district-level. The intra-annual analysis examined fluctuations in a district's hydroclimatic pattern from month to month (within a year) within a district and across districts amongst both Rehab districts and No Rehab districts. To conduct this analysis, the same dataset as that utilised for the interannual rainfall analysis was utilised for 30 districts from 2005-2014. For the 31st district, Katni, monthly rainfall values were available from 2005-2013 as 2014 was not available. As monsoon rainfall is important for

determining agricultural yields and productivity, I limited the intra-annual variability analysis to the four monsoon months (June – September) across all ten years.

The first step was to determine a monthly value for each district based on a sum of the daily values of rainfall in mm of all the rainfall gauge stations in each district. Thus, monthly values were calculated for the four monsoon months across all 31 districts for all available years from 2005-2014. The second step was to calculate "*monthly climatology*", which is the mean value of rainfall for each month over the time period 2005-2014. Therefore, mean values for each of the four months were calculated by taking an average of the monthly value of each month for the ten-year period. Rainfall anomalies for each district were computed by subtracting observed values of monthly data from the monthly climatology values for all 31 districts. The third step was to determine if seasonal variations are present within the monsoon months. Standardised anomalies, also referred to as normalised anomalies, are calculated by dividing the "*rainfall anomaly*" values by the climatological standard deviation. Thus, the climatological standard deviation of the rainfall was calculated for each of the monsoon months for all 31 districts. Once standard deviations were determined, the standardised anomaly was determined by dividing the rainfall anomaly for the monsoon months from the standard deviation values of each respective month. This was calculated using the following formula:

$$I_t = (R_{it} - \mu_i)/ \sigma_{it} \qquad (1)$$

The standardised anomaly is depicted as a random variable I_t at the tth month. The parameters are R_{it} which represents the observed monsoon rainfall value during the tth month for the ith district which is subtracted from the mean climatology value of the ith district. This is then divided by the standard deviation σ_{it} of the ith district for tth month (Kraus 1977; Katz and Glantz, 1986).

Standardised anomalies generally provide more information about the magnitude of the anomalies because influences of dispersion have been removed. Once again, I classified each year from 2005-2014 into the three rainfall zones for all 31 districts. The classification was calculated based on an average of the monthly rainfall values of the four

monsoon months for each year in comparison to the average annual rainfall of 10 years for that district. Based on the calculation, each year from 2005-2014 was classified as high, average, or low rainfall. The results of the intra-annual classification of the districts and the 31 standardised anomaly graphs for each district are presented in Chapter 4. This was the first part of the methodological approach for understanding how sub-basin rainfall patterns differ from district to district within the six focus river basins in Madhya Pradesh. This analysis partly contributed to the research question posed in Chapter 4, however, in order to understand the impact of irrigation investments on crop yields; it was necessary to collect data on agricultural yields and crop prices.

3.2.2.2 Crop yield and crop price data analysis

In order to address the research question in Chapter 4, three key staple crops were selected for analysis. I selected the crops rice (paddy), wheat, and chickpeas (gram) because 60-80% of all the cultivated land area in Madhya Pradesh is dedicated to the production of these crops. Agriculture yield data was obtained directly from the Madhya Pradesh Commissioner Land Records Office in Gwalior district. The data was collected for each of the three selected crops (paddy, wheat, and gram) on the total area of the crop in the district in thousands of hectares, total production of that crop in each district in thousands of ton units, and total yield was obtained in kilograms per hectare. Data on the yield values for each crop for each district from 2005-2014 was collected to analyse trends and patterns between districts with investments from MPWSRP in comparison to districts with no investments as well as to interact rainfall patterns within each district with crop yield values.

Next, data were also compiled on the Minimum Support Price for paddy, wheat, and gram for the same time from 2005 to 2014. In order to test the relationships between a_1, a_2, and a_3 as depicted in the analytical framework in Figure 1, MSP was added as a variable of analysis into the econometric fixed effects model to test the statistically significant effect on crop yields in these districts as a result of rainfall factors versus policy factors such as the availability of an MSP for these crops. As described in Chapter 4, the

MSP programme of the Government of India is a national policy designed to protect farmers from commodity price shocks and maintain food security among the rural poor. In the MSP scheme, state governments set a minimum price for specific commodities, for which there is guaranteed purchase from the government. Data on MSP for paddy, wheat, and gram for the years 2005 to 2014 were obtained from the Madhya Pradesh Directorate of Economics and Statistics, Department of Agriculture, Cooperation and Farmers Welfare. Data on annual average crop yields per district for 31 districts from 2005-2014, crop price data for each crop for the same time period, and the rainfall data was used to build a cross-sectional fixed effects regression model that is described in detail in Chapter 4. The final layer of data collection to address the research question posed in Chapter 4 included specifications of irrigation investments made by the MPWSRP.

3.2.2.3 Irrigation investment data analysis

In order to understand the characteristics of the 228 irrigation schemes that were modernised by the MPWSRP, data were collected on the following: a) location of investment (e.g., district and river basin where systems is located); b) total command area of the system rehabilitated; c) the percentage of irrigated area rehabilitated in each district by the project; d) the total investment made by the project (in USD) in each district; e) the dollar amount invested per hectare in each district; and, f) the start and completion year of each irrigation rehabilitation project in each district. To categorise the diversity in the type of investments made by MPWSRP, I developed a three by three analytical framework to classify the 31 districts of study into distinct "irrigation investment categories" and the three rainfall zones.

To determine the degree of investment in each of the 31 districts, I divided the districts into three irrigation investment categories. If a district had less than 10% of their irrigated area rehabilitated by investments from the MPWSRP, it was classified as "*Low Rehab*". If the district had more than 30% of their irrigated area rehabilitated by the programme, then the district was classified as "*Medium-High Rehab*". "*No Rehab"* signified that no MPWSRP investments were made in irrigation systems in the district. In some cases, districts received MPWSRP rehabilitation investments in specific parts of their

command areas and not in others, and thus fell into both categories (No Rehab or one of the two Rehab categories). Thus, all 31 districts were assigned to one of the three categories. A table summarising the classification of the districts into investment categories and rainfall zones is provided in Chapter 4. Complete details of how the fixed effects regression model is constructed building upon the data on monsoon rainfall patterns, annual crop yields for the three crops, crop price data for each crop, and degree of investment made in each district are presented in Chapter 4.

3.2.3 Household surveys and primary data collection

The second part of the data collection is based on primary data from household surveys of farmers residing in districts with access to rehabilitated irrigation systems from the MPWSRP and farmers residing in districts (or areas of districts) where no investments were made. In order to design a robust methodological approach for addressing the research question in Chapter 5, *does modernised irrigation infrastructure influence the well-being of smallholder farmers in Madhya Pradesh?* and the research question *in Chapter 6, do investments in irrigation infrastructure and technology subsidy policies influence farmer irrigation practices?,* I led the design and execution of a cross-sectional household survey of 918 farmer members of WUAs in 2015-2016, followed by semi-structured telephone interviews of a subset of the same population of farmers in 2018.

3.2.3.1 Cross-sectional household survey

From August 2015 to early 2016, I designed and led a team to carry out a cross-sectional, household survey across the 31 districts of study in Madhya Pradesh. The survey sampling, questionnaire design, pilot of the survey, and the full survey was conducted in mid to late 2015 and the survey responses were translated and transcribed in early 2016. The objective of the survey was to identify trends among a sample of rural farming households living within a selection of districts within the overall population of rural households across the 31 districts. The household survey elicited data about individual farmer members of WUAs on four domains after informed consent was verbally provided by each respondent including: a) respondent and household demographics; b) well-being perceptions,

household and farm assets owned including land ownership status; c) agriculture practices; and d) irrigation practices[7].

The main survey instrument was structured interviews of members of Water User Associations based on a pre-defined set of questions. In consultation with officials from the WRD, for the analysis carried out in Chapter 6, I determined the target sample size of the survey by following a multistage clustering procedure, followed by a random, stratified sampling approach from the clustered group (Fowler 2002). The first cluster was determined by selecting MPWSRP irrigation projects where irrigation rehabilitation works were completed for at least three years. This ensured that WUA members would have access to rehabilitated irrigation infrastructure for at least three years. This reduced the original population size from 228 projects to 38 projects across 10 districts as illustrated in the tables in Chapters 5 and 6.

Once the 38 projects were identified, then the stratified sampling of households was randomly determined from this sub-group. The sample of 38 projects comprised of 1 major, 4 medium, and 33 minor irrigation projects. This represented a ratio of 1:4:33; whereby major projects are defined as projects with a Cumulative Command Area (CCA) of more than 10,000 ha, medium projects have a CCA between 2000 to 10,000 ha, and minor projects have a CCA less than 2000 ha. Out of the 38 projects, a sub-set of 27 projects were selected at random. This sample consisted of 1 major, 3 medium, and 23 minor projects. The sole major project was an automatic sample, as there was only one data point of its kind. The medium and minor projects were chosen at random. For the sample of irrigation schemes from districts with no investment from MPWSRP, a similar approach was used to determine the sample size for the No Rehab districts. This resulted in a sample size of 15 irrigation projects across 5 districts from the original population size of 10 districts.

The second stage of stratification from the number of projects was the number of WUAs to be surveyed within the selected irrigation projects in the selected samples.

[7] The 2015 survey questionnaires are included in Appendix 2 and 3.

Amongst the category of districts that received investments from MPWSRP, a total of 51 WUAs across the 27 projects were registered with the authorities of the Water Resources Department and 14 WUAs were registered across the 15 irrigation projects in the No Rehab category. Once again, a randomised sample of 34 WUAs was selected to be surveyed from the Rehab areas and 12 WUAs for the No Rehab areas. The third stage stratification was to determine the number of individual farmers to be surveyed from the sample size of WUAs. A random stratified sample size of 408 farmers, which was increased to 485 farmers to buffer post-survey data cleaning, were selected. A similar process was followed for the No Rehab districts, which was stratified from 15 irrigation projects to 12 WUAs and then down to 372 households, with a final sample size of 433 respondents with a similar buffer. Thus, in the first household survey, a total of 918 farmers were surveyed. The full sample size of 918 farmers is used to build the logit regression model in Chapter 6. In Chapter 5, to determine changes in well-being among farmers, the sampling approach utilised resulted in a smaller sample size of 707 farmers across five districts from the Rehab and No Rehab categories due to the specifications of the logistic regression model. The methodology used for selecting the sample farmers is described in detail in Chapter 5.

Overall, individual farmers selected across the sample of survey respondents for each district included an equal ratio of the head, middle, and tail-end farmers in the canal systems. In the design of the survey sampling, I attempted to target both male and female respondents, however, the majority of the WUA members in Madhya Pradesh are male as legal statues of WUA membership require farmers to own land. Lastly, districts from each of the three rainfall zones were selected to ensure all three rainfall zones are covered in the sampling. Summary tables in Chapters 5 and 6 provide evidence of the stratified samples across irrigation investment categories (Rehab vs. No Rehab), size of irrigation schemes, number of WUAs, number of households targeted for the analysis specific to the econometric model of each chapter. Lastly, questions posed in the survey were based on recall of households' status in the present (at the time of the survey) and in the past (in 2005) at the start of the MPWSRP. Both groups of households were posed each question twice to differentiate the status quo for the farmer in the current scenario (post-MPWSRP rehabilitation works) as well as in the past scenario (prior to rehabilitation works or in

2005, at the start of the MPWSRP). Due to the lack of baseline data on farming households at the start of the MPWSRP, questionnaires had to be designed based on present scenarios as well as recall of the past to enable *before* and *after* comparisons in the empirical analyses. Analysis of the household survey results with respect to queries posed on well-being and related indicators are presented in Chapter 5. Results of the household survey with respect to farmer irrigation practices and technology adoption choices as well as other related indicators are presented in Chapter 6.

3.2.3.2 Semi-structured telephone interviews

Following the 2015-16 survey, in order to delve deeper into the research question for Chapter 6, a follow-up set of semi-structured telephone interviews were conducted with a sub-set of farmers from the wider sample of 918 farmers. I conducted telephone interviews with 80 farmers, out of which 26 interviews were successfully recorded across nine districts and 19 villages in late 2018. The purpose of the survey was to further investigate farmer preferences for sprinkler or drip adoption by posing questions related to a) major factors that contribute to their decisions to adopt or not adopt sprinkler or drip technologies (e.g., hydrological, infrastructure, income, community and social norms, legal, and personal reputation factors, etc.); b) determine whether they have knowledge and awareness of farming techniques of other farmers including which farmers are using sprinkler or drip systems in their village; and, c) determine the degree to which farmer's share information about farming techniques/irrigation methods with others in their community or social circle[8].

The survey stratified sampling by geographic sublocation (e.g., sampling farmers from districts that received MWPSRP investments as well as districts that have canal irrigation systems but did not receive MPWSRP investment). Building on the larger household survey of 918 farmers conducted in 2015-2016, a total of 80 farmers were selected at random to participate in the telephone interviews (49 farmers out of the 918 who replied "yes" and 31 farmers who replied "no" to using sprinkler or drip technologies

[8] The 2018 survey questionnaire is included in Appendix 4.

from the original survey results). Out of the 80 farmers targeted, 26 surveys were successfully completed. Out of the 26 completed surveys, 18 came from districts where irrigation systems were modernised under MPWSRP and eight farmers were from districts with no investments. Figures 3-5 below illustrate evidence of 1 respondent who shared photographic evidence with me on the use of sprinklers and drip systems on his farm.

Figure 3. Photo of farmer plot showing evidence of sprinkler technologies used on the farm (Photo credit: farmer)[9]

[9] Personal photos shared by 1 interviewee farmer of the evidence of how he was applying sprinkler systems on his farm. Permission to disseminate photo obtained from farmer.

Figure 4. Photo of farm plot showing evidence of drip irrigation systems used to grow tomatoes and onions (Photo credit: farmer)

Figure 5. Farmer holding up sprinkler irrigation equipment on his farm (Photo credit: farmer)

I conducted individual interviews with each farmer by telephone in Hindi. All farmers interviewed were male with farm plots ranging from 0.5 hectares to 16 ha. Summary of the districts and villages from which farmers were surveyed, names of irrigation projects, and whether they were rehabilitated by MPWSRP, the size of their farm plots are provided in Chapter 6. I explicitly provided information on the background and academic interests of the questionnaire for research purposes and observed all ethical standards in order to avoid priming interviewees to suggest any possible connection with the Madhya Pradesh government or from a sprinkler or drip supplier or third-party seller. The results of these interviews provided additional qualitative insights into farmer preferences around sprinkler or drip adoption, their community and village norms and practices, their personal experiences accessing the financial subsidies for sprinkler or drip equipment from the government, and to explore whether social learning from other farmers or personal networks influences farmer choices for irrigation methods or types of crops grown. These insights enhanced the quantitative analysis of the main household survey results in Chapter 6. The results of the telephone interview analysis are presented in Chapter 6.

3.2.3.3 Ethics, roles and responsibilities of data collection

This research was conceptualised based on prior engagement in the MPWSRP as a member of the World Bank implementation support team from 2010-2014. Thus, I developed the methodological strategy for the study by building on my past work experience in supervising the implementation of the MPWSRP as well as my technical background knowledge of the water and irrigation sector in Madhya Pradesh. However, the design of the research methods, the data collection, and the survey design were developed in close collaboration with the senior Government of Madhya Pradesh officials and with close supervision from my supervisors. Based on my previous history of working closely with senior government officials in the Government of Madhya Pradesh, such as the Principal Secretary of the Water Resources Department, the project director for the MPWSRP, the Engineer-in-Chief of the WRD, and the lead irrigation specialist from the World Bank, I was able to gain access to data, obtain consensus and approvals for data collection, and

also ensure buy-in from key government counterparts for the outcomes of the research. At every step of the research process for this study, the state government provided concrete and invaluable support throughout the primary household and secondary data collection, the survey design, training, execution, data compilation, and data entry. It is important to note that the government staff I engaged with remained neutral observers to the research design and methodological development of the surveys, econometric approaches, and results development. The government aimed to facilitate the data collection and did not at any point influence my methodological approach or attempt to direct decisions on how to carry out the research.

The main household survey in 2015-16 was funded by the generous financial support of the Madhya Pradesh Water Resources Department. Funding was provided to the MP Water and Land Management Institute (WALMI), which was responsible for conducting the survey, with whom I had worked closely with for several years during my time at the World Bank. In order to execute the household survey, a strict code of ethics was followed in alignment with the University of Oxford Central University Research Ethics Committee requirements[10]. As the survey interviewed adult male and female farmers above the age of 18, the CUREC checklist was filled and approved by the Ethics Committee prior to the commencement of fieldwork in MP. In addition, prior to the start of the household surveys, I led a one-day enumerator training in Bhopal in November 2015 in partnership with WALMI and WRD officials, to prime the enumerators from WALMI on the objectives, approach, and questions related to the survey. For the semi-structured telephone interviews, I obtained oral consent from each of the farmers prior to commencing the interview. During the telephone interviews, I disclosed that I was asking follow-up questions from an original set of questions that were posed to them in 2015, and I explained the rationale for the research as well as described the purpose of the research. These steps are considered a core part of the ethical considerations for this doctoral project.

During the training of enumerators, I stressed the need to respect the ethics code of conduct and I focused a training session for enumerators on respectful behaviour towards

[10] The survey participant oral consent form is provided in Appendix 5

respondents during the execution of the survey. Secondly, it was agreed that enumerators would not require respondents to sign consent forms directly to be sensitive to illiterate participants in the survey as well as understanding the context that when farmers in rural parts of India “sign” forms in official surveys they can misunderstand the nature of the survey. Thus, this raises expectations from respondents to receive benefits from government authorities for answered questions. Therefore, oral consent was obtained from each of the farmer respondents prior to the start of the survey in 2015 both for the pilot survey and the final survey. A formal process of obtaining oral permission from respondents for consent to participate in the survey, as well as permission for taking direct quotes from participants, was initiated during the implementation of the survey. Table 1 below summarises my roles and responsibilities during the surveys.

Table 1. Roles and responsibilities for data collection during surveys

Data collection	Timeframe	My roles and responsibilities
2015-16 WUA household survey		
WUA farmer survey across 15 districts	August 2015 – January 2016	• Designed initial survey questionnaire with supervision from supervisor Professor Robert Hope (RH) • Designed survey sampling strategy in consultation with MPWRD and WALMI officials • Conducted a pilot survey with support from WRD officials • Refined survey questionnaire based on feedback from pilot survey responses • Led training of WALMI enumerators for final survey completion • Close supervision of enumerator team while the survey was conducted • Cleaned and coded data once the final raw database received from WALMI in Hindi and English for analysis in the econometric models
Semi-structured telephone interviews with farmers		
Semi-structured telephone interviews	August 2018	• Designed interview questionnaires with supervision from RH • Conducted 80 interviews • Transcribed, cleaned, and developed response database stemming from 26 successful interviewee responses

Following publication of the first research paper presented in Chapter 4, I designed and executed a one-day technical workshop and public lecture at Somerville College in October 2018, where the Principal Secretary of the WRD, the former project manager of the MPWSRP, the Indian High Commission, the World Bank, and senior academics from the School of Geography attended. The purpose of the workshop was to present research findings emerging from the results in Chapters 4-6 as well as validate the outputs of the research with key decision-makers from the World Bank, MP, and Indian government. Secondly, I designed the workshop to ensure that senior Oxford academics, World Bank officials and government policymakers have an opportunity to engage together on the research, to determine whether the findings are relevant for future infrastructure and policy-related decisions in the state, which are further discussed in the conclusions in Chapter 7.

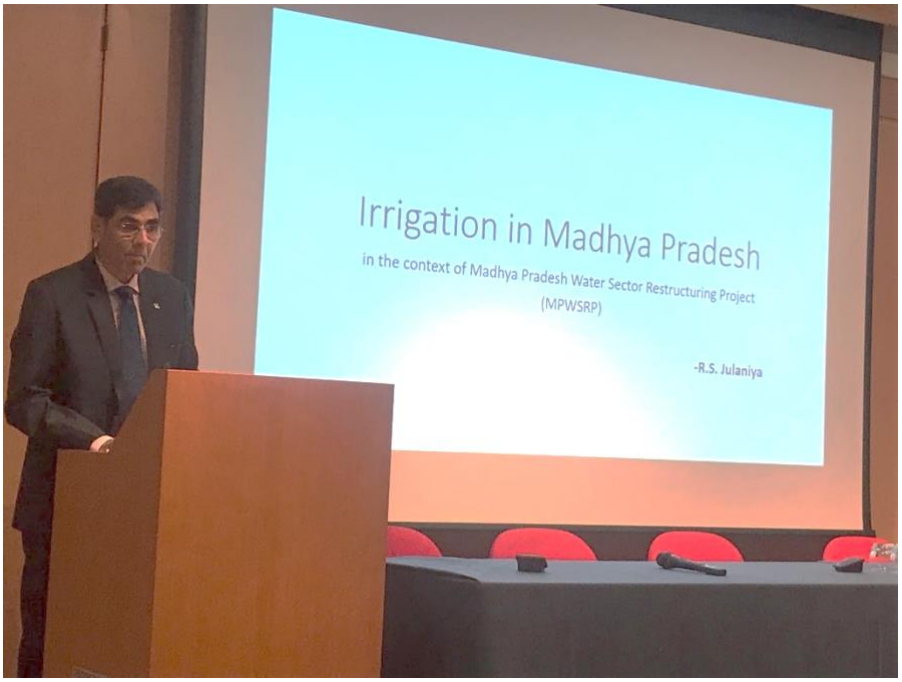


Figure 6. Former Principal Secretary of MP Water Resources Department, R.S. Julaniya, speaking at Somerville College during the public lecture in October 2018 (Photo: author)

Figure 7. A panel discussion led by author presenting research findings during public lecture facilitated by Dr Radhika Khosla, Smith School of Environment and Enterprise with panellists Principal Secretary R.S. Julaniya, Professors Robert Hope, Simon Dadson and Associate Professor Dustin Garrick (Photo: Sara Kalim, Oxford India Centre for Sustainable Development)

3.2.4 Other data sources

Other data sources were also incorporated into the methodological analysis including data on the general characteristics of each district of study including total population, rural and urban populations, average literacy rate, number of Scheduled Caste and number of cultivators for the last Census 2011 in India. This data was obtained from the District Census Handbook for Madhya Pradesh compiled by The Registrar General & Census Commissioner of India as part of the Ministry of Home Affairs, Government of India. Data on characteristics for the percentage of the rural population below the poverty line was compiled from the Madhya Pradesh State Planning Commission district-wise poverty estimates report for 2004-05. The main source of data for this study is the "Consumer Expenditure Surveys" undertaken by the National Sample Survey Organisation (NSSO).

District-wise per capita income at current prices from 2004-05 to 2012-2013 was obtained from the Open Government Data platform that compiles data from the Madhya Pradesh Economic Survey 2013-2014. Per capita income is the mean income of the people in the district. Per capita income is calculated based on a measure of all sources of income in the aggregate (such as GDP or Gross National Income) and then dividing it by the total population of that district[11].

Data on the gross and net irrigated area for each district was obtained from the Madhya Pradesh Commissioner Land Records Office in Gwalior district. This data provided the gross and net irrigated area by the source of irrigation such as canals, tanks, tube wells, wells, other sources. Total irrigated area in gross and net was also available for each district. Data was provided from 2006-07 to 2013-14. For the purposes of the analysis in Chapter 4, I used data only on the gross canal irrigated area for each of the 31 districts for the year 2006-07 and 2011-12 to coincide with the start of the MPWSRP as well as with the Census 2011 data.

3.3 Empirical modelling approaches

The crop yield and crop price data collection, rainfall anomaly analysis, and results of the surveys described above were collated into large datasets. These datasets were instrumental in enabling me to respond to the three core research questions related to understanding the overarching question of whether investments in irrigation modernisation enhance specific outcomes related to agricultural water security in Madhya Pradesh. The application of the data for the empirical analysis is described in detail in each of the empirical chapters in their respective methodology sections. Here I provide a brief overview.

Chapter 4: To determine whether investments in irrigation modernisation enhance crop yields once heterogeneity in district-level interannual and intra-annual rainfall and degree of investments is incorporated, a fixed-effects regression model is built to test the influence of irrigation investments on crop yields of paddy, wheat, and gram. The model draws on aggregated crop yield data for the three crops and compares variations in yield between

[11] Summary tables of the general characteristics of survey districts is provided in Chapters 4-6

intervention and non-intervention districts by controlling for the fluctuations in monsoon rainfall for all selected districts over a period of ten years. The model is unique as it utilises a novel dataset, specifically created for this analysis, which collates high-resolution data at a sub-national and sub-basin scale on crop yield responses to investments in irrigation rehabilitation while accounting for district-level monsoon rainfall as well as controls for the influence of crop-specific MSP policies on yields. A fixed-effects model was utilised as it enabled me to test the statistical relationship between the treatment (investments by MPWSRP in system modernisation), and outcome variables (crop yields), controlling for district-level rainfall variability, variations in MSP over time, and other district and time-related variations.

Chapter 5: To examine the influence of modernised irrigation systems on farmer well-being, this chapter draws upon data from 707 household survey results to build a logistic regression model with a dichotomous dependent variable representing subjective well-being. The model specification includes controls for exogenous variables such as district-specific rainfall patterns, district fixed effects, socio-economic indicators, and irrigation and agricultural management practices of farming households in areas with investment (treatment) and areas without investment (control). The unique dataset combines results of the interannual rainfall analysis in Chapter 4 with survey responses to queries related to well-being changes, among other characteristics in command areas where the MPWSRP made investments and in command areas with no investments. The results obtained demonstrate a more nuanced understanding of how investments in irrigation modernisation effect farmers' well-being, beyond the traditional income and expenditure outcome measures.

Chapter 6: I construct a logit regression model in order to analyse how irrigation modernisation programmes and financial incentive policies influence the irrigation practices of smallholder farmers in differing hydrological contexts. The model is based on results of the household survey data (n=918) and interviews (n=80) with farmers about their water use practices, main sources of irrigation for farming, and whether they use sprinkler and drip technologies for irrigation on their farms, among other factors of interest. The model is constructed based on the survey results from households with and without

access to rehabilitated canals, with varying socio-economic profiles, and across 10 districts. The findings of the study provide insights into how irrigation modernisation programmes and financial incentive policies influence the irrigation practices of smallholder farmers in differing hydrological contexts.

3.4 Limitations of the research

This section outlines the overall limitations of the thesis. Limitations of the empirical analysis are highlighted in each of the chapters (4-6). Beyond the limitations referred to in the Literature Review chapter, nine key limitations regarding research design, groundwater data collection gaps, spatial and temporal resolution of the rainfall analysis, intra-household dynamics between genders in farming households, institutional governance and political economy-related aspects are presented below.

First, as the focus of this thesis is on exploring the role of improved canal irrigation infrastructure in influencing specific agricultural, socio-economic, and behavioural outcomes in Madhya Pradesh, the thesis does not examine broader water security benefits from infrastructure investments with respect to drinking water, sanitation, ecosystems, energy, water quality, or environmental flows, among others which are out of the scope of this study. Next, aspects related to the impacts of infrastructure related to volumetric irrigation pricing, food and nutrition, land rights and water markets, and agronomic concerns related to farming techniques around soil management and other farm-level inputs such as fertilisers and pesticides are absent as these topics are covered extensively in the rich body of literature on India and in other developing countries. These factors, however, can and should be incorporated in future iterations of this work.

Second, as discussed in Chapter 2, quasi-experimental methods were preferable for the analysis conducted in this thesis. By the time this research project started in 2015, the MPWSRP had concluded all repair and construction works on specific irrigation systems in treatment districts. During implementation, I was exposed to details on how “treatment” projects were selected for investments by the MPWSRP. As detailed in Chapter 4, selection for treatment was randomly assigned based on two criteria: a) location (whether it was

located in one of the six intervention river basins) and b) whether the system was built before 1986 (and thus degraded past designed performance standards) (see Chapters 4 and 7 for a discussion on this). Based on this insight, the regression analyses within each of the three empirical chapters assumes that treatment (or the choice of which irrigation canal, tank, or system was upgraded by the MPWSRP) is randomly assigned, which partially reduces the risks of selection bias, which can occur in quasi-experimental studies. In addition, I considered, limited, and controlled for bias in data-set observations by conducting specific robustness checks to the models using various statistical techniques as well as grounding the quantitative analysis in a statistically sufficient sample size (see methods of Chapters 4-6 for a discussion on this). Despite these measures, the use of quasi-experimental, variable-based regression analysis methods signifies that causal conclusions cannot be drawn from the correlation results obtained from the empirical analyses in Chapters 4-6. However, as a novel, cross-sectional, time series, dataset of observations across multiple variables has been constructed, inferences can be generated from the statistically significant correlations, which signal underlying patterns or changes in the study area as a result of investments to rehabilitate and modernise irrigation infrastructure.

Third, due to data gaps, analysis of the influence of groundwater availability relative to surface water on the outcomes examined in the study is limited. Groundwater is a very important source of irrigation in India and its usage for farming is often influenced by the availability of surface irrigation. Despite data limitations, this thesis attempts to partially incorporate the role of groundwater use into the empirical investigation by a) comparing relative changes in aggregate crop yields over a period of ten years across multiple districts with and without access to modernised surface irrigation (Chapter 4); and, b) examining the relative changes in preferences of farmers for groundwater use versus canal irrigation in areas with and without modernised canal systems to understand how the improved availability of surface water influences reliance on groundwater sources of irrigation in the study area and the implications of this for drip and sprinkler use (Chapter 6). During the data collection phase for Chapter 4, I learned that the Madhya Pradesh Water Resources Department does not differentiate crop yield data from different sources of irrigation (rain-fed vs. groundwater vs. surface irrigated yields). This represents a

limitation of the findings presented in Chapter 4 as the fixed effects model was built on *aggregated* crop yield data at the district-scale, which could not be differentiated by source of water (rain-fed, groundwater, or surface sources). Not being able to differentiate crop yield data by source of water (groundwater or surface) implies that the results from Chapter 4 likely underestimate the effect of rehabilitated and modernised canals on crop yields (see Chapter 4 limitations for a discussion on this topic). Further analysis is also needed to build on the observations in Chapter 6, to analyse *why* farmers in the study area who were exposed to MPWSRP investments reduced their reliance on groundwater use after canals are upgraded (see Chapter 6 for a detailed discussion on this).

Next, I was not able to explore changes in the amount of groundwater abstraction on farms in Madhya Pradesh as data on water consumption by source of water, per crop, and for specific cropping seasons is not available at the farm-level in India (see Chapter 7 for a discussion on future avenues of research to address this limitation). Determining how much, how often, of what quality groundwater was utilised by farmers versus surface irrigation (before and after, with and without the MPWSRP investments) and how this influences farm-level access to water is an area of enquiry that could have shed further light on the role of upgraded surface irrigation on crop yields, well-being, and irrigation practices of farmers in comparison to the role of groundwater in influencing these outcomes. This limitation also presents a gap in the data collection processes of the Water Resources Department and the Madhya Pradesh Commissioner Land Records Office, offering an opportunity for reforms in the way public sector institutions in the Indian government collect and analyse state-wide crop yield data. In future studies, additional panel data can be collected on the changes in groundwater depths, seasonal drawdown for specific cropping seasons, geological aquifer properties, and farmer preferences for ground vs. surface sources in areas with modernised canals compared to areas without modernised canals over a longer period of time. These aspects related to groundwater usage patterns can be incorporated into research studies that aim to generate additional contextual analysis into the role of infrastructure investments in influencing outcomes stemming from agricultural water security interventions in rural India. However, as the primary data collection in this thesis was based on a cross-sectional household survey at a single point

in time, it was not possible to collect primary household data on changes in groundwater patterns. Trends related to the depletion of groundwater resources take place gradually and over a long period of time, thus, it was not possible to fully perceive the costs or the benefits of the MPWSRP investments on groundwater factors within the timeframe of this thesis. To assess the full range of the impacts of MPWSRP infrastructure investments related to 'slow-changing' variables such as groundwater depths in a holistic manner would involve intensive monitoring of multiple biophysical indicators on different spatial scales over longer periods of time, which was not feasible in the timeline of this doctoral research project.

The fourth limitation is the use of cross-sectional data to determine outcomes related to irrigation modernisation investments at the individual, farm, and district-scale. The lack of baseline data prior to the start of the MPWSRP in 2005 prevented longitudinal comparison between the group of farmers exposed to the MPWSRP and the group with no exposure to investments at the close of the project in 2015. As a result, the findings in the thesis, based on cross-sectional data provide insightful learning into individual farmer socio-economic characteristics, their well-being responses, their preferred choices for flood irrigation methods compared to their choices for sprinkler or drip technologies, among other factors, at a single point in time. However, the resulting observational dataset is not as rich as studies that have explored information on farmers before and after irrigation systems have been upgraded. As the data from the household surveys in the thesis on the "before and after" observations are largely based on recall of the past, the findings must be carefully interpreted as they may suffer from recall and selection biases in the results as explained in Chapter 2 Literature Review and the limitations of Chapters 5 and 6. To better understand the changes in irrigation practices of farmers over time as well as the environmental consequences of their water use choices, responses would be ideally analysed with panel data on the same set of farmers (Baltagi 2001; Nerlove 2002; Doss 2006). Others point out that cross-sectional analyses can only show short-term impacts, thus, they may underestimate the effects of the infrastructure over time (Munnell 1992; Fan and Zhang, 2004). Building a panel dataset was not feasible for this research project. However, this presents an opportunity for future studies that can generate panel data from

the dataset of household survey responses collected from 2015-2018 for this study (see the discussion on avenues for future research in Chapter 7).

Fifth, analysis of the behavioural outcomes with respect to farmer irrigation practices in Chapter 6 was limited due to data gaps on volumetric water use patterns. The survey results in Chapter 6 identified data gaps in terms of the quantity of water consumed per crop at the farm-level under flood irrigation methods compared to sprinkler or drip methods. During the data collection phase for this study, I learned that neither farmers nor WRD engineers in Madhya Pradesh are aware of the exact quantity of water used for crop irrigation at the farm-level. This posed methodological challenges in determining volumetric water savings, if any, from sprinkler or drip irrigation methods versus flood irrigation methods, except for inferences made from global literature on this topic (Venot, et al., 2017; Grafton et al., 2018). Thus, a more in-depth analysis of water consumption or water-use efficiency implications of a majority of farmers preferring to use flood irrigation methods compared with the small percentage of farmers using sprinkler and drip technologies in areas with rehabilitated irrigation systems in the study area could not be carried out. This data gap limited further understanding of the environmental and ecological consequences of improved access to surface irrigation and farmer irrigation practices. This presents an opportunity for further research building on the results presented in Chapter 6.

The sixth limitation of the thesis is related to the temporal and spatial resolution of the rainfall variability analysis. First, the interannual and intra-annual analysis focused on a ten-year time period, as the study design was anchored to the MPWSRP timeline (2005-2015). Studies that examine spatial variability and heterogeneity in Indian summer monsoon and annual rainfall patterns traditionally utilise rainfall data for a 50-year time period (or longer) in order to minimise potential temporal inconsistencies (Ghosh et al., 2009). Incorporating rainfall data for a longer time horizon for the climatological analysis including the standardised monsoon anomaly analysis would undoubtedly strengthen the results presented in Chapter 4 but was out of the scope of the study design. However, this presents an opportunity to build upon the approach taken and to incorporate longer time

series rainfall data in future research. Second, as the density of rain gauge stations in different districts across Madhya Pradesh (as well as across India) is not uniform, daily rainfall data is traditionally interpolated to a grid using a weighted sum based on the methodology developed by the Global Precipitation Climatology Project (Rajeevan et al., 2006). The use of interpolated daily rainfall data may result in potentially more robust monsoon rainfall trend analysis outcomes. This presents a limitation as the sampling and analysis of the daily data from the rain gauge stations could have been carried out with higher spatial precision. However, comparisons across multiple farms and districts were necessary for the study. Thus, I aggregated daily station data within each district to monthly, annual, and ten-year averages. This method, although resulted in a loss of precision, enabled ease of comparison across multiple layers of data related to districts and river basins, yields, crop prices, investments, socio-economic variables, and the ability to incorporate district-specific rainfall profiles as a control variable into the econometric models in Chapters 4-6.

Seventh, the selectivity of variables that are controlled for in the regression analyses represent a limitation of the econometric modelling results. Hussain and Hanjra (2004) point out that simultaneity and the concurrent nature of interventions and multiplicity of linkages pose methodological problems in assessing and separating impacts of irrigation interventions. For instance, multiple exogenous variables may simultaneously influence crop yields (in addition to hydrological factors) as well as farmer choices for specific crops and willingness to purchase sprinkler or drip equipment such as access to labour, access to markets for produce, quality of roads, pricing of crops, soil quality, land rights, and other input factors (e.g., seed quality, fertilisers used, pesticide types) which are excluded from the variables tested in the models. The modelling results represent a slice of the overall reality for farmers of Madhya Pradesh at a specific point in time, which can in future studies be enhanced by controlling for additional factors or conducting contextual analysis to generate CMO configurations using realist evaluation techniques, for instance. These can include areas of exploration such as a) number and type of extension services available to farmers related to crop and technology demonstrations and their influence on farmer crop and irrigation choices, b) availability of labour in local markets, c) the role of property

rights and entitlements, d) electoral and political factors related to the voting behaviours of the farming households, e) the impact of social networks in driving farmer irrigation and crop choices, and, f) the nature of how corruption in Indian canal irrigation and the power dynamics between farmers and engineers can influence the water security outcomes of irrigated infrastructure as has been explored in previous studies (Boahene et al., 1999; Ouma et al., 2002; Herath and Takeya, 2003; Mollinga 2016).

Eighth, the role of women in farming households and the intra-household dynamics between men and women and how this influences decision-making related to irrigation technology adoption, well-being, crop choices, and the consequential outcomes from rehabilitated infrastructure are absent from the thesis. The assumption that the WUA member farmer (typically male) who was surveyed is the sole and only decision-maker of the household represents a limitation. Even though I include a variable for being female in the econometric approach in Chapter 5, studies have found that gender can affect whether farmers adopt specific agricultural practices. Doss and Morris (2001) who explore whether gender influences the adoption of improved types of maize crops in Ghana found that male and female farmers made the same adoption decisions if they were in male-headed households. However, farmers in female-headed households were less likely to adopt improved varieties (Doss and Morris, 2001). Udry (1996) found that households in Burkina Faso were less likely to use fertilizer on women's plots than on men's plots, and that total household production could be increased by reallocating fertilizer from men's plots to women's plots. In addition, the thesis does not explore the role of female farmers in WUAs in Madhya Pradesh. It is important to determine whether gender influences specific outcomes related to canal irrigation investments in WUAs with female members compared to WUAs that have only male farmers (Girard 2014). This also raises important issues of equity and inclusion of women in farming communities where surface irrigated systems are upgraded and how these aspects influence water security outcomes of infrastructure investments, which were not considered. This is an area of further exploration that should be incorporated in future studies.

The ninth limitation of the thesis is related to policy, governance, and institutional factors. Although, the investigation in the thesis is focused on disentangling the role of infrastructure in influencing to specific water security outcomes related to changes in crop yields, well-being, and irrigation practices, the role of institutions and policy factors is partially and indirectly embedded into the general analytical framework (Chapter 2, Figure 1). In order to generate insights into the complex, multiscale, and contextual nature of the relationship between infrastructure and outcomes related to water security, the study approach incorporates institutional and policy factors by a) surveying individual farmers who are members of farmer-led institutions such as Water User Associations, b) examining the impacts of rehabilitation interventions, which are primarily undertaken by the Madhya Pradesh Water Resources Department, the central public sector institution in the state responsible for irrigation and drainage works, c) exploring the relationship with food security, water sector, and rural development policy and governance instruments by exploring how national and state government policies such as the Minimum Support Price, Kisan credit cards, BPL cards, and subsidy policies for promoting sprinkler and drip irrigation technologies which are implemented by specific Government of Madhya Pradesh public sector agencies (e.g. Agriculture and Horticulture Departments) influence outcomes in the study area and d) incorporating contextual factors of the socio-economic characteristics of caste, household asset ownership, and diverse agricultural techniques adopted by farmers incorporated as variables of interest into the econometric models in Chapters 5 and 6.

Despite the fact that these contextual institutional and policy factors are incorporated as variables for analysis into the study, these are not representative of the plethora of institutional governance, political economy arrangements, and rural politics at play at the village, district, state, and national levels in India. As the analysis is centred on agricultural, socio-economic poverty, and behavioural outcomes, the thesis does not incorporate all of the potential policy, institutional, and political dynamics that influence the governance of water and agriculture systems at a national, state, or village scale in India (Wade 1975, 1982, 1988a, 1988b). However, this thesis presents a framework for analysis that can be expanded in future studies by incorporating additional governance and political

economy dimensions into the preliminary exploration conducted in this body of work. The investigation also does not delve into additional institutional factors related to testing WUA performance and the effectiveness of WUAs in Madhya Pradesh, for instance, or interviewing farmers who are not members of WUAs (Mollinga 2000, Mollinga 2003), as the analysis centred on responses among individual farmers (within collective institutions) rather than focusing on the performance of collective institutions. Thus, the findings of this doctoral research pave the way for future longitudinal, institutional, governance, and political economy studies of irrigation systems in Madhya Pradesh. This work offers initial insights into the consequences of rehabilitating and modernising irrigation infrastructure on a set of interdisciplinary factors related to crop yields, well-being, and irrigation practices at multiple scales that open new windows of enquiry to understand the complex nature of how infrastructure-led interventions to enhance agricultural water security influence district and farm-scale dynamics in rural India.

4. Understanding the effectiveness of investments in irrigation system modernization: evidence from Madhya Pradesh, India

"In India, one has to plan according to the monsoons."

Roland Joffe

Chapter 4

Understanding the effectiveness of investments in irrigation system modernization: evidence from Madhya Pradesh, India

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Note:

This chapter is presented as published. To improve the layout, some tables and figures have been modified as compared to the published article.

Abstract

Investments in modernising irrigation infrastructure are key to enhance water security for agriculture. However, outcomes of investments are insufficiently understood, potentially limiting the future design of interventions. This article applies a fixed-effects regression model to test whether modernisation of irrigation systems in Madhya Pradesh leads to improvements in district-level yields and protection of yields against sub-basin rainfall variability. Findings suggest that investments fail to improve yields in districts with deficient rainfall and fail to buffer yields against monsoon variability compared to control districts with no investments. Interventions should be designed to respond to the complexities of sub-basin rainfall variability.

Keywords: Water security; India; irrigation modernisation; rainfall variability; food security.

4.1 Introduction

Global debates on water security suggest that countries facing water resource challenges should invest in physical infrastructure as well as institutions for water management to reduce water-related risks (Grey & Sadoff, 2007; Grey et al., 2013; Sadoff et al., 2015). For water-insecure developing countries, investing in water-related infrastructure in the agriculture sector is expected to increase economic growth and protect against shocks from rainfall variability. India has invested in irrigation infrastructure to reduce the vulnerability of the agricultural sector to hydrological variability (Dhawan, 1993; Duflo & Pande, 2007; Shah & Kumar, 2008; World Bank, 2002b). Multiple state governments in India have focused on public investment in construction, modernization, and rehabilitation of major and medium-sized irrigation projects (Biswas-Tortajada, 2014; Thatte, 2017). Areas with investment in surface irrigation have seen higher yields, changed cropping patterns, larger gross cropped area, and transition from a mono-crop regime to double-cropping, in comparison to areas wholly dependent on rainfed agriculture (Jagdeeshan and Kumar, 2015; Kumar, Jagadeesan, & Sivamohan, 2014; Institute of Applied Manpower Research, Planning Commission of India, 2011).

Despite the extensive literature on the effectiveness of irrigation in developing countries, there is little evidence on the relationship between district-level rainfall variability, investments in the modernisation of irrigation infrastructure, and impacts on crop yields (Wade 1988a; Thakkar 1999; Mosse 2006; Hope 2007; Mollinga 2014). Specifically, it is unclear (a) how rainfall patterns vary at a sub-basin level (e.g. district to district); (b) how surface irrigation investments impact crop yields at the district scale; and (c) whether irrigation investments can buffer yields from district-level rainfall variability. To answer these questions, this article explores whether investments in system modernization are effective once heterogeneity in sub-basin rainfall and degree of investment are analyzed against changes in crop yields. We built a fixed effects regression model to test the influence of irrigation investments on district-level crop yields of three staple crops (paddy, wheat, and gram) in the Indian state of Madhya Pradesh (MP). The model is based on investments in modernisation and rehabilitation of irrigation systems by

the Madhya Pradesh Water Sector Restructuring Project (MPWSRP), funded by the World Bank (World Bank 2005; Table 2).

The MPWSRP was initiated in 2005 by the government of MP in order to improve the productivity of water for sustainable growth, and poverty reduction across 31 districts in selected river basins of Madhya Pradesh (World Bank 2005; Sapre 2014). The economy of MP is predominantly agrarian, with agriculture, animal husbandry, and fisheries as the primary sectors of the state. However, there have been large-scale fluctuations in the agriculture sector's performance in recent years, with growth rates from −2.44% (2007–08) to more than 11.18% (2010–11) (Sapre 2014). By targeting investments in the water and agriculture sector in 2005, the state government aimed to address the development objectives of income and employment generation for farmers, poverty alleviation, and agricultural growth (Government of Madhya Pradesh, 2011).

The rationale for investments in irrigation system rehabilitation was based on a hydrological basin approach (World Bank 2005). The MP government aimed to shift the focus of its Water Resources Department (WRD) towards integrated river basin management (World Bank, 2005). MP has 10 river systems (Mahi, Chambal, Sindh, Betwa, Ken, Tons, Son, Narmada, Wainganga and Tapi; see Figure 8). Irrigation systems were rehabilitated in 6 out of the 10 river basins (Chambal, Sindh, Betwa, Ken, Tons and Wainganga). The secondary justification was to address the engineering needs of the systems. Systems that were 20 years or older, which had not been adequately maintained by the WRD and were no longer operating at optimal standards, received investments.

To analyze the impact of the infrastructure investments made in the MPWSRP, we tested this hypothesis:

> Investments in irrigation infrastructure modernization lead to higher crop yields and buffer yields from fluctuations in rainfall at the district level.

Table 2. Summary of data on Madhya Pradesh Water Sector Restructuring Project investments and district-wise irrigation investment categories

No.	District Name	River Basin	MPWSRP Investment?	Number of irrigation schemes rehabilitated	Total irrigated area of surface & groundwater (ha)	Total command area of systems rehabilitated (ha)	% irrigated area rehabilitated by MPWSRP	Irrigation Investment Category	Investments under MPWSRP (USD millions)	Investments (USD/ha)
1	Ashoknagar	Betwa	Yes	17	196,341	14,106	7	Low	3.56	252
2	Balaghat	Wainganga	Yes	1	143,254	43,136	30	Medium-High	18.57	430
3	Bhopal	Betwa	Partial	8	107,412	3166	3	Low	2.19	692
4	Bhind	Sindh	Yes	1	206,218	84,955	41	Medium-High	45.22	532
5	Chhatarpur	Ken	Yes	1	279,145	4170	1	Low	2.12	508
6	Damoh	Ken	Yes	6	203,069	5928	3	Low	2.93	494
7	Datia	Sindh	None	N/A	191,034	N/A	0	N/A	N/A	N/A
8	Dewas	Chambal	Yes	15	304,605	1987	1	Low	0.99	498
9	Dhar	Chambal	Yes	3	394,539	161	0	Low	0.1	621
10	Guna	Chambal, Sindh	Yes	5	232,357	1768	1	Low	0.67	379
11	Gwalior	Sindh	Partial	6	139,695	75,035	54	Medium-High	37.61	501
12	Indore	Chambal	None	N/A	212,165	N/A	0	N/A	N/A	N/A
13	Katni	Ken	Yes	11	128,700	2399	2	Low	2.91	1213
14	Mandsaur	Chambal	Yes	5	254,982	962	0	Low	0.36	374
15	Morena	Chambal, Sindh	Yes	3	212,561	212,561	100	Medium-High	125.86	592
16	Neemuch	Chambal	Partial	2	127,848	4989	4	Low	1	200
17	Panna	Ken	None	N/A	121,814	N/A	0	N/A	N/A	0
18	Raisen	Betwa	Yes	9	431,709	9752	2	Low	3.45	354
19	Rajgarh	Chambal	Yes	17	343,861	4050	1	Low	1.86	459
20	Ratlam	Chambal	None	N/A	206,692	N/A	0	N/A	N/A	0

21	Rewa	Tons	Yes	8	117,450	11,643	10	Low	3.76	323
22	Sagar	Ken	Yes	6	367,574	24,221	7	Low	9.79	404
23	Satna	Tons	Yes	25	165,729	13,303	8	Low	2.38	179
24	Sehore	Chambal	Yes	8	328,315	4545	1	Low	1.38	304
25	Seoni	Wainganga	None	N/A	202,758	N/A	0	N/A	N/A	0
26	Shajapur	Chambal	Yes	11	196,040	4834	2	Low	1.99	412
27	Sheopur	Chambal, Sindh	Yes	3	142,592	75,825	53	Medium-High	45.24	597
28	Shivpuri	Sindh	Yes	1	302,306	2614	1	Low	0.72	275
29	Tikamgarh	Betwa	Yes	23	223,049	2114	1	Low	0.81	383
30	Ujjain	Chambal	Partial	22	347,571	6994	2	Low	2.37	339
31	Vidisha	Betwa	Partial	12	412,572	35,716	9	Low	8.56	240
	Total (average)			228	7,243,957	650,934	11		12.55	398

Note: Data in Columns 6 and 7 are from India Agristat 2014–15, www.indiaagristat.com. Data in Columns 1–5 and 8–11 are derived from monitoring data collected by the Water Resources Department, Government of Madhya Pradesh, for the MPWSRP based on personal communication; not available in public data-sets. The values in the last row in columns 5, 6 and 7 are summed values. The values in the last row in columns 8, 10, and 11 are averages of all the values in the column.

We tested this hypothesis by analyzing the impact of investments in irrigation rehabilitation on crop yields across 31 districts, with and without investments, using a fixed-effects regression model. Data on aggregated gram, paddy and wheat yields were assessed to compare variations in yield between intervention and non-intervention districts as well as differing rainfall variability. Yield is an impact indicator of irrigation investment because, among the multiple factors contributing to crop yield, access to adequate irrigation is one of the key determinants (Damania et al., 2017; Minten & Barrett, 2008). Therefore, improving irrigation system performance by means of investments to rehabilitate aging infrastructure is a critical production factor that can help lift the hydrological constraints on agricultural productivity (Ostrom, Lam, Pradhan, & Shivakoti, 2011). Studies have found that crops typically show the greatest yield increases when cultivation shifts from rainfed to surface irrigation in semi-arid regions (Elliott et al., 2014; Rockstrom, Wani, Hatibu, & Qiang, 2010). Paddy and wheat were selected because of all the cereal crops grown in MP, 80% of the cultivated land area is dedicated to these crops (Government of Madhya Pradesh Economic Survey, 2014). And, of the pulses, about 60% of the cultivable area is dedicated to gram production (Planning, Economics and Statistics Department, 2014). To examine fluctuations in rainfall at the district level, we analyzed data on rainfall patterns from 2005 to 2014 for all selected districts and determined standardized anomaly patterns for each district's monsoons over the last 10 years.

This study, therefore, is not only relevant for MP but contributes to the wider literature on irrigation modernisation impacts, rainfall variability and economic outcomes in India, as well as other populous, water-stressed countries. Studies that examine the challenges of economic growth and rainfall variability or analyse the role of investments in water-related infrastructure and water institutions tend to use national, regional and global data-sets to make assertions at regional and country levels (Brown & Lall, 2006; Duflo & Pande, 2007; Falkenmark 1997; Narayanamoorthy, 2018; Sadoff et al., 2015). These studies often overlook post-investment impacts on crop yields and the role of sub-basin variability on crop yields at a sub-national scale, as data at this scale are typically not available. In addition, studies that explore the importance of intra-annual precipitation variability on crop yields rarely examine more than two years of intra-annual data in one

location, and often do not incorporate the combination of infrastructure and crop price effects (Damania et al., 2017; Fishman 2016; Verón, De Abelleyra, & Lobell, 2015). This article attempts to address these gaps in the wider literature by conducting a detailed analysis of crop yield responses to investments in irrigation rehabilitation while accounting for inter- and intra-annual district-level monsoon anomalies as well as examining the influence of crop price factors on yields over a period of 10 years. This new dataset, which collates high-resolution data at sub-national and sub-basin scales, was specifically created for this study and represents one of the unique contributions of this article. Unlike a majority of the economic analysis studies in the water and agriculture sector, which use publicly available, national-level, datasets to determine outcomes, this article was able to use data at the district and sub-basin scales that are typically not available to researchers.

The next section describes the methodology, and the section after that describes the results. We then discuss the results and their limitations; the last section presents conclusions.

4.2 Methods and data analysis

4.2.1 Characteristics of the study area

MP is the third-largest state in India, with a total geographical area of about 40 million hectares (ha). The state has a population of 72 million per the 2011 census, with an estimated 36% of the rural population living below the poverty line. The economy is dominated by agriculture, which accounts for 26.5% of the net state domestic product (Planning, Economics & Statistics Department, 2011). The agricultural sector employs 73% of the working population (Sapre 2014).

MP has 10 agro-climatic zones and five main crop zones (De, Singh, & Chandra, 2001) (Table 3). The state also has five regions, with 52,143 villages, 23,044 panchayats (village councils) and 323 development blocks in 51 districts. Districts in India are local administrative units that form the tier of local government just below the Indian state. The analysis in this study focuses on 31 districts in the six river basins where the MPWSRP made interventions (Figure 8). We collected and analyzed data at the district scale rather than river basin scale to identify variations in impacts across different districts within a river basin. Basin-level analysis alone tends to mask heterogeneity in rainfall patterns among districts within a state.

Annual rainfall in MP ranges from 800 mm to 1600 mm from west to east, occurring mainly during the summer monsoon (June to September) (Planning, Economics and Statistics Department, 2011). Historical analysis of rainfall variability indicates that the summer monsoon in central India changed significantly between 1950 and 2000 (Sushant, 2013). The frequency of days with heavy rainfall (100 mm/day) increased from 45 to 65 per year, while the frequency of extreme rainfall events (150 mm/day) doubled, from 9 to 18 days per year, during this period (Sushant, 2013). In contrast, the frequency of days with moderate rainfall (5–100 mm/day) has decreased. The higher frequency of extreme events and erratic rainfall, along with fewer moderate-rainfall days, indicates that MP is facing high hydroclimatic variability. At present, 60% of the total net sown (cropped) area in MP is served by surface and groundwater sources of irrigation, and 40% of the cropped area is rainfed.

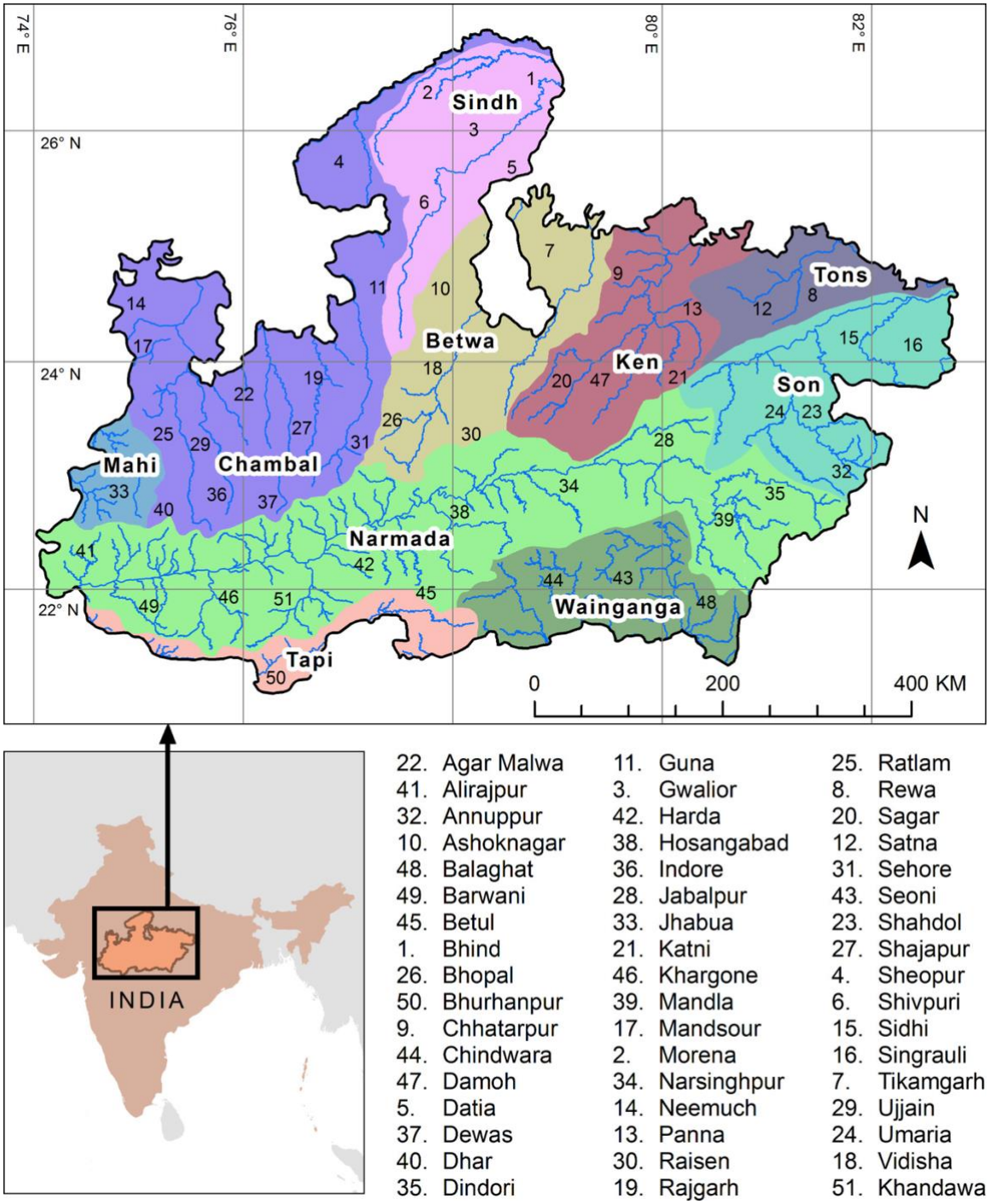

Figure 8. River basins and districts of Madhya Pradesh, India

Table 3. District-wise 10-year annual average rainfall, rainfall zones, investment categorization, and agro-climatic zone

No.	Name of District	Number of Rain Gauge Stations	Average Annual Rainfall Value 2005-2014 (mm)	Rainfall Category (Low, Average, High)	Investment Category	Agro-climatic & Crop Zone
1	Ashoknagar	4	960	Average	Low Rehab	Grid region (wheat, jowar zone)
2	Balaghat	24	1332	High	Medium-High Rehab	Chhatisgarh plains (rice zone)
3	Bhopal	2	1119	High	Partial Low Rehab	Vindhya plateau (wheat zone)
4	Bhind	4	685	Low	Medium-High Rehab	Grid region (wheat, jowar zone)
5	Chhatarpur	10	902	Average	Low Rehab	Bundelkhand (wheat-jowar zone)
6	Damoh	7	1152	High	Low Rehab	Vindhya plateau (wheat zone)
7	Datia	3	742	Low	No Rehab	Bundelkhand (wheat-jowar zone)
8	Dewas	7	919	Average	Low Rehab	Malwa plateau (Cotton, jowar zone)
9	Dhar	13	859	Low	Low Rehab	Malwa plateau (Cotton, jowar zone)
10	Guna	5	1024	Average	Low Rehab	Vindhya plateau (wheat zone)
11	Gwalior	8	725	Low	Partial Medium-High Rehab	Grid region (wheat, jowar zone)
12	Indore	5	993	Average	No Rehab	Malwa plateau (Cotton, jowar zone)
13	Katni	2	922	Average	Low Rehab	Kymore plateau & Satpura hills (wheat, rice zone)
14	Mandsaur	6	896	Average	Low Rehab	Malwa plateau (Cotton, jowar zone)
15	Morena	6	688	Low	Medium-High Rehab	Grid region (wheat, jowar zone)
16	Neemuch	3	897	Average	Partial Low Rehab	Malwa plateau (Cotton, jowar zone)
17	Panna	5	932	Average	No Rehab	Kymore plateau & Satpura hills (wheat, rice zone)
18	Raisen	8	1111	High	Low Rehab	Vindhya plateau (wheat zone)
19	Rajgarh	6	1019	Average	Low Rehab	Malwa plateau (Cotton, jowar zone)

20	Ratlam	8	983	Average	No Rehab	Malwa plateau (Cotton, jowar zone)
21	Rewa	7	963	Average	Low Rehab	Kymore plateau & Satpura hills (wheat, rice zone)
22	Sagar	12	1141	High	Low Rehab	Vindhya plateau (wheat zone)
23	Satna	11	942	Average	Low Rehab	Kymore plateau & Satpura hills (wheat, rice zone)
24	Sehore	5	1048	Average	Low Rehab	Vindhya plateau (wheat zone)
25	Seoni	18	1204	High	No Rehab	Kymore plateau & Satpura hills (wheat, rice zone)
26	Shajapur	7	950	Average	Low Rehab	Malwa plateau (Cotton, jowar zone)
27	Sheopur	2	706	Low	Medium-High Rehab	Grid region (wheat, jowar zone)
28	Shivpuri	8	826	Low	Low Rehab	Grid region (wheat, jowar zone)
29	Tikamgarh	7	822	Low	Low Rehab	Bundelkhand (wheat-jowar zone)
30	Ujjain	7	975	Average	Partial Low Rehab	Malwa plateau (Cotton, jowar zone)
31	Vidisha	7	1094	High	Partial Low Rehab	Vindhya plateau (wheat zone)
	Total (average)	227	942			

Note: Data derived from personal communication with the Water Resources Department, Government of Madhya Pradesh.
*The total value in the last row in column 3 is a summed value. The value in the last row in column 4 is an average of all the values in the column.

4.2.2 Madhya Pradesh Water Sector Restructuring Project

The MPWSRP focused on maximizing water productivity in all its uses in 495,000 ha of designed potential irrigation command areas in six basins, of which only half the area was served by canal irrigation when the project began (World Bank, 2005). Over half (61%) of the 193,000 farms in the project area are small farms with an average landholding size of less than one hectare. Therefore, most of the farmers in the study area are the poorest members of rural society in India, mainly coming from the most vulnerable caste groups, holding Below the Poverty Line cards, and living in temporary housing. The Food and Supplies Departments of state governments in India issue Below Poverty Line ration cards to individuals who are earning an income below the national poverty line of USD 1.90 per day. This card entitles individuals to subsidized allocations of rice and wheat from state government Public Distribution Schemes. The MPWSRP made a total investment of USD 440 million across four components, with the costs and objectives listed in Table 4. The analysis in this study will focus on Component C, as this component made investments in modernization and rehabilitation of irrigation canals and tanks.

Upon closure in 2015, the MPWSRP modernized and rehabilitated 5 major, 21 medium, and 202 minor irrigation schemes. A major irrigation system provides irrigation to more than 5000 ha of farmland; a medium system serves 2000–4999 ha; and minor systems can serve 200–1999 ha. A total of 228 investments in system modernization were made. This included activities such as repairing old canals by lining with concrete to reduce seepage and improve water distribution. These investments represent expenditure arising from the need to repair systems where the government had failed to maintain existing irrigation structures. The project aimed to improve cropping intensity, irrigation efficiency of the surface irrigation canals, and crop production for Kharif (summer) crops (e.g., paddy) and Rabi (winter) crops (e.g., wheat and gram) (World Bank, 2005).

Table 4. Component-wise description of the Madhya Pradesh Water Sector Restructuring Project (World Bank, 2005)

Component	Name	Cost (USD millions)	Description
A	Water Resources Management – Institutions and Instruments	7.27	To support the establishment and operationalization of the proposed planning, allocation and regulatory institutions, and instruments at the state and basin-levels.
B	Service Delivery – Irrigation and Drainage Institutions	38.35	To support measures related to delivering reliable irrigation services at rationalized cost by financially viable entities.
C	Improving the productivity of selected existing irrigation and drainage assets in six basins	388.09	To provide the necessary investments in six basins (Chambal, Sindh, Betwa, Ken, Tons, and Wainganga) for (i) reliable delivery of water on an appropriate volumetric basis in the irrigation systems of these basins to improve system performance, cost recovery and accountability of the service provider; (ii) an outcome-oriented approach with integrated sustainable agricultural intensification and diversification; and (iii) improved operation and management of the irrigation and drainage schemes.
D	Project Management Support	5.52	Project activities would be coordinated by a multi-disciplinary Project Implementation Coordination Unit (PICU).
Total		440	

The project focused on achieving these objectives by adding new capacity to manage risk as well as restoring lost productivity benefits of older systems.

4.2.3 Sampling framework

To compare crop yields and rainfall patterns between the 31 districts, we developed a sampling framework. The framework was built on secondary data on (a) the size, scale and timing of the irrigation investments by the MPWSRP in treatment districts, (b) interannual and intra-annual rainfall data for 31 districts for 2005–14; and (c) average crop yield data for the three main crops across 31 districts in the same timeframe. The selection of the 228 irrigation projects was based on systems that were built before 1986 and those that exceeded certain degradation thresholds of designed performance (World Bank 2005). Thus, some districts received more investment than others, and some received no investment.

4.2.4 Irrigation investment data

To analyse the 228 irrigation schemes, we obtained data on the total command area of the systems; the percentage of irrigated area rehabilitated in each district by the project; the total investment made by the project (in USD) in each district; the dollar amount invested per hectare in each district; and the start and completion year of each irrigation rehabilitation project in each district. This information is summarised in Table 2. For the sampling framework, we divided the 31 districts into two irrigation investment categories. Districts were classified as Rehab if they were rehabilitated by the MPWSRP and No Rehab if no MPWSRP investment was made in their command areas. Districts that received rehabilitation investments only in specific parts of their command areas and not in others fell into both categories (* in Table 4). Within the Rehab category, districts were further divided into two investment categories. Low Rehab represents districts that had less than 10% of their irrigated area rehabilitated by investments from the MPWSRP. Medium-High Rehab represents districts that had more than 30% of their irrigated area rehabilitated.

The data on district-wise crop yields used in this study represent average yields from a combination of rainfed, groundwater, and surface-irrigated sources. Therefore, the

yield values used for the analysis are a combination of these three irrigation sources, as MP government yield data do not differentiate yields by the source of irrigation. However, we can assume that there are variations in the irrigation sources used by farmers in different districts. The data collected on yields at the district level include farm plots in command areas for both Rehab and No Rehab districts. Therefore, we operate under the assumption that farmers in districts in the Medium-High Rehab category are more likely to irrigate their crops with surface irrigation rather than relying on rainfall and pump irrigation, relative to farmers in districts in the No Rehab category. We, therefore, assume that outputs of crops from Medium-High Rehab and to some extent Low Rehab districts are more likely to be from command areas with modernized, surface-irrigated sources. In comparison, crops in the No Rehab districts will most likely be irrigated with groundwater and/or rainfall due to the absence of reliable surface irrigation. It is important to note the arguments put forth by Shah and others that the different irrigation needs of farmers in South Asia are increasingly being met by groundwater sources rather than gravity flow from canals (Kumar & Singh, 2007; Kumar et al., 2011; Shah, 2009). Shah (2009) argues that the main factors behind the rapid decline in canal irrigation are the poor performance of surface irrigation systems throughout India, market failures, failure of participation of irrigating communities, and failure of public-sector agencies to deliver irrigation water to crops in the right quantity and at the right time. The work of Molle and Berkoff (2007) also indicates that when groundwater is available to farmers on demand, this offers 'security of supply' for reliable irrigation when rainfall and canal supplies are variable. The fact that groundwater is so readily available to farmers has reduced the need for surface irrigation to meet 'diversified demands' for water for different crops (Molle & Berkoff, 2007).

The MPWSRP, however, specifically aimed to address the concerns of Shah (2009) and others. The MPWSRP made investments in rehabilitation of specific deteriorated major, medium and minor tanks in command areas in target districts, with emphasis on desiltation, repairing of sluice gates, and also investing in building the capacity of water-user associations (WUAs), to increase the participation of farmers in field-level canal operation and maintenance. Palanisami, Meinzen-Dick, and Giordano (2010) argue that addressing these concerns would improve water supply in the tanks, improve storage

capacity, and assist farmers in coping with the impacts of climate change in the future. In addition, registering WUAs would enable member farmers to undertake regular repairs and maintenance, improving the usage of tank irrigation by WUAs themselves (Palanisami, 2000; Palanisami et. al 2010). Therefore, the fact that the MPWSRP targeted investments to improve canal systems enables us to assume that the overall supply of irrigation water improved, coinciding with increased usage of tank irrigation by beneficiary farmers in the respective command areas.

Lastly, the yields presented in this study are lower on average than yields from purely surface-irrigated sources. This is because our data include yield values that are not differentiated by the source of irrigation. At present secondary data on crop yields solely from groundwater or surface sources at the district and farm levels are not available in MP, so it was not possible for us to differentiate crop yield data from rainfed and groundwater irrigation versus gravity irrigation. Thus, the results of the empirical model can be interpreted as the treatment effect on crop yield based on a mix of irrigation sources. This suggests that our results are, if anything, underestimates of the treatment effect on yields from farms using surface irrigation.

4.2.5 Interannual rainfall data

Interannual variation in the monsoon cycle is determined by the relative contribution of multiple external and internal air-sea interactions and oscillations, with heavy or light rainfall resulting in floods or droughts (Neena, Suhas, & Goswami, 2011; Ratna, Sikka, Dalvi, & Ratnam, 2011). To analyse interannual variability in MP, we divided the 31 districts into three rainfall categories: low, average, and high (Table 5). This was to determine whether there was significant diversity in the interannual rainfall patterns among the Rehab and No Rehab districts and to identify how many of these 31 districts tend to have low, average, or high rainfall. Monthly rainfall data were provided for all districts for every month of 2005–14 by the MP WRD. Annual averages in 2005–14 were determined by averaging the 12 monthly rainfall values for all available rain gauge stations in each district. Once the monthly average for each year was calculated, we calculated the 10-year

average for that district and classified each district according to its corresponding rainfall zone.

If a district's 10-year average is within 10% of the 10-year average of all districts, it is classified as having Average Rainfall. The boundary for Average Rainfall is 869–1062 mm. If a district's average rainfall is more than 10% below the 10-year average of all districts, it is classified as Low Rainfall. The boundary is below 869 mm. If a district's 10-year average rainfall is more than 10% above the 10-year average of the selected districts, it is in the High Rainfall Zone.

Table 5. Sampling framework classification of 31 districts into irrigation investment categories and rainfall zones

		Interannual Rainfall Variability Zones		
Irrigation investment category by percentage of irrigated area rehabilitated	**Investment Category**	**Average**	**Low**	**High**
	Low Rehab (Less than 10% of irrigated area rehabilitated)	Ashoknagar, Rajgarh, Ujjain*, Guna, Dewas, Mandsaur, Shajapur, Katni, Neemuch*, Chhatarpur, Satna, Rewa, Sehore	Dhar, Shivpuri, Tikamgarh,	Bhopal*, Sagar, Damoh, Raisen, Vidisha*
	Medium-High Rehab (More than 30% of irrigated area rehabilitated)	N/A	Gwalior*, Sheopur, Morena, Bhind	Balaghat
	No Rehab	Panna, Indore, Ratlam, Ujjain*, Neemuch*	Gwalior*, Datia	Seoni, Vidisha*, Bhopal*

*Districts that have partial areas where systems were rehabilitated and some areas where systems were not rehabilitated hence fall under both categories

The boundary is above 1062 mm. Table 3 provides the rainfall categories for each district. The sampling framework is given in Table 5. Table 5 indicates that there is heterogeneity in the interannual rainfall averages in the Low and Medium- High Rehab districts as well as between the Rehab and No Rehab districts. Not all districts received the same level of investment, and not all districts have the same patterns of rainfall when examined over a 10-year period.

4.2.6 Intra-annual rainfall data

To determine whether investments in irrigation modernization buffer crop yields from fluctuations in rainfall at the district level, we examined intra-annual rainfall. As monsoon rainfall is important for determining agricultural yields and productivity, the four monsoon months (June–September) across all 10 years were used to examine intra-annual variability. The rainfall dataset consists of observed rainfall compiled by the Irrigation Department rather than satellite data. To calculate the standardized monsoon anomaly of each district, the first step was to average the observed monthly rainfall for each district from June to September for all years from 2005 to 2014. Standardized anomalies generally provide more information about the magnitude of the anomalies because influences of dispersion have been removed. The second step was to calculate monthly rainfall climatology, which is the mean value of rainfall for each month in 2005–2014. Rainfall anomalies for each district were computed by subtracting the observed monthly data from the monthly average for all 31 districts. The third step was to determine whether seasonal variations are present in the monsoon months.

Standardized anomalies are calculated by dividing the rainfall anomaly by the climatological standard deviation. Thus, the climatological standard deviation of the rainfall was calculated for each of the monsoon months for all 31 districts. Once standard deviations were determined, the standardized anomaly was determined by dividing the rainfall anomaly for the monsoon months from the standard deviation of each respective month. The results of all the 31 standardized anomaly graphs for each district are in Figures

9-13 in supplementary materials at the end of this chapter. Lastly, we classified each year from 2005 to 2014 into the three rainfall zones for all 31 districts. The results are given in Table 6.

4.2.7 Crop yield and minimum support price

For the crop yield analysis, secondary data were compiled for each district on average yields in kg/ha for the panel data used in the regression models. Interannual monsoon rainfall for each district was also included in order to compare how yield changed in average, low or high rainfall years. Agriculture yield data were obtained from the Madhya Pradesh Commissioner Land Records Office in Gwalior District. Data were also compiled on the Minimum Support Price (MSP) for each of these three crops from 2005 to 2014. MSP was added as an additional variable of analysis into the fixed effects model to test whether yields in these districts were influenced by the MSP for these crops.

The MSP is a national scheme of the Government of India to protect farmers from exogenous price shocks. In this scheme, the government declares a minimum price for specific commodities, for which the government will guarantee that farmers can sell their produce. Data on MSP for the three crops from 2005 to 2014 were obtained from the Madhya Pradesh Directorate of Economics and Statistics, Department of Agriculture, Cooperation and Farmers Welfare.

4.2.8 Fixed effects regression model

We tested the hypothesis by using panel data for 31 districts for 2005–14. This panel consists of data on crop yields for paddy, wheat, and gram; inter- and intra-annual monsoon rainfall; the timing, size, and degree of irrigation investment in districts where irrigation systems were rehabilitated by the MPWSRP; and annual MSP for each crop. To measure the effectiveness of the MPWSRP irrigation investment (treatment) on crop yields over time, we determined that a fixed effects model would be optimal. A fixed-effects model enables us to test the statistical relationship between the treatment (investments in system modernization) and outcome variables (crop yields), controlling for district-level rainfall

variability, variations in MSP over time, and other district-level variations. To test whether investments in irrigation rehabilitation and modernization lead to higher crop yields at the district level, we estimated the following equation. This equation is estimated once for each crop (paddy, wheat, and gram):

$$Yield_{it} = \beta_1 T_{it}\, Z_i^{Low} + \beta_2 T_{it}\, Z_i^{Average} + \beta_3 T_{it}\, Z_i^{High} + \beta_4 R_{it} + \beta_5 P_t + y_t + \mu_I + \varepsilon_{it} \quad (2)$$

In this equation, $yield_{it}$ is the dependent variable of yield for each crop (paddy, wheat, or gram), where I = district and t = time. Yield is measured in log (kg/ha). T_{it} is the treatment intensity of irrigation investment. This is measured as the cumulative command area that was rehabilitated by the MPWSRP for the district *I* at time *t*. This gives the coefficient β_1 the interpretation of being the percentage change in yield for every 1000 ha of cumulative command area rehabilitated. We used this approach to identify the treatment effect because the rehabilitation of tanks within a district was implemented by means of successive projects, which began in different years and were completed at different times. Therefore, we needed to identify exactly how much rehabilitation was completed within a given year and within a given district. The rehabilitated cumulative command area is a good indicator of this. Z_i is the rainfall zone of the district. This is a categorical dummy variable. Therefore, $T_{it}Z_i^{low}$ represents the interaction between treatment intensity and districts in the low-rainfall zone. We used this interaction term to explore the differential impact of irrigation investments in districts with low, average and high rainfall. This enables us to test whether irrigation investment had a larger impact on crop yields in districts with predominantly low rainfall compared to average or high-rainfall districts. The resulting interpretation of the coefficients is that β_1 represents the response to treatment in low-rainfall zones, β_2 is the response to treatment in average-rainfall zones, and so on.

R_{it} represents interannual monsoon rainfall (in mm) for the district *I* at time *t*. P_t is the explanatory variable representing the MSP (in (Rs./kg) for the corresponding crop (e.g. paddy, wheat or gram) of the dependent variable at time t. Both monsoon rainfall and MSP are standardized to have a mean of zero and a standard deviation of one. These variables are standardized to facilitate a comparison of their importance in predicting crop yield.

Also, we have found that standardizing these two variables using z-scores is an appropriate measure to avoid collinearity in analyses of their association with the outcome variable (Abraham & Sheeran, 2003; Kahan et al., 2012). The variable y_t represents time fixed effects. The time dummy variable picks up all the unobserved variables that may vary in the state on an annual basis and which are unaccounted for in our panel data. For instance, if the MP government introduced new programmes for agricultural inputs or technologies from one year to the next throughout the state, this variable would capture the resulting variations in crop yields. Finally, μ_i is the district fixed effect, which controls for unobserved heterogeneity at the district level, and ε_{it} is the error term.

Our empirical analysis is based on the assumption that 'treatment' (or investments in system modernization by the MWPSRP) is randomly assigned, conditional on the (unobserved) level of deterioration of existing irrigation infrastructure in selected river basins. This is captured in the district fixed effect variable. This information was based on direct reports from the World Bank and the MP WRD on how investment decisions are made. However, there may be cases where specific investment projects were selected based on socio-economic or political grounds rather than solely on technical specifications. In these cases, we assume that treatment would not be randomly assigned. This is a limitation of the fixed-effects model. In the present study, we found no evidence from government officials or World Bank representatives that selection of projects took place on political or socio-economic grounds, and so we assume here that treatment was randomly assigned.

4.3 Results

4.3.1 Rainfall analysis

The standardized monsoon anomaly plots indicate that no two districts are alike. Across the 10-year period, each of the 31 districts has a unique anomaly pattern. Also, the classification of each year (2005–14) into low, average, or high-rainfall years according to their intra-annual monsoon values illustrates that there are some years where the weather is consistently wet or dry, and others where the variability between districts dominates (Table 6). Therefore, water availability in the annual cropping season can vary drastically, both within a monsoon season from district to district, and from one year to another within a single district.

Analysis of data from the MP Meteorology Department indicates that from 2007 to 2010, 37–41 districts experienced severe drought and rainfall deficiency ranging from 26 days to 30 days (Planning Department, GoMP, 2011). However, in 2007, even though a majority of districts had low rainfall, some districts had wet monsoons (Table 6). Districts such as Dhar, Ratlam, Shajahapur, and Dewas saw high rainfall, with an extreme positive anomaly away from the mean. Conversely, from 2011 to 2013, there was a trend of relatively ‘wetter’ monsoons across a majority of districts, but some districts still had deficient rainfall (e.g., Bhind, Shivpuri, and Ujjain) (Table 6).

Thus, there is evidence of heterogeneity in the sub-basin hydrological climate among districts in MP, which could be influencing district-level crop yields. Multiple districts within a river basin in MP have diverse rainfall patterns within a single year and within one monsoon season. This can range from extremes of wet monsoons to dry monsoons within one cropping season.

Table 6. District-wise classification of rainfall zones for monsoon months, June–September 2005–2014. Light shading represents low monsoon rainfall; medium shading represents average monsoon rain; dark shading represents high monsoon rainfall

	District-wise Classification of Monsoon Rainfall Jun-Sep 2005-2014									
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Ashoknagar										
Balaghat										
Bhopal										
Bhind										
Chhatarpur										
Damoh										
Datia										
Dewas										
Dhar										
Guna										
Gwalior										
Indore										
Katni										
Mandsaur										
Morena										
Neemuch										
Panna										
Raisen										
Rajgarh										
Ratlam										
Rewa										
Sagar										
Satna										
Sehore										
Seoni										
Shajapur										
Sheopur										
Shivpuri										
Tikamgarh										
Ujjain										
Vidisha										
		Key:								
			Low	Average	High	Data Gap				

4.3.2 Fixed effects model

4.3.2.1 Results of hypothesis test

As we analysed three staple crops, we ran the regression separately for paddy, wheat, and gram. For each crop, we ran two regressions. The first does not include time fixed effects; the second does. To show their robustness, the results of both regressions are shown in Table 7 for each crop. Columns 1, 3 and 5 in Table 7 presents the results of the model without time fixed effects, and Columns 2, 4 and 6 include time fixed effects.

Table 7. Fixed effects regression model results of the influence of irrigation investment, rainfall, and MSP on major crops in Madhya Pradesh

	(1)	(2)	(3)	(4)	(5)	(6)
	Wheat	**Wheat**	**Paddy**	**Paddy**	**Gram**	**Gram**
	District Fixed Effects	District and Year Fixed Effects	District Fixed Effects	District and Year Fixed Effects	District Fixed Effects	District and Year Fixed Effects
Treatment in Average Rainfall Zone	0.0470***	0.0242**	0.0493***	0.0384***	0.00140	-0.00422
	(0.0133)	(0.0108)	(0.0148)	(0.0132)	(0.0125)	(0.0135)
Treatment in High Rainfall Zone	0.0141	-0.0177	0.0177	0.000493	-0.0155	-0.0228
	(0.0155)	(0.0167)	(0.0335)	(0.0294)	(0.0159)	(0.0137)
Treatment in Low Rainfall Zone	0.00176***	4.86e-05	-0.00397***	-0.00509***	0.00266***	0.00256***
	(0.000512)	(0.000633)	(0.000645)	(0.000826)	(0.000529)	(0.000537)
Monsoon Rain	0.0285**	-7.09e-05	0.120***	0.0640**	0.0319**	-0.0102
	(0.0104)	(0.0114)	(0.0188)	(0.0239)	(0.0134)	(0.0124)
Wheat MSP	0.128***	0.114***				
	(0.0194)	(0.0205)				
Paddy MSP			0.286***	0.268***		
			(0.0257)	(0.0330)		
Gram MSP					0.0242	-0.0555
					(0.0219)	(0.0382)
Constant	7.553***	7.691***	6.993***	7.112***	6.839***	6.747***
	(0.00929)	(0.0244)	(0.0126)	(0.0370)	(0.00960)	(0.0337)
Observations	309	309	293	293	309	309
R-squared	0.392	0.634	0.636	0.720	0.042	0.382
Number of districts	31	31	31	31	31	31
District FE	YES	YES	YES	YES	YES	YES
Year FE	NO	YES	NO	YES	NO	YES

Treatment refers to the cumulative command area rehabilitated by the MWSRP. This treatment is interacted with rainfall zones to obtain the treatment effect in each zone. Robust standard errors in parentheses. Rain and MSP are both measured using standardised z-scores with mean of zero and standard deviation of one. ***p < 0.01, **p < 0.05, *p < 0.1

Results of the regression with time fixed effects are preferred, as they control for external factors that changed in MP over time.

Irrigation investments improved wheat and paddy yields in districts with average rainfall. For wheat, in column 2 (with year fixed effects), we see that yields improved by 2.4% for every 1000 ha of treatment. To illustrate the impact of the treatment, results are applied to a specific district in our study area. Ashoknagar, for instance, is in the average-rainfall zone and had 12,900 ha of command area rehabilitated by the MPWSRP by 2014. Based on the results in Table 7, we calculate that wheat yields rose by 31% due to the irrigation investment in Ashoknagar. This increase seems reasonable, although it only explains a small portion of the increase in crop yields in Ashoknagar. Based on the secondary data collected, we know that wheat yields grew from 1086 kg/ha in 2005 to 2702 kg/ha in 2014. Therefore, other variables in our regression model may also contribute to the growth in yields in wheat for a district such as Ashoknagar. One potential contributing factor could be the MSP of wheat. Our results show that a one standard deviation increase in the MSP of wheat leads to a highly statistically significant 11.4% increase in wheat yields while controlling for time fixed effects (Column 2). Here, one standard deviation is equivalent to a Rs. 2.3 increase compared to a mean MSP of Rs. 11.3.

For paddy, the treatment had a slightly larger impact than wheat, with time fixed effects showing yield improved by 3.8% for every 1000 ha of treatment (column 4, Table 7). For all crops, the treatment effect is larger without year fixed effects, so we view the results from the regression that includes the year fixed effects as more conservative. But we prefer these values because they control for variations over time in MP and thus represent more robust results. Therefore, in the districts with average rainfall and for paddy and wheat crops, our hypothesis is supported.

In the case of the gram crop, however, we do not find evidence that the rehabilitation programme increased crop yields. There were no significant results for gram. The investments had no significant impact on gram yields in districts with average rainfall.

And for all three crops, treatment effects were not statistically different from zero in the high-rainfall zone. This trend indicates that in districts with above-average rainfall, farmers rely less on surface and groundwater irrigation sources. In addition, the MSP variable was not significant for the gram crop, unlike for the wheat and paddy crops. As gram is a relatively water-efficient Rabi crop, farmers in MP tend to plant gram when there is limited access to irrigation, or rainfall is low, or both. Therefore, in the model, we see that the treatment effect for gram is slightly positive and significant only in the low-rainfall zone (Column 6). However, gram yields tend to be robust despite reduced irrigation, unlike wheat, which is highly sensitive to irrigation quantity. As a result, we see that gram does not follow the same pattern as paddy and wheat in our model. Lastly, the state government does not procure gram at the same scale as wheat and paddy, and therefore we see that the MSP of gram also does not have a significant relationship to yield. As a result, farmers will tend to produce more wheat and paddy than gram in average and above-average rainfall zones and place more emphasis on paddy and wheat, for which there is a larger scale of procurement from the government (Reddy, 2004).

In the low-rainfall zone, treatment has a very small impact on paddy and gram yield, with gram showing only a 0.25% increase, while paddy yields seem to go down by 0.51% as a result of treatment (Columns 4 and 6). This indicates that for most districts in the high- and low-rainfall zones, the treatment effect was zero, except for a few instances where there was a small positive and small negative effect for gram and paddy, respectively, in the low-rainfall zones. The effect is statistically significant but too small to be of practical interest.

For the monsoon rain variable, we see that the correlation between monsoon rain and crop yields is largest for paddy. These regression results are consistent with previous research showing that rice yields are highly sensitive to variation in rainfall. We find that a one-standard-deviation increase in monsoon rain increases paddy yields by 6.4%, while wheat and gram yields are unaffected (Column 4). This is consistent with research by Saseendran, Singh, Rathore, Singh, and Sinha (2000), who find that an increase in rainfall above observed values leads to an exponential increase in rice yields, while a decrease in

rainfall results in a constant 8% loss in yields for every reduction in rainfall of 2 mm to 16 mm per day.

Our regression results also shed light on a current debate regarding the impact of MSP on crop yields. We had specifically included MSP as a variable to test the difference between the influence of irrigation investments on yields versus other variables of production (e.g., crop price). Research on the impact of MSP indicates that it has often induced farmers in India to produce surplus grains (e.g., wheat), resulting in excessive stock and placing a high burden of storage of excess wheat supply on the Indian government (Gouel, Gautam, & Martin, 2016). This trend of increasing wheat and paddy yields in response to increasing MSP is supported by the model. A one standard deviation increase in the MSP of wheat results in an increase of yield by 11.4%, and for paddy an even larger 26.8% increase (Columns 2 and 4). As discussed, gram is the exception. These results contradict the work of Ali, Sidhu, and Vatta (2012), who argue that 'non-price factors' such as improved seed varieties, assured irrigation through tube wells, and fertilizer are more important determinants of agricultural growth in paddy production than price. Our model indicates that for wheat and paddy, MSP has a higher influence on yield than monsoon rain. This finding warrants a deeper analysis of the differential impact of MSP versus irrigation investment on farmer behaviour. This is out of the scope of this article and needs to be explored in further research.

In Table 7, wheat and paddy have R-squared values of 0.63 and 0.72, respectively; the R-squared for gram is only 0.38. This implies that our variables in the regression have good predictive power for paddy and wheat and slightly less predictive power for gram yields in these districts.

4.3.2.2 Robustness checks on regression results

To test the robustness of the regression results reported in Table 7, we checked for multicollinearity of MSP and rainfall. We used the variance inflation factor (VIF) to test for multicollinearity (Graham, 2003; Lin, 2008; Marquardt, 1980). A variable that has a VIF greater than 10 merits further investigation. To check for collinearity, a tolerance value is calculated. This is defined as 1/VIF. A tolerance value lower than 0.1 is comparable to a VIF of 10. This indicates that the variable could be considered a linear combination of other independent variables. The VIF tests showed no evidence of multicollinearity.

In a previous version of the regression results, we encountered multicollinearity between rainfall and MSP when these variables were included as levels rather than as z-scores. To address this issue, we converted these variables to z-scores in our baseline regression results. This is a common standardisation that is designed to reduce the impact of outliers on the regression results and facilitates comparison between the impact of rainfall and MSP on crop yields, by putting the two explanatory variables into common units.

4.4 Discussion and limitations

4.4.1 Discussion of results

4.4.1.1 Accounting for district-level rainfall variability

The intra-annual rainfall analysis reveals that no two districts are alike when it comes to standardized monsoon anomaly. Monsoon variability dominates not only on a temporal scale but also at a spatial, sub-basin or district scale. As farmers in MP continue to rely on rainfed and increasingly groundwater-fed irrigation in districts where surface irrigation is absent or variable, crop yields, as a result, continue to be sensitive to hydrology, particularly to sub-basin rainfall variability.

The current design of investments in system rehabilitation in MP does not consider crop sensitivity to this district-level rainfall heterogeneity. A process-driven approach (e.g., investing in modernizing aging systems in selected basins) can benefit the existing distribution of infrastructure, with positive results for districts with average patterns of rainfall. But this approach can have inequitable impacts for systems in districts with drier-than-average or wetter-than-average rainfall patterns. Therefore, it is important not only to address the structural, engineering needs of infrastructure but also to design investments based on an understanding of the monsoon patterns at interannual and intra-annual scales in each district, thus improving the ability of irrigation departments to reliably and flexibly deliver irrigation services adapted to diversity in localized rainfall patterns. This finding complements existing literature, which argues that investments to improve canal systems in India do not consider all potential costs and benefits when designing investment programmes (Shah & Kumar, 2008; Kumar 2017). We argue that district-level monsoon anomalies impose a diverse set of 'costs' on canal irrigation systems, which needs to be considered in the design of future investment programmes.

A caveat to this finding is that further analysis of district-specific rainfall patterns is necessary to determine the robustness of the observed patterns over a longer time period (e.g., beyond the 10-year monsoon cycle) and therefore determine the types of rainfall anomaly patterns that may emerge and the types of irrigation systems that are needed. If a specific rainfall pattern in a district is evident only over a 10- year period, then it may be unwise to design systems solely on the sub-basin variability of that period. Although it is not possible to reliably predict future rainfall trends with 100% accuracy, it is critical to couple the engineering concerns of irrigation systems with more in-depth climatological analysis at the sub-basin level (Conway & Schipper, 2011).

4.4.1.2 Limited ability of irrigation infrastructure to buffer against rainfall variability

Our analysis finds little to no effect of treatment on crop yields in low-rainfall areas. This leads us to believe that crop yields in these districts are still, to some extent, coupled with rainfall variability. This also indicates some reliance on rainfed and groundwater irrigation

by farmers in these districts, despite rehabilitated irrigation systems. But to further substantiate this finding, primary data on crop yields from groundwater withdrawals at the farm level in gravity-irrigation command areas would need to be collected and incorporated into the model. Unfortunately, at present, such data are not available in MP. Despite this limitation, the results validate and add nuance to the existing literature on the connections between investments in water resources development and impact on growth in agriculture-dominated economies.

Specifically, studies indicate that regions where agriculture forms a major part of the economy tend to be more sensitive to hydroclimatic variability, and persistent negative precipitation anomalies seem to exert a significant influence on GDP per capita growth (Brown, Meeks, Hunu, & Yu, 2011; Khan, Morzuch, & Brown, 2017). Lundqvist and Falkenmark (2010) point out that despite management and efficiency improvements in physical water management infrastructure, periods of severe water scarcity cannot be managed with 'conventional measures' alone. Gilmont et al. (2018) determine that increased use of groundwater (rather than surface sources) for irrigation does not, in fact, buffer agriculture growth from rainfall variability. The literature on water resources management approaches in India highlights the need to resolve supply-side interventions to include adaptation to the increasing likelihood of a higher frequency of extreme events (Thatte, 2017). With an expected increase in variability of the monsoon climate in India, however, tank irrigation is still considered one of the major strategies for coping with rainfall variability (Kumar, Kamala, Rajagopalan et al., 2011; Mathison et al., 2013; Siderius et al., 2015). Studies in other countries have also illustrated the potential for infrastructure investments to decouple economic growth from rainfall variability (Gilmont 2014; Damania et al., 2017). This substantiates the need to design future investments in system modernization to adapt more effectively to localized hydrological challenges in sub-basins in India. However, it is also important to note that investments are only one of the instruments in a basket of other necessary legal, economic, social and institutional reforms necessary to cope with climate change induced hydrological variability in India (Tortajada, 2014).

4.4.1.3 Influence of MSP on crop yields

The model indicates that MSP has a positive and highly significant influence on crop yields for wheat and paddy crops in treatment and non-treatment districts in MP. This price influence is statistically larger than district monsoon rainfall factors. The strong influence of MSP, however, is not necessarily a positive factor, as farmers tend to over-produce crops such as wheat and paddy, leading to an excess supply of cheap grain crops in the Indian market. The guaranteed MSP for cereal crops may be disincentivizing farmers from switching to higher-value and more profitable horticulture crops, for which there is no government-guaranteed purchase prices. Many studies have determined that due to MSP farmers tend to prefer rice and wheat cultivation over pulses and oilseeds (Chand 2003; Jha, 2009; Jha & Srinivasan, 2006; Mittal & Hariharan, 2016). Other studies that have analysed the effect of MSP on area and production of food crops state that MSP as an instrument seems to encourage wheat crops over paddy cultivation among Indian farmers (Raj & Anjugam, 2016). The MSP results advance empirical evidence that price factors exert a stronger influence on farmer cropping choices, and consequently yields, compared to the influence of rainfall. Previous work on this topic has argued that irrigation improvements, not price factors, are instrumental in enabling farmers to have a consistent source of water, leading to higher yield, higher cropping intensity, and crop diversification (Del Carpio, Loayza, & Datar, 2011). For the benefits of irrigation rehabilitation and modernization to be truly realised, farmer choices around crops and water-use also need to become more sustainable. Thus, the potential limiting role of MSP in influencing farmer cropping choices towards lower-value cereal crops needs to be further examined.

4.4.2 Limitations

We identify four core limitations of this study. First, crop yield response to irrigation water is a highly complex relationship that depends on multiple production factors (e.g., soil conditions, evapotranspiration rates, seepage, percolation, and drainage capacity in the canals) and the socio-economic dynamics at play at the village and farm levels in individual districts, as well as in the command area (Mahapatra, 2012; Mehta, 2005; Rosegrant, 1992;

Swyngedouw, 2009). A major source of complexity is the suite of highly intricate village-level relationships, institutions, and processes in India, which has been shown to influence agricultural productivity and the outcomes of water-sector reforms (Maertens & Barrett, 2013; Tanka and Fuller, 2010; Wade 1988b). Variations from one village to another in how irrigation systems are managed at the community level also play a role in variations in agricultural production (Meinzen-Dick, Raju, & Gulati, 2002; Mollinga 2010; Mosse, 2005, 2006; National Research Council, 1986; Wade, 1987). Therefore, a detailed examination of the interplay between the village and farm dynamics and irrigation investments to rehabilitate existing canals is necessary to further nuance our results.

Second, the construction quality of the systems that were rehabilitated may impact crop yield outcomes, as well as the subsequent operation and maintenance of the systems by WRD engineers and WUAs once rehabilitation is completed. Third, the consequences of the scarcity of water and unpredictable supply in the tail-end areas of irrigation systems can limit yields and cropping intensity. Therefore, the different rules of water delivery and differences between actual and expected deliveries are also worthy of consideration and might be expected to impact the efficacy of the investments and the quality of crop yields (Mahapatra, 2012; Singh, Visha Kumari, Gupta, Singh, & Solomon, 2018; Wade, 1988a). Lastly, the degree of reliance on groundwater irrigation will also determine how resilient crop yields are to rainfall variability, because areas with high reliance on groundwater may still produce high crop yields despite lack of surface supply and/or highly variable monsoons. We were unable to test this outcome due to data limitations, and we recommend that future studies of this nature analyse farm-level crop yields from groundwater irrigation sources.

4.5 Conclusions

Integrated Water Resources Management is a process that generally does not consider the marginal benefits and costs of investments. Where marginal benefits vary by the nature of the production function (yield, revenue, profit), a more selective strategy for investment is required. This includes rainfall variability in determining where the marginal costs of infrastructure are uneconomical. Therefore, there is no guaranteed positive relationship between crop yields and investments in modernization and rehabilitation of water-related infrastructure (e.g., surface irrigation) – instead, yields depend on the interaction between sub-basin hydrology and the available infrastructure.

Planning modernization of systems based on multiple layers of hydrological, infrastructure and agricultural data may maximize benefits from investments. This result suggests that the traditional engineering-driven, basin-level planning model may be improved by investing in more robust systems for classifying district-level rainfall anomalies and their links to rainfall availability and crop yields at the district and even farm level. However, additional data on crop yields from farm-level groundwater usage are necessary to further nuance our findings. Lastly, there is also a need to better understand productivity differences from MSP versus surface irrigation and to understand whether price or irrigation availability has a stronger impact on farmer behaviour around cropping choices and water-use-efficiency practices. In India, understanding whether investments in irrigation modernization reduce the vulnerability of smallholder farmers to climatological and agricultural risks is essential, as similar investment models have been implemented across multiple states.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Chapter 4

International Journal of Water Resources Development

Supplemental File for

Understanding the effectiveness of investments in irrigation system modernisation: Evidence om Madhya Pradesh, India

Figure 9. District-wise Standardised Monsoon Anomaly Graphs (Shivpuri – Katni)

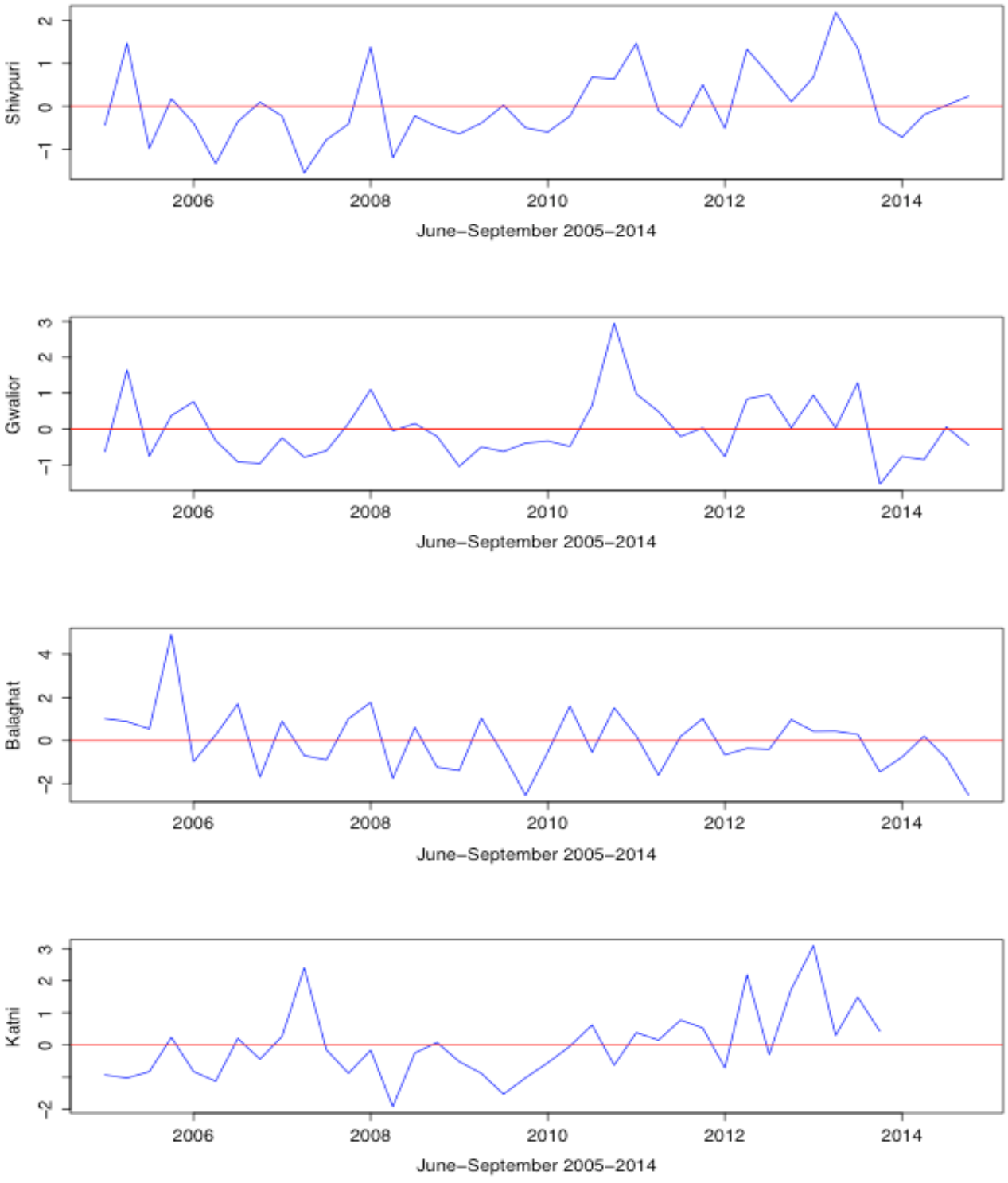


Figure 10. District-wise Standardised Monsoon Anomaly Graphs (Rewa – Damoh)

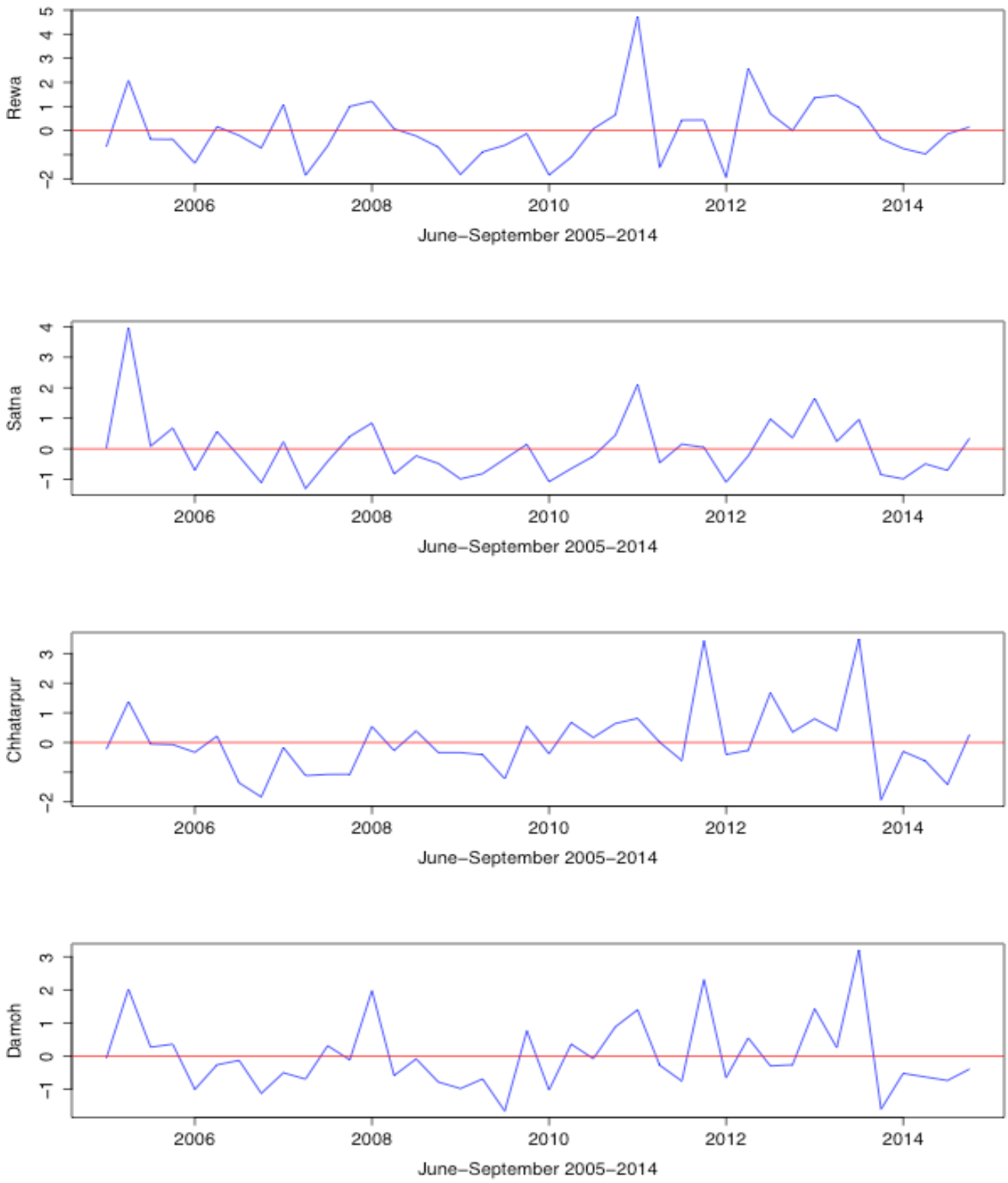


Figure 11. District-wise Standardised Monsoon Anomaly Graphs (Sagar – Shajapur)

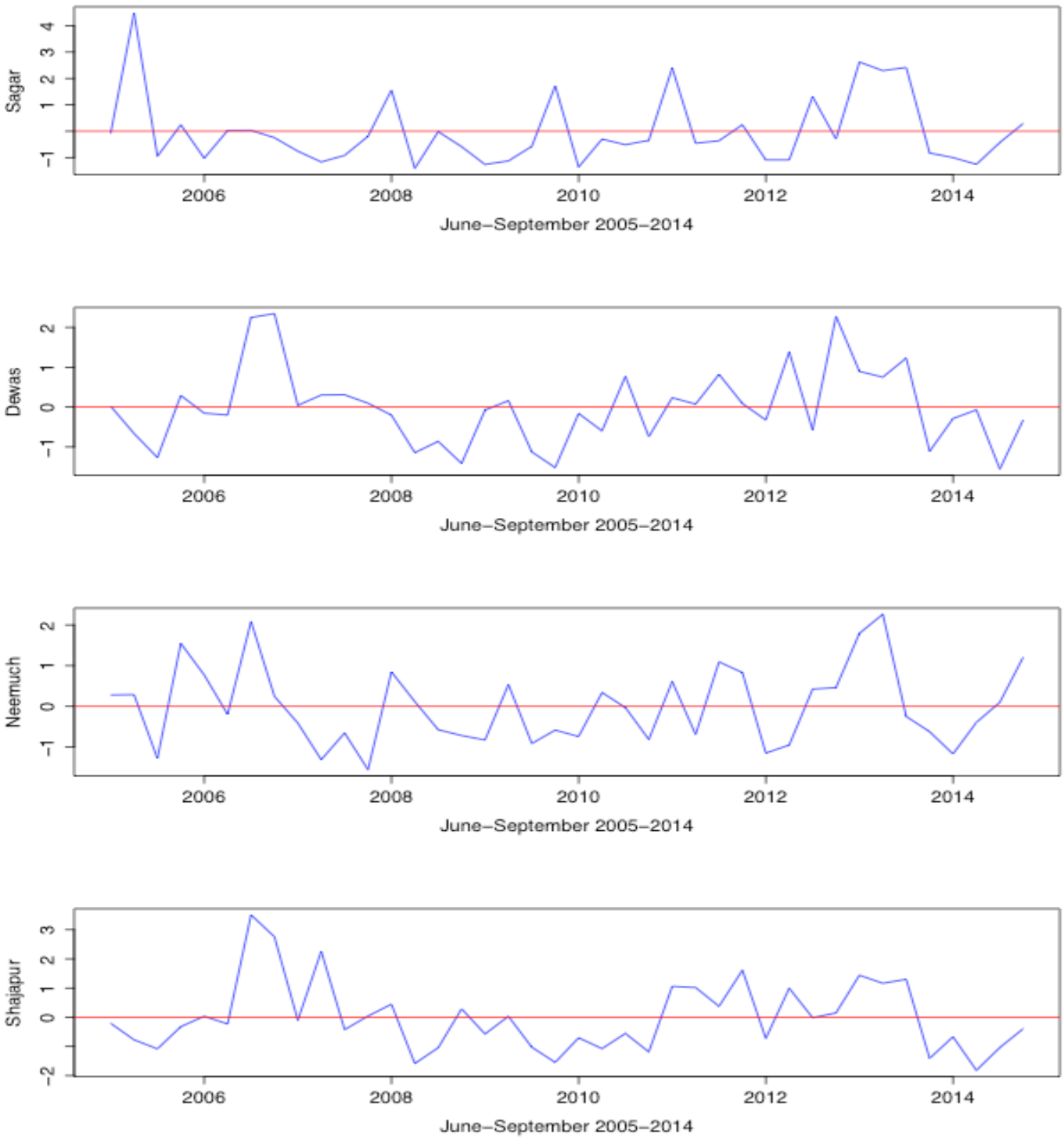
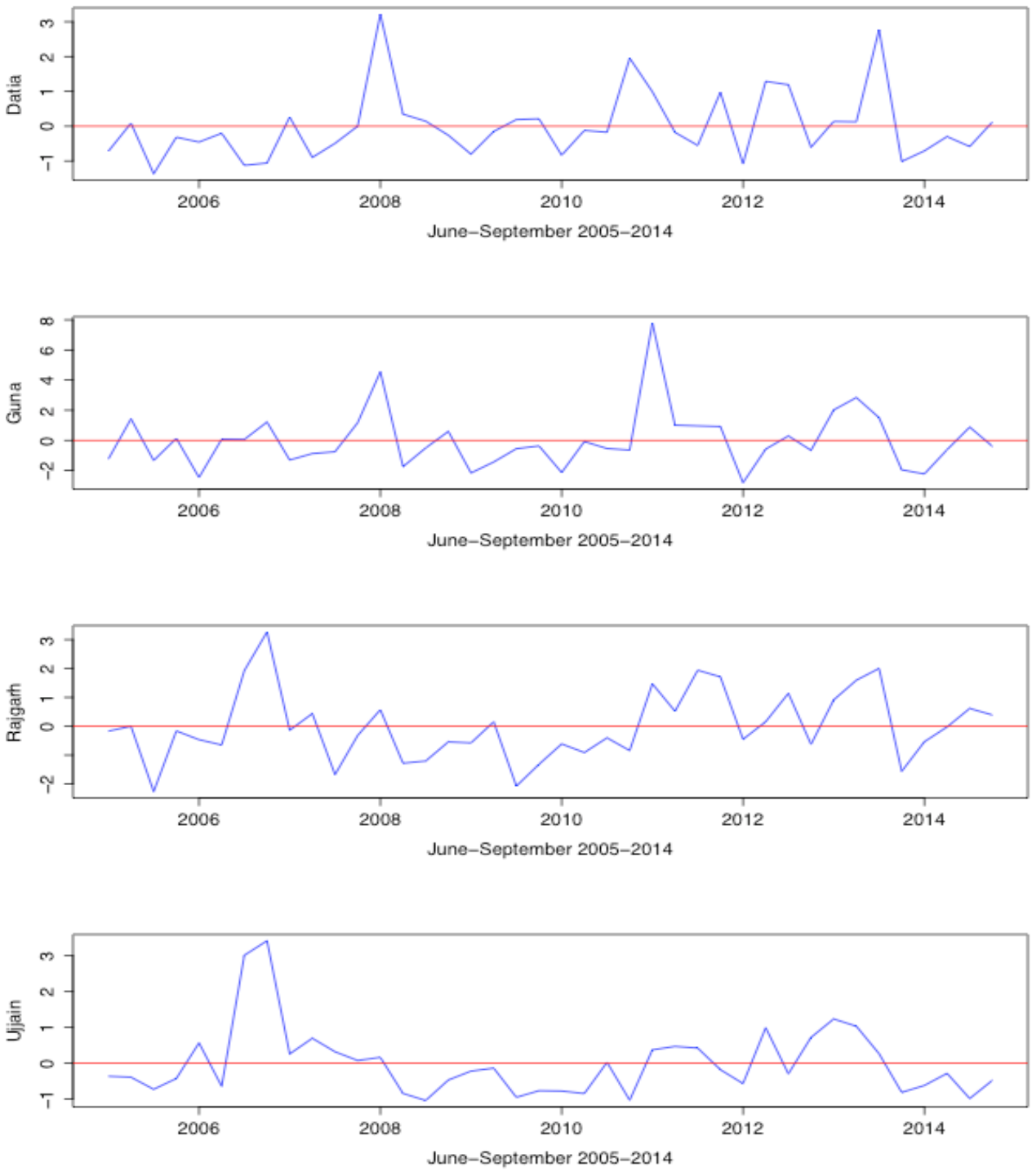


Figure 12. District-wise Standardised Monsoon Anomaly Graphs (Seoni – Indore)

Figure 13. District-wise Standardised Monsoon Anomaly Graphs (Datia – Ujjain)



5. Does irrigation infrastructure influence the well-being of smallholder farmers? Empirical evidence from Madhya Pradesh, India

"Poverty is not just a lack of money; it is not having the capability to realize one's full potential as a human being."

Amartya Sen

Chapter 5

Does irrigation infrastructure influence the well-being of smallholder farmers? Empirical evidence from Madhya Pradesh, India

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Abstract

Studies that seek to evaluate returns from investments in irrigation modernisation primarily focus on agricultural and income-related outcomes for smallholder farmers. There is limited evidence, however, on the association between modernised irrigation infrastructure and well-being among rural farmers in India. Drawing on data from 707 households in Madhya Pradesh, India, we explore whether investments in irrigation systems are associated with changes in subjective well-being among smallholder farmers. Our findings show a positive relationship between farmers with access to modernised surface irrigation infrastructure and well-being improvements. Results reveal that access to modernised irrigation systems are associated with well-being gains of 20-30%, which disguise an even larger effect when disaggregating gains in low rainfall areas compared to high rainfall areas. Ancillary investments from non-farm, poverty alleviation programmes coupled with access to modernised canals indicate greater advances in well-being for farmers. Finally, a third of farmers whose main income is from dairy products as well as farmers who grow horticulture crops experience stronger well-being gains regardless of irrigation investments. However, we note low adoption rates of horticulture crops and innovative agricultural practices (e.g., use of hybrid seeds) among farmers; reinforcing the need to explore how access to irrigation infrastructure influences choices of farmers around sustainable agricultural practices.

Keywords: Subjective well-being; irrigation modernisation; poverty alleviation; rainfall variability; Madhya Pradesh.

5.1 Introduction

The close relationship between income poverty and water poverty is well established; households with access to adequate quantity and quality of water supply are likely to be wealthier (Ifabiyi and Ogunbode, 2014; Lawrence et al., 2002; Sullivan et al., 2002; Sullivan and Meigh, 2003). But does improved access to water only influence income-related outcomes or does it also have consequences for subjective well-being? A growing body of work has established that subjective measures of well-being that attempt to understand whether people perceive themselves to be poor or not are crucial instruments for assessing welfare and measuring poverty (Asadullah and Chaudhry, 2012; Diener, 1994; Ravallion, 2012). Multidimensional analyses of household poverty now support the use of more subjective measures of an individual's well-being in order to assess beyond income (Alkire 2015; Alkire and Seth, 2015; Dasgupta 1990; Mendola and Simtowe, 2015; Rogers et al., 2012; Stiglitz et al., 2009a). Kahneman and Krueger (2006) find that measures of poverty that only examine income and consumption data do not capture a holistic measure of well-being.

In the context of understanding the multidimensional nature of water poverty for rural households in developing countries, several studies have gone beyond income to illustrate direct linkages between water accessibility, social welfare, and subjective well-being gains (Bookwalter and Dalenberg, 2004; Hope 2006; Hope 2007; Guardiola et al., 2013; Nadeem et al., 2018). Work by Dasgupta (1993) and Dasgupta and Maler (2001) has identified that commodity determinants of well-being include inputs into the production of well-being such as "food, clothing, *potable water*, shelter, access to knowledge and information, and resources devoted to national security". However, studies on the relationship between subjective well-being and water poverty primarily focus on access to drinking water supply and sanitation, whereas the role of irrigation infrastructure (e.g., access to surface irrigation for food production) has received limited attention.

It is well established that irrigation systems enhance opportunities for farmers to diversify their income base and reduce vulnerability to the seasonality of agricultural production and external water-related shocks; thereby reducing their income poverty (David and Otsuka, 1994; Freebairn, 1995; Hussain and Hanjra, 2004). In Asia, investments in irrigation modernisation have enabled rural communities to increase their agricultural production and farm incomes (Hussain and Hanjra, 2003). In the context of India, a number of benefits have been attributed to the availability of surface irrigation systems including a) higher cropping intensity in irrigated areas compared to rain-fed areas, which enables farmers to grow extra crops each year, leading to higher household food security; b) increased land productivity of major crops including rice and wheat in irrigated versus rain-fed areas; c) higher wage rates per hectare; and, d) increased labour employment in irrigated areas compared to non-irrigated areas (Alexandridis et al., 2008; Fan et al., 2000 a, b; Kishore 2002; Kumar et al., 2018; Sinha et al., 2018).

Although the availability of surface irrigation is central to income gains for farmers, multiple studies have shown that benefits of irrigation investments are not evenly distributed among all members of a community, and existing social, political and institutional barriers limit its impacts and reach to more vulnerable and poorer communities (Barker and Molle, 2004; Berkoff 2013; Burney and Naylor, 2011; De Silva et al., 2013; Kerr 2002; Mehta 2001; Mollinga 2001; Mollinga 2003; Shah et al., 2002; Shah 2005). As a result, irrigation infrastructure has had variable and often weakly understood impacts (Von Carnap, 2017). While investing in improvements in surface irrigation systems and reducing rural poverty continues to be a high priority for national and state governments across India, there is no clear understanding of how rural farmers perceive investments in irrigation infrastructure modernisation on their well-being.

The literature on subjective well-being in the Indian context, thus far, has not focused on empirical investigations of the relation between the availability of surface irrigation and perceptions of well-being. Instead studies have considered subjective well-being responses among Indian households with respect to the consumption of goods (Linssen et al., 2011),

privilege and deprivation in access to water, electricity, and toilet facilities (Mishra and Shukla, 2016), household well-being and aquifer sustainability in Indian watersheds (Ward et al., 2016), and the importance of natural capital over economic capital for satisfying well-being of rural and indigenous societies in India (Zorondo-Rodriquez et al., 2016), among others. On the other hand, many of the studies that analyse the impact of irrigation systems in India focus on the change in the amount of irrigated area serviced by the rehabilitated systems, collective action by water-users around canal systems, failures of institutional governance in Indian Irrigation Departments, and the consequential impact of weak irrigation systems and income poverty for farmers (Fan et al., 2000b; Meinzen-Dick et al., 2002; Wade 1982). Such studies tend to overlook how farmers with diverse socio-economic profiles perceive the outcomes of interventions on their well-being (Bacha et al., 2011; Jana et al., 2018; Passarelli et al., 2018; Wade 1975). Thus, investigations of the role that improved access to modernised irrigation infrastructure plays in determining subjective well-being responses among rural farmers in India is not considered in any studies, as far as we are aware.

This paper contributes to the literature aimed at understanding the role of surface irrigated infrastructure in determining well-being outcomes for smallholder farmers. Due to the importance of surface irrigation availability in the lives of millions of farmers across India, there is a need for research to understand the relationship between improvements in the availability of surface irrigation infrastructure and subjective well-being. In testing the relationship between surface irrigation assets and well-being; we nuance past studies that examine the commodity determinants of well-being (Dasgupta and Maler, 2001). This type of study also provides complimentary evidence to existing studies that examine crop yield and income-related impacts of investments in irrigation modernisation as well as to studies that attempt to understand the causes and consequences of water poverty (Beegle et al., 2012; Fafchamps and Shilipi, 2009; Ferreira and Lugo, 2012; Filmer and Pritchett, 2001; Hope 2007; Komnenic et al. 2009; Molle and Mollinga 2003). To this end, this study examines whether investments to modernise irrigation infrastructure contributes to changes in farmers' perceptions of their well-being compared to the perceptions of well-being among farmers in command areas without modernised irrigation systems. Our study

measures the influence of modernised irrigation systems on subjective well-being responses of smallholder farmers using a sample of 707 households from a primary household survey across five districts of Madhya Pradesh, India. The results obtained enable us to develop a more nuanced understanding of how investments in irrigation modernisation affect farmers' lives, beyond the traditional income and expenditure outcome measures.

The paper is structured as follows. Section 2 describes the methodology including details of the study site in Madhya Pradesh, the data collected, and our estimation strategy for determining well-being responses among farmers. Section 3 presents the sample characteristics of the farmers surveyed. Section 4 presents the results of the model followed by robustness checks. Section 5 synthesises the results into a broader discussion as well as presents the limitations of the study. Section 6 concludes with wider implications.

5.2 Methodology

5.2.1 Study area and overview of methodology

Madhya Pradesh is the third largest state in India with a total geographical area of about 308,000 square kilometres. The state has a population of 72 million as per the 2011 Census, with an estimated 36% of the rural population living below the poverty line. More than 26% of the Net State Domestic Product (NSDP) is generated from the agriculture sector, which employs 73% of the population (Government of Madhya Pradesh 2011). Madhya Pradesh has ten river basins, five regions with 52,000 villages, 23,000 panchayats and 323 development blocks in 51 districts (Figure 14).

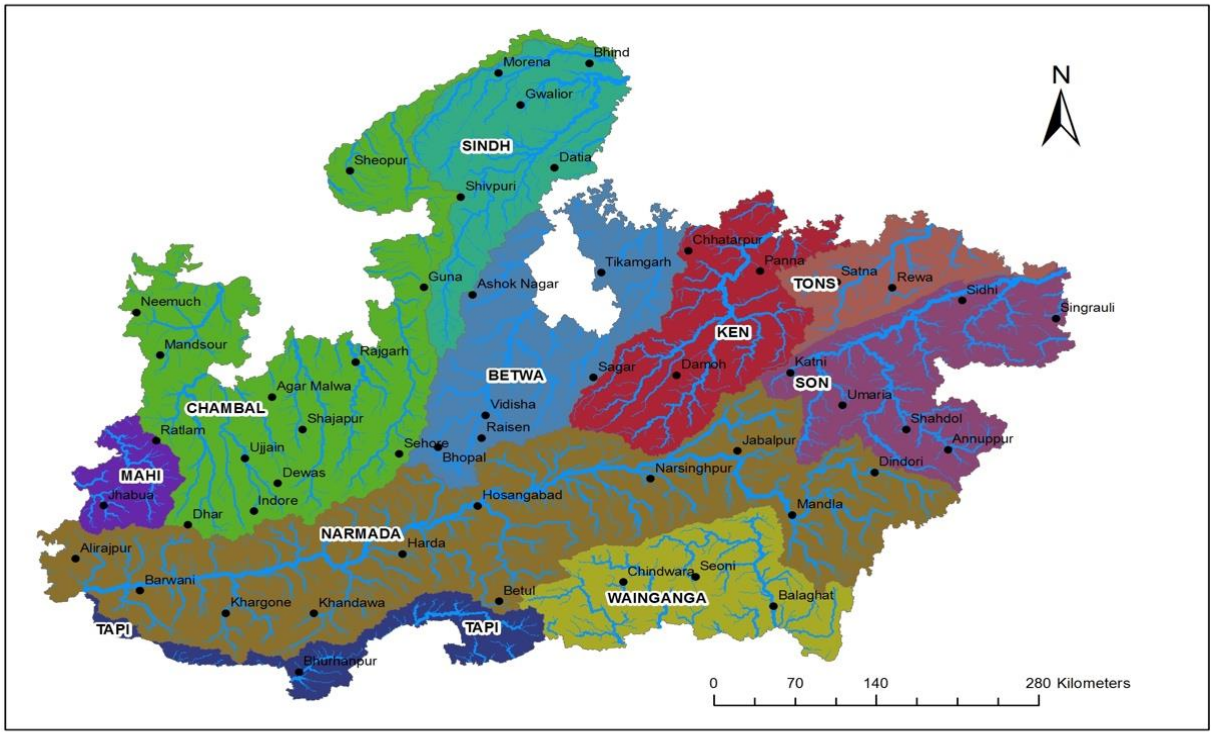


Figure 14. Map of River Basins and Districts of Madhya Pradesh (Biswas, S. (2017). Water Resources Department. Government of Madhya Pradesh).

The state faces water resources challenges in the form of droughts and floods with strong linkages between economic growth and rainfall variability in its monsoons (Kundu et al., 2015; Singh 1997). Data on monthly district-wise rainfall indicate that rainfall in most districts has been deficient in comparison to long-period averages of monthly rainfall for the period 2009-2011 (Gilmont et al., 2018; Sinha et al., 2018). In order to address the complexities of hydrological variability, the Madhya Pradesh Water Sector Restructuring Project (MPWSRP) aimed to invest in modernising and rehabilitating surface irrigation systems and other capacity building interventions to improve the productivity of water resources for sustainable growth, and poverty reduction across 31 districts in six out of the ten river basins of the state (Chambal, Sindh, Betwa, Ken, Tons, and Wainganga) (Figure 14).

The Madhya Pradesh Water Sector Restructuring Project focused on maximizing water productivity in all its usage in 495,000 hectares (ha) of designed potential irrigation Culturable Command Areas (CCA)[12] within the six basins. Upon closure, the project made a total investment of USD$ 440 million to rehabilitate 202 minor, 21 medium, and 5 major irrigation schemes for a total of 228 projects across the six river basins (Sinha et al., 2018). Specific irrigation schemes were selected to receive investments based on two criteria: a) *geographic* – they were located in the target six river basins for the project; and b) *engineering* - systems that were built before 1986 and those that exceeded certain degradation thresholds of designed performance due to lack of maintenance were selected (Sinha et al., 2018; World Bank 2005). Major projects are defined as projects with a CCA of more than 10,000 ha, medium projects have a CCA between 2000 to 10,000 ha, and minor projects have a CCA less than 2000 ha. MPWSRP rehabilitation investment projects included repairing dams and embankments, addressing seepage and drainage issues, improving boundary stones, repairing sluice and radial gates on the infrastructure, and lining old canals with concrete to reduce seepage and improve water distribution (Sinha et al., 2018).

[12] Culturable Command Area (CCA): The areas that could be irrigated from an irrigation scheme and are fit for cultivation.

The aim of the MPWSRP was to improve cropping intensity, irrigation efficiency of the modernised surface irrigation canals, and crop production for summer (*Kharif*) crops (e.g., rice) and winter (*Rabi*) crops (e.g., wheat and gram) (Sinha et al., 2018; World Bank 2005). By closure in 2015, the project claimed to have reached its goal of irrigating 495,000 ha with 228 modernised and improved irrigation systems (World Bank 2005). The project also created and trained over 400 Water User Associations (WUAs)[13]. Over half (61%) of the 193,000 farms in the project area are small farms with an average landholding size of less than one hectare (Sinha et al., 2018). Most of the respondent farmers in the study area are the poorest members of rural society in India, mainly coming from the most vulnerable caste groups (Sinha et al., 2018). Out of the 31 districts within the six river basins, 21 districts received investments to modernise irrigation systems and 10 districts received no funding from the MPWSRP. In order to understand farmer preferences, we conducted a household survey of WUA members from command areas in districts that received investments and areas that did not.

The household survey examined the impact of investments in irrigation rehabilitation across five districts in surface irrigated command areas where the World Bank supported investments to rehabilitate and modernise irrigation systems under the Madhya Pradesh Water Sector Restructuring Project and in command areas where the MPWSRP made no investments. The household survey questioned farmers on multiple factors – including their age, education, household assets owned, land and property ownership, caste, preferred irrigation methods, types of agricultural practices adopted on their farms, and perceptions of well-being – in order to understand the variables that contribute to their overall sense of well-being. This data gave us a detailed understanding of individual farmer economic, social vulnerability, irrigation, agricultural, and well-being preferences based on information self-reported by farmers during survey interviews in the present (at the time of the survey in late 2015) and based on questions requesting respondents to recall their preferences in the past (prior to irrigation investments).

[13] Water User Association (WUA) is a group of water-users, such as irrigators, who pool their financial, technical, material, and human resources for the operation and maintenance of an irrigation system.

As survey respondents were questioned on multiple factors related to their individual, household, socio-economic, farming and irrigation preferences in addition to a specific query on well-being; the study was not presented to farmers as a survey seeking to explicitly determine well-being responses to modernised irrigation infrastructure. This unique dataset, therefore, represents an important opportunity to establish a link between modernised irrigation infrastructure and subjective well-being perceptions based on primary evidence from farmers across several related variables. We use the survey data to build a logistic regression model with a dichotomous dependent variable representing subjective well-being controlling for exogenous variables such as district-specific rainfall patterns, district fixed effects, socio-economic indicators, and irrigation and agricultural management practices of farming households in control and treatment areas.

5.2.2 Data source

5.2.2.1 District selection and sampling framework

For the household survey, five districts were selected to survey farming households in command areas that received MPWSRP investment (treatment households) and in command areas that did not receive any investment (control households). The selection was based on a multistage purposive and random sampling techniques. Socio-demographic data of the five survey districts in terms of land area, population figures, per capita income and other information are provided in Table 8. Table 8 illustrates that per capita income from the 2004-05 period to 2011-12 has roughly doubled across all districts. Total canal irrigated area fluctuates with two out of the five districts reporting a decrease in the irrigated area over time. District-specific data is derived from the Government of India Census 2011 unless specified.

Households selected for the survey for both control and treatment groups were from WUA farming households with farmland in district command areas, therefore, survey households are sub-sets of the population from rural areas. We exclude sampling from

urban areas (specifically with respect to households from Bhopal and Gwalior districts, which have large urban populations). As surveys were conducted in surface irrigated command areas of the selected districts, total canal irrigated area is indicated for each district rather than the total cultivated area, which would include rain-fed and groundwater irrigated cultivated areas in addition to areas with surface irrigation (Table 8).

Table 8. Attributes of Five Survey Districts [14]

District Name	Population (2011) Area (Sq. Km)	Rural population (%) (2011)	Per capita income (USD) (2004-05)[15]	Per capita income (USD) (2011-12) [16]	Average literacy (%) (2011)	Total canal irrigated area (2006-07) (Ha)	Total canal irrigated area (2011-12) (Ha)	Number of total cultivators (2011) (No. & %)	Number of scheduled caste (2011) (No. & %)
Bhopal	2,371,061	19	629	1479	80.37	5,700	4,637	73,346	357,516
	(2,772)							(8.46)	(15.08)
Gwalior	2,032,036	37	480	1135	76.65	52,900	64,666	130,586	393,068
	(4,560)							(19.05)	(19.34)
Neemuch	826,067	70	397	822	70.80	3,300	10,461	175,602	111,162
	(4,256)							(41.94)	(13.46)
Ujjain	1,986,864	61	439	998	72.34	2,200	8,290	289,013	523,869
	(6,091)							(32.20)	(26.37)
Vidisha	1,458,875	77	307	668	70.53	39,900	34,674	168,615	292,144
	(7,371)							(30.63)	(20.03)

[14] All selected districts have BOTH areas that received MPWSRP investment and those that did not.

[15] See https://data.gov.in/catalog/district-wise-capita-income-current-prices#web_catalog_tabs_block_10

[16] See https://data.gov.in/catalog/district-wise-capita-income-current-prices#web_catalog_tabs_block_10

We incorporated rainfall profiles of the study area districts into our analysis to determine if rainfall patterns in the areas where households live, and farm have an influence on the well-being of farmers. In order to analyse rainfall, we use the same approach as previous research by Sinha et al., (2018). We analyse decadal intra-annual rainfall data to categorise the five districts into three rainfall zones: low rainfall, average rainfall, and high rainfall. These categories were used to determine whether the sample districts have low, average, or high rainfall over the same time horizon as the duration of the MPWSRP (2005-2015). Interannual rainfall levels for each district were determined by identifying the annual rainfall averages from 2005-2014 by averaging the 12 monthly rainfall values for all available rain gauge stations in each district[8]. Once the monthly average for each year was calculated, we then calculated the ten-year average for that district and classified each district according to its corresponding rainfall zone. If a district's 10-year average is within 10% of the 10-year average of all districts, it is classified as having *average rainfall* if the value is between 869–1062 mm (Sinha et al., 2018). If a district's average rainfall is more than 10% below the 10-year average of all districts, it is classified into the *low rainfall* zone if the value is below 869 mm (Sinha et al., 2018). If a district's 10-year average rainfall is more than 10% above the 10-year average of the selected districts, it is in the *high rainfall* zone if the value is above 1062 mm (Sinha et al., 2018).

[8] Monthly rainfall data from 2005-2014 for all districts was obtained from the Government of Madhya Pradesh (GoMP) Water Resources Department. Data was provided for all districts for each month (Jan – Dec) for the years 2005-2014. For each district, monthly rainfall values in millimeters are available for each of the rain gauge stations within the district. Data obtained was actual observed values for rainfall compiled by the Water Resources Department rather than satellite data.

Table 9 presents the selected survey districts divided into three distinct rainfall zones. We ensured that individuals were surveyed in districts from each of the three rainfall zones (Table 9).

Table 9. Categorisation of Survey Districts into Rainfall Zones

	Interannual Rainfall Variability Zones		
Sample survey districts	**Average**	**Low**	**High**
	Ujjain, Neemuch	Gwalior	Bhopal, Vidisha

5.2.2.2 Sampling of farmers participating in the survey

In late 2015, a cross-sectional household survey was designed and led by the corresponding author and a team of enumerators from the Madhya Pradesh Water and Land Management Institute (WALMI). To determine the sample size of the household survey, a multi-stage purposive and random sampling technique was utilised (Fowler, 2002; Gebreyes and Muller-Mahn, 2019).

The first stage purposive selection used two criteria: a) selection of MPWSRP projects where irrigation rehabilitation works were completed for at least three years and where farmers would have access to rehabilitated irrigation infrastructure for a minimum of three years (at the time of the survey) and b) inclusion of major, medium, and minor irrigation schemes. This criteria for selection reduced the original population size from a total of 228 MPWSRP investments in irrigation schemes across 6 river basins and 21 treatment districts to 38 projects across 10 districts and 5 river basins as illustrated in the table in supplementary Table 23. This unique access to data about the MPWSRP irrigation projects was provided to us directly by the Madhya Pradesh Water Resources Department (WRD). As indicated in Table 23, the cluster of 38 projects comprised of 1 major, 4

medium, and 33 minor irrigation projects. From the cluster of 38 projects, a total of 10 MPWSRP irrigation projects were randomly selected consisting of 1 major, 2 medium and 7 minor projects across five districts and three river basins (supplementary Table 24).

The second stage was to identify the number of WUAs to be surveyed within the selected MPWSRP projects. We identified a total of 19 WUAs registered to the corresponding command areas of the selected 10 MPWSRP investment projects (supplementary Table 24). Lastly, to determine the number of households to be surveyed within each WUA, individual farmers were selected at random within each WUA. However, we attempted to include an equal ratio of the head, middle, and tail-end farmers based on the location of WUA member farmer plots within their respective command areas. We also attempted to include both male and female respondents, however, the majority of the WUA members in MP are men. This resulted in a proposed sample size of 277 farmers surveyed from the treatment areas across the five districts and ten MPWSRP irrigation projects (supplementary Table 24).

A similar process was followed for the selection of irrigation projects for the control households. First, it was important that we selected "no-investment" irrigation projects from the same five districts where treatment MPWSRP projects, WUAs, and farmers were selected. From a long list of irrigation projects provided to us by the MP WRD, a total of 15 irrigation projects (that did not receive investments from the MPWSRP or from any other government sources) were randomly selected across the same five districts (supplementary Table 25). This implies that the "control irrigation projects" were not modernised or rehabilitated by investments from MPWSRP or from other Government of Madhya Pradesh programmes at the time of the survey. Second, the final sample of selected irrigation projects was associated with a total of 12 WUAs from which a total of 430 farming households, were randomly selected to participate in the survey (supplementary Table 25). We recognise that the treatment and control samples are not the same size and that the control group size is larger, which could lead to biased treatment effects. We partly address this potential limitation in the robustness checks to the main model.

5.2.2.3 Instrumentation & Survey Questionnaire

As mentioned in the Introductory section, previous studies have illustrated the existence of a positive relationship between water access and gains in subjective well-being in developing countries. However, to the best of our knowledge, no study has assessed whether this same relationship holds for the availability of rehabilitated irrigation systems among rural smallholder farmers in India. We, therefore, wish to fill this gap and answer the following research question: *does modernised irrigation infrastructure influence the well-being of smallholder farmers in Madhya Pradesh?*

In order to estimate an answer to this research question, the household survey elicited data about individual farmer members of WUAs on four individual, household, and farm-level domains after each respondent verbally provided informed consent. The categories included a) respondent and household characteristics; b) household assets including land ownership status; c) agricultural methods used; and d) irrigation practices preferred. Agricultural practices related to the choice of crops grown and crop yield responses to irrigation infrastructure modernisation are excluded from this study as these variables are central to the study conducted by Sinha et al., (2018). It is important to note that the survey was not explicitly presented as a *well-being* survey. Instead, prior to posing a specific question regarding "well-being" to farmer respondents, both control and treatment households were asked about (in addition to queries about their assets and socio-economic characteristics) their primary sources of irrigation, the status of their irrigation canals in specific cropping seasons, canal conditions (in the past (2005) and present (at the time of the survey)), dates of canal gate openings, distribution schedule of irrigation systems, and conditions of their sluice gates. The same questions were posed to both treatment and control groups and therefore primed both groups about irrigation quality and access to canal water related to the irrigation systems in their respective command areas.

With respect to enquiring about subjective well-being, respondents in the treatment cohort were asked to assess the influence of the modernised irrigation system on their perceived well-being and whether this was different from the perception of their well-being

prior to the system being rehabilitated (in the past). For the control group, respondents were asked to assess the influence of the irrigation systems in their command area on their perceived well-being and whether this was different from their perception in the past (in 2005). For both the treated and the control group, the question refers specifically to irrigation systems that are in the command areas of the WUAs that we surveyed and from which respondent farmers directly withdraw irrigation water to irrigate their crops (when available). Although the MPWSRP officially began in 2005, specific rehabilitation projects began at different times in different districts with a mean start date of 2008 (Sinha et al., 2018). In the sample of farmers in the treatment cohort, four out of ten of the MPWSRP rehabilitation projects selected for the survey began in 2008 (40% of the sample), while three out of ten began in 2006 (30% of the sample) (supplementary Table 24). Thus, the survey questionnaire requests farmers to recall the "past" for their well-being perceptions between nine to seven years ago with respect to the "present" (2015). However, the "past" in the case of the control group is in reference to farmer perceptions of their well-being in 2005, a ten-year recall period.

This difference presents a limitation of the results of the analysis as the treatment and control recall periods are not the same (e.g., nine to seven years recall period for the treatment group and 10 years for the control group). We address this limitation by presenting t-test results of well-being responses among survey respondents as well as graphical analysis of the differential levels of improvement in well-being between farmers with access to modernised irrigation canals versus farmers with surface systems that were never modernised, prior to running estimations of the logistic model. We also run a series of robustness checks with different stratifications or subclassifications of the sample, which is a technique that can be used to partly reduce bias due to the unequal sample size (D'Agostino 1998). One robustness check, specifically, selects households from the treatment population that reside in command areas where irrigation rehabilitation began in 2006 and 2007. This reduced our sample size to 201 farmers and limited the analysis to only two out of the five districts studied. This robustness check enables us to repeat the analysis with a recall horizon gap that is smaller between the treatment and control groups.

The characteristics of our data represent the main strength of our study. In fact, previous research on the impacts of irrigation and agricultural programs on rural poverty in India tend to generalise their findings across multiple states (Bathla et al., 2017; Fan et al., 1999, 2008) or limit their analysis to public expenditure and resulting income and wage effects for the rural poor from irrigation infrastructure interventions (Bathla et al., 2019). We believe that the richness of our dataset allows us to avoid these gaps in previous studies. Our study relies on a unique mix of data at a sub-national and sub-basin scale including data on district-specific rainfall patterns across multiple river basins (Betwa, Chambal, and Sindh), secondary data on specific irrigation infrastructure projects from the Government of Madhya Pradesh, and over 700 responses from smallholder farmer individuals farming in command areas with differential access to surface irrigation representing diverse hydrological environments, agricultural preferences, and socio-economic profiles. Among those surveyed, some farmers had access to renovated and rehabilitated irrigation systems while farming households in control areas had access to surface systems that were never modernised or upgraded by the WRD (at the time of the survey). Similarly, the nuanced nature of the household survey, which did not explicitly focus on well-being alone and the resulting dataset allows us to include in our empirical analysis the respondents' current age, educational background, household assets owned, caste profile, and access to government-supported "poverty" alleviation programmes, which provides a rich picture of the socio-economic characteristics in addition to the well-being responses of the individuals surveyed beyond household wages and farm income variables.

5.2.3 Empirical Methods

5.2.3.1 Summary statistics

We analysed summary statistics of our sample and performed t-tests based on three themes: a) district rainfall zones and location of households among survey districts; b) household, well-being, and socio-economic characteristics of respondents; and c) irrigation and agricultural practices. For the household, well-being, and socio-economic characteristics of respondents, we examined variables such as age, sex, number of household members,

whether the household reported improvements in well-being, education, caste, house ownership, main sources of income, ownership of physical assets such as media assets (radio and television), communications assets (computer, having access to Internet, telephone, and mobile phone), and ownership of transport assets (bicycle, motorbike, and automobile). We also included variables that determine the socio-economic poverty status of farmers such as ownership of a Below the Poverty Line (BPL) card[17] as well as a Kisan Credit Card[18].

Under the irrigation and agricultural practices theme, we analysed differences in respondent farm plot location in their canal systems (e.g. head, middle, or tail), preferred irrigation methods (flood, check basin, drip or sprinkler methods, ridge and furrow, and border strip), and whether farmers adopted the following advanced agricultural practices or used the following machinery: 1) use of High Yielding Varieties/hybrid seeds, 2) use of sprinkler and drip technologies, 3) tractor, 4) thresher, 5) automatic seed drill, and 6) harvester.

5.2.3.2. Estimation of logit model

We develop and estimate empirical models of changes in subjective well-being to specifically test the effect of rehabilitated irrigation infrastructure after controlling for the specific individual, household, hydrological, socio-economic, irrigation and agricultural characteristics that could potentially influence the well-being of farmers in our sample. The core of our analysis relies on the estimation of a logit model with district fixed effects. We take note of each farmer's self-reported response to the survey question related to well-being by constructing a binary dependent variable on subjective well-being. The responses were combined into a single variable labelled "well-being improved" = 1 if farmers

[17] The Food and Supplies Departments of state governments in India issues "Below Poverty Line" ration cards to individuals who are earning an income below the official Government of India poverty line of $1.90 per day. This card entitles individuals holding these cards to be given subsidized allocations of rice and wheat by the state governments Public Distribution Scheme.
[18] Kisan Credit Card is a credit card to provide affordable credit for farmers in India. It was started by the Government of India, Reserve Bank of India (RBI), and National Bank for Agriculture and Rural Development (NABARD) in 1998-99 to help farmers obtain access to timely and adequate credit.

reported "yes" that irrigation systems led to an improvement in their well-being and "well-being improved" = 0 if farmers reported their well-being stayed the same or got worse. The basic specification is presented in equation 3.

$$Pr(WellImp_{i,d} = 1) = F(\alpha + \beta Rehab_{i,d} + \theta X_{i,d} + u_d + e_{i,d}) \qquad (3)$$

where $WellImp_{i,d}$, our binary dependent variable, indicates a farmer's degree of change in well-being, where *i* indicates the farmer respondent and *d* the district location of their farm plot. This variable is equal to 1 if the farmer states an improvement in their well-being as a result of irrigation systems, and 0 otherwise. The term u_d stands for the district fixed effects which are included in all regressions to remove the impact on the well-being of fixed district-specific characteristics, which could be potentially correlated with our main regressor. $e_{i,d}$ is a random error term, which we assume to follow a logistic distribution.

The variable $Rehab_{i,d}$ is an indicator variable which is equal to 1 if the farmer respondent has a farm plot in a command area of the sample district which received investments from MPWSRP and 0 if the farmer has a farm plot in a command area of the district with no investments from MPWSRP. This variable represents our main explanatory variable.

$X_{i,d}$ identifies a vector of controls. We seek to ascertain the degree to which modernised irrigation systems influence well-being responses of farmers in comparison to other important individual, physical, household capitals and socio-demographic, and irrigation/agricultural characteristics and practices. Socio-demographic variables of interest include gender, number of household members, number of years of education, main sources of income for the farmer (as we do not assume all farmers only obtain their income from agricultural sources). These variables are included as they might independently affect farmer perceptions of their well-being (Berchoux and Hutton, 2019). We also control for specific household assets owned by the farmer such as ownership of a house (whether

permanent or semi-permanent), media assets, communications assets, and transport assets. Lastly, further advancing work by Zorondo and Rodriguez (2016) and Nadeem et al. (2018) we add controls for farm location (accounting for varying timescales in access to irrigation water depending on the location of the farm plot in the command area), irrigation methods used, and innovative agricultural practices adopted.

5.2.3.3 Robustness checks

As described in the previous section, we assume that the randomised approach used for sample selection is robust and is not limited by identification errors with the potential exception of unequal sample sizes of the treatment and control groups. However, in order to test the validity of our identification strategy, we introduce a set of robustness checks by controlling for a set of additional variables. As identification issues may arise when trying to establish a relationship between subjective well-being and rehabilitated irrigation infrastructure, as the exogenous independent variable for rehabilitated irrigation may exert diverse effects on well-being responses of farmers, we include new controls for socio-economic poverty, irrigation methods, and agricultural practices. To this end, we introduced additional variables to our model by (a) intentionally dropping some control variables and instead controlling for a subclassification of covariates such as district-specific rainfall interactions, BPL card ownership interactions, membership in specific caste groups, and Kisan credit card ownership interactions with the dichotomous dependent variable for well-being; and (b) running regressions with selected parts of the sample where the recall time horizon between treatment and control districts is reduced and the sample size between both groups is equal.

Specifically, in line with previous literature which identifies that environmental conditions (elevation, rainfall, soil quality) are a significant component of rural livelihoods and poverty, we include interactions with the rainfall zones of the sample districts and our binary independent variable for treatment (Iiyama et al., 2008; Kim, Mohanty, & Subramanian, 2016; Palmer-Jones & Sen, 2006). Literature evidence also highlights the hierarchical social complexity of class, caste, and gender in India, which are reflected in both men's and women's roles and participation in the labour market, including engagement

in agricultural activities (Ray-Bennett, 2009; Savath et al., 2014). Work by Berchoux and Hutton (2019) in India shows that members of socio-economically deprived caste groups (e.g., scheduled caste and scheduled tribe) suffer from social and economic exclusion, from a lack of access to certain types of assets and even from a social unacceptability to undertake some activities. Thus, we include robustness checks controlling for possible non-linear effects between specific socio-economic vulnerability variables (e.g., the caste of the farmer, whether the farmer owns a BPL card or a Kisan Credit card) as interactions with the binary explanatory variable or treatment. This type of analysis enables us to test whether rehabilitating and modernising irrigation systems matters more for the most economically and socially vulnerable households in our sample in comparison to parts of the sample that are relatively 'non-poor' (e.g., members of the general caste, who do not own BPL cards, etc.). We, therefore, check whether changing the way in which household poverty is measured affects the subjective well-being of farmers.

Lastly, we address the issue of varying time horizons for the recall period as well as the unequal sample size between treatment and control households by running an additional regression with a limited set of households. This regression includes 201 households restricted to farmers from Ujjain and Gwalior districts where MPWSRP projects began in 2006 and 2007. Although this significantly reduces our sample size, the findings are likely more robust.

5.3 Sample characteristics

In the full survey sample (e.g., 707 farmers), 39% have farm plots in the sample districts where MPWSRP made rehabilitation investments (277 farmers) and 61% have farm plots where no investments were made (e.g., 430 respondents). Tables 10-12 provides some details on the characteristics of these 707 respondents. These are reported for the sample by separating characteristics of respondents who have access to modernised and rehabilitated irrigation canals and those who do not.

In the first rows of Table 10, we can observe respondents' geographic distribution across the five survey districts as well as the distribution of the sample across the three rainfall zones. The table shows that farmers with rehabilitated irrigation systems are significantly more likely to live in high rainfall districts; less likely to live in average rainfall districts; and have no significant difference between the groups for the low rainfall districts. Farmers in the rehabilitated cohort are more likely to have their farms in Gwalior and Vidisha; less likely to be from Bhopal and Neemuch, and are equally distributed in Ujjain.

From Table 11 we observe that most farmers we sampled in both groups are male, as the number of female respondents is only 3% in the no rehabilitation group and 1% in the rehabilitation group. Despite the attempt to survey both male and female respondents, this finding is not surprising. Our survey targeted farmers who are members of WUAs, which in India tend to be predominantly male. This is due to formal and informal rules of WUA membership in India such as a) limited to farmers who have the rights to land ownership and b) cultural taboos around women participating in water management committees such as WUAs, which is seen as a male-dominated activity and tends to exclude female participation (IFPRI 2009; Meinzen-Dick and Zwarteveen, 1998; Panda, 2006; Quisumbing and Pandolfelli, 2010).

Next, respondents with access to rehabilitated irrigation canals are likely to have more household members, more likely to own a Kisan Credit Card, own a house and more likely to have a "semi-permanent" house; more likely to be in the Other Backwards Caste (OBC) caste (a socio-economically deprived and vulnerable caste group in India (Borooah et al., 2014)); more likely to own a radio, motorcycle, and an automobile; more likely to obtain income from poultry/meat production, business, services; more likely to own land; more likely to use hybrid seeds, automatic seed drills and harvesters on their farms (Table 11). Farmers with access to rehabilitated irrigation systems are also more likely to use flood irrigation methods compared to farmers with no access to investments from MPWSRP. Farmers without rehabilitated irrigation canals are more likely to have a rented house and "other" house ownership; more likely to live in a temporary house; more likely to be in the General Caste category, and more likely to own a bicycle. From Tables 11 and 12, we also observe that there is no significant difference in terms of the main source of income as 99%

of the sample in both groups obtain their income from agriculture production, are evenly distributed at the head, middle and tail-ends of their respective command areas, and have no significant difference in BPL card ownership.

Overall, the summary statistics reveal that respondents from the MPWSRP investment or treatment group are not identical in all characteristics with the sample from the no-investment group. Thus, the results of the model estimations are not comparing identical households as there are characteristics that are specific to farmers with farm plots in districts where systems were modernised. Lastly, the summary statistics on well-being reveals that farmers with access to modernised surface systems have a significantly higher probability of improved well-being (20%) in comparison to farmers with no irrigation investment from MPWSRP (Table 11). We illustrate this effect in Figure 15. The figure indicates that on average, although both groups in the sample experienced well-being that improved over time, farmers with modernised irrigation systems have a significantly higher improvement in their well-being in comparison to the no-investment group. Respondents with improvement in well-being are more likely, therefore, to be in areas with modernised irrigation systems. Farmers in the no-investment group, on the other hand, have a significantly higher probability (27%) of well-being that deteriorated or remained the same as in the past (Table 11).

Table 10. Summary statistics of sample rainfall zone & district-wise distribution

Independent Variables	No Rehabilitation (n=430) Mean (SD)	Rehabilitation by MWSRP (n=277) Mean (SD)	Difference in Means T-test (%) (p-value)
Rainfall zones			
Low	0.40 (0.49)	0.37 (0.48)	3% (0.43)
Average	0.38 (0.49)	0.27 (0.45)	11% (0.00)***
High	0.22 (0.42)	0.36 (0.48)	-14% (0.00)***
District of farm plot			
Bhopal	0.17 (0.37)	0.05 (0.22)	12% (0.00)***
Gwalior	0.34 (0.47)	0.49 (0.50)	-15% (0.00)***
Neemuch	0.25 (0.43)	0.05 (0.22)	20% (0.00)***
Ujjain	0.17 (0.37)	0.15 (0.36)	2% (0.58)
Vidisha	0.08 (0.27)	0.26 (0.44)	-18% (0.00)***

*p<0.05, **p<0.01, *** p<0.001

Table 11. Summary statistics of sample socio-economic characteristics, household assets, well-being, and main sources of income[19]

Independent Variables	No Rehabilitation (n=430) Mean (SD)	Rehabilitation by MWSRP (n=277) Mean (SD)	Difference in Means T-test (%) (p-value)
Age (years)	48 (11.4)	48 (14)	0 (0.90)
Female	0.03 (0.16)	0.01 (0.12)	2% (0.24)
HH members (persons)	7 (5.18)	8 (5.11)	-1% (0.01)**
Holds (BPL) card	0.17 (0.37)	0.15 (0.36)	-2% (0.54)
Holds Kisan credit card	0.23 (0.42)	0.40 (0.49)	-17% (0.00)***
Well-being response			
Well-being improved	0.34 (0.48)	0.53 (0.50)	-20% (0.00)***
Well-being same or worse	0.66 (0.47)	0.34 (0.47)	27% (0.00)***
House Ownership & Type			
Owned house	0.86 (0.35)	0.99 (0.12)	-13% (0.00)***
Rented house	0.06 (0.23)	0.004 (0.06)	6% (0.00)***
Other house ownership	0.08 (0.27)	0.01 (0.10)	7% (0.00)***
Permanent house	0.32 (0.47)	0.41 (0.49)	-9% (0.02)*
Semi-permanent house	0.002 (0.05)	0.09 (0.29)	-9% (0.00)***
Temporary house	0.68 (0.47)	0.50 (0.50)	18% (0.00)***
Education			
Highest Education (years)	8 (2.9)	8 (2.7)	0 (0.35)
Caste			
General	0.41 (0.49)	0.30 (0.46)	11% (0.00)***
OBC	0.52 (0.50)	0.60 (0.49)	-8% (0.04)*
Scheduled Caste	0.06 (0.24)	0.10 (0.30)	-4% (0.06)
Scheduled Tribe	0.007 (0.08)	0 (0)	0.7% (0.16)
Household Assets Owned			

[19] Below Poverty Line (BPL), Other Backwards Caste (OBC), household (hh), acres (ac).

Radio	0.28 (0.45)	0.13 (0.34)	-15% (0.00)***
Television	0.45 (0.50)	0.52 (0.50)	-7% (0.08)
Computer	0.01 (0.08)	0.02 (0.13)	-1% (0.17)
Internet	0.002 (0.05)	0.01 (0.12)	-0.8% (0.06)
Telephone	0.03 (0.16)	0.04 (0.19)	-1% (0.42)
Mobile phone	0.14 (0.34)	0.46 (0.50)	-32% (0.00)***
Bicycle	0.65 (0.48)	0.42 (0.49)	22% (0.00)***
Motorcycle	0.17 (0.38)	0.39 (0.49)	-22% (0.00)***
Automobile	0.03 (0.16)	0.06 (0.25)	-3% (0.01)**
Main source of income			
Agriculture	0.99 (0.08)	0.99 (0.10)	0 (0.59)
Horticulture	0.01 (0.08)	0.01 (0.10)	0 (0.59)
Dairy	0.30 (0.46)	0.33 (0.47)	-3% (0.41)
Poultry/meat	0 (0)	0.01 (0.12)	-1% (0.01)**
Business	0.01 (0.11)	0.06 (0.23)	-5% (0.00)***
Services	0.01 (0.10)	0.05 (0.22)	-4% (0.00)***
Leasing of agricultural tools	0.01 (0.11)	0.04 (0.19)	-3% (0.28)
Loans	0 (0)	0.01 (0.08)	-1% (0.08)
Farm Labourer	0.004 (0.07)	0 (0)	0.4% (0.25)
Other	0.07 (0.25)	.11 (0.31)	-4% (0.04)*
Land ownership			
Land owned (acres)	6 (5.6)	10 (13.8)	-4% (0.00)***
Land leased (acres)	11 (12.7) (n=2)	7 (5.4) (n=8)	4% (0.44)
Owned plot	0.99 (0.11)	0.99 (0.0)	0 (0.54)
Rented plot	0.01 (0.08)	0.01 (0.08)	0 (0.99)

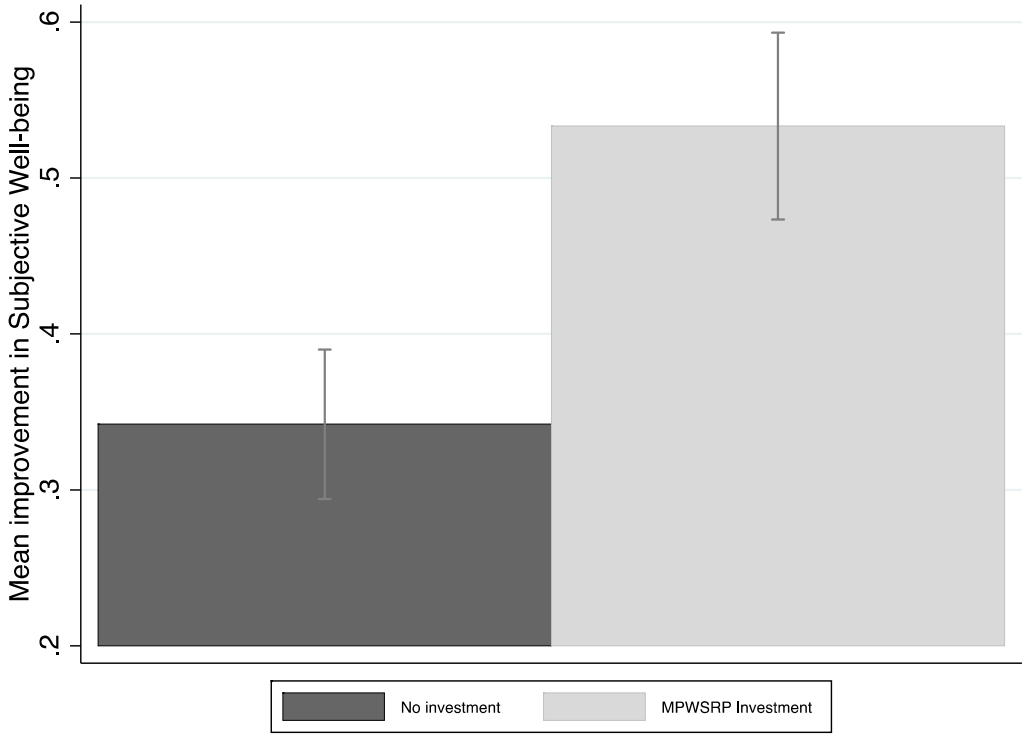
*p<0.05, **p<0.01, *** p<0.001

Table 12. Summary statistics of sample farm locations, irrigation, and agricultural practices

Independent Variables	No Rehabilitation (n=430) Mean (SD)	Rehabilitation by MWSRP (n=277) Mean (SD)	Difference in Means T-test (%) (p-value)
Farm location			
Head	0.34 (0.47)	0.32 (0.47)	2% (0.71)
Middle	0.32 (0.47)	0.35 (0.48)	-3% (0.47)
Tail	0.35 (0.48)	0.33 (0.47)	-2% (0.72)
Irrigation method			
Flood	0.83 (0.37)	0.90 (0.30)	-7% (0.01)**
Check basin	0 (0)	0 (0)	N/A
Drip/sprinkler	0.01 (0.10)	0.004 (0.06)	0.6% (0.35)
Ridge and furrow	0.02 (0.13)	0.01 (0.09)	1% (0.26)
Border strip	0.14 (0.35)	0.09 (0.28)	5% (0.03)*
Adoption of modern agriculture practices			
High yield varieties of seeds; hybrid seeds	0.39 (0.49)	0.67 (0.47)	-28% (0.00)***
Micro-irrigation technologies	*0.02 (0.14)*	*0.04 (0.19)*	-2% (0.16)
Tractor	0.91 (0.28)	0.95 (0.22)	-4% (0.08)
Thresher	0.71 (0.46)	0.74 (0.44)	-3% (0.30)
Automatic seed drill	*0.39 (0.49)*	*0.76 (0.42)*	-37% (0.00)***
Harvester	*0.28 (0.45)*	*0.63 (0.48)*	-35% (0.00)***

*p<0.05, **p<0.01, *** p<0.001

Figure 15. Mean subjective well-being response among farmers with MPWSRP investments in modernised systems and farmers without MPWSRP investments.



Note: The error bars follow a 95% confidence interval.

5.4 Results

5.4.1 Logistic regression analysis

To answer our research question, *does modernised irrigation infrastructure influence the well-being of smallholder farmers in Madhya Pradesh?* we formulate a hypothesis that access to rehabilitated irrigation infrastructure leads to improvements in well-being among farmers. This hypothesis is tested by analysing the impact of MPWSRP investments to modernise irrigation systems on a binary dependent variable representing a farmer's degree of change in well-being. We report our results in Table 13.

The first column reports the estimates of our basic logit specification where we include the explanatory treatment variable "rehabilitation" and a set of controls related to sex, household members, years of education and main source of income. The results reveal that rehabilitated and modernised irrigation canals have a positive and significant relationship with well-being improvement among farmers exposed to the treatment. In the second column, we consider additional controls including house ownership, house type, physical assets owned, farm location, preferred irrigation methods, and advanced agricultural practices adopted. We include additional controls for ownership of assets and house ownership as research indicates that households that are asset poor are more likely to be economically poor and vice versa (Filmer and Pritchett, 2001). Thus, one could argue that owning more physical assets implies economically better-off households, which could also potentially imply well-being gains. However, others such as Harttgen et al. (2013) and Howe et al. (2009) argue that asset indices correlate poorly with household consumption data and tend to over-estimate well-being improvements. Thus, we do not rely only on physical assets as control variables but also include other indicator variables that could potentially influence farmer well-being such as being located at the head of an irrigation canal (ensuring first rights of access to irrigation water), adopting irrigation technologies (e.g., using sprinkler or drip systems), and/or using other advanced agricultural practices on their farms which may contribute to improved agricultural outputs and thus contribute to gains in well-being (Foster and Rosenzweig et al., 1995; Makate et al., 2019; Ogandari and Bolarinwa, 2019).

The results in the first and second columns in Table 13 indicate that both coefficients are positive and highly significant as the coefficient of the main regressor is relatively unaltered (after additional controls). This indicates that there is a relationship between modernised irrigation systems and well-being improvements for farmers with respect to areas where no investments were made to upgrade irrigation infrastructure. To further interpret this result, we compute an Average Marginal Effect (AME) (Table 14). The first column in Table 14 indicates that keeping all other factors fixed, the probability of farmers on average reporting positive gains in well-being is 29% greater for farmers with rehabilitated irrigation systems than for farmers without; coinciding with a positive and significant coefficient in column 1, Table 13. In the second column of Table 14, when additional controls for physical asset ownership, irrigation methods, and agriculture variables are added; well-being improvements among farmers with rehabilitated irrigation canals is on average 28% greater in comparison to farmers without access to modernised irrigation infrastructure.

As mentioned in the summary statistics, agriculture is the main source of income for 99% of the sample, nonetheless, it is worth evaluating whether our results hold for all types of income sources including various types of agricultural activities. Indeed, column two results indicate that farmers who grow horticultural crops have a highly positive and significant well-being improvement as well as farmers who engage in dairy production (Table 13). Results of the summary statistics, however, reveal that only 1% of the sample in both groups is reporting horticulture production as their main source of income whereas 30-33% report dairy as their main source of income (Table 11). Lastly, owning a semi-permanent house as well as owning communications assets also illustrates a positive correlation with well-being gains. This illustrates that specific types of communication assets (e.g., owning a mobile phone) has a positive impact on well-being for farmers. We do not find any evidence that gender, number of years of education, or number of family members in the household has a significant effect on farmer well-being although as noted above, very few respondents in our sample are female. The location of the farm plot in the irrigation command area also does not enhance the well-being of farmers, nor does using

drip/sprinkler systems or other irrigation methods, except the ridge and furrow irrigation method.

Table 13. The influence of rehabilitated irrigation systems on the subjective well-being of farmers

	Influence on well-being	
Variables	**Full sample** (1)	**Full sample with physical assets, irrigation, and agriculture variables** (2)
Rehabilitation	1.788**	2.109***
	(0.82)	(0.76)
Female	-0.664	0.051
	(1.01)	(0.81)
Household Members	-0.00454	-0.012
	(0.04)	(0.04)
Highest years of education	0.147	0.130
	(0.12)	(0.13)
Income variables		
Main source of income: horticulture	3.753***	3.602***
	(0.75)	(0.84)
Main source of income: Dairy	0.538**	0.561***
	(0.26)	(0.21)
Main source of income: Business	-0.302	-1.531***
	(0.49)	(0.59)
Main source of income: Services	0.749*	0.0556
	(0.43)	(0.69)
Main source of income: Leasing agricultural tools	-1.962*	-2.635**
	(1.18)	(1.38)
Main source of income: other	0.839**	0.958***
	(0.40)	(0.35)
Physical assets owned		
Permanent house		0.489
		(0.39)
Semi-permanent house		0.748*
		(0.42)
Media assets		0.157
		(0.40)
Communications assets		0.784*
		(0.42)
Transport assets		-0.00397
		(0.42)
Irrigation and agriculture variables		
Farm location: middle of canal		0.336
		(0.30)
Farm location: head of canal		0.269
		(0.29)

Irrigation method: drip & sprinkler		0.575
		(1.34)
Irrigation method: Border strip		0.691
		(0.76)
Irrigation method: ridge & furrow		4.042***
		(0.84)
Use of hybrid seeds		1.004
		(1.51)
Use of micro-irrigation techniques		-3.073
		(1.98)
Constant	0.565	0.0082
	(0.87)	(0.91)
District Dummies	YES	YES
N	427	387
bic	-209.23	-160.05
Pseudo R^2	0.29	0.40
Note:	Robust standard errors in parenthesis. standard errors clustered at the district-level *p<0.05, **p<0.01, *** p<0.001	

Table 14. Average Marginal Effects (AME) of the effect of rehabilitated irrigation systems on well-being

	Influence on well-being	
Variables	**Full sample (dy/dx)** (Standard error)	**Full sample with physical assets, irrigation and agriculture variables (dy/dx)** (Standard error)
	(1)	(2)
Rehabilitation	0.29	0.28
	(0.12)	(0.09)
N	427	387

5.4.2 Robustness checks

To ensure the robustness of our results, we present in this section a set of alternative model specifications. Our goal is to check that a re-formulation of the main model still generates consistent results, which align with the findings presented in Tables 6 and 7. First, we explore whether interactions with the rainfall variability profiles of the districts exerts a stronger effect on well-being, second we examine whether controlling for different socio-economic poverty indicators changes well-being responses, and lastly, we reduce the time recall period between the two cohorts and test whether the results of the logit estimation hold.

5.4.2.1 Rainfall variability and subjective well-being

As discussed in previous sections, it can be argued that the degree of rainfall variability of a specific district (e.g., districts in the low rainfall zone imply that intra-annual rainfall is below average) may exert a stronger effect on well-being than an "investment in infrastructure effect". Sinha et al. (2018) determine that MPWSRP investments in irrigation rehabilitation have little to no effect on crop yields in low rainfall areas of Madhya Pradesh; implying that crop yields, despite rehabilitated and modernised irrigation canals, are still sensitive to fluctuations in rainfall patterns. As yields tend to influence farmer incomes directly, it can be argued that rainfall availability is likely to exert a stronger effect on farmer well-being than modernised irrigation systems. To assess the validity of this conjecture, we run our full model by including a dummy variable for rainfall zones. We also include an interaction term between rainfall and rehabilitation. By including an interaction term, we can further our understanding of whether the rainfall zone of a sample district moderates the effect of rehabilitated irrigation systems on farmer well-being. We report the results of our estimates in Table 15.

Overall, the results presented in columns one and two in Table 15 show that independent of rainfall zones, the influence of rehabilitated irrigation systems on well-being among farmers remains stable, positive, and significant. To further interpret the results, we present predictive margins results of the main results by comparing findings across the three rainfall zones when treatment=0 (no investment from MPWSRP) and when treatment =1 (investment by MPWSRP) (Table 16).

Table 15. Rainfall variability interactions and subjective well-being

Variables	**Influence on well-being**	
	Rainfall Zones	
	(1)	(2)
Rehabilitation	2.052**	3.637**
	(0.890)	(1.466)
Rainfall zone	-1.939**	-1.261
	(0.812)	(1.525)
Rehabilitation x Rainfall zone		-0.937
		(1.137)
Main source of income: horticulture	3.302***	2.884***
	(1.060)	(1.068)
Main source of income: Dairy	0.987***	0.923***
	(0.326)	(0.353)
Main source of income: Business	1.032**	1.178**
	(0.508)	(0.559)
Main source of income: Services	1.498**	1.471**
	(0.606)	(0.606)
Main source of income: Leasing agricultural tools	-0.200	-0.219
	(0.922)	(0.884)
Main source of income: other	0.438	0.390
	(0.521)	(0.544)
Female	-0.737	-0.753
	(0.792)	(0.762)
Number of household members	0.0156	0.0171
	(0.0402)	(0.0395)
Highest years of education	0.191	0.173
	(0.133)	(0.135)
Permanent house	0.630	0.600
	(0.716)	(0.703)
Semi-permanent house	1.813***	1.825***
	(0.189)	(0.226)
Constant	5.53	1.47
	(2.44)	(3.80)

District Dummies	YES	YES
N	427	427
bic	-183.98	-182.12
Pseudo R^2	0.37	0.38
Note:	Robust standard errors in parenthesis. standard errors clustered at the district-level *p<0.05, **p<0.01, *** p<0.001	

Table 16. Predictive margins

Influence on well-being (n=427)		
Variables	**No rehabilitation** **Predictive Margins** (Standard error) (1)	**Rehabilitation** **Predictive Margins** (Standard error) (2)
Low rainfall zone	0.48	0.87
	(0.19)	(0.07)
Average rainfall zone	0.29	0.56
	(0.05)	(0.06)
High rainfall zone	0.17	0.25
	(0.11)	(0.12)

Based on the analysis of the predictive margins, we compare the relative difference in predictive margins results between the rehabilitated group (column 2, Table 16) and the no investment group (column 1, Table 16), keeping rainfall constant. The difference in the predictive margins results illustrates that, keeping all factors constant, in areas with low rainfall and rehabilitated infrastructure well-being gains are 39% higher compared to no-investment areas. In areas with average rainfall, we see that rehabilitated areas have well-being improvements that are 27% more than in no-investment areas, and 8% more in high rainfall zone districts with rehabilitated systems (Table 16). This implies that in districts with rehabilitated irrigation systems and lower than average rainfall, well-being gains were five times higher in comparison to the high rainfall zone and gains were three times higher in areas with average rainfall in comparison to the high rainfall zone.

This finding extends the work of Sinha et al. (2018) who find that modernised irrigation canals contribute to increases in crop yields for rice and wheat crops in districts with average rainfall in Madhya Pradesh. These results enhance the findings that modernised irrigation systems lead to relatively higher crop yields, where simultaneously there are greater well-being improvements for farmers in average rainfall zones in comparison with areas with no investments and similar rainfall variability patterns.

In contrast, Sinha et al. (2018) identify that in low rainfall districts, irrigation investments have little to no effect on improvements in crop yields for rice and wheat crops. However, we see from the relative difference in the predictive margins results that despite lower than average rainfall levels; the relative gains in well-being are strongest in low rainfall areas with rehabilitated irrigation systems in comparison to areas with no investments as well as average and high rainfall areas. However, we note the interaction term between rehabilitation and rainfall zone on the well-being of farmers is not significant, but the coefficient for rehabilitation is larger, positive, and significant. Additionally, the results presented in Table 15 columns 1 and 2 align with the main results that obtaining income from horticulture, dairy, business, and services as well as owning a semi-permanent house are positive and significant predictors for well-being improvements even when controlling for variations in rainfall variability at the district-level.

5.4.2.2 Socio-economic poverty indicators and subjective well-being

We measure household socio-economic poverty (in addition to queries around physical asset ownership) by including survey questions to determine an individual's caste group (e.g., general, OBC, scheduled caste, scheduled tribe), whether they own a BPL card (yes or no), and whether they own a Kisan credit card (yes or no). In addition, we also include interaction terms between each of these variables and rehabilitation. We include these additional variables as they are different ways to measure household poverty levels. In this robustness check, we are controlling for whether changing the way in which household poverty is measured affects well-being responses to the availability of irrigation. We also

run this check to test for possible non-linear effects between these varying poverty measures and rehabilitation. We report the results of our estimates in Table 17.

Table 17. Ownership of BPL card, Kisan credit card, caste membership, and subjective well-being

	Influence on well-being					
Variables	**Owning a BPL card** (1)	**Owning a BPL card** (2)	**Owning a Kisan credit card** (3)	**Owning a Kisan credit card** (4)	**Caste** (5)	**Caste** (6)
Rehabilitation	1.80**	1.607**	1.885**	1.704**	1.735**	0.781
	(0.811)	(0.80)	(0.809)	(0.862)	(0.812)	(0.537)
BPL Card	-0.617	-1.374***				
	(0.852)	(0.399)				
Rehabilitation x BPL card		1.955				
		(1.313)				
Kisan credit card			-0.505	-0.817**		
			(0.430)	(0.382)		
Rehabilitation x Kisan credit card				0.618		
				(0.376)		
Caste					-0.192	-0.487***
					(0.152)	(0.167)
Rehabilitation x Caste						0.508
						(0.377)
Main source of income: horticulture	3.953***	4.325***	3.843***	3.948***	3.723***	3.767***
	(0.569)	(0.982)	(0.752)	(0.810)	(0.706)	(0.757)
Main source of income: Dairy	0.508**	0.472**	0.511**	0.508**	0.504*	0.546**
	(0.207)	(0.231)	(0.251)	(0.249)	(0.279)	(0.227)
Main source of income: Business	-0.357	-0.292	-0.443	-0.382	-0.346	-0.338
	(0.488)	(0.488)	(0.420)	(0.415)	(0.475)	(0.487)
Main source of income: Services	0.730	0.723**	0.662	0.697	0.860*	0.711
	(0.467)	(0.365)	(0.461)	(0.457)	(0.498)	(0.511)

Main source of income: Leasing tools	-1.850	-1.565	-1.773	-1.883	-2.090*	-2.079*
	(1.392)	(1.328)	(1.133)	(1.177)	(1.088)	(1.069)
Main source of income: other	0.886**	0.761**	0.810**	0.861**	0.848**	0.901**
	(0.374)	(0.342)	(0.375)	(0.355)	(0.373)	(0.358)
Female	-0.747	-0.776	-0.521	-0.566	-0.574	-0.387
	(0.937)	(0.971)	(1.014)	(1.036)	(1.069)	(1.018)
Number of household members	-0.0023	0.0025	-0.0035	-0.0022	-0.0070	-0.0096
	(0.0355)	(0.0374)	(0.0346)	(0.0327)	(0.0399)	(0.0382)
Highest years of education	0.135	0.130	0.148	0.146	0.150	0.142
	(0.104)	(0.112)	(0.117)	(0.117)	(0.119)	(0.124)
Permanent house	0.691	0.704	0.810	0.849	0.740	0.759
	(0.600)	(0.618)	(0.604)	(0.592)	(0.556)	(0.559)
Semi-permanent house	1.302***	1.346***	1.522***	1.447***	1.290***	1.311***
	(0.284)	(0.324)	(0.405)	(0.440)	(0.302)	(0.312)
Constant	0.757	0.873	0.567	0.611	0.882	1.46
	(0.775)	(0.883)	(0.821)	(0.837)	(0.833)	(1.04)
District Dummies	YES	YES	YES	YES	YES	YES
N	426	426	426	426	427	427
bic	-207.54	-203.84	-207.49	-206.82	-208.47	-207.18
Pseudo R^2	0.292	0.305	0.292	0.295	0.291	0.296
Note:	Robust standard errors in parenthesis. standard errors clustered at the district level *p<0.05, **p<0.01, *** p<0.001					

Table 18. Predictive margins and BPL card ownership

Influence on well-being (n=426)		
Variables	**No rehabilitation Predictive Margins** (Standard error) (1)	**Rehabilitation Predictive Margins** (Standard error) (2)
Holds BPL Card (0)	0.35	0.61
	(0.06)	(0.05)
Holds BPL Card (1)	0.18	0.70
	(0.06)	(0.20)

Table 19. Predictive margins and Kisan credit card ownership

Influence on well-being (n= 426)		
Variables	**No rehabilitation Predictive Margins** (Standard error) (1)	**Rehabilitation Predictive Margins** (Standard error) (2)
Holds Kisan credit card (0)	0.35	0.63
	(0.06)	(0.06)
Holds Kisan credit card (1)	0.24	0.60
	(0.06)	(0.08)

Table 20. Predictive margins and caste membership

Influence on well-being (n= 427)		
Variables	**No rehabilitation Predictive Margins** (Standard error) (1)	**Rehabilitation Predictive Margins** (Standard error) (2)
Other Backwards Caste (OBC)	0.38	0.597
	(0.05)	(0.04)
Scheduled Caste	0.30	0.600
	(0.06)	(0.07)
General Caste	0.23	0.604
	(0.06)	(0.10)

Overall, the results presented in Table 17 allow us to conclude that rehabilitation significantly increases the likelihood of well-being improvements, even after controlling for whether a farmer owns a BPL card, owns a Kisan credit card, and membership in a specific caste group. Our main results reported earlier remain stable, however, the exception is column 6, where rehabilitation has a positive coefficient but is no longer significant. Also as expected, the influence of rehabilitation reduces slightly but not too much from the results reported in Table 13.

Looking at columns 1 and 2, the rehabilitation coefficient is positive and significant and the coefficient for ownership of a BPL card is significant yet negative. The comparative predictive margins result for BPL card ownership in Table 18 illustrates that farmers who own a BPL card in areas with rehabilitated irrigation systems are 52% more likely to experience well-being improvements compared to farmers who own a BPL card but are in command areas with irrigation systems that were not rehabilitated. Farmers who do not own a BPL card are 26% more likely to experience positive gains in well-being if they are in areas with rehabilitated systems versus areas without investments (Table 18). This illustrates that farmers who own a BPL card, implying that they are more economically poor, and have access to rehabilitated irrigation canals, on average, have a greater

likelihood of experiencing well-being improvements in comparison to farmers who do not own a BPL card yet have access to modernised irrigation systems. Looking at column 2 in Table 17, there is no significant interaction between owning a BPL card and irrigation infrastructure rehabilitation. It could be *a priori* argued that modernised irrigation systems might not be a determinant for well-being gains if a farmer is socio-economically poor and owns a BPL card. However, the coefficient is positive, which implies that the influence on well-being is independent of whether a farmer owns a BPL card.

The findings of columns 3 and 4 in Table 17 show that rehabilitation of irrigation systems is a significant predictor of positive changes in well-being even after controlling for ownership of a Kisan credit card. Although the influence of rehabilitation on well-being remains stable, positive, and significant, it is lower than the results in Table 13. This indicates that the main results of the model are robust. The comparative predictive margins results presented in Table 19 show that on average the probability of farmers experiencing well-being improvements is once again higher in rehabilitated areas (and even higher for farmers who own a Kisan credit card). Once again examining the relative differences in predictive margins values, farmers who own a Kisan credit card and are located in areas with rehabilitated systems, on average, see their well-being improve by 36% more than farmers who own a Kisan credit card but do not have access to rehabilitated irrigation systems (Table 19). Farmers who do not own a Kisan credit card yet have access to rehabilitated irrigation see a 28% higher improvement in their well-being compared to farmers without access (Table 19). In comparison, farmers who do not own a credit card and are in areas with rehabilitated systems witness slightly higher gains in well-being (63%) than for farmers who own a Kisan credit card (60%) and are in rehabilitated areas. This finding may imply that farmers in rehabilitated areas with Kisan credit cards are more likely to have the ability to purchase farm inputs, machinery, etc. on credit for their farming needs, which may enhance well-being from rehabilitated infrastructure compared to farmers without a credit card and with no access to modernised canal irrigation. Column 4 in Table 17, however, illustrates that the interaction term between rehabilitation and Kisan credit card ownership is positive but not significant. Like findings for BPL card ownership,

this implies that gains in well-being for farmers with access to modernised irrigation canals are independent of whether they own a Kisan credit card.

Column 5 in Table 17 shows that rehabilitation is a significant predictor of well-being improvements after controlling for a farmer's caste. However, column 6 shows that when the interaction term between caste and rehabilitation is included, then rehabilitation is positive but no longer significant. The coefficient for caste and improvement in well-being is negative and significant; this indicates that farmers in more socially vulnerable and deprived caste groups are less likely to experience well-being gains compared to farmers in the General Caste group. This is reflected in the predictive margins results presented in Table 20. In alignment with previous predictive margins results, keeping caste membership constant, farmers with access to rehabilitated irrigation systems, on average, see their well-being improve to a greater degree than for farmers in no investment areas (Table 20). However, the comparative relative differences in results indicate that farmers with access to rehabilitated irrigation systems from the General Caste group see their well-being improve by 37% more than for farmers in the same caste group but without access to modernised systems. Farmers in the scheduled caste group see 30% more gains in well-being and farmers in the OBC group see 22% higher well-being improvement than among farmers in similar castes groups without access to modernised irrigation (Table 20). Overall, this illustrates that the gains in well-being are nearly double in the General Caste group compared to gains in well-being in the OBC group and slightly higher in comparison to the scheduled caste group (Table 20).

Overall, across all columns, farmers for whom the main source of income is horticulture production, dairy, as well as the "other" category; owning a semi-permanent house remains strong significant and positive determinants of well-being regardless of controls for diverse measures of poverty (Table 17). On the other hand, variables such as gender, education, number of household members and owning a permanent house are never significant predictors of well-being improvements for farmers in our sample.

5.4.2.3 Reduced recall period and subjective well-being

In this robustness check, we reduced the "recall time horizon" between farmers in the rehabilitation cohort and non-rehabilitation cohorts by running our main model specification with households only from Ujjain and Gwalior districts, where irrigation systems began to be modernised in 2006 or 2007 for the treatment group. This reduced the overall sample size to 201 households with an equal number of households in the control and treatment groups. In Table 21, we report the results of our estimates by running the main regression of the full sample with added controls for number of household members, highest years of education, house ownership, physical assets owned, farm location, and advanced agricultural practices.

Results indicate that there is a significant and positive influence on well-being as a result of rehabilitation for farmers in Gwalior and Ujjain districts. These results are reassuring and confirm the robustness of the main model estimation despite the limitation in our survey design of diverse recall periods and unequal sample sizes between the treated and the non-treated groups. This illustrates that despite the reduction in the sample size the coefficient remains stable, positive, and significant aligning with previous model results. This gives us confidence in the main model's specifications that there is indeed a positive and significant association with individual well-being due to modernised surface irrigation systems compared to farmers who do not have upgraded irrigation systems.

Next, we present the Average Marginal Effect results in Table 22. The AME results indicate that, on average, farmers in Ujjain and Gwalior have a 21% higher likelihood of experiencing well-being improvements in areas where irrigation systems are rehabilitated compared to farmers in areas where irrigation systems are not upgraded (Table 22). As expected, this number is slightly lower than the 29% and 28% AME results presented in Table 14, respectively for the different regressions. This aligns with the fact that we are running the model with smaller sample size. However, in contrast to the results in Table 13, we now see that the number of household members has a positive and significant relationship with well-being; the AME difference on average is only 1% greater

improvement in well-being for farmers relative to the number of members in their household. Increased number of years of education has a negative but significant relationship with well-being; the AME indicates that this is a relatively small difference in well-being of 2%. For farmers in Gwalior and Ujjain, we see that the use of hybrid seed varieties, on average, has a positive and significant influence on well-being, unlike in the main set of results, for which this control is never significant. Farmers who are using hybrid seeds, on average, see their well-being improve by 33% more compared to farmers who are not using hybrid seeds (Table 22). Being located at the head of an irrigation system also has a positive influence on the well-being of farmers in Gwalior and Ujjain but by a relatively small percentage of 5%. Lastly, farmers who own media assets, on average, experience a 13% negative and significant change in well-being compared to farmers who do not own media assets.

Table 21. Reduced recall time period and subjective well-being

Variables	**Influence on subjective well-being**
	Full sample with physical assets, irrigation and agricultural variables
	(1)
Rehabilitation	2.106***
	(0.211)
Number of Household members	0.140***
	(0.0213)
Highest years of education	-0.163***
	(0.0137)
Permanent house	-0.131
	(0.482)
Semi-permanent house	0.917***
	(0.0306)
Media assets	-1.325*
	(0.677)
Communications assets	1.536
	(0.971)
Transport assets	-0.284
	(1.087)
Farm location: Middle of canal	0.105
	(0.175)
Farm location: Head of canal	0.465***
	(0.0722)
Use of hybrid seeds	3.219***
	(0.668)
Constant	-3.012***
	(0.319)
District Dummies	YES
N	201
bic	-66.87
Pseudo R^2	0.52
Note:	Robust standard errors in parenthesis. standard errors clustered at the district level *p<0.05, **p<0.01, *** p<0.001

Table 22. Average Marginal Effects (AME) of the effect of rehabilitated irrigation systems on farmer well-being for reduced recall period

Variables	**Full sample (dy/dx)** (Standard error) (1)
Rehabilitation	0.21
	(0.03)
Number of HH members	0.01
	(0.003)
Highest years of education	-0.02
	(0.0004)
Semi-permanent house	0.10
	(0.10)
Media assets	-0.13
	(0.08)
Farm location: head of canal	0.05
	(0.01)
Hybrid seeds	0.33
	(0.05)
N	201

5.5 Discussion & Limitations

5.5.1 Discussion

The consequences of investments to modernise irrigation infrastructure are complex, multidimensional, and poorly understood in terms of the relationship with water poverty and well-being, as previous research has shown. This paper investigates how modernised irrigation systems influence well-being among smallholder farmers in Madhya Pradesh.

We find strong support for our hypothesis: having access to rehabilitated and modernised irrigation canals significantly increases the probability that a farmer will experience positive well-being changes compared to farmers without access to modernised surface systems. *Ceteris paribus*, farmers with improved irrigation systems are likely to report 20-30% improvement in well-being compared to farmers without access to modernised infrastructure. This result remains stable and consistent across most model specifications. The role that rehabilitated irrigation infrastructure plays in a farmers' perception of his or her well-being is independent of other confounding factors such as intra-annual rainfall variability of the district, owning a BPL card, owning a Kisan credit card, and membership in a socio-economically deprived caste. This is a signal that smallholder farmers perceive modernised irrigation assets to be a positive contributing factor to their well-being as this is a critical input into improved agricultural productivity. Therefore, our results further nuance the work of Dasgupta and Maeler (2001).

Our analysis shows that well-being improvements were higher in areas with rehabilitated infrastructure and deficient rainfall in comparison to average or high rainfall zones. This result could be a signal of farmers responding positively to improved access to surface irrigation thereby enabling them to irrigate their crops despite lower than average rainfall. However, it could also be a signal of farmers responding positively to other interventions that were simultaneously introduced along with the infrastructure modernisation such as participation in training programs for WUAs, which were part of the capacity building interventions under MPWSRP. However, we note that these factors were out of the scope of analysis of this study. Whether or not a farmer's WUA received

training along with technical details on how the selection of crops, soil conditions changed before and after the MPWSRP investments, as well as the role of groundwater irrigation in determining well-being outcomes for farmers were not analysed in this study. These aspects need to be explored in further research in order to enhance the understanding of how modernised and rehabilitated infrastructure availability combined with hydroclimatic change influences agricultural and well-being responses among farmers.

Our results show that there are subtle differences between respondents who are more socio-economically deprived (own a BPL card, own a Kisan credit card, are in the scheduled caste group) and how rehabilitated infrastructure influences their well-being. Although we note that the General Caste group experienced relatively higher well-being gains, our results reveal that scheduled caste and OBC farmers with access to modernised irrigation systems reported stronger well-being improvements than farmers in the same caste groups but with no access to modernised irrigation. The results show that the effect of modernisation on well-being matters more for the poorest sub-segments of the sample than the non-poor segments. The households that are considered the poorest among Indian society (holders of BPL cards, members of marginalized caste groups, holders of Kisan credit cards) are reporting positive changes in their well-being when exposed to modernised irrigation infrastructure compared to farmers without access. This finding, however, needs to be further explored to understand the role of exogenous factors such as external government policies and their influence on well-being for these communities. Our initial results seem to point to a promising effect of coupling government policies for rural poverty alleviation with modernised irrigation infrastructure, potentially resulting in even higher well-being gains for farming households. In other words, the combined effect of public investments in upgrading irrigation infrastructure *and* poverty alleviation policies (e.g., access to BPL cards and Kisan credit cards) contributes to stronger well-being responses among farmers.

The results also highlight that specific types of agricultural activities (e.g., growing horticulture crops, producing dairy products, using hybrid seeds and ridge and furrow

irrigation methods), represent a key determinant of well-being for farmers. Across all model specifications, independent of additional controls, growing horticulture crops and producing dairy is positive and significantly associated with well-being gains. Our findings align with existing literature, which finds positive income poverty-related benefits of farmers in India who diversify into high-value crops and more advanced farming techniques (Barrett et al., 2012; Brithal et al., 2015). This also implies a strong linkage between income poverty gains and well-being improvements, crop diversification, and modernised irrigation infrastructure. A caveat to this finding, however, is that most of the sample reported agriculture as their main source of income. Only 1% of the sample reported horticulture as their main source of income, implying low rates of adoption of horticulture crops in our sample, despite the strong gains in well-being reported in our results. The nature of why such few farmers adopted horticulture and whether this is associated with the availability of modernised surface irrigation requires further investigation. On the other hand, dairy production, with about 30% of the sample reporting dairy as their main source of income, is correlated with a strong positive and significant influence on well-being for farmers, regardless of respective controls. Other forms of income such as services and the "other" category also revealed positive and robust well-being responses.

We note that when we limited our sample size in the last robustness check, the use of hybrid seeds became positive and significant, whereas in the previous model specifications it was not significant. This potentially provides insight into how advanced practices of farming (both choice of crop type (cereal vs. horticulture), dairy, and use of different farm inputs such as hybrid seeds) can further enhance well-being for farmers when these practices are coupled with access to modernised irrigation infrastructure. However, the factors driving farmers to adopt these practices were out of the scope of this study. Further research is needed to investigate the underlying causes of well-being gains for diverse sources of income, for the use of hybrid seeds, and preferences for irrigation methods such as ridge and furrow. Assets such as owning a semi-permanent house and owning a mobile or landline telephone were also positive contributors to well-being for farmers, whereas, adopting water-efficient irrigation technologies and non-seed related advanced agricultural practices did not contribute to well-being gains.

5.5.2 Limitations

We recognize that there are limitations to studies that measure subjective well-being outcomes. Diener (1994) points out that subjective well-being is not a static measure; instead, it is composed of multiple ongoing reactions in the individual and these reactions are best understood as processes, not as discrete one-off measurements. Subjective measures are also typically prone to strategic, cognitive, comparative or reference point bias (Dolan and White, 2007; Kelman 2005; Schwarz and Strack, 1999). We caveat our findings as they are based on the use of cross-sectional survey questionnaires posed at one point in time for individual farmers and not from panel data; thus, we could not control for time and individual fixed effects that might affect well-being (Ferrer-i-Carbonell and Frijters 2004; Godoy et al. 2009). Additionally, results from this study might suffer from measurement errors in the outcome and the explanatory variables as subjective measures are an ordinal measure. Further limitations may also stem from the survey design which by the nature of the questions posed may induce compliance of positive well-being responses to rehabilitated irrigation infrastructure among farmers. It is often difficult to compare between individuals, as subjective measures are individual and unique to each person (Sen, 1979). However, as Dolan and White (2007) argue that although subjective well-being measurements can be crude at the individual level, they are less so at the aggregate level. Therefore, a measure to ensure the validity of subjective well-being results is to compare self-reports of individual well-being responses among a cross-section of the population as well as compare well-being changes among farmers in areas where investments were made and where investments were not made as we did in the analysis in this paper (Lepper 1998; Sandvik, Diener and Siedlitz, 1993).

Next, we are aware that measurement errors might also arise as people might not have an accurate memory of factors that influence their well-being in the present and the past, or may not have provided accurate information on their socio-economic conditions, irrigation infrastructure quality, and agricultural practices. It also may well be that a

person's assessment of their own well-being now and in the past is conditioned by material and psychological conditions that have little to do with the effectiveness of the MPWSRP irrigation program. We address the risk of these errors by means of the reduced recall period robustness check. However, another potential approach to address this limitation, for future studies would be to include a control in the regression for an individual who is inclined to be more optimistic or less optimistic which would control for whether a farmer is more likely to report positive changes in well-being.

There is also the potential that there is bias in our estimation, which would have either underestimated or overestimated the impact of rehabilitated irrigation infrastructure due to omitted variable bias driven by unobservable factors (Zaman et al., 2001). For instance, our analysis omitted variables that contribute to farm productivity and could thus influence well-being of farmers (e.g., how irrigation rehabilitation influences farm-level access to water, farm management decisions, access and quality of groundwater, quality of soils, access to other farm inputs, access to markets for crops, quality of road transport, and other exogenous factors that determine agricultural productivity). Variables such as farm-level gains from membership in a WUA, well-being impacts of attending training for WUA members funded by the MPWSRP, as well as the influence of political dynamics of irrigation in India on well-being were also excluded from our analysis. However, we attempted to minimize this limitation in the study design by random selection of households from the treatment and control group across districts, across rainfall zones, the inclusion of district dummies, and by introducing modifications to the core model in our robustness checks and constantly comparing between the two different cohorts to determine relative differences in well-being. Results suggest that our estimates are stable, consistent, and robust despite these limitations. Lastly, in future research collecting gender-disaggregated data on these parameters, which was out of the scope of this study, can also further contribute to understanding how women in rural farming communities experience well-being changes as a result of canal irrigated systems. This can contribute to existing work that explores differences in subjective well-being responses between men and women (Gartaula et al., 2012; Meisenberg and Woodley, 2015).

5.6 Conclusions

Our study focused on understanding the influence of modernised irrigation systems on a subjective measure of well-being, which enabled us to explore a complementary set of indicators beyond crop yield, farm income, and material goods measures alone (Stiglitz et al., 2009b). We find that in areas that are experiencing low rainfall, irrigation investments matter more for the well-being of farming households than in areas where there is average or high rainfall. These results extend the earlier work by Sinha et al., (2018) as gains in well-being can still occur even when crop yields do not respond positively to less than average rainfall after irrigation systems are modernised. Overall, our findings shed light on the need to evaluate returns from investments in irrigation modernisation not only from the perspective of irrigation supply improved or crop income increased but also from the perspective of changes in well-being experienced among rural farmers exposed to the investments.

The distributional impacts from this study suggest that farmers in the lowest and most socio-economically deprived sub-categories of our sample experienced gains in well-being. This has implications in the design of policies promoting agricultural water security and rural poverty alleviation in India. Often decisions around infrastructure investments are made based on engineering standards of physical systems or location in terms of the river basin, among other criteria (Sinha et al., 2018). Yet our results find that improved access to surface infrastructure, if combined with rural poverty alleviation programmes (e.g., access to BPL cards or Kisan credit cards), can enhance the well-being of vulnerable rural farmers in comparison to farmers who do not have access to or do not require pro-poor benefits nor have access to modernised irrigation infrastructure. Dairy production and to a lesser degree, horticulture production, as well as the use of hybrid seeds, illustrate that cereal crop production is not the only driver of well-being for farmers and that diversification into advanced farming practices may contribute to well-being improvements among smallholders.

Our findings call for greater attention to coupling data on rainfall variability patterns with multi-factor decision-making for future irrigation infrastructure investment projects. This also reinforces the need for policies that couple investments in modernised infrastructure with targeted poverty alleviation and farm-level extension interventions for poor and vulnerable farmers. Finally, the nature of why most farmers did not adopt horticulture crops or why specific types of advanced irrigation practices (e.g., using micro-irrigation) did not yield well-being gains is not well understood. This warrants further research into how the availability of surface irrigation influences the choices of farmers to adopt advanced agricultural practices and the resulting consequences for well-being outcomes.

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Supplementary Tables for Does irrigation infrastructure influence the well-being of smallholder farmers? Empirical Evidence from Madhya Pradesh, India

Table 23. First stage cluster sample of 38 MPWSRP projects

No.	Project name (38)	River basin	District	Scheme type
1	Langarpura	Betwa	Bhopal	Minor
2	Ghuwara Tank	Betwa	Sagar	Minor
3	Paniya Tank	Betwa	Sagar	Minor
4	Nanhi Tehri Tank	Betwa	Tikamgarh	Minor
5	Prem Sagar Mabai Tank	Betwa	Tikamgarh	Minor
6	Airora	Betwa	Tikamgarh	Minor
7	Bhitarwar Tank	Betwa	Tikamgarh	Minor
8	Bilwari	Betwa	Tikamgarh	Minor
9	Bund ka Murrah	Betwa	Tikamgarh	Minor
10	Chhutaki Tank	Betwa	Tikamgarh	Minor
11	Gidwasan	Betwa	Tikamgarh	Minor
12	Kandwa	Betwa	Tikamgarh	Minor
13	Kharon	Betwa	Tikamgarh	Minor
14	Kudiyala	Betwa	Tikamgarh	Minor
15	Mamon Tank	Betwa	Tikamgarh	Minor
16	Morpariya	Betwa	Tikamgarh	Minor
17	Para Tank (Badagaon)	Betwa	Tikamgarh	Minor
18	Shahpur	Betwa	Tikamgarh	Minor
19	Kethan Medium Tank	Betwa	Vidisha	Medium
20	Bardha Tank	Betwa	Vidisha	Minor
21	Ghaterapura Tank	Betwa	Vidisha	Minor
22	Jamwar Tank	Betwa	Vidisha	Minor
23	Jajon Minor Tank	Betwa	Vidisha	Minor
24	Morwan Tank	Chambal	Neemuch	Medium
25	Siloda Tank	Chambal	Shajapur	Minor
26	Koyalkhedi Tank	Chambal	Ujjain	Minor
27	Laxmipura Tank	Chambal	Ujjain	Minor
28	Pachola Tank	Chambal	Ujjain	Minor

29	Silarkhedi	Chambal	Ujjain	Minor
30	Narela	Chambal	Ujjain	Minor
31	Bhat Kamaria	Ken	Damoh	Minor
32	Bhartala Tank	Ken	Katni	Minor
33	Pabra Tank	Ken	Katni	Minor
34	Pali Tank	Ken	Katni	Minor
35	Bhonhari Tank	Ken	Sagar	Minor
36	Harsi	Sindh	Gwalior	Major
37	Paronch	Sindh	Shivpuri	Medium
38	Gurma Tank	Tons	Rewa	Medium

Table 24. Summary of stratified sample size of MPWSRP projects, WUAs, and farmers

No.	Name of project & start year of the project (10)	Name of District (5)	River basin	Scheme size	Number of WUAs (19)	Number of WUA farmers (277)
1	Harsi (2006)	Gwalior	Sindh	Major	9	135
2	Kethan medium tank (2007)	Vidisha	Betwa	Medium	2	27
3	Bardha tank (2008)	Vidisha	Betwa	Minor	1	15
4	Ghaterapura tank (2008)	Vidisha	Betwa	Minor	1	15
5	Jajon minor tank (2008)	Vidisha	Betwa	Minor	1	15
6	Morwan tank (2008)	Neemuch	Chambal	Medium	1	14
7	Langarpura tank (2009)	Bhopal	Betwa	Minor	1	14
8	Koyalkhedi tank (2006)	Ujjain	Chambal	Minor	1	14
9	Laxmipura tank (2006)	Ujjain	Chambal	Minor	1	14
10	Silarkhedi tank (2007)	Ujjain	Chambal	Minor	1	14

Table 25. Summary of stratified sample size for control districts

No.	Name of the project (15)	Name of District (5)	Number of WUAs (12)	Number of WUA Farmers (430)
1	Bahadurpur canal project	Gwalior	1	37
2	Ramowa canal project	Gwalior	1	36
3	Himmatgarh tank project	Gwalior	1	36
4	Sirsa dam project	Gwalior	1	36
5	Muradpur tank	Vidisha	1	33
6	Naren tank	Vidisha	0	Linked to other tanks
7	Bani tank	Neemuch	1	36
8	Dhangaon tank	Neemuch	1	36
9, 10	Malgarh and Lasur tanks	Neemuch	1	36
11	Kervan tank	Bhopal	1	36
12	Hataikheda tank	Bhopal	1	36
13	Jastakhedi tank	Ujjain	1	36
14	Undadasa tank	Ujjain	1	36
15	Tankaria	Ujjain	0	Linked to other tanks

6. Do modernized canals influence irrigation technology choices? Evidence from smallholders in Madhya Pradesh, India

"When the well's dry, we know the worth of water"

Benjamin Franklin

Chapter 6

Do modernized canals influence irrigation technology choices? Evidence from smallholders in Madhya Pradesh, India

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Abstract

Investments to modernize irrigation systems and subsidies to incentivize adoption of drip and sprinkler irrigation technologies are promoted to enhance agricultural productivity and sustainability of on-farm water use across India. We examine the effect of these two policies on farmer irrigation choices in surface irrigated farms in Madhya Pradesh. A logistic regression based on novel survey data from 918 farmers estimates a five per cent reduction in the probability that farmers will adopt drip or sprinkler technologies once irrigation systems are rehabilitated. Quantitative results are complemented with semi-structured interviews of farmers adopting drip or sprinkler irrigation, which suggest that: (1) open, gravity canals do not restrict drip and sprinkler adoption, (2) socio-economically vulnerable farmers are more likely to adopt these technologies when faced with water scarcity, and (3) social networks provide a stronger incentive for adoption as smallholders struggle to access government subsidies. Understanding the role of social networks in influencing the irrigation practices of farmers can complement supply-side infrastructure investments and financial incentive policies to enhance the water security of smallholders facing climatic risks to food production.

Keywords: Canal modernization; irrigation technology; subsidies; farmer behavior; India

6.1 Introduction

Meeting rising food demands while maintaining the sustainability of land and water resources is one of the greatest policy challenges of the 21st century (Hoekstra and Chapagain, 2008; Hoekstra and Mekonnen, 2012). Irrigation is the largest water consumer in the world, accounting for 70 percent of global annual freshwater withdrawals (FAO, 2018). Based on current water use patterns, water demand for food production is predicted to increase by 70 to 90 percent by 2050, far exceeding available freshwater resources (De Fraiture et al., 2007; Odegard and Van Der Voet, 2014). As such, interventions to grow more food with the same or reduced volumes of water, commonly known as 'more crop per drop', and improve canal irrigation are being promoted worldwide (Scheierling et al. 2016; Giordano et al. 2019). These interventions are also encouraged to adapt irrigated agriculture to some of the inevitable impacts of climate change (Kahil et al. 2015; Zaveri and Lobell, 2019) and, increasingly, returning water to ecosystems (Crossman et al. 2010). Surface irrigation infrastructure modernization and subsidies for modern irrigation technologies such as drip and sprinkler irrigation are two key policy actions adopted to accomplish these twin goals of increased productivity and resilience in the face of water scarcity and climatological change.

While modernization and increased irrigation efficiency can provide benefits, such as reduced labor requirements and improved crop yields, they also have some well-known limits. Particularly in relation to efficiency measures, Grafton et al. (2018) highlight the "paradox of irrigation efficiency" where switching from flood to drip and sprinkler systems does not automatically lead to a decline in water consumption. Instead, adoption of advanced irrigation technologies tends to result in increased on-farm water consumption, groundwater extractions, and higher water consumption per hectare as farmers switch to more water intensive crops (Venot, et al., 2017; Song et al. 2018). Pérez Blanco et al. (2019) reviewed over 240 water productivity intervention studies, finding that "higher irrigation efficiency typically contributes to intensification of water scarcity through increased water consumption in the agricultural process." Finally, while modernization and

subsidy programs often use water productivity (i.e., amount of crop production, either mass or monetary value divided by amount of supplied irrigation water) as a key indicator to measure performance, the literature also highlights that it cannot be pursued in isolation from other water management dimensions (e.g., ensuring equal access to subsidies and extension services, equality in water allocation) (Wichelns, 2015; Zhu et al. 2019).

The paradox of irrigation efficiency highlights the importance of understanding the complex issues involved in water use on surface irrigated farms, policy interactions and the behavioral responses of irrigators to diverse policy instruments (Garrick et al. 2020). Simply encouraging irrigators to adopt more efficient irrigation technologies via subsidies may not achieve intended outcomes (Wheleer et al. 2015). In fact, the benefits of behaviour change through financial incentives encouraging adoption of improved agricultural technologies and practices are often-overestimated (Thornton et al., 2017; Wheeler et al. 2020). This is in part due to the inherent limitations of supply-led approaches to development and the lack of understanding of the effects of policy actions on the behavior of irrigators, including limited attention to context-specificity and to farmers' priorities beyond increased agricultural productivity, and lack of appreciation of the socio-cultural contexts within which smallholder farmers operate (Orr, 2012; Lankford, 2009; Levidow et al., 2014; Venot et al., 2017; Liyama et al., 2018; Pilarova et al., 2018). In addition, little is known about the effects of multiple policy actions (e.g., irrigation modernization and subsidies) on farmers' water use and choices for irrigation technologies. Lankford (2013) points out that understanding the complexities of water management within irrigation systems has significance for resource efficiency complexity and debates around efficiency, which he argues reinforces the need to understand the details of water management at the spatial scale of the field and from the perspective of the farmer (Lankford, 2013, Chapter 3, pg. 45).

This paper sheds light on the debates surrounding the paradox of irrigation efficiency by examining farmers' choices for irrigation technology adoption in the context of two policy interventions in Madhya Pradesh, India. First, irrigation modernization as

part of the Madhya Pradesh Water Sector Restructuring Project (MPWSRP), a 400 million USD program funded by the World Bank in the Indian state of Madhya Pradesh aimed at improving water productivity[20]. Second, a state-wide subsidies program promoting the use of modern irrigation technologies (i.e., sprinklers and drip systems) among farmers in Madhya Pradesh. These policies were simultaneously introduced; offering an opportunity to examine the behavioural responses of infrastructure and technology subsidies on farmer irrigation practices.

The paper aims to explore changes in adoption choices for modern irrigation technologies among smallholder farmers in the context of these two policies. To achieve this aim, it employs a mixed methods approach combining logistic regression analysis of household survey data of 918 farmers with semi-structured interviews. To our knowledge this is the first study applying a mixed methods approach to understand how farmers' irrigation choices change in response to irrigation modernization interventions and subsidies, and whether these policies influence adoption behavior among farmers for drip and sprinkler technologies. The mixed methods approach helps to understand the paradox of irrigation efficiency and demonstrate *how* and *why* farmer choices for irrigation technologies differ after surface systems are upgraded and the implications of these behavioral responses on on-farm irrigation practices. In turn, this offers an analytical basis to better understand the drivers of water use behaviors among smallholders, contributing knowledge on the impacts of financial incentives and irrigation modernization investment measures for achieving water and food security, with implications for India and beyond.

[20] In the context of the MPWSRP, water productivity is defined as "the sum of the net multi-sectoral benefits per unit of water use in a river basin framework. This would include the net benefits of irrigated agriculture, fisheries, hydropower, drinking water, industries, navigation, and environmental or other uses of water" (World Bank, 2005).

6.2 Study Area

6.2.1 Irrigation policy in India

India has the largest irrigated area in the world, accounting for a fifth of the world's total share, and irrigation has played a major role in meeting national food demand (Shah and Kumar, 2008; Saleth, 2009; Manjunatha et al., 2016). Surface irrigation canals established during the British rule have historically been the main policy instrument for addressing hunger and famine risk across India (Jurriens, Mollinga, & Wester, 1996). Following independence, from the 1950s to 2001, the proportion of surface water to net irrigated area decreased and, in the 1990s, it decreased by 23% as growing reliance on groundwater irrigation contributed to the increase in the net irrigated area (Bhaduri et al., 2006). Agricultural sector growth in India, known as the 'Green Revolution' during 1967–68 and 1977–78, was largely dependent on groundwater irrigation with 55–60% of the Indian population directly or indirectly relying on groundwater for their livelihoods (Shah et al., 2003). Although groundwater irrigation contributed to the crop productivity gains of the Green Revolution, it was also associated with negative externalities (e.g., groundwater depletion, waterlogging, salinity of soil, water pollution, and biodiversity loss (Alauddin and Quiggin, 2008; Rasul, 2016). Shah et al. (2009) argue that the main factors behind the rapid decline in canal irrigation across India were the poor performance of surface irrigation systems, market failures, failure of participation of irrigation communities, and failure of public-sector agencies to deliver irrigation water.

Considering these environmental challenges, since the early 2000s irrigation policy priorities across Indian states have shifted from canal construction to large-scale public investments to rehabilitate and modernize aging irrigation systems to reduce dependence on unsustainable groundwater abstraction (Sinha et al., 2018). In particular, state governments across India focused on policies on irrigation modernization, defined here as the technical and managerial upgrading of irrigation schemes (including rehabilitation of physical infrastructure) combined with institutional reforms, with the objective to improve resource utilization (notably water) and water delivery services to farms (Burt 2013;

Biswas and Venkatachalam, 2015). Modernization was also accompanied by subsidies to incentivize farmers to adopt modern irrigation technologies such as drip or sprinklers to promote on-farm irrigation efficiency (Smith, 2004; Hussain and Hanjra, 2004; Narayanamoorthy, 2009a, b). Priorities of international donors shifted accordingly, with the World Bank providing support to multiple Indian states for canal modernization as well as capacity building for state irrigation agencies, institutional support to farmers and Water Users Associations (WUAs) within the context of Participatory Irrigation Management (PIM)[21](FAO 2012). As a result, irrigation engineers within Indian public sector agencies began focusing on the physical infrastructure part of canal modernization, which consists of canal lining and upgrading control structures, among other solutions. These measures aim to improve irrigation system efficiency and reliability of water delivery to farmers (Yu 2020).

In terms of demand management, high precision irrigation technologies (e.g. drip, sprinklers) have been widely promoted across India under the assumption that widespread adoption may enhance farm-level irrigation efficiencies, thereby benefiting the farmer with respect to reduced costs of labor, precision application of fertilizers and chemicals, minimizing leaching of nitrates and other pollutants, diversifying crops, and reduction in on-farm water use (Shreshta & Gopalakrishnan, 1993; Dhawan, 2002; MOWR, 2006; Narayanamoorthy, 2009a; Singh, 2017; Arya et al., 2017). However, Indian government subsidy policies to promote large scale demand for precision irrigation technologies have failed to take off (Sivanappan, 1994; Narayanamoorthy, 2003; Namara et al., 2007; Narayanamoorthy, 2009b; GoI, 2011; Venot et al., 2014; Malik et al., 2018; Suresh et al., 2018). Suresh et al. (2018) estimate that only 10 percent of the total modern irrigation potential in India has been achieved.

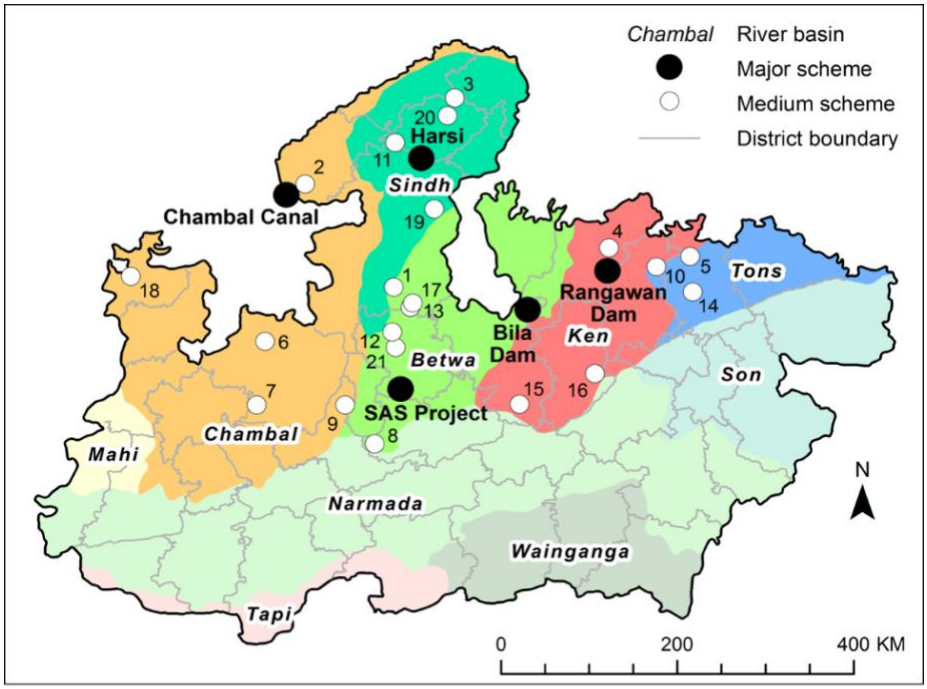
[21] Water User Association is a group of water users, such as irrigators, who pool their financial, technical, material, and human resources for the operation and maintenance of an irrigation system.

6.2.2 Irrigation modernization in the state of Madhya Pradesh

In 2005, the Madhya Pradesh government initiated a large-scale irrigation modernization program- the Madhya Pradesh Water Sector Restructuring Project (MPWSRP) - funded by the World Bank. The purpose of the project was to improve the productivity of water in the state through institutional reforms and technical upgrading of physical infrastructure across 26 districts in six out of the ten river basins of the state (Betwa, Chambal, Ken, Sindh, Tons, and Wainganga) (see Figure 1). A second-level objective was to increase the reliability of canal water in the state and reduce dependence on withdrawal of groundwater resources. Agriculture is one of the main employment and economic growth drivers for the state, with more than 70% of its labor force employ in agriculture (Sapre, 2014; World Bank 2016).

Upon closure in 2015, the project's impact evaluation reported that water productivity had been maximized in all target areas: 495,000 hectares of designed potential irrigation Culturable Command Areas (CCA)[22] was achieved within the six basins (Sinha et al., 2018). The project made a total investment of USD$ 443 million to rehabilitate 202 minor, 21 medium, and 5 major irrigation schemes for a total of 228 projects across 26 districts within the six river basins (Figure 1). Major projects are defined as projects with a CCA of more than 10,000 ha, medium projects have a CCA between 2000 to 10,000 ha, and minor projects have a CCA less than 2000 ha. MPWSRP investments in physical infrastructure included repair works on dams and embankments, reducing seepage, improving drainage, adding boundary stones, and fixing sluice and radial gates on irrigation tanks and canals that were no longer operational (Sinha et al., 2018).

[22] Culturable Command Area (CCA): The area that can be irrigated from an irrigation scheme and are fit for cultivation.



Medium schemes

1 Amahi	8 Dahod Tank	15 Machhariya Tank
2 AODA Medium Tank	9 Doraha Tank	16 Mala Tank
3 Bahadurpur Canal Project	10 Gurma Tank	17 Mola
4 Benisagar	11 Kaketo	18 Morwan Tank
5 Bhaiswar Tank	12 Kethan Medium Tank	19 Paronch
6 Chhapi	13 Koncha	20 Ramowa
7 Chillar Tank	14 Kulgarhi Tank	21 Ratapani Tank

Figure 16. Map of Major & Medium Irrigation Schemes Rehabilitated by MPWSRP

The project also created and trained over 400 Water User Associations to operate and maintain these systems in the project area. Kumar (2016) finds that following closure of the MPWSRP in 2015 and as a result of over 10-12 years of public investments in canal modernization, there was a substantial increase in the area irrigated by surface systems in MP. For instance, in the Chambal basin, the area irrigated by canals increased from 150,000 ha to 290,000 ha (Kumar 2016). This contributed to high levels of growth in the agriculture sector and a reduction in the percentage area under groundwater irrigation from 28.2% in 2002-03 to 16.2% in 2012-13 during the kharif cropping season (Kumar, 2016).

6.2.3 Subsidy policy for promoting modern irrigation technologies in Madhya Pradesh

The Indian government invested heavily in state-wide subsidy programs to promote the adoption of sprinkler, drip, and other relevant modern irrigation technologies by launching the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) in 2015 (GoI, 2017). This program was an extension of a previous scheme called the National Mission on Micro- irrigation (NMMI), which was implemented from 2010-2014. The objective of the PMKSY program is to target investments in the irrigation sector at the field level and provide subsidies for the adoption of modern irrigation technologies within Indian states. The scheme aims to assist Indian states to: a) increase the area under advanced irrigation technology (i.e., drip/sprinkler systems) to enhance water use efficiency; b) increase productivity of crops and income of farmers through precision water management; and c) promote relevant modern irrigation technologies in water intensive crops such as sugarcane, banana, cotton, as well as incentivize farmers to extend coverage of field crops under applicable modern irrigation technologies (e.g. sprinkler systems) (GoI, 2017). Coinciding with World Bank funding for MPWSRP, Madhya Pradesh benefited from central government funds for promoting modern irrigation from PMKSY.

In 2014-15, the central government allocated US$ 12.8 million to Madhya Pradesh for promoting on-farm water management and subsidizing adoption of modern irrigation technologies. The main objective of the state *Micro-irrigation Scheme* launched by the Government of Madhya Pradesh was to increase agricultural production by maximizing available irrigation water. Within this program, farmers are given financial assistance for purchasing micro-irrigation technologies for their farms based on the following: a) sprinklers – 80% subsidy up to a total maximum cost of Rs 12,000 Indian Rupees (approximately US$ 160) per hectare, b) drip irrigation – 80% subsidy up to a total maximum cost of Rs 40,000 (approximately US$ 530) per hectare, and, c) mobile rain gun – 50% subsidy up to a total maximum cost of Rs 15,000 (approximately US$200) per hectare (Government of Madhya Pradesh, 2020). The required eligibility conditions for applying for the state *Micro-irrigation Scheme* (which was funded by the national

Government of India PMKSY) are the following: a) all farmer residents of Madhya Pradesh are eligible, and b) all owners of agricultural land (Government of Madhya Pradesh, 2020).

The total land suitable for modern irrigation technology coverage in Madhya Pradesh is 1.38 million hectares, however, in 2015, the total area under sprinkler and drip irrigation against potential penetration was only 2.3 percent, below the national average of 5.5 percent (Grant Thornton India, 2016). As of 2008, the state's total drip irrigated area was 20,432 ha (about 1 percent of the potential) and as of 2015 this only went up to 352,117 ha (Grant Thornton India, 2016; Malik et al., 2018). Some studies find that drip and sprinkler technology adoption rates are limited in India because farmers with low levels of education, from vulnerable castes and at low poverty levels do not have the resources to adopt these technologies (Sivanappan, 1994; Narayanamoorthy, 2003; Maryena and Barrett, 2007; Namara et al., 2007; Narayanamoorthy, 2009b; Suresh et al., 2018). However, past studies analyzing drivers of irrigation technology often overlook perceptions towards irrigation technologies "through the eyes of farmers" (Lankford, 2013) as well as fail to analyze the nuances of adoption choices among farmers in areas where canal systems are modernized compared to areas where systems are not modernized.

6.2.4 Policy interactions

While the World Bank funded the MPWSRP infrastructure rehabilitation program (infrastructure reforms for enhanced canal water supply) and the Government of India PMKSY funded the state subsidy program (financial incentives for technology adoption) both policies aimed to improve water productivity. However, there was no *explicit* attempt by the Government of Madhya Pradesh to integrate these different policy approaches to harmonize interventions at the farm, system, and basin-scales. Despite being two distinct policy interventions, both programs shared the common goals of enhancing water productivity and were implemented roughly within the same timeframe, within the same study area districts, and targeted land-owning rural farmers with access to surface, ground, and/or rain-fed irrigation. Hence, these two distinct policy instruments provide a good case study to examine the interplay of infrastructure modernization and technology subsidy policies and their impact on farm-level irrigation practices.

To understand the impact of these policies on farmer irrigation choices in areas with and without modernized canal irrigation systems, we conducted surveys of farming households in six river basins in MP. We sampled farmers in districts where state subsidies and MPWSRP investments were made as well as within districts where only state-wide subsidies for drip and sprinklers were available but no MPWSRP investments were made to modernize existing surface irrigation systems. It is important to note that the state subsidy program was technically available to all farmers in Madhya Pradesh, agnostic of their source of water (canal, tank, tube well, well, or rain-fed). Farmers in our study area, including farmers residing in districts where canal systems were upgraded by the MPWSRP were equally eligible to access the government subsidy program as farmers in districts where no MPWSRP investments were made. This implies that all farmers in our study sample, regardless of their irrigation profiles could technically avail the subsidy. Next, in addition to MPWSRP and the state micro-irrigation scheme, a number of other government-funded programs that focused on promoting horticulture crop adoption, soil health, organic farming, rainwater harvesting, and other agriculture sector efficiency interventions were also available to the same farmers in the same river basins and districts as the study area. However, in order to tease out behavioral responses by farmers to the combination of modernized irrigation canals and financial subsidies, we restrict our focus to two policy interventions which directly target the management of water supply and demand in surface irrigated farms and exclude analysis of additional agricultural interventions at this stage.

6.3 Data and Methods

6.3.1 Household survey

6.3.1.1 Sampling strategy for household surveys

A cross sectional survey of 918 farmer households was conducted in late 2015. To identify districts to be surveyed, we classify them based on the attributes and size of irrigation investments they received, following earlier work (Sinha et al., 2018):

- *No rehabilitation*. Districts where subsidies were available, but farmers reside in surface command areas where canals and tanks were not rehabilitated by the MPWSRP. This is taken as the control group in our empirical analysis.
- *Low Rehabilitation*. Districts with irrigation systems where less than 10% of the irrigated area rehabilitated by MPWSRP and where subsidies were available to farmers. This is taken as the treatment group 1 in our empirical analysis.
- *High Rehabilitation*. Districts with irrigation systems where 30% or more of the irrigated area was rehabilitated by MPWSRP and where subsidies were available to farmers. This is taken as the treatment group 2 in our empirical analysis.

We select ten districts to survey farming households with investments in irrigation infrastructure ('Rehabilitation') and five districts which received no MPWSRP infrastructure funding (control or No rehabilitation districts) (Appendix A and B). Within both control and treatment districts, all target farmers participating in the survey had the following common characteristics: (i) membership in WUAs, (ii) access to surface and groundwater irrigation (through private tube or bore wells), and (iii) access to irrigation subsidies.

We also examine annual average rainfall availability for each district. The rainfall analysis was incorporated to ascertain whether there is a relationship between district level rainfall, which influences local water availability, and farmer irrigation technology choices. Spatial rainfall variability across Madhya Pradesh is high, and we group districts according to three categories following Sinha et al. (2018): low rainfall, average rainfall, and high rainfall. Table 26 shows the sample of districts selected following with this strategy. The sample was stratified into the number of irrigation projects within each district, number of

WUAs within each irrigation project, and number of farmers within each WUA. For the treatment or Rehab groups (treatment 1 & 2) districts, 27 MPWSRP irrigation projects (out of the total sample of 228 projects) were selected among the 10 total survey districts, 34 WUAs, and within the WUAs, a total of 408 famers, which was increased to 485 farmers to buffer post survey data cleaning. The final 27 projects were selected out of the original list of 228 MPWSRP irrigation rehabilitation projects within the treatment districts, as we selected projects where farmers would have access to water supply from rehabilitated irrigation infrastructure for at least three years at the time of the survey in 2015. The sample size of 27 projects consisted of 1 major, 3 medium and 23 minor projects. For the No Rehab or control group, 15 irrigation projects were selected among the 5 survey districts, 14 WUAs and 372 farmers, with a final sample size of 433 respondents. Summary tables of the stratified sample for both the Rehab and No Rehab categories treatment and control groups are included in supplementary Tables 32 and 33.

Table 26. Sampling approach of survey districts and interannual rainfall analysis

		Rainfall Zones		
Irrigation investment category by percentage of irrigated area rehabilitated	**Selected Survey Districts by Rehab Category**	**Average**	**Low**	**High**
	Low Rehabilitation (Treatment Group 1) (Less than 10% of irrigated area rehabilitated)	Ujjain*, Shajapur, Katni, Neemuch*	Shivpuri, Tikamgarh,	Bhopal*, Sagar, Vidisha*
	High Rehabilitation (Treatment Group 2) (More than 30% of irrigated area rehabilitated)	N/A	Gwalior*	N/A
	No Rehabilitation (Control Group)	Ujjain*, Neemuch*	Gwalior*	Vidisha*, Bhopal*

*Districts that fall into BOTH Rehab and No Rehab as some systems within these districts were rehabilitated and some irrigations systems were not rehabilitated under MPWSRP

6.3.1.2 Survey approach and focus

The purpose of the household survey was to determine a change (if any) in choices for irrigation technologies and farmer irrigation methods before and after the MPWSRP and state subsidy program. This was achieved by comparing farmer irrigation methods and technology choices observed at the time of the survey and MPWSRP project closure in 2015 with practices as the project began in 2005.

Due to the absence of baseline household data at the start of MPWSRP and state subsidy schemes, farmers were asked to provide two responses to each question: first, a response based on their current choices (in 2015 at the time of the survey) and second, a response based on their past choices (in 2005 at the start of the MPWSRP). Across all districts, all farmers were asked to respond to questions based on their current choices and

then recall their choices in 2005. We recognize that testing farmer choices based on memory has potential recall bias (Eisenhower et al., 1991; Arthi et al., 2018, Dillman et al., 2014). Given the presence of recall bias, it was important for us to include a control group to whom we asked the same questions as to the treatment cohort. This approach attempts to limit recall bias by comparison with the control group.

The survey focused on three main themes: (i) primary source of irrigation for the last Rabi or winter cropping season (bore well, tube well, or canal water); (ii) main method of irrigation for the last (Rabi season) (flood, drip or sprinkler, ridge and furrow, border strip, or check basin); and (iii) adoption of modern irrigation technology (either mini sprinkler, sprinkler or drip) for all crops across both cropping seasons (yes or no). In addition, farmer demographic, socio-economic data were also gathered to better understand the poverty profile of surveyed households. The sample survey questionnaire is shown in Appendices 2 and 3[23]. The sample sizes for both groups are provided in Tables 32 and 33.

6.3.2 Logistic regression

To assess the impact of the MPWSRP irrigation investment program (the treatment) on farmers' choice of irrigation technology, we construct a multivariate model using a logistic regression. The model is constructed to determine the choice probability of a farmer adopting either drip or sprinklers on their farms. A logistic regression is suitable for the analysis as it enables measurement of the difference between the expected change in the outcome variable of interest (whether a farmer uses modern irrigation technologies) among the farmers in the treatment vs. control districts.

[23] The Madhya Pradesh Water and Land Management Institute (WALMI) was responsible for conducting the survey. In order to execute the household survey, a strict code of ethics was followed in alignment with the University of Oxford Central University Research Ethics Committee requirements. Prior to the start of the household surveys, the lead author led a one-day enumerator training in Bhopal, Madhya Pradesh in November 2015 in partnership with WALMI and Water Resources Department officials, to prime the enumerators from WALMI on the objectives, approach, and questions related to the survey.

A potential endogeneity problem could occur if districts in the sample were pre-selected to receive investments from MPWSRP based on their low agriculture growth rates. This endogeneity issue could bias our results downward if we used a simple cross-sectional regression, as outcome variables might be lower in treatment districts. We address this issue of endogeneity by using a difference-in-differences estimator, using self-reported data from two different time periods to compare changes in outcome variables in 2015 and in 2005 in both treatment and control districts. This allows us to recognize and partially address the endogeneity issue by making the less strenuous assumption that these districts were faced with similar trends over time, with the one exception being the decision by the World Bank and state government to modernize irrigation infrastructure in districts which fell into target project river basins. Therefore, even if the treatment was applied to districts with lower agricultural growth, we will still be able to capture the treatment effect by comparing the change in districts which received investments from MPWSRP to the change in control districts.

In the model, we examine the following indicators: degree of treatment (none, low and high rehabilitation) and choice of irrigation technology (whether the farmer preferred to use drip or sprinklers). In addition, we include a fixed effect for farmers in the treatment group, as the initial choice probabilities within the two groups may be different and it is important to control for this initial difference, in order to measure the treatment effect. In our first specification, we include no additional control variables, other than the fixed effects for time and location. In the second specification, we include controls for: age, caste, Kisan credit card ownership, rainfall zone of district, land ownership status (owned, rented or farm labourer), and location of farm plot (head, middle, or tail-end of canal) representing a range of exogenous demographic, geographic, hydrological, socio-economic and farm location relevant variables which can exert an influence on farmer irrigation choices.

The model is computed using the following equations:

$$\text{Micro}_{it} = \frac{e^{Uit}}{1 - e^{Uit}} \quad (4)$$

$$\text{Where } U_{it} = ß_1 + ß_2 * \text{TreatmentDistrict_i} + ß_3 * \text{PostTreatment_t} + ß_4 * \text{TreatmentDistrict_i} * \text{PostTreatment_t} + ß * \text{Controls} + \varepsilon_{it} \quad (5)$$

In equation (4) Micro_{it} is defined as the choice to use drip or sprinkler technologies (0 or 1). e^{Uit} is the potential utility from using sprinklers or drip systems. In a random utility model, individuals choose modern irrigation technologies if their potential utility from using either sprinklers or drip is higher than their potential utility from the alternative (e.g., flood irrigation). Within the potential utility function, equation (5), β_1 represents the constant, β_2 represents the fixed effect within the treatment group, β_3 represents the time fixed effect, β_4 represents the treatment effect, and the β* indicates a vector of coefficients for the control variables. We also incorporated "degrees" of rehabilitation (e.g., low vs high) into the regression to determine whether "more" or "less" investment has a statistically significant relationship on a farmers' irrigation choice. We control for time effects by the inclusion of the variable *PostTreatment_t*.

6.3.3 Semi-structured interviews

In August-September 2018 we conducted telephone interviews[24] with a smaller sub-sample of farmers from the 918 households to develop a qualitative understanding of the drivers of irrigation adoption choices and nuance the household survey results. We pre-selected all farmers who had previously been surveyed in 2015, who responded "yes" to sprinkler/drip use and a small percentage of farmers who had responded "no" to sprinkler/drip use. Out of the total sample of 918 farmers surveyed, 49 farmers (5.3%) reported using either sprinkler (mini and normal) or drip technologies. A total of 80 farmers were selected at

[24] While face-to-face interviews would have been preferred, telephone interviews enabled us to have the opportunity to discuss factors driving farmer choices for modern irrigation technology adoption, broader farming practices, and develop a better understanding of the social context of farming households in the study area.

random to participate in the telephone interviews (49 farmers out of the 918 who replied "yes" and 31 farmers who replied "no"). All farmers who participated in the telephone surveys are male and members of WUAs. Out of the 80 farmers contacted for the telephone surveys, 26 (32.5%) survey responses were successfully recorded and analysed, due to issues of availability.

An overview of the profile and location of each of the 26 farmers interviewed is provided in supplementary Table 34. All farmers were interviewed directly by the main author in Hindi, following clearance from the University of Oxford's Central University Research Ethics Committee. Interviews were recorded and transcribed verbatim. Each interview lasted between 30-45 minutes as each question was designed in an open-ended manner to enable respondents to provide as much detail as they wished. The questionnaire utilized for the semi-structured telephone interviews is provided in Appendix 4. While the sample of semi-structured interviews (n=80) is small and does not represent a robust sample size for statistical tests to determine causality and isolation of the effects of the two programs under review in this study, it does provide nuance to our statistical and household survey results. This allows us to build a multifaceted analysis of drivers of irrigation practices of a sample of farmers.

6.4 Results

6.4.1 Empirical results

6.4.1.1 Socio-economic characteristics and well-being perceptions

Table 27 presents descriptive statistics results related to the socio-economic and well-being characteristics of farmers in the household survey. We present characteristics by dividing the sample among the farmers who reported never using irrigation technologies (n=866) and adopting drip or sprinkler technologies (n=49), with three responses dropped for lack of data. Farmers who never adopt irrigation technologies are more likely to live in a permanent house, to be a member of the General caste group, and to report better-off well-being perceptions with respect to the past at the 5% significance level. Farmers who report

using drip or sprinkler irrigation are more likely to hold a BPL card and are more like to be a member of the Scheduled Tribe caste group at the 5% significance level.

More than half (52 percent) of farmers adopting advanced irrigation technologies perceive their living standards to be worse off when compared to the past and are less likely to perceive their well-being to have improved. In contrast, a greater share (43 percent) of non-adopting farmers perceive their welfare to have improved (column C, Table 27). These initial results suggest that adopting farmers are relatively more socio-economically vulnerable than farmers not using sprinklers or drip systems on their farms.

Table 27. Farmer socio-economic status and well-being perceptions by technology adoption. Italicized p-values denotes cases where p-values are less than 0.05 and the mean between columns A and B is non-zero.

Independent Variables	A. No adoption (n=866)	B. Adoption (n=49)	C. Difference in mean (%)
	Mean (st.dev)	Mean (st.dev)	(A-B) (p-value)
Age (years)	47 (12.2)	44 (12.5)	3% (0.17)
Poverty – Holds (BPL) Card	0.25 (0.43)	0.52 (0.50)	*-27% (0.00)*
Holds Kisan Credit Card	0.53 (0.50)	0.45 (0.50)	8% (0.24)
House Type			
Permanent House	0.54 (0.50)	0.35 (0.48)	*19% (0.00)*
Semi-permanent house	0.105 (0.31)	0.16 (0.37)	-5.5% (0.21)
Temporary house	0.35 (0.48)	0.49 (0.51)	-14% (0.05)
Highest Education (years)	0.0842 (3.52)	0.0924 (2.90)	-0.8% (0.16)
Caste			
General	0.33 (0.47)	0.16 (0.37)	*17% (0.01)*
OBC	0.58 (0.49)	0.65 (0.48)	-7% (0.29)
Scheduled Tribe	0.08 (0.28)	0.18 (0.39)	*-10% (0.01)*
Well-being perceptions			
Worse off with respect to the past	0.19 (0.39)	0.52 (0.51)	*-33% (0.00)*
Same with respect to the past	0.38 (0.49)	0.20 (0.41)	*-18% (0.01)*
Better off with respect to the past	0.43 (0.49)	0.27 (0.45)	*16% (0.04)*

6.4.1.2 Quality of irrigation infrastructure, irrigation sources, and technology adoption

Tables 28 and 29 present descriptive statistics results related to the irrigation sources, quality of irrigation infrastructure, and preferred irrigation technology of farmers in the sample. Table 28 shows that in the control areas, farmers are significantly more likely to use groundwater (45%) (defined as the use of dug wells or bore wells or both in our survey) for irrigation compared to 18% of farmers residing in districts where MPWSRP investments were made (treatment areas). Farmers in the treatment areas are more likely to rely on canal irrigation (57%) compared to farmers in the control areas (41%). Reliance on canal water in treatment areas increased from 41% (in 2005) to 57% (in 2015), with t-test results in 2015 showing statistically significant p-values for use of canal irrigation if a farmer is located in a treatment area. This signals that the MPWSRP modernization investments did lead to some change in the primary source of irrigation for farmers, with more farmers relying on surface irrigation and reducing their groundwater use compared to 2005 in treatment areas. On the other hand, reliance on groundwater irrigation remained the same (45%) in the control areas from 2005 to 2015.

Table 28. Source of irrigation by irrigation investment category in 2005 and 2015. Italicized p-values denotes cases where p-values are less than 0.05 and the mean between columns A and B is non-zero.

Independent Variables	A. Control No rehabilitation (n=431)	B. Treatment Rehabilitation (n=485)	C. Difference in mean (%)
	Mean (st.dev)	Mean (st.dev)	(A-B) (p-value)
Primary Source of Irrigation (Rabi cropping season) 2005			
Groundwater (dug well and/or bore well)	0.45 (0.50)	0.21 (0.41)	*24% (0.00)*
Canal water	0.38 (0.49)	0.41 (0.49)	3% (0.31)
Primary Source of Irrigation (Rabi cropping season) 2015			
Groundwater (dug well and/or bore well)	0.45 (0.50)	0.18 (0.36)	*27% (0.00)*
Canal water	0.41 (0.49)	0.57 (0.43)	*-16% (0.00)*

Table 29 presents details about the differences in irrigation sources and irrigation methods, farm plot location and irrigation infrastructure availability between adopting and non-adopting farmers. Results indicate that adopting farmers are more likely to: a) use groundwater as their primary source of irrigation, b) use drip/sprinkler as well as check basin irrigation methods, c) experience deteriorated irrigation flow, canal breaches and siltation, at the 5% significance level. These farmers are situated at the tail-end of the canal system (45%), where traditionally water availability is limited if the canal networks are poorly maintained, compared to non-adopting farmers (33%) (Table 29). Non-adopting farmers are evenly distributed at the head (32%), middle (35%) and tail-end (33%) of the canal. Non-adopting farmers are more likely to use canal irrigation and use flood irrigation, have improved irrigation water flow in canals, experience improved canal breaches and silt conditions of the canals. Rainfall profiles are not significant in influencing outcomes across all farmer categories.

In summary, the results indicate that farmers are more likely to use drip and/or sprinkler technologies when they have limited surface water availability, due to declining canal water flow, breached, and silted canals. In this case, they tend to rely more on groundwater for irrigation. The results also indicate, however, that close to 20% of the sample of adopting farmers report canal irrigation as their primary source of irrigation, while also using drip or sprinklers on their farms (Table 29). Conversely, non-adopters identifying canal water as their main source of irrigation are more likely to be located on farms in districts where canal systems have been upgraded and modernized by the MPWSRP, as a higher percentage have improved breach and siltation conditions.

Table 29. Difference in irrigation source, irrigation methods, and quality of irrigation infrastructure by technology adoption. Italicized p-values denotes cases where p-values are less than 0.05 and the mean between columns A and B is non-zero.

Independent Variables	A. No adoption (n=866) Mean (st.dev)	B. Adoption (n=49) Mean (st.dev)	C. Difference in mean (%) (A-B) (p-value)
Farm Plot Location in Command Area			
Head of canal	0.32 (0.47)	0.31 (0.47)	1% (0.86)
Middle of canal	0.35 (0.48)	0.24 (0.43)	11% (0.14)
Tail-end of canal	0.33 (0.47)	0.45 (0.50)	-12% (0.10)
Primary Source of Irrigation (Rabi cropping season)			
Groundwater (dug well and/or bore well)	0.30 (0.46)	0.47 (0.50)	*-17% (0.01)*
Canal	0.51 (0.50)	0.20 (0.41)	*31% (0.00)*
Main Irrigation Method (Rabi cropping season)			
Flood irrigation	0.86 (0.35)	0.60 (0.36)	*27% (0.00)*
Drip/sprinkler	0.00 (0.00)	0.24 (0.43)	*-24% (0.00)*
Ridge & furrow	0.015 (0.12)	0.04 (0.20)	-2.5% (0.18)
Border strip	0.12 (0.32)	0.08 (0.28)	4% (0.43)
Check basin	0.005 (0.07)	0.041(0.20)	*-3.6% (0.00)*
Irrigation Water Flow in Canals			
Improved irrigation flow	0.29 (0.45)	0.1 (0.31)	*19% (0.00)*
Deteriorated irrigation flow	0.38 (0.49)	0.71 (0.46)	*-33% (0.00)*
Flow unchanged	0.23 (0.42)	0.12 (0.33)	11% (0.08)
Repair of Canal Breaches			
Improved breaches	0.24 (0.43)	0.02 (0.14)	*22% (0.00)*
Deteriorated breaches	0.34 (.48)	0.37 (0.49)	-3% (0.72)
Breaches unchanged	0.26 (.44)	0.60 (0.05)	*-34% (0.00)*
Siltation Condition of Canals			
Improved condition	0.27 (0.44)	0.04 (0.20)	*23% (0.00)*
Deteriorated condition	0.34 (0.48)	0.57 (0.50)	*-23% (0.00)*
Siltation unchanged	0.22 (0.42)	0.31 (0.47)	-9% (0.16)
Rainfall Zones of Farm Location			
Low	0.46 (0.50)	0.43 (0.50)	3% (0.66)
Average	0.3 (0.46)	0.265 (0.45)	3.5% (0.58)
High	0.24 (0.43)	0.31 (0.47)	-7% (0.27)

6.4.1.3 MPWSRP investments and choice probability for irrigation technology adoption

Results show a statistically significant and negative impact of irrigation infrastructure rehabilitation on the probability of a farmer adopting modern irrigation technologies (Table 30). The interaction of low rehabilitation (treatment 1) districts with control districts did not present any significant results and is excluded from the results in Table 30. In terms of control variables, results are negative and significant for the probability of a farmer using advanced irrigation technologies if a farmers' farm plot is located at the head (62%) and middle (43%) of an irrigation command system. Annual average rainfall availability for each district is not a statistically significant factor influencing adoption choices.

Table 31 shows the logistic regression results in terms of marginal effects, which illustrate the change in the choice probability of farmers adopting drip or sprinklers in treatment and control areas. This is determined by calculating the difference in choice probabilities of farmers adopting in control districts in 2015 with choice probabilities in 2005 compared to the difference in the treatment 2 districts in 2015 vs. 2005 (i.e., high rehab areas). Table 31 indicates that in districts where MPWSRP made a higher degree of investment covering a larger percentage of CCA, there is a greater reduction in a farmer's choice probability of choosing to use drip or sprinklers. Figure 3 graphically illustrates this. There is a four-percentage point decrease in the probability of a farmer adopting as a result of MPWSRP investment in the regression without controls. When controls are included, there is an even stronger five percentage point decrease in the probability of a farmer adopting (Figure 17)[25].

[25] The full list of controls used in the regression included ownership of a BPL card, ownership of a Kisan credit card, perceptions of well-being following rehabilitation (better, same, or worse off), location of farm plot in the command area (head, middle, or tail-end of the canal), land ownership, rainfall profile of district where farmer plots are located, ownership status of farm plot, and condition of irrigation canal. Regression table in Table 4 illustrates only partial list of control variables.

Table 30. Results of logistic regression analysis

	Probability of adopting drip/sprinklers		
	Coefficient (Standard Errors)	Logit average marginal effects (%) (without controls)	Logit average marginal effects (%) (with controls)
Rehabilitation			
High rehabilitation (Treatment)	0.26 (-0.32)	4.70%	5.70%
No rehabilitation (Control districts)	0 (0.00)	6.30%	6.40%
Years			
2005	0 (0.00)	7.20%	7.60%
2014	-0.25 (0.00)	4.40%	4.60%
Interaction			
Treatment districts in 2005	0 (0.00)	7.50%	9.00%
Treatment districts in 2014	-1.17** (-0.53)	2.00%	2.30%
Control districts in 2005	0 (0.00)	7.00%	7.10%
Control districts in 2014	0 (0.00)	5.50%	5.60%
Independent Variables			
Kisan Credit Card - 2005	-0.23 (-0.27)		
Kisan Credit Card 2014	0.24 (-0.25)		
Rainfall Zones			
Low	0.05 (-0.3)		
Average	-0.01 (-0.27)		
High	0 (0.00)		
Farm Plot Location			
Head	-0.62** (-0.26)		
Middle	-0.43* (-0.24)		
Tail	0 (0.00)		
N	1724		
LR chi^2	29.99		
Prob. >chi^2	<0.005		
Pseudo-R^2	0.04		

Notes:*p<0.05, **p<0.01, *** p<0.00

Table 31. Summary results of the difference in difference in choice probabilities in treatment group 2 (high rehabilitation) and control (no rehabilitation) districts.

	Choice probability of modern irrigation use (without controls)	**Choice probability of modern irrigation use (with controls)**
Change in the Control Districts	5.5% (2015) - 7% (2005)	5.6% (2015) - 7.1% (2005)
	-1.50%	-1.50%
Change in the Treatment Districts	2% (2015) - 7.5% (2005)	2.3% (2015) -9% (2005)
	-5.50%	-6.70%
Treatment Effect	-4%	-5.20%

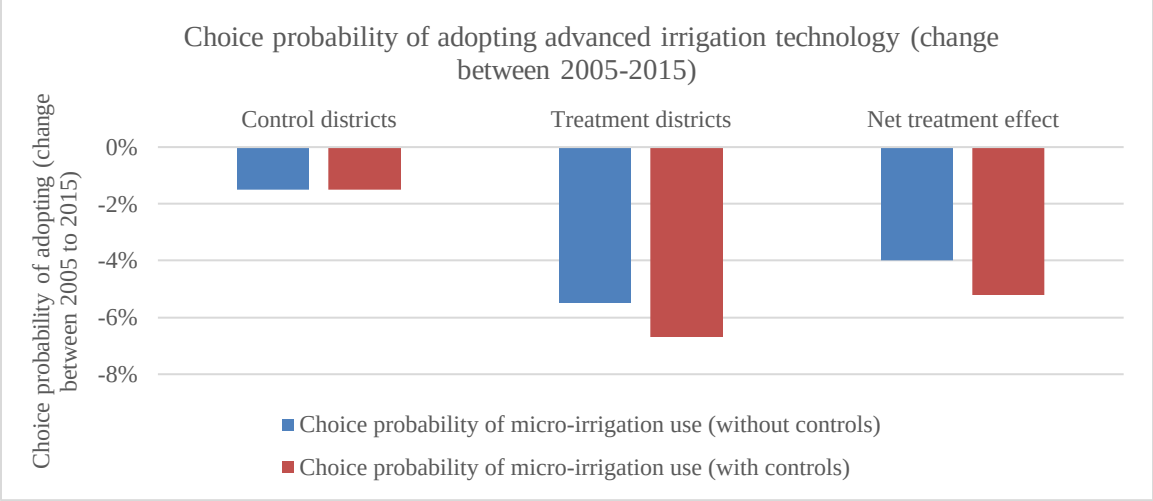


Figure 17. Marginal effects of degree of MPWSRP modernization investment on irrigation technology adoption choice probabilities.

The statistically significant results from the model specification illustrate that farmers with rehabilitated canals are less likely to adopt modern irrigation technologies and are also more likely to prefer to flood irrigate their farms when surface water from irrigation canals is available.

6.4.2 Attitudes, perceptions, and beliefs: evidence from semi-structured interviews

Of the 26 farmers interviewed in 2018, 18 (69%) reported "never" having used drip or sprinklers either in the past or at present, 7 (27%) reported "always" using modern irrigation technologies (prior to 2015 and continuing to the present), and only 1 (4%) farmer was not using drip or sprinklers in 2005 but was using it at the time of interview. All adopting farmers self-reported using sprinkler systems (either mini or large sprinklers) and only 2 farmers out of the 8 reported using both drip and sprinkler systems simultaneously. Adopting farmers were evenly split in terms of geographical distribution of farms, with 4 coming from treatment districts and 4 from control districts, which complements the results in Table 29, that farmers with access to open gravity canal systems (which were the predominant systems upgraded by the MPWSRP) are able to adopt. Interviewees reported that they have farm plots ranging from less than 1 ha, 1.5 ha to 3-5 ha, and up to 10 ha in size. Adopting farmers reported growing wheat with sprinklers during the Rabi season along with crops such as chickpeas, mustard, onions, garlic, and coriander. Those using drip systems reported growing chilies and 1 farmer reported growing a variety of golden apples with mini sprinklers.

A total of 14 (78%) out of the 18 non-adopting farmers live in districts where modernization investments were made and four (22%) live in control districts (Table 34). Among the non-adopting farmers, farm plots ranged from small sizes of less than 1 ha (5 farmers), to 4-5 ha, to larger plots ranging from 10 ha up to a maximum of 20 ha (Table 34). These farmers reported growing a mixture of soybeans, lentils, corn, peanuts and/or rice during the kharif or summer cropping season and wheat and/or chickpeas during the Rabi or winter cropping season – with some growing crops such as mustard and peas, in addition to wheat.

Five common themes emerged from analysis of the interviewee responses and are described below, supplemented with direct quotes from the interviews.

Water stress influences adoption: A majority of adopting farmers (7 out of 8) stated that one of the main reasons for adoption was due to deficient monsoons resulting in limited irrigation water and/or inadequate availability of water from canal systems. Water stress, therefore, seems to be influencing farmers' decisions to start using sprinkler or drip systems, which enables them to continue to farm the same basket of crops while reducing water consumption. In contrast, non-adopting farmers (15 out of 18) decided not to use sprinkler or drip systems because of the increased and more reliable irrigation water availability following modernization, which enabled them to flood irrigate their farms. Non-adopting farmers who have farms in districts with MPWSRP investments all reported using flood irrigation methods.

> *When the rains were deficient, farming became very difficult for me. Now there are new technologies for irrigation even when there is deficient rain, I use modern irrigation systems. For example, this monsoon season, rainfall is very deficient, and I see that my sprinkler systems are very effective - I can still grow my crops. Now I see that many farmers are using this technique on their farms in my village* (Farmer in Neemuch, no rehabilitation district, average rainfall, 1.5 ha, August 2018).

> *I have adequate surface irrigation canals and I get good access to water and I don't need to do micro-irrigation (Farmer in Katni, low rehabilitation district, average rainfall, 5 ha, August 2018).*

Adoption leads to time and efficiency gains: Adopting farmers reported time and efficiency gains, as they found that they could irrigate a larger area of land in less time. In contrast, farmers using flood irrigation reported spending more time on their farm to ensure water flows into their fields and physically move pipes.

> *I decided to switch to sprinklers - because it was hard to always do flood irrigation and it used to take a lot of hard work, now I can set the sprinklers and do my own housework and I can just leave them to irrigate my farm field; they take less time to irrigate and I don't have to be continuously sitting at my farm field and wait for*

> *the water to flood the field*" (Farmer in Katni, low rehabilitation district, average rainfall, 9 ha, August 2018).

Information changes behavior: Information about advanced irrigation technologies, its utility and benefits, and state subsidy opportunities, emerged as a key factor influencing adoption. Non-adopting farmers, especially farmers that self-reported good surface irrigation supply, stated that they had received little to no information on how to use sprinklers or drip technologies and their benefits. Farmers also pointed out the difficulties they faced in accessing information about the state subsidy, which contributed to reduced willingness to adopt. Lastly, farmers claimed that improved knowledge and training about irrigation technology would increase their willingness to adopt.

> *No one has explained modern irrigation techniques to us - we do not know how to use them, and we don't have any information about them - no one in our local market has explained anything about the subsidies we can receive from the government. I am currently doing flood irrigation in my farm – all farmers in my village are doing irrigation in the same way* (Farmer in Tikamgarh, low rehabilitation district, low rainfall, 10-11 ha, August 2018).

> *We are very stressed from big farmers (like me) to small farmers in my village, as we have not received any information on the government subsidy programs for purchasing micro-irrigation technologies and I have tried in several places to find out how it works but I have not been able to find out anything. I want to find out how to get the subsidy, so I can start using modern irrigation techniques* (Farmer in Shivpuri, WUA president, low rehabilitation district, low rainfall, 16 ha, August 2018).

Social networks influence farmer irrigation choices: The power of personal family and social networks emerges as a key driver influencing adoption. All eight adopting farmers reported first meeting a family member, relative, neighbour, or friend using drip/sprinkler systems and benefiting from the use, which encouraged them to subsequently adopt. Non-adopting farmers stated that they did not adopt these technologies because they did not

know anyone in their social network or village using them and preferred using flood irrigation. Farmers indicated that their irrigation choices are heavily influenced by the behavior of their neighbors. Specifically, among close knit farming communities, farmers reported that they preferred to watch, learn, and imitate one another.

> *If no one is doing micro-irrigation then I am not doing it - my big brother who has a farm next to mine - doesn't use these technologies - so I also don't do it* (Farmer in Gwalior, High Rehabilitation district, low rainfall, 1 ha, August 2018).

> *I first saw that my relative was using sprinklers and he lived close to me (about 15-20 km away) and I went to see his farm and he has been using irrigation technologies since 2001. He taught me how to do it and then I saw it and started doing it as well. In 2010, I bought the equipment in the market and there was no information on the subsidy then, so I bought it at full price.* (Farmer in Katni, low rehabilitation district, average rainfall zone, 9 ha, August 2018).

> *Yes, neighbors we watch each other – we all see each other's techniques easily because we have a small village - we copy each other, and we see what the other is doing and then we imitate it. We all have the same techniques; we are all using mini-sprinklers now on our farms.* (Farmer in Neemuch, no rehabilitation district, average rainfall, 1.5 ha, August 2018).

Access to the state subsidy matters: Several farmers reported issues of affordability, restrictions to subsidy access, and high upfront costs required to purchase modern irrigation equipment as factors prohibiting adoption. Specifically, lack of access to the state-wide subsidy scheme emerged as a major barrier to adoption. Out of the farmers that were aware of the subsidy, many reported that they were unsuccessful as local government officers in charge of administering the subsidy often asked for a bribe.

> *Buying the equipment from the market at full price is not possible for me, I would need to get access to the subsidy from the government, but I have no information*

about the subsidy" (Farmer in Katni, low rehabilitation district, average rainfall zone, 2.5 ha, August 2018).

Yes I would think about doing micro- irrigation - in the past some people have come to tell us about the subsidy for purchasing drip or sprinklers and have told us this is what you need to do to get the subsidy but I went to the Tehsil village leader and I wanted to access the subsidy - I couldn't get access to the funds because they wanted a "cut" from all the farmers (he refers to local officials who are in charge of providing the subsidy) - as I refused to pay the bribe they refused to give me the subsidy. This issue is everywhere, if you don't pay the bribe to the official - you don't get the benefits. I would use modern irrigation technologies if the subsidy were provided to me (Farmer in Katni, low rehabilitation district, average rainfall, 5 ha, August 2018).

6.5 Policy implications and conclusions

Governments and donors around the world spend millions of dollars improving irrigation infrastructure and subsidizing water efficient irrigation technologies to incentivize farmers to enhance the productivity and sustainability of water use in the face of climate change. This study takes the case of a World Bank and Government of Madhya Pradesh irrigation modernization and subsidy program to understand how these policy actions interact with farmer's water use behaviors and choices for adopting modern irrigation technologies.

The findings suggest that modernization investments were successful in achieving the intended objective of reducing farm dependence on groundwater irrigation and increasing reliance on canal water for food production. However, results suggest that after modernization, farmers are half as likely to adopt advanced irrigation technologies compared to areas where systems are not modernized. Although multiple factors contribute to farmer adoption decisions, insights from the descriptive statistics and semi-structured interviews reveal that better quality of canals and adequate quantity and timing of surface irrigation water to farm fields disincentivize farmers from adopting sprinkler or drip systems. The qualitative findings expose that in the absence of observing someone in their

social network adopt or receiving information about the benefits of modern irrigation technologies, farmers perceive that sprinkler and drip technologies are not relevant for them once access to surface water supply is improved.

These findings reinforce evidence of the “paradox of irrigation efficiency": simply modernizing irrigation infrastructure and encouraging adoption of advanced irrigation technology through subsidies may not necessarily lead farmers to conserve water and adjust their water use and crop choices towards efficient irrigation practices (e.g., see Pradham and Ranjan (2015) for a case study from India). This paper adds nuance to this established insight, showing the interaction between infrastructure modernization, subsidies for advanced irrigation technology adoption, and farmers’ irrigation choices. Results show evidence of a behavioral response among farmers to the increased availability of surface water supply. An infrastructure-related investment (supply-side modernization) appears to exert an influence on choices of irrigation methods (demand-side outcome) as farmers prefer flood irrigation methods when canal water is available. The results reveal that in areas where MPWSRP upgraded canals, and where canal water is a primary source of irrigation, flood irrigation is preferred. This preference stems from how farmers value and perceive the efficacy of advanced irrigation technologies after canal systems are upgraded. These findings have three key policy implications.

First, analysis of the irrigation profiles of the adopting farmers in our sample reveals that upgraded, gravity-fed, open surface canals did not prevent some farmers from adopting sprinkler or drip systems. This challenges the commonly held assumption that sprinkler and drip irrigation technologies are alternatives or substitutes to surface irrigation from canal water. Instead, our results reveal that irrigation technology adoption is feasible for farmers in gravity systems where farmers are growing cereal crops. Nearly a quarter (20%) of the adopting farmers reported canal water as their main source of irrigation, with a trend towards reduction in groundwater use over time as canal systems were upgraded by the MPWSRP. Next, farmer interviews revealed that all adopting farmers self-reported using sprinkler systems (either mini or large sprinklers). These farmers were evenly split in terms

of geographical distribution of their farms, with 4 coming from districts where systems were upgraded by the MPWSRP and 4 from farms where no MPWSRP interventions were made. These farmers reported using sprinklers to irrigate wheat crops in the Rabi season, with farm plots ranging from less than 1 ha in size up to 9 ha. This finding reveals that surface canals and irrigation technologies can be complementary water management options for smallholder farmers in rural India instead of substitutes, however, further investigation is necessary. The research results raise additional questions of what factors influenced a limited number of farmers in areas with improved, open (and non-pressurized) irrigation canals to transition away from traditional flood irrigation methods to use sprinklers while a majority of farmers in the same areas did not? This query is worth further analysis in future research.

The second policy implication that emerges from the analysis is that adopting farmers in the sample were predominantly from lower socio-economic profiles and more vulnerable caste groups, in contrast to farmers with relatively better-off socio-economic conditions and improved canal systems who preferred not to adopt. This indicates that socio-economic constraints are not necessarily preventing farmers from adopting, as the study finds that the choice of adoption is welfare neutral. Next, as the Government of Madhya Pradesh subsidy program did not specifically target socio-economically vulnerable farmers, the study reveals that water scarcity appears to be a stronger driver for farmers to adopt, despite financial constraints.

The third policy implication is that farmer learning through social ties seem to be a strong incentive driving farmers to adopt, in some cases more than financial subsidy programs, which fail to reach most poor farmers, due to high barriers of access. When farmers in our sample learned about the benefits of sprinklers or drip systems from their neighbors, friends, family (both in close physical proximity as well as in more remote locations to their farms) they chose to adopt despite financial and socio-economic constraints. This confirms findings from other studies showing that knowledge-sharing of agricultural technologies through interpersonal ties leads to higher rates of adoption (Thaler and Sunstein, 2009; Guiteras et al., 2015; Beaman et al., 2016; Wang et al. 2016). This

presents emerging evidence that warrants further exploration; whether aligning delivery of water sector policies through farmer networks specifically in areas where surface irrigated systems are modernized could play a significant role in changing irrigation behaviors of smallholder farmers over financial or hydrological incentives? At present, subsidy and infrastructure modernization policies across Indian states are developed without adequate consideration for the consequences on the behaviors of irrigating farmers. Demand for water among farming communities is not homogenous or stationary, it is complex and changing – and much more emphasis on understanding demand behaviors is needed prior to designing modernization programs, subsidies, limits, or price-based incentives in canal irrigated areas in India. As Lankford (2013) points out fluctuations in irrigation water demand is "*created by a complex mix of soil type, moisture content, crop type and stage, and farmer influence on distribution*" (Lankford, 2013, Chapter 3, pg. 43). Yet few studies have analyzed how *farmer influence* changes in command areas after irrigation systems are upgraded. Laboratory and field experiments could provide greater insights into the social contexts and behaviors of farmers in target areas (for an example, see Pham et al. 2019).

These findings raise additional questions about whether upgraded irrigation systems are contributing to relative increases in on-farm water demand (as farmers prefer flood irrigation methods) compared to farmers in groundwater irrigated areas using drip or sprinkler systems. Future studies are needed to develop comprehensive water accounts to fully quantify the water productivity gains/losses associated with farms using flood irrigation methods compared to farms adopting irrigation technologies in modernized surface systems. Existing evidence for Madhya Pradesh suggests that flood irrigation methods (even the optimal approaches to flood irrigation) are relatively less yield enhancing and entail higher consumptive water use per crop when compared to drip or sprinkler technologies. Studies on Madhya Pradesh by Mandal et al., (2019) show that grain yields average 5.5 tons ha^{-1} with 6316 m^3 water used (irrigation plus rainfall) in sub-surface drip irrigation compared to 5.5 tons ha^{-1} with 8420 m^3 water used with traditional flood irrigation with water productivity of 0.88 and 0.59 kg m^3 respectively as recorded in 2014-15 in Morena district of Madhya Pradesh. The initial insights from this study can be

further advanced with granular data on farm-level water accounts where farmers are adopting sprinklers or drip systems compared to farms where conventional flood irrigation dominates in both groundwater and modernized surface irrigated systems.

Overall, the results necessitate further exploration of whether water security in modernized irrigation systems can be further enhanced by coupling infrastructure and financial subsidy investments with behavioral change policies tailored to the social norms of farming communities. This may include field-level studies that a) target technology awareness and knowledge campaigns specifically for farmers in command areas after canals are rehabilitated, and b) phasing and scaling information about irrigation technologies and financial subsidy programs through farmer-led community groups (such as WUAs) instead of through government extension workers. These nuanced approaches may catalyse higher rates of technology adoption and changes in irrigation practices among farmers by diffusion of knowledge about farm-level innovations through trusted social networks. This study presents evidence of the need to rethink the design and sequencing of infrastructure and financial incentive policies for promoting water and food security in surface irrigated systems in India.

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Supplementary Tables for Do modernized canals influence irrigation technology choices? Evidence from smallholders in Madhya Pradesh, India

Table 32. Summary of stratified sample size for Rehab or Treatment districts

Name of project (27)	Name of District (10)	Number of WUAs (34)	Number of WUA farmers (485)
Harsi	Gwalior	9	125
Paronch tank	Shivpuri	2	29
Kethan medium tank	Vidisha	2	29
Bardha tank	Vidisha	1	14
Ghaterapura tank	Vidisha	1	14
Jajon minor tank	Vidisha	1	14
Morwan tank	Neemuch	1	15
Langarpura tank	Bhopal	1	15
Ghuwara tank	Sagar	1	15
Kudiyala tank	Tikamgarh	1	15
Bhitarwar tank	Tikamgarh	1	15
Bilwari tank	Tikamgarh	1	15
Shahpur tank	Tikamgarh	0	Linked to Bilwari tank
Chhutaki tank	Tikamgarh	1	15
Gidwasan tank	Tikamgarh	1	15
Kandwa tank	Tikamgarh	1	15
Kharon tank	Tikamgarh	1	15
Morpariya tank	Tikamgarh	0	Linked to Kharon tank
Para tank (Badagaon)	Tikamgarh	1	14
Siloda tank	Shajapur	1	14
Koyalkhedi tank	Ujjain	1	14
Laxmipura tank	Ujjain	1	14
Silarkhedi tank	Ujjain	1	14
Bhartala tank	Katni	1	14
Pabra tank	Katni	1	14
Pali tank	Katni	0	Linked to Pabra tank
Bhonhari	Katni	1	14

Table 33. Summary of stratified sample size for No Rehab or Control districts

Name of project (15)	**Name of District (5)**	**Number of WUAs (12)**	**Number of WUA Farmers (433)**
Bahadurpur canal project	Gwalior	1	37
Ramowa canal project	Gwalior	1	36
Himmatgarh tank project	Gwalior	1	36
Sirsa dam project	Gwalior	1	36
Muradpur tank	Vidisha	1	36
Naren tank	Vidisha	0	Linked to other tanks
Bani tank	Neemuch	1	36
Dhangaon tank	Neemuch	1	36
Malgarh and Lasur tanks	Neemuch	1	36
Kervan tank	Bhopal	1	36
Hataikheda tank	Bhopal	1	36
Jastakhedi tank	Ujjain	1	36
Undadasa tank	Ujjain	1	36
Tankaria	Ujjain	0	Linked to other tanks

Table 34. Summary of farmer profiles

No.	District	Name of Village	Name of Irrigation Canal/Tank	MPWSRP Rehabilitated Tank (Yes/No)	Size of the farm (Ha)
1	Bhopal	Bandarua	N/A	No	1
2	Bhopal	Langarpura	Langarpura Tank	Yes	4
3	Gwalior	Gram Bajna	Harsi	Yes	1
4	Gwalior	Adampur	Harsi	Yes	5
5	Katni	Bhartala	Bhartala Tank	Yes	9
6	Katni	Bhartala	Bhartala Tank	Yes	2.5
7	Katni	Bhartala	Bhartala Tank	Yes	5
8	Neemuch	Bani	Bani Tank	No	1.5
9	Neemuch	Bani	Bani Tank	No	3.5
10	Neemuch	Bani	Bani Tank	No	4-5
11	Neemuch	Dhangaon	Dhangaon Tank	No	4
12	Neemuch	Barada	Bani Tank	No	Less than 1 Ha
13	Neemuch	Dhangaon	Dhangaon Tank	No	Less than 1 Ha
14	Neemuch	Morwan	Morwan Tank	Yes	12.5
15	Sagar	Bamhori	Bhonhari Tank	Yes	Less than 1 Ha
16	Shivpuri	Gram Miliya	Paronch Tank	Yes	16
17	Shivpuri	Gram Miliya	Paronch Tank	Yes	2.5
18	Shivpuri	Mahaubath	Paronch Tank	Yes	2.5
19	Tikamgarh	Dhimar Pura	Chhutaki Tank	Yes	5
20	Tikamgarh	Chhutaki	Chhutaki Tank	Yes	Less than 1 Ha
21	Tikamgarh	Mudara	Bilwari Tank	Yes	10-11
22	Tikamgarh	Bari	Gidwasan Tank	Yes	Less than 1 Ha
23	Tikamgarh	Bari	Gidwasan Tank	Yes	Less than 1 Ha
24	Tikamgarh	Kharon	Kharon Tank	Yes	10
25	Ujjain	Kirkhipur	Undasa Tank	No	13
26	Vidisha	Bamankhedi	Kethan Medium Tank	Yes	20

7. CONCLUSIONS

"The world as a living being – one nature, one soul. Keep that in mind and how everything feeds into that single experience, moves with a single motion. And how everything helps produce everything else. Spun and woven together."

Marcus Aurelius

7.1 Understanding outcomes of improved irrigation infrastructure in Madhya Pradesh

In concluding this thesis, I reflect on the wider implications of the findings reached in each of the three empirical chapters, to respond to the overarching research question: *do investments to modernise and rehabilitate irrigation infrastructure enhance outcomes related to agricultural water security in Madhya Pradesh?* In this study, I have explored the nature and magnitude of the impacts that occurred, along multiple dimensions, *after* irrigation systems were rehabilitated and modernised in specific river basins and districts of Madhya Pradesh. The collective evidence gathered from the analysis in this study exposes three concluding insights, which raise further questions for future exploration to deepen the understanding of how irrigation infrastructure modernisation contributes (or not) to the enhancement of water security as well as how it leads to the purported benefits attributed to the MPWSRP. The three concluding insights are discussed in the sub-sections below.

7.1.1 Process-driven approaches to improving canal irrigation do not adequately account for the influence of sub-basin hydrological variability on agricultural outcomes

The current infrastructure investment strategy of the Madhya Pradesh Water Resources Department for rehabilitating and modernising irrigation canals targets surface systems across specific river basins in the state based on the age of existing canals. As described in the thesis, major, medium, and minor surface systems that were ageing and had degraded beyond a designed threshold of performance were targeted for repairs and upgrades by the MPWSRP (World Bank 2005). This process-driven investment strategy of the Department focused on improving the engineering standards of the canal infrastructure for optimal performance based on a) selecting degraded canals that were built before 1986 and are located in a target river basin and b) determining an appropriate mix of engineering repairs (e.g. whether to address seepage losses, improve gradient and flow rates, add sluice gates, or other related interventions) for the selected canals based on enhancing technical

efficiency of water distribution and minimising 'water losses' to respective irrigated areas. In the context of the MPWSRP, all 228 irrigation projects were upgraded based on this approach. As the MPWSRP closed in 2015, the Government of Madhya Pradesh and the World Bank regarded the process-driven strategy of targeting investments towards degraded canals and tanks to improve water supply as successful for improving crop yields in the state (Sinha et al., 2018; Sinha 2018). Donor reports and government assessments attributed the MPWSRP investment strategy for improving irrigation system performance, to the increase in net irrigated area from 6.9 million ha in 2009-10 to 8.6 million ha in 2012-13 (ADB 2018).

This thesis examined the impact of the rehabilitated systems on crop yields, in specific districts in MP by incorporating analysis of changes in rainfall patterns at a more granular, sub-basin scale. The results indicate there is significant variability in rainfall patterns spatially and temporally at the district scale in Madhya Pradesh, which is not accounted for in the MPWRD investment strategy (Chapter 4). Next, evidence from the analysis in Chapter 4 reveals that rehabilitated canals and tanks are associated with improvements in crop yields in districts where rainfall variability over a period of ten years was closer to the mean, but not to improvements in yields in districts where variability was lower or higher than the mean. This implies that ageing tanks and canals which had seepage issues, boundary walls, sluice gates, and channels lined and repaired *and* were located in districts where sub-basin rainfall patterns were closer to mean rainfall, the improved water distribution from the repaired systems was one of the factors enabling yield improvements of rice and wheat crops in these areas, in comparison to areas that never had any systems repaired by the MPSWRP. This finding partially supports the main premise of the MPWSRP, that rehabilitating and modernising irrigation canals would enable enhanced water security for farmers due to improvements in surface water supply resulting in improvements in crop yields. However, this association did not hold true in areas where sub-basin rainfall deviated from the mean. Despite data uncertainty around groundwater sources of irrigation and the consequential impacts on crop yields, the thesis finds that unless there are alternative sources of water for irrigation (e.g., groundwater access), localised hydrological patterns influence farm-level water availability from surface

irrigation systems, regardless of whether they are rehabilitated, which in turn affects crop yields for certain crops, holding other factors of crop production constant (Chapter 4). This analysis leads me to conclude that the MPWSRP rehabilitation works did not consistently succeed in enhancing the resilience of crops against hydrological stress. Building on this, I infer that *sub-basin scale* hydrological variability matters in relation to crop yields in Madhya Pradesh.

The existing infrastructure design approach of the World Bank and the MP government, which focused on improving water distribution based on the engineering criteria for designed performance of the canals, does not incorporate data on sub-basin (district-scale) hydrological variability profiles into infrastructure investment decisions of which systems to upgrade and how to upgrade them. The implications of this strategy are two-fold: 1) due to the age criteria, the WRD did not upgrade or modify tanks or canals that are "relatively" younger (built after the late 80s) within districts where rainfall is deficient or abundant as they did not fall into the selection criteria for systems which would be considered for rehabilitation by the MPWSRP; and, 2) the design choices of how to rehabilitate canals and tanks focused on lining canals and tanks agnostic of the historical, district-scale rainfall trends and patterns. Instead, the investment strategy focused on water availability scenarios for 1-2 monsoon seasons averaged for the state as a whole (World Bank 2015; Sinha et al., 2018). Thus, rehabilitation options for adding or increasing tank storage availability within districts facing an increasing sub-basin drying trend over the past ten years or enhancing structural protection against flood risks in districts with increasing rainfall were excluded as potential investment options for the systems selected for repairs by the MPWSRP. The process-driven strategy of the MPWSRP limited modifications of specific tanks and canals to canal conveyance capacity of ageing canals regardless of how hydroclimatic patterns of the districts in the river basins of intervention were changing over a longer period of time. Based on this insight, I conclude that alternative infrastructure design strategies to enhance water security by means of canal system rehabilitation have to be further explored and developed by donors and WRD irrigation engineers in the state.

This finding highlights the potential relevance of incorporating contextual knowledge, specific to daily rainfall data, at a more granular temporal and spatial scale, specifically over a longer historical time period than what is currently the norm in the MPWRD into the canal infrastructure investment approach of how and which canals are selected for engineering repairs in the state. However, to validate this insight, further exploration is needed of how localised hydrological factors are influencing crop yield outcomes in Madhya Pradesh, and whether adapting infrastructure improvement strategies to sub-basin hydrological trends, among a basket of other interventions, contributes to gains in crop yields in Madhya Pradesh.

7.1.2 Improved infrastructure influences the well-being and water use behaviours of farmers in surface irrigated areas in Madhya Pradesh – the case for multi-criteria appraisal of irrigation investments

Building on the findings related to sub-basin hydrology and crop yield results, this thesis has illustrated some insights on how improved canal infrastructure and non-hydrological (e.g., socio-economic and policy) factors influence well-being and behavioural outcomes among a sample of farmers. Specifically, the evidence shows that having access to an improved irrigation canal is positively related with gains in well-being as well as constitutes a behavioural response with respect to the irrigation methods preferred among the smallholders surveyed. In terms of the distributional implications of this finding, farmers with access to rehabilitated and modernised irrigation canals in the lowest and most socio-economically deprived sub-categories of the sample and farmers residing in areas with lower than average rainfall experienced stronger gains in well-being compared to farmers without improved canals (Chapter 5). In addition, the small percentage of farmers growing horticulture reported higher well-being gains (Chapter 5) compared to farmers not growing horticulture; however, only 1% of the sample of farmers surveyed reported horticulture production as their main source of income[26].

[26] This trend may partially be explained by the results from Chapter 4, which illustrate that Minimum Support Price policies for rice and wheat in Madhya Pradesh are associated with increased crop yields of rice and wheat, more so than monsoon rainfall. Wider literature on India has demonstrated that a guaranteed MSP for cereal crops may pose consequences such as a) distorting the production of cereal crops; b) disincentivising

The implication of these findings is that improved access to irrigation in the context of Madhya Pradesh does not necessarily catalyse *improvements* in farming techniques, such as guaranteed crop diversification (Singh et al., 2010), as has been argued in the literature (Carey and Zilberman, 2002; Barker and Molle, 2004; Molle et al., 2009; Olen et al., 2016, among others). Nor does it support the conclusion in the literature that *insufficient* irrigation infrastructure is one of the bottlenecks for the successful utilisation of agricultural technologies by farmers in India (Bourguignon and Pleskovic, 2007). Furthermore, the analysis in Chapter 6 demonstrates that farmers in the study area adopted irrigation technologies because of the hydrological constraints they experienced (either limited surface and/or groundwater supply) as well as learning of the benefits of the technologies from neighbours, relatives, and/or trusted input suppliers in their local villages. In fact, the results indicate that farmers *without* improved canals, from socially deprived caste groups (e.g., Scheduled Tribe) were more likely to adopt sprinkler or drip systems compared to farmers in the General Caste groups with improved and rehabilitated canals (Chapter 6).

While affordability of sprinkler or drip systems is reported by farmers as a constraining factor, subsidy policies neither addressed these constraints; nor were less well-off farmers deterred from adopting, when hydrological constraints (due to lack of surface irrigation access) limited access to water for crops. Thus, socio-economically vulnerable farmers experiencing hydrological distress adopted sprinklers or drip systems despite limited access to the subsidy (Chapter 6). On the other hand, a small number of farmers in areas with rehabilitated canals did adopt sprinklers, illustrating that surface systems are not necessarily alternatives to irrigation technologies and that technically it is feasible for farms with open, gravity canals to use sprinklers (Chapter 6), however, very few farmers chose

farmers from switching to higher-value horticulture crops, for which there are no government guaranteed purchase prices; and c) reduced relevance for using sprinkler or drip technologies due to the preference of cereal crops over fruits and vegetables driven by the MSP (IWMI 2006). Whether MSP was driving farmers in the study sample to opt-out of growing horticulture crops or whether other factors contributed to this decision could not be determined based on the analysis in this thesis but warrants further exploration in future research building on these findings.

to do so in the study sample. These results suggest that enhanced access to surface irrigation has influenced, to a certain degree, farmers to opt for flood irrigation techniques and choose to not use sprinkler or drip technologies despite the availability of financial subsidies to purchase the equipment at a lower cost, holding other factors influencing irrigation technology adoption constant (Chapter 6). Based on these findings, I conclude that rehabilitated surface irrigation infrastructure in Madhya Pradesh does constitute a well-being and behavioural response with respect to irrigation practices among different segments of smallholder farmers surveyed. This insight has implications for how irrigation investment projects are assessed for performance in MP.

The existing approach for monitoring and evaluating the impacts of canal infrastructure investments in Madhya Pradesh as well as in other states in India, endorsed by the World Bank, excludes consideration of well-being and behavioural implications of the investments among farming communities (Burton et al., 2011; World Bank 2015). This presents a contribution of this thesis, which reveals that for smallholders in Madhya Pradesh, canal infrastructure matters in terms of well-being changes among differing farming populations as well as to some degree influences their irrigation practices. However, analytical studies of the impacts of the MPWSRP (Kumar 2016), following the closure of the project, have overlooked the fact that rehabilitated canal irrigation infrastructure may play a role in influencing farmer wellbeing and behavioural shifts in irrigation methods and technology choices before and after the project and among communities with and without exposure to the infrastructure investments.

Studies that attempt to understand how improved water security from irrigation infrastructure drives outcomes tend to focus on quantitative metrics of equity and reliability in canal irrigation networks (Siddiqui et al., 2020), enhancement of irrigation efficiency by means of increases in irrigation withdrawal (Zhu et al., 2019), crop-water demand scenarios (Davis et al., 2017), how irrigation expansion drives environmental problems (Shah 2005; Ommani et al., 2009) and often do not include combined quantitative and qualitative analysis of the intersection between infrastructure-policy-wellbeing-social dynamics and farmer irrigation practices. While some authors claim that improvements in irrigation

generate large and significant economic gains, their findings are limited in that they are unable to provide causal linkages between irrigation and the well-being impacts of irrigation on farming households, and farmer behaviour, among other factors of interest (Datt and Ravallion 1997; Rosegrant et al. 1998; Barker et al. 2004; Hussain and Hanjra 2004; Huang et al. 2005). To date, studies on the impacts of investments in irrigation systems in India have focused on understanding the role of upgraded canals in influencing agricultural intensification, crop yields, and implications on income-based poverty reduction for farmers (Chambers 1988; Fan et al., 1999; Narayanamoorthy 2001; Shah and Singh, 2002). Duflo and Pande (2007) examined linkages between household poverty and water sector infrastructure in India at the district-level but excluded interactions with national food security and technology subsidy policies, the influence on the well-being of farming households, and the behavioural influences on the irrigation technology choices of farmers.

Building on the results of the empirical analyses in this thesis, I conclude that contextual well-being and behavioural indicators (e.g., related to crop choices and irrigation practices) are important elements for building a more comprehensive and distributional picture of how smallholder farmers are impacted after infrastructure interventions are completed. I argue that these indicators should be integrated into future multi-criteria appraisals of the impacts of canal infrastructure interventions in Madhya Pradesh, with relevance for other states in India. In the context of Madhya Pradesh, this finding exposes a new area of exploration that complements ongoing studies on the socio-hydrology of water security (White et al., 2007; Di Baldassarre et al., 2015), with relevance for future studies examining how rehabilitated and modernised canal irrigation systems impact farming communities (FAO 2018). Literature for several decades has argued that cross-sectoral (e.g., agricultural, land, food, and energy) policies are all crucial contributors to water security, and thus researchers consistently promote coordinated policy analysis and implementation across these sectors to avoid unintended impacts and to maximise synergies (Ringler et al., 2013; Pahl-Wostl et al., 2020). However, these cross-sectoral and distributional considerations are rarely incorporated into the project impact evaluations of

irrigation investments in India (Burton et al., 2011) and were certainly not included in the performance evaluations and audits of the MPWSRP (World Bank 2015). This warrants further exploration of how and in what manner farmer well-being and behavioural responses (e.g., crop and irrigation choices) change *after* canal infrastructure is modernised and diverse crop price and technology subsidy policies are implemented in future appraisals of large-scale infrastructure programs in Madhya Pradesh as well as in other Indian states.

At present, the government in MP is in the process of increasing investments in new irrigation infrastructure construction throughout the state. From 2019 onwards, the Narmada Valley Development Authority (NVDA) of the Government of Madhya Pradesh is planning a series of major and medium irrigation projects to conserve and store rainwater for enhancing irrigation potential in water-scarce regions of the state (Government of Madhya Pradesh, 2019). In late 2018, the Asian Development Bank (ADB) and the Government of Madhya Pradesh launched a $375 million funded infrastructure project to construct 125,000 hectares of large-scale pressurised and automated irrigation systems, which aim to assist farmers to adopt micro-irrigation for high-value crops (ADB 2018). Yet, presently the state government and donors are designing, implementing, and monitoring these large-scale infrastructure programmes without considering the distributional well-being responses, the influences of the MSP or subsidy policies, as well as the social dynamics driving the crop and irrigation choices of farmers who were previously exposed to the infrastructure investments of the MPWSRP. I argue that developing a better understanding of the socio-economic and behavioural influences of canal irrigation on smallholder communities matters in order to a) obtain a more comprehensive and distributional picture of how diverse groups of farmers respond to infrastructure-related interventions across diverse hydrological and socio-economic contexts and b) to enhance learning about the well-being and behavioural consequences of interventions in canal irrigation in Madhya Pradesh. Thus, this thesis exposes an opportunity to rethink the norms surrounding how donors and the state government in Madhya Pradesh evaluate the performance of canal infrastructure projects and the impacts of the investments on farming communities. Incorporating well-being and behavioural

criteria as key factors of interest into project appraisals may enable donors, scholars, and government officials in the state to develop a more detailed and nuanced picture of how smallholders are impacted by current approaches to advance water security through infrastructure interventions with implications for the design of future investment strategies. Next, methodological techniques for how to obtain this more nuanced picture in future infrastructure investment appraisals and evaluations are discussed.

7.1.3 Mixed method evaluation approaches are needed to determine causal contributions of irrigation infrastructure – a call to experimentalists and realists

The evidence presented in this thesis are derived from experimental methods, which provide a necessary, yet partial picture of the causal mechanisms derived from surface irrigation infrastructure in Madhya Pradesh. In undertaking an *ex post* analysis grounded in experimental methods of how improved irrigation infrastructure influences certain outcomes in the complex setting of rural India, this thesis has exposed some inferences and patterns that were previously less understood in the context of how rehabilitation of canal irrigation systems are designed and monitored in Madhya Pradesh. However, due to methodological limitations, this thesis cannot resolve the question, '*what are the root causes of the observed changes*?' (Pawson 2008) or why are they happening the way they are happening?

Although, the experimental approach taken in this thesis has generated a large, comparative, dataset of observations with a broad enough set of contextual variables related to canal irrigation in Madhya Pradesh, the results cannot determine causality (Rogers 2009; Snowden and Boone, 2007). However, I conclude that the inferences generated from this study can be further tested using 'thicker' realist approaches (Sandelowski & Barroso, 2007; Ton et al., 2011). Combined methodological techniques which integrate generative approaches and theory building using realist evaluation methods are necessary to further the evidence gathered from the analysis in this thesis. Specifically, the dynamic contexts and the increasing levels of complexity of the hydrological, economic, social, and

behavioural systems within which infrastructure interventions are implemented lend themselves to an inherently coupled experimental and realist approach. The study of the dynamic impacts of efforts to improve water security by means of canal irrigation infrastructure and its causal linkages to specific developmental outcomes calls for researchers to overcome epistemological differences, which may pose barriers to an inter and transdisciplinary dialogue (Mollinga 2020). Instead, the complexity and scale of the evaluative challenge associated with studies of irrigation infrastructure and water security highlights the need for multiple methodological approaches and cross-disciplinary dialogues, which can benefit from studying social phenomena "eclectically," by assuming "multiple perspectives" (Tashakkori & Teddlie, 2010), and by pursuing "multiple mental models" (Greene, 2007, p. 30).

Next, future studies using combined methodological techniques can be more effective if those with the responsibility of program implementation (policy makers, technocrats, donors) take cognisance of the methodological learning process; that it is iterative, time consuming, and that change occurs incrementally, which necessitates further refinements using multiple evaluative approaches over time (e.g., a combination of quantitative experimental *and* qualitative realist methods). Thus, prior to the selection of the methods or theory-based approaches, practitioners in the irrigation sector equally need to be cognisant, familiar with, and confident in these approaches. I argue that ensuring buy-in of methodological approaches (realist or experimentalist or others) are integral to truly building a transdisciplinary dialogue between the academic and practitioner communities in the study of canal irrigation systems. Therefore, the emerging insights from the quantitative analysis in this thesis requires further examination to determine the inherent causal interactions that are occurring at multiple scales, among different segments of a farming population, with more contextual factors of interest, and over a longer period of time after infrastructure investments are implemented (Merrey et al., 2007; Andersson and Ostrom, 2008; Ostrom 2010). Thus, the exploration of outcomes from canal irrigation undertaken in this thesis present an important opportunity for future studies, which combine experimental and realist methodological approaches, to advance and build upon the evidence generated from this work.

7.2 Avenues for future research

To build a more detailed picture of the underlying impacts of the pathways to water security from investments in canal irrigation, this thesis has exposed some contextual insights that are driving specific outcomes in Madhya Pradesh. However, the causal picture is incomplete, which presents emerging questions to be explored in future research. Specifically, three areas for further study are highlighted below.

First, a diagnostic next step is to apply realist evaluation methodologies to advance validity of the conclusion that the current irrigation infrastructure investment strategy endorsed by the World Bank and the MP government needs to be modified, grounded on a richer contextual information base of district-specific hydrological profiles as well as age and location concerns. To test the efficacy of this insight, further exploration is needed of the optimal balance between investments in *more* information (e.g. improving the spatial and temporal hydrological monitoring capacities of the irrigation department in MP) versus investments in more concrete (e.g. continuing the strategy of upgrading canals that have aged beyond a certain threshold of performance for enhanced water distribution and reduced seepage) and whether this balanced approach is the trigger that makes a causal difference in crop yield outcomes. This inference can benefit from realist evaluation techniques, which may build theories derived from context-mechanism-outcome observations of whether integrating district-scale spatial and temporal rainfall data changes the structural design choices of how the WRD modernises canals and tanks. And whether the shift in selection and engineering choices of how to upgrade existing irrigation systems makes a significant difference in crop yield outcomes in areas where systems are upgraded, and district-level rainfall is deviating from the mean? This approach can also incorporate and account for important contextual aspects influencing crop yields (e.g., groundwater access, agronomic, as well as institutional factors) This query can provide the next stage of methodological framing for uncovering the causal mechanisms that may contribute to certain water security outcomes in Madhya Pradesh and potentially other states in India.

A second area for future research is to expand the cross-sectional database built during this research into panel data studies to advance the analysis carried out in this thesis. The cross-sectional survey results present a methodological limitation in that they convey sentiments and realities for farmers at one moment in time and with limitations stemming from the recall of past realities. This provides some insights into the present and past experiences but can be further advanced with future surveys that return to the same cohort of farmers. It is important to test changes in infrastructure interactions across the variables of interest over longer periods of time. This is particularly important for slow changing biophysical variables such as aquifer depths as well as behavioural factors such as groundwater use and abstraction patterns of farmers over time. As modernised infrastructure ages, as new policies and new environmental, social, and political dynamics occur at the farm, basin, state, and national scales in India, and as rainfall patterns shift and aquifers are depleted these changes can influence the predicted agricultural, socio-economic, and farming benefits of upgraded canal irrigation systems. For instance, rapid urbanisation and population growth in India are changing land-use patterns dramatically (Harishankar et al., 2019).

Thus, panel studies enable researchers to evaluate changes in rural farming households over time and determine how benefits of agricultural water security are distributed across different farming households as well as how they are influenced over longer periods by urbanisation and demographic shifts as well as biophysical factors such as river flow, rainfall, and groundwater access. In addition, the analytical framework built for this study can be tested iteratively by applying additional as well as emerging contextual factors such as more qualitative information on the political drivers and relationships between water, agriculture, rural development agencies, the role of WUAs, and more insights on what factors are driving surface and groundwater use practices and cropping behaviours among farmers. This is relevant both for the same cohort of farmers in Madhya Pradesh, as well as with farmers in surface irrigated systems of other Indian states and countries with large populations of smallholder farmers (e.g., Egypt, China) facing a high degree of hydrological variability.

Third, combining advancements in remote sensing through satellite-borne radar instruments that provide information on rainfall patterns, land use changes, and soil moisture coupled with observational or field-level insights on farmer surface and groundwater use patterns as well as how social networks among farming communities influence irrigation technology choices can advance the growing field of socio-hydrology (Sivapalan et al., 2014). Recent advancements in instruments include a) the joint NASA-JAXA Tropical Rainfall Measuring Mission (TRMM), b) the recent Global Precipitation Measurement (GPM) instrument, and c) the Gravity Recovery and Climate Experiment (GRACE) spacecraft (Dadson et al., 2019). Both the TRMM and GPM are satellite-based instruments with sensors that can dramatically improve traditional approaches to rainfall data collection across Indian Water Resources Departments. Such tools can provide information on precipitation patterns across large areas. However, the drawback of such instruments remains the uncertainties in ground truthing the data. GRACE, for instance, has been used for both hydrological and hydrogeological monitoring enhancing large-scale assessments of changes in water storage (Owor et al. 2009; Rodell et al, 2018; Bernknopf et al, 2018; Dadson et al., 2019). However, Dadson et al. (2019) argue that the outputs of sophisticated tools like GRACE are only effective if interpreted in conjunction with locally available water management information, which could be acquired for instance via mobile phones and citizen scientists.

Incorporating self-measurement or self-reporting methods of monitoring water productivity, cropping choices, irrigation behaviours, and groundwater abstraction patterns by members of Water User Associations can offer interesting insights into how complex human agents respond to hydrological changes in irrigated command areas and the consequences of these behaviours on farm to basin-scale water availability with implications for longer term basin to basin water security in agricultural production in the state. Coupling rainfall data with additional insights on farm-level cropping and irrigation behaviour patterns in irrigated command areas can address the challenges in understanding the interactions between infrastructure, humans, hydrological cycles, and natural river and aquifer systems. Dadson et al., (2019, p.12) stress the need for future research that can

improve understanding of "*human decision-making related to water-use and incorporate these responses into Global Hydrology and Water Resources Models (GHWMs)*". Thus, advancing data collection techniques on water use patterns for specific crops, seasons, aquifers, and under diverse hydrological conditions by engaging farmers directly is imperative. Next, understanding how wider governance and political influences at a village, district, state, and national level shift the agricultural practices of farmers can also be tracked over time. This is an important area for future research, which is relatively understudied in the context of irrigated agriculture in India.

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In this thesis, I have analysed how rehabilitated and modernised irrigation systems influence selected outcomes within six river basins and over 30 districts in the Indian state of Madhya Pradesh (MP). As more than 70% of Madhya Pradesh's 72 million people work in the rural agriculture sector, a thesis that examines the consequences of interventions that aim to enhance crop yields, reduce poverty, and improve irrigation efficiency for smallholder farmers is timely. The findings of this work have presented some insights on how improved irrigation canals are driving certain observed trends in surface irrigated command areas in Madhya Pradesh. The findings of the thesis indicate that the contextual complexities around sub-basin hydrological variability, relationships between infrastructure and diverse policy instruments, coupled with the distributional well-being and irrigation choices among farmer communities have important implications for understanding how surface irrigation systems enhance agricultural water security within rural farming communities in Madhya Pradesh with relevance for other Indian states where similar hydrological, infrastructure, and poverty challenges are present.

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Appendices

Appendix 1: Declaration of Authorship

I, Ranu Sinha, hereby declare that this thesis is my own work, except where otherwise stated.

Signed:

Date: 24 November 2019

Place: Oxford

Co-author agreements:

Detailed contribution of co-authors for Paper 1 (Chapter 4)

Title: Understanding the effectiveness of investments in irrigation system modernization: evidence from Madhya Pradesh, India

First author: Ranu Sinha (School of Geography and the Environment (SoGE) and Oxford India Centre for Sustainable Development (OICSD), Somerville College, University of Oxford)

Co-authors:

Rob Hope (SoGE, SSEE)
• Provided conceptual supervision for the development of the analytical framework
• Feedback for the development of the methodological design
• Provided substantial edits and comments for the paper

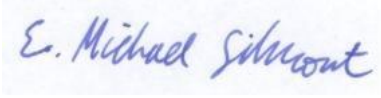
Michael Gilmont (Environmental Change Institute, University of Oxford)
• Provided overall edits and comments for the paper

Simon Dadson (SoGE, University of Oxford)
• Substantial feedback for the development of the methodological approach
• Substantial feedback for the development of the paper data analysis
• Provided substantial edits and comments for the paper

We confirm that Ranu Sinha led the paper design and methodology, collected and analysed the data, led the development of the results and findings, drafted the paper and managed the submission and revision process – with our contributions as specified above.

Rob Hope, 31 October 2019

Michael Gilmont, 31 October 2019



Simon Dadson, 31 October 2019

Detailed contribution of co-authors for Paper 2 (Chapter 5)

Title: Does irrigation infrastructure influence the well-being of smallholder farmers? Empirical evidence from Madhya Pradesh, India

First author: Ranu Sinha (School of Geography and the Environment (SoGE) and Oxford India Centre for Sustainable Development (OICSD), Somerville College, University of Oxford)

Co-authors:

Simon Dadson (SoGE, University of Oxford)

• Provided substantial edits and comments for the paper

Rob Hope (SoGE, SSEE)

• Provided substantial supervision for the development of survey design, econometric methods, and results analysis

• Provided substantial edits and comments for the paper

We confirm that Ranu Sinha led the paper design and methodology, collected and analysed the data, led the development of the results and findings, drafted the paper and managed the submission and revision process – with our contributions as specified above.

Rob Hope, 31 October 2019

Simon Dadson, 31 October 2019

Detailed contribution of co-authors for Paper 3 (chapter 6)

Title: Do modernized canals influence irrigation technology choices? Evidence from smallholders in Madhya Pradesh, India

First author: Ranu Sinha (School of Geography and the Environment (SoGE) and Oxford India Centre for Sustainable Development (OICSD), Somerville College, University of Oxford)

Co-author:

Rob Hope (SoGE, SSEE)
• Substantial supervision for the development of the methodological approach
• Substantial feedback for the development of the survey design and analysis of the results
• Provided substantial edits and comments for the paper

I confirm that Ranu Sinha led the paper design and methodology, collected and analysed the data, led the development of the results and findings, drafted the paper and managed the submission and revision process – with my contribution as specified above.

Rob Hope, 31 October 2019

Appendix 2: Survey questionnaire (2015) with Water User Association farmers in MPWSRP rehabilitated command areas

I. General Information

a. Name of district
b. Name of Tehsil
c. Name of block
d. Name of village
e. Name of irrigation project
f. Name of WUA

II. Personal Details

a. Name of respondent
b. Telephone/mobile
c. Sex (Male/Female)
d. Age (years)
e. Highest educational qualification
f. Farm location in canal system (Tick one)
- Head
- Middle
- Tail

g. Are you the main farmer in the household?
- Yes
- No

h. Status of Farming (Select One - for the respondent)
- Owned plot
- Rented plot
- Farm labourer

III. Socio-economic Details

a. Total number of members in the family

b. Number of family members (specify numbers)
- Age less than 6 years
- Between 6 and 15 years
- Age 16 years or more

c. House Ownership Status (Please tick – this is unprompted – don't read from the list)

Before Rehabilitation of scheme

1. Owned

2. Rented
3. Other
4. No response
0. Don't Know

Current Status

1. Owned
2. Rented
3. Other
4. Don't Know
0. No response

d. What is the type of house?

Before Rehabilitation of scheme

1. Permanent
2. Semi-permanent
3. Temporary
0. Don't Know

Current Status

1. Permanent
2. Semi-permanent
3. Temporary
0. Don't Know

e. Type of Latrine Facility

Before rehabilitation of scheme

1. Flush/pour flush latrine connected to piped sewer system
2. Flush/pour flush latrine connected to septic tank
3. Flush/pour flush latrine connected to other system
4. Pit latrine with slab/ventilated improved pit
5. Pit latrine Without slab/ open pit
6. Night soil disposed into open drain
7. Service Latrine Night soil removed by human
8. Service Latrine Night Soil Service by animal
9. Alternative source due to not having latrine facility within the premises:
   0 Public latrine
   1 Open

0. Don't know

Current status

1. Flush/pour flush latrine connected to piped sewer system

2. Flush/pour flush latrine connected to septic tank
3. Flush/pour flush latrine connected to other system
4. Pit latrine with slab/ventilated improved pit
5. Pit latrine Without slab/ open pit
6. Night soil disposed into open drain
7. Service Latrine Night soil removed by human
8. Service Latrine Night Soil Service by animal
9. Alternative source due to not having latrine facility within the premises:
   0. Public latrine
   1. Open
0. Don't know

f. Household drinking water source (Please place one tick under each category)

Before rehabilitation of scheme

1. Main source of drinking water from treated source
2. Main source of drinking water from untreated source
3. Main source of drinking water: covered well
4. Main source of drinking water un-covered well
5. Main source of drinking water handpump
6. Main source of drinking water Tube well/bore hole
7. Main source of drinking water: spring
8. Main source of drinking water: river/canal
9. Main source of drinking water: pond/lake
10. Other sources (please specify)
0. Don't know

Current status

1. Main source of drinking water from treated source
2. Main source of drinking water from untreated source
3. Main source of drinking water: covered well
4. Main source of drinking water un-covered well
5. Main source of drinking water handpump
6. Main source of drinking water tube well/bore hole
7. Main source of drinking water: spring
8. Main source of drinking water: river/canal
9. Main source of drinking water: pond/lake
10. Other sources (please specify)
0. Don't know

g. Type of fuel used for cooking (Please place one tick under each category)

Before rehabilitation of scheme

1. Firewood
2. Crop residue
3. Cow dung cake
4. Coal/lignite/charcoal

5. Kerosene
6. LPG/PNG
7. Electricity
8. Biogas
9. Any other (please specify)
10. No cooking
0. Don't know

Current status

11. Firewood
12. Crop residue
13. Cow dung cake
14. Coal/lignite/charcoal
15. Kerosene
16. LPG/PNG
17. Electricity
18. Biogas
19. Any other (please specify)
20. No cooking
0. Don't know

h. Belongings Possessed (This question needs to be answered twice (once for the scenario of the farmer prior to rehabilitation works and again for the present situation). Please tick ALL that apply (for each column – could you tell me now the possessions the household owns and not the household).

Before rehabilitation of scheme

1. Radio/Transistor
2. Television
3. Computer/laptop
4. Access to Internet (yes/No)
5. Landline Telephone
6. Mobile Telephone
7. Bicycle
8. Scooter/ motorcycle/moped
9. Car/jeep/van
10. Thresher
11. Harvester
12. Tractor
13. Any other (please specify)
0. Don't know

Current status

1. Radio/Transistor
2. Television
3. Computer/laptop
4. Access to Internet (Yes/No)

5. Landline Telephone
6. Mobile Telephone
7. Bicycle
8. Scooter/ motorcycle/moped
9. Car/jeep/van
10. Thresher
11. Harvester
12. Tractor
13. Any other (please specify)
0. Don't know

i. Major sources of income – (Did you regularly generate income from any of these sources? (break-up between farm and non-farm; rank from 1-3 highest to lowest – of the identified which are the top 3; first tick and then rank) This question is asking from where the farmer made most of his income both at present and also in the past before the canal rehabilitation works were completed. Please tick ALL that apply (for each column)

In 2005

1. Agriculture
2. Horticulture
3. Fisheries
4. Dairy
5. Poultry/meat
6. Business
7. Services
8. Hiring of agricultural implements
9. Loans
10. Hired Labour
11. Others

Current status of the scheme

1. Agriculture
2. Horticulture
3. Fisheries
4. Dairy
5. Poultry/meat
6. Business
7. Services
8. Hiring of agricultural implements
9. Loans
10. Hired Labour
11. Others

IV. Land Holding Details

a. Total land owned (acres)

Before rehabilitation
Current status

b. Land taken on lease (acres)

Before rehabilitation
Current status

c. Land leased out (acres)

Before rehabilitation
Current status

V. Irrigation Details

a. In your village, which is/was the primary source of irrigation during the Rabi cropping season?

Before Rehabilitation of scheme

1. Rain-fed
2. Dug well
3. Bore well
4. Canal
0. Don't Know

Current Status

1. Rain-fed
2. Dug well
3. Bore well
4. Canal
0. Don't Know

b. What was the status of irrigation before modernization works in the canal in each specific season?

Parameters (before rehabilitation of scheme)	**Kharif (Yes/No)**	**Rabi (Yes/No)**
Desired number of irrigations		
At desired time of irrigations		
Quantity of irrigation as desired in each watering		

Don't know		
No response		

Parameters (current status of scheme)	**Kharif (for last Kharif cropping season) (Yes/No)**	**Rabi (for last Rabi cropping season) (Yes/No)**
Desired number of irrigations		
At desired time of irrigations		
Quantity of irrigation as desired in each watering		
Don't know		
No response		

c. What is the status of the canal condition post-rehabilitation of the scheme? (Perception based question for individual survey respondent, one tick to be given for each parameter)

Parameter	**Improvement**	**Deterioration**	**No change**	**Don't Know**
Amount of flow				
Siltation/Vegetation				
Canal breaches				
Seepage alongside canal banks				
Condition of Canal structures				
Quality of maintenance				
Other (please specify) 1…… 2…. 3…. 4……				

d. Prior to irrigation season, are you informed about the date of the opening of the canal?

1. Yes
2. No
0. Don't Know

e. If yes, what is the source of the information?

1. WRD
2. WUA
3. Other (specify)

0. Don't know

f. Condition of sluice gate delivering water to WUA since rehabilitation of scheme?

1. Good and functioning
2. Needs minor repairs
3. Needs major repairs
4. No gate at all
0. Don't know

g. Do you believe that the rehabilitation works on the irrigation scheme have an influence on your well-being? Is this perception different prior to the rehabiliation works?

1. Yes, there is an influence, it has improved my well-being from the past
2. No, there is no influence, my well-being is the same as before
3. Yes, there is an influence, it has made my well-being worse-off from the past
4. No, there is no influence, but my well-being is worse-off from the past
0. Don't know

h. Irrigation water distribution during last Rabi cropping season (Please provide one tick for each before rehabilitation and current status)

Type of Distribution	**Before rehabilitation of scheme**	**Current Status**
From head to tail		
From tail to head		
No defined sequence of distribution		
As demanded by farmer on individual basis		
Through warabandi		
Any other (specify)		
Don't know		

i. Please specify the main method of irrigation for last main Rabi cropping season:

Before rehabilitation of scheme (please tick one)

1. Flooding
2. Drip
3. Ridge & Furrow
4. Border strip
5. Check basin

Current status (please tick one)

1. Flooding
2. Drip
3. Ridge & Furrow
4. Border strip
5. Check basin

j. Irrigation Table

	Irrigation			
Crop	Before rehabilitation of scheme		Current status of last cropping season	
	No. of watering		**No. of watering**	
	canal	**groundwater**	**canal**	**groundwater**
Kharif				
Soybean				
Paddy				
.....				

Rabi				
Wheat				
Gram				
.....				
.....				
Summer				
.....				
.....				

VI. Agriculture Details

a. Adoption of modern agriculture technology by farmers in general for all crops for both Rabi and Kharif seasons

Before rehabilitation of scheme

1. Fertilizer use (Kg/acre/don't know)
2. HYV/Hybrid (Yes/no/don't know)
3. Pesticide use (litre/acre/don't know)
4. Organic manure use (Kg/acre/ don't know)
5. Micro-irrigation technology (yes/no/don't know)
6. Tractor (yes/no/don't know)
7. Thresher (yes/no/don't know)
8. Automatic seed drill (yes/no/don't know)
9. Harvester (yes/no/don't know)
10. Other machinery (please specify)
11. None of the above

Current status

1. Fertilizer use (Kg/acre/don't know)
2. HYV/Hybrid (Yes/no/don't know)
3. Pesticide use (litre/acre/don't know)
4. Organic manure use (Kg/acre/ don't know)
5. Micro-irrigation technology (yes/no/don't know)
6. Tractor (yes/no/don't know)
7. Thresher (yes/no/don't know)
8. Automatic seed drill (yes/no/don't know)
9. Harvester (yes/no/don't know)
10. Other machinery (please specify)
11. None of the above

b. Horticulture crops

	Horticulture crops		Current		Before rehabilitation	
	Crop	**Source of irrigation (Canal/ Groundwater/ Conjunctive use)**	**Area at present (acres)**	**Productivity at present (Q/acres)**	**Area prior to rehab (acres)**	**Productivity prior to rehab (Q/acres)**
1	Vegetables					
2	Fruits					
3	Spices					
4	Medicinal and Aromatic plants					
5	Floriculture					

c. Crop-wise cultivation (before rehabilitation of scheme)

	Crop-wise cost of cultivation	**Before Rehabilitation**				
Crop	Area (in acres)	Productivity (quintals/acre)	Cost of seed (Rs/ acre)	Material cost (Fertilizers, Pesticides, Machinery hire etc) (Rs/ acre)	Labour input (Rs/ acre)	Other costs (Rs/ acre)
Kharif						
Soybean						
Paddy						
.....						

Rabi						
Wheat						
Gram						
.....						
.....						
Summer						

d. Crop-wise cultivation (current status)

	Crop-wise cost of cultivation	**Current**				
Crop	Area (in acres)	Productivity (quintals/acre)	Cost of seed (Rs/ acre)	Material cost (Fertilizers, Pesticides, Machinery hire etc) (Rs/acre)	Labour input (Rs/ acre)	Other costs (Rs/ acre)
Kharif						
Soybean						
Paddy						
.....						
---------- --						
Rabi						
Wheat						
Gram						
.....						
.....						
Summer						

e. Livestock Holdings

	Livestock Holdings	(in nos.)	
		Before rehabilitation	Current status
1	Cow		
2	Buffalo		
3	Bullocks		
4	Goat		
5	Sheep		
6	Poultry		

f. What determines when you plant your kharif crop (specify for last cropping season)?

1. Timing of rainfall
2. Quantity of rainfall
3. Labour availability
4. Price information
5. Market dates for selling of crop
6. Other (please specify)

g. Has there been any change in rainfall patterns from last years' Kharif cropping season to this year?

1. Yes
2. No
0. Don't know

h. If yes, please specify reason (please tick all that apply)?

1. Early rains
2. Delayed rains
3. Reduced intensity of rainfall
4. Increased quantity of rainfall
5. Increased duration of dry spells
6. Increased number of days of rainfall
7. Other

i. Have these changes caused any losses to your Kharif crops for last cropping season?

1.Yes
2. No
0. Don't know

j. If yes losses have occurred, have the improvements in rehabilitation works made a difference in mitigating your losses?

1. Significant improvement
2. Moderate improvement
3. No difference
4. Moderate loss
5. Significant loss
0. Don't know

VII. Questions on accuracy and comprehension (for enumerators)

a. Do you think the respondent's answers were answered accurately?

- Yes, in all cases
- Yes, but not in all cases
- No, not at all

b. Do you think the respondent understood all the questions asked?

- Yes, in all cases
- Yes, but in some cases
- No, not at all

Appendix 3: Survey questionnaire (2015) with Water User Association farmers in command areas with no rehabilitation investments from MPWSRP

I. General Information

a. Name of district
b. Name of Tehsil
c. Name of block
d. Name of village
e. Name of irrigation project
f. Name of WUA

II. Personal Details

a. Name of respondent
b. Telephone/mobile
c. Sex (Male/Female)
d. Age (years)
e. Highest educational qualification
f. Farm location in canal system (Tick one)
- Head
- Middle
- Tail

g. Are you the main farmer in the household?
- Yes
- No

h. Status of Farming (Select One - for the respondent)
- Owned plot
- Rented plot
- Farm labourer

III. Socio-economic Details

a. Total number of members in the family

b. Number of family members (specify numbers)
- Age less than 6 years
- Between 6 and 15 years
- Age 16 years or more

c. House Ownership Status (Please tick – this is unprompted – don't read from the list)

In 2005

1. Owned
2. Rented
3. Other
4. No response
0. Don't Know

Current Status

1. Owned
2. Rented
3. Other
4. Don't Know
0. No response

d. What is the type of house?

In 2005

1. Permanent
2. Semi-permanent
3. Temporary
0. Don't Know

Current Status

1. Permanent
2. Semi-permanent
3. Temporary
0. Don't Know

e. Type of Latrine Facility

In 2005

1. Flush/pour flush latrine connected to piped sewer system
2. Flush/pour flush latrine connected to septic tank
3. Flush/pour flush latrine connected to other system
4. Pit latrine with slab/ventilated improved pit
5. Pit latrine Without slab/ open pit
6. Night soil disposed into open drain
7. Service Latrine Night soil removed by human
8. Service Latrine Night Soil Service by animal
9. Alternative source due to not having latrine facility within the premises:

- Public latrine
- Open

0. Don't know

Current status

1. Flush/pour flush latrine connected to piped sewer system
2. Flush/pour flush latrine connected to septic tank
3. Flush/pour flush latrine connected to other system
4. Pit latrine with slab/ventilated improved pit
5. Pit latrine Without slab/ open pit
6. Night soil disposed into open drain
7. Service Latrine Night soil removed by human
8. Service Latrine Night Soil Service by animal
9. Alternative source due to not having latrine facility within the premises:
    - Public latrine
    - Open

0. Don't know

f. Household drinking water source (Please place one tick under each category)

In 2005

1. Main source of drinking water from treated source
2. Main source of drinking water from untreated source
3. Main source of drinking water: covered well
4. Main source of drinking water un-covered well
5. Main source of drinking water handpump
6. Main source of drinking water tube well/bore hole
7. Main source of drinking water: spring
8. Main source of drinking water: river/canal
9. Main source of drinking water: pond/lake
10. Other sources (please specify)
0. Don't know

Current status

1. Main source of drinking water from treated source
2. Main source of drinking water from untreated source
3. Main source of drinking water: covered well
4. Main source of drinking water un-covered well
5. Main source of drinking water handpump
6. Main source of drinking water tube well/bore hole
7. Main source of drinking water: spring
8. Main source of drinking water: river/canal
9. Main source of drinking water: pond/lake
10. Other sources (please specify)

0. Don't know

g. Type of fuel used for cooking (Please place one tick under each category)

In 2005

1. Firewood
2. Crop residue
3. Cow dung cake
4. Coal/lignite/charcoal
5. Kerosene
6. LPG/PNG
7. Electricity
8. Biogas
9. Any other (please specify)
10. No cooking
0. Don't know

Current status

1. Firewood
2. Crop residue
3. Cow dung cake
4. Coal/lignite/charcoal
5. Kerosene
6. LPG/PNG
7. Electricity
8. Biogas
9. Any other (please specify)
10. No cooking
0. Don't know

h. Belongings Possessed (This question needs to be answered twice (once for the scenario of the farmer in 2005 and again for the present situation). Please tick ALL that apply (for each column – could you tell me now the possessions the household owns and not the household; DHS surveys have; welfare index can be created).

In 2005

1. Radio/Transistor
2. Television
3. Computer/laptop
4. Access to Internet (yes/No)
5. Landline Telephone
6. Mobile Telephone
7. Bicycle
8. Scooter/ motorcycle/moped
9. Car/jeep/van

10. Thresher
11. Harvester
12. Tractor
13. Any other (please specify)
0. Don't know

Current status

1. Radio/Transistor
5. Television
6. Computer/laptop
7. Access to Internet (Yes/No)
8. Landline Telephone
9. Mobile Telephone
10. Bicycle
10. Scooter/ motorcycle/moped
11. Car/jeep/van
12. Thresher
13. Harvester
14. Tractor
15. Any other (please specify)
0. Don't know

i. Major sources of income – (Did you regularly generate income from any of these sources? (break-up between farm and non-farm; rank from 1-3 highest to lowest – of the identified which are the top 3; first tick and then rank) This question is asking from where the farmer made most of his income both at present and in 2005. Please tick ALL that apply (for each column)

In 2005

1. Agriculture
2. Horticulture
3. Fisheries
4. Dairy
5. Poultry/meat
6. Business
7. Services
8. Hiring of agricultural implements
9. Loans
10. Hired Labour
11. Others

Current status of the scheme

12. Agriculture
13. Horticulture
14. Fisheries
15. Dairy

16. Poultry/meat
17. Business
18. Services
19. Hiring of agricultural implements
20. Loans
21. Hired Labour
22. Others

IV. Land Holding Details

a. Total land owned (acres)
In 2005
Current status

b. Land taken on lease (acres)
In 2005
Current status

c. Land leased out (acres)
In 2005
Current status

V. Irrigation Details

a. In your village, which is/was the primary source of irrigation during the Rabi cropping season?

In 2005

1. Rain-fed
2. Dug well
3. Bore well
4. Canal
0. Don't Know

Current Status

1. Rain-fed
2. Dug well
3. Bore well
4. Canal
0. Don't Know

b. What was the status of irrigation in 2005 and at present in the canal in each specific season?

Parameters (In 2005)	**Kharif (Yes/No)**	**Rabi (Yes/No)**
Desired number of irrigations		
At desired time of irrigations		
Quantity of irrigation as desired in each watering		
Don't know		
No response		

Parameters (current status of scheme)	**Kharif (for last Kharif cropping season) (Yes/No)**	**Rabi (for last Rabi cropping season) (Yes/No)**
Desired number of irrigations		
At desired time of irrigations		
Quantity of irrigation as desired in each watering		
Don't know		
No response		

c. What is the status of the canal condition at present? (Perception based question for individual survey respondent, one tick to be given for each parameter)

Parameter	**Improvement**	**Deterioration**	**No change**	**Don't Know**
Amount of flow				
Siltation/Vegetation				
Canal breaches				
Seepage alongside canal banks				
Condition of Canal structures				
Quality of maintenance				
Other (please specify) 1…… 2…. 3…. 4……				

d. Prior to irrigation season, are you informed about the date of the opening of the canal?

1. Yes
2. No

0. Don't Know

e. If yes, what is the source of the information?

1. WRD
2. WUA
3. Other (specify)

0. Don't know

f. Condition of sluice gate delivering water to WUA at present?

1. Good and functioning
2. Needs minor repairs
3. Needs major repairs
4. No gate at all

0. Don't know

g. Do you believe that the irrigation schemes in your command area have an influence on your well-being? Is this perception different your perception in 2005?
   1. Yes, there is an influence, it has improved my well-being from the past
   2. No, there is no influence, my well-being is the same as before
   3. Yes, there is an influence, it has made my well-being worse-off from the past
   4. No, there is no influence, but my well-being is worse-off from the past
   0. Don't know

h. Irrigation water distribution during last Rabi cropping season (Please provide one tick for each in 2005 and current status)

Type of Distribution	**In 2005**	**Current Status**
From head to tail		
From tail to head		
No defined sequence of distribution		
As demanded by farmer on individual basis		
Through warabandi		
Any other (specify)		
Don't know		

i. Please specify the main method of irrigation for last main Rabi cropping season:

In 2005 (please tick one)
1. Flooding
2. Drip
3. Ridge & Furrow
4. Border strip
5. Check basin

Current status (please tick one)
1. Flooding
2. Drip
3. Ridge & Furrow
4. Border strip
5. Check basin

j. Irrigation Table

	Irrigation			
Crop	In 2005		Current status of last cropping season	
	No. of watering		**No. of watering**	
	canal	**groundwater**	**canal**	**groundwater**
Kharif				
Soybean				
Paddy				
.....				

Rabi				
Wheat				
Gram				
.....				
.....				
Summer				
.....				
.....				

VI. Agriculture Details

a. Adoption of modern agriculture technology by farmers in general for all crops for both Rabi and Kharif seasons

In 2005

1. Fertilizer use (Kg/acre/don't know)
2. HYV/Hybrid (Yes/no/don't know)
3. Pesticide use (litre/acre/don't know)
4. Organic manure use (Kg/acre/ don't know)
5. Micro-irrigation technology (yes/no/don't know)
6. Tractor (yes/no/don't know)
7. Thresher (yes/no/don't know)
8. Automatic seed drill (yes/no/don't know)
9. Harvester (yes/no/don't know)
10. Other machinery (please specify)
11. None of the above

Current status

1. Fertilizer use (Kg/acre/don't know)
2. HYV/Hybrid (Yes/no/don't know)
3. Pesticide use (litre/acre/don't know)
4. Organic manure use (Kg/acre/ don't know)
5. Micro-irrigation technology (yes/no/don't know)
6. Tractor (yes/no/don't know)
7. Thresher (yes/no/don't know)
8. Automatic seed drill (yes/no/don't know)
9. Harvester (yes/no/don't know)
10. Other machinery (please specify)
11. None of the above

b. Horticulture crops

	Horticulture crops		Current		In 2005	
	Crop	**Source of irrigation (Canal/ Groundwater /Conjunctive use)**	**Area at present (acres)**	**Productivity at present (Q/acres)**	**Area prior in 2005 (acres)**	**Productivity in 2005 (Q/acres)**
1	Vegetables					
2	Fruits					
3	Spices					
4	Medicinal and Aromatic plants					
5	Floriculture					

c. Crop-wise cultivation (In 2005)

	Crop-wise cost of cultivation	**In 2005**				
Crop	Area (in acres)	Productivity (quintals/acre)	Cost of seed (Rs/ acre)	Material cost (Fertilizers, Pesticides, Machinery hire etc) (Rs/ acre)	Labour input (Rs/ acre)	Other costs (Rs/ acre)
Kharif						
Soybean						
Paddy						
.....						

Rabi						
Wheat						
Gram						
.....						
.....						
Summer						

d. Crop-wise cultivation (current status)

	Crop-wise cost of cultivation	**Current**				
Crop	Area (in acres)	Productivity (quintals/acre)	Cost of seed (Rs/ acre)	Material cost (Fertilizers, Pesticides, Machinery hire etc) (Rs/acre)	Labour input (Rs/ acre)	Other costs (Rs/ acre)
Kharif						
Soybean						
Paddy						
.....						
---------- --						
Rabi						
Wheat						
Gram						
.....						
.....						
Summer						

e. Livestock Holdings

	Livestock Holdings	(in nos.)	
		In 2005	Current status
1	Cow		
2	Buffalo		
3	Bullocks		
4	Goat		
5	Sheep		
6	Poultry		

f. What determines when you plant your kharif crop (specify for last cropping season)?

1. Timing of rainfall
2. Quantity of rainfall
3. Labour availability
4. Price information
5. Market dates for selling of crop
6. Other (please specify)

g. Has there been any change in rainfall patterns from last years' Kharif cropping season to this year?

1. Yes
2. No
0. Don't know

h. If yes, please specify reason (please tick all that apply)?

1. Early rains
2. Delayed rains
3. Reduced intensity of rainfall

4. Increased quantity of rainfall
5. Increased duration of dry spells
6. Increased number of days of rainfall
7. Other

i. Have these changes caused any losses to your Kharif crops for last cropping season?

1. Yes
2. No
0. Don't know

VII. Questions on accuracy and comprehension (for enumerators)

a. Do you think the respondent's answers were answered accurately?

- Yes, in all cases
- Yes, but not in all cases
- No, not at all

b. Do you think the respondent understood all the questions asked?

- Yes, in all cases
- Yes, but in some cases
- No, not at all

Appendix 4: Telephone interview survey questionnaire (2018) with Water User Association farmers

Farmer Telephone Interview Survey Questionnaire: WUA members previously surveyed in 2015

This questionnaire will provide insights into farmer preferences for using micro-irrigation technologies as well as insights into how farmers interact with one another, access micro-irrigation subsidies, and the other related aspects around their agricultural practices.

NB: This survey was conducted in August 2018.

I. Personal and Geographic Information

a. What is the name of the farmer?
b. What is the name of the WUA of the farmer?
c. What is the name of the district?
d. What is the name of the village?
e. What is the name of the irrigation project?
f. Did the irrigation project receive investments from the MPWSRP for rehabilitation?
    1. Yes
    2. No

II. Farm Characteristics

a. What is average plot size of your farm? (Ha) _____
b. What is the average distance between your farm and neigbouring farms around you? _____

III. Modern irrigation Category of the Farmer (select one):

Category (A) – I was using modern irrigation technologies in 2015 and I am still using them?

Category (B) – I didn't use modern irrigation technologies in 2015 but now I do use them.

Category (C) – I was using modern irrigation technologies in 2015 but now I have stopped using all such technologies.

Category (D) – I never used modern irrigation technologies in 2015 and I still do not use them.

IV. Modern irrigation technologies (For category A & B farmers only)

a. Which type of modern irrigation technology are you using?
_____

b. What types of crops do you irrigate with modern irrigation technologies?
_____

V. Pre-Modern Irrigation Technology Use Questions (Only for Farmers in Category A, B, C) (Open-ended questions)

a. What type of irrigation methods was the farmer using before adopting modern irrigation?

b. For farmers who do not use modern irrigation technologies at all, what type of irrigation methods do you use on your farm? (Category D farmers only)

c. When did you start using modern irrigation technologies on your farm? (Provide the year (estimate))

d. How and why did you switch to using modern irrigation technologies?

e. Who helped you to start using modern irrigation technologies? (Select all that apply and ask the farmer to speak about why they chose that response)

1. **The Government**: I was offered a subsidy from a government scheme in 2015
2. **Civil Society**: Local NGOs helped me
3. **Private Firm**: A private firm helped me
4. **Community**: I saw my neighbors/family/friends using it and benefiting from it
5. **Ambition**: I wanted to improve my crop yields
6. **Economic**: I wanted to improve my income
7. **Hydrological distress**: I wanted to reduce my water usage as I faced severe water shortages for irrigation
8. **Other reasons** – please specify why

VI. Factors driving farmers to use modern irrigation technologies (Only for Farmers in Category A, B, C) (Open-ended questions)

a. **Income**: When I decided to use modern irrigation technologies, getting a satisfactory income was and is important to my decision (ask them to rank on a scale of 1-10)

0: This aspect has no impact on my decision
1
2
3
4
5: This aspect has some impact on my decision
6
7
8
9
10: This is the aspect that most affects my decision

b. **Community and Local Norms**: When I decided to use modern irrigation technologies, adhering to local norms was and is important to my decision (ask them to rank on a scale of 1-10)

0: This aspect has no impact on my decision
1
2
3
4
5: This aspect has some impact on my decision
6
7
8
9
10: This is the aspect that most affects my decision

c. **Legal**: When I decide how or when to use modern irrigation technologies, adhering to local laws is important to my decision (ask them to rank on a scale of 1-10)

0: This aspect has no impact on my decision
1
2
3
4
5: This aspect has some impact on my decision
6
7
8
9
10: This is the aspect that most affects my decision

d. **Personal reputation**: When I decide to use modern irrigation technologies, making sure my personal reputation is not negatively impacted is important to my decision (ask them to rank on a scale of 1-10)

0: This aspect has no impact on my decision
1
2
3
4
5: This aspect has some impact on my decision
6
7
8
9
10: This is the aspect that most affects my decision

VII. Post adoption experiences (Only for Farmers in Category A and B) (Open-ended questions)

a. How have your costs of cultivation changed since you started using modern irrigation technologies? (Provide estimate of monthly costs now that you are using them vs before when you were not using them)
   1. Costs estimates now
   2. Has this gone up? If yes, why?
   3. Has this gone down? If yes, why?
   4. Costs have remained the same? If yes, why?

b. What input differences has modern irrigation technologies made in terms of labour needs? (select one and explain why)

    1. More labour needed

    2. Less labour needed

    3. Labour is the same

c. What differences has modern irrigation technologies made in terms of the time needed to cultivate your crops? (select one and explain why)

    1. More time needed (how much more – days, hours, etc)

    2. Less time needed (how much less – days, hours, etc)

    3. Time is the same

d. What differences has modern irrigation technologies made in terms of the inputs you use to farm?

e. What differences has modern irrigation technologies made in terms of yield outcomes you have seen? (specify for which crops you are talking about) (Question refers to quantity of crops produced in T/Ha)
    1. Quantity of crop is more

    2. Quantity of crop is less

    3. Quantity of crop is the same

f. What differences have you experienced in the quality of your crops since using modern irrigation technologies? (specify for which crops you are talking about) (Question refers to crop quality)
   1. Quality of crop is better

   2. Quality of crop is worse

   3. Quality of crop is the same

g. Would you say you have more "income" (Kamai) from farming because of your choice to use modern irrigation technologies?

   1. Yes, I do (please explain why)

   2. No, I do not (please explain why)

   3. My funds are the same – no change (please explain why)

h. **Income Satisfaction**: Tell me a little about your choices (please explain your response)

   1. I have a minimum income target that I need to achieve every month (yes/no)
      If yes, what is the minimum target _____?

   2. If I earn less than my target, it has been an unsatisfactory month (yes/no)

   3. If you had knowledge of the income of your neighbors, and if your income was below the average income of your neighbors, would this be unsatisfactory for you? (response: yes/no)

4. If you had knowledge of the income of the highest earner in your village, and if your income were below that amount, would this be unsatisfactory for you? (response: yes/no)

5. I know which farmers in my village are using modern irrigation technologies? (response: yes/no)
   If yes, how many (rough estimate is OK)

i. **Sharing Information on Income**:

1. I share information about my income with my friends? (yes/no)
   If yes, how many friends (0-100)

2. I know how much farmers in my local community earn on average (yes/no)
   If yes, how much do they earn (approximate)

3. I know how much the farmer who earns the most in my local community earns (yes/no)
   If yes, how much do they earn (approximate)

j. Why have you kept using modern irrigation? Can you tell us the top three factors that have influenced you to keep using it?

k. What challenges have you experienced in using modern irrigation? Can you tell us the top three challenges that you have faced?

l. How did you address these three challenges identified in the previous question, if any?

VIII. Community-level norms among farmers (All categories) (Open-ended questions)

a. I know the farming techniques of farmers in my local community? (yes/no)

b. If yes, what do you think are the main reasons, your neighbours and local farmers in the command have NOT used modern irrigation technologies? (Category C and D farmers only)

c. Do you share information about your farming techniques (including your irrigation methods) with your friends in the village and/or command area (yes/no)

If yes, how many friends (0-100)

d. Is imitation of other farmers' techniques in your village socially acceptable? (yes/no)

IX. **Future irrigation technology adoption scenario** (Only for Farmers in Category A & B)

a. Do you intend to keep on using modern irrigation technologies? (Yes/No)
   1. If Yes, why?

   2. If No, can you give three reasons why not?

X. **Non-Adoption Questions** (Only for Farmers in Category C & D)

a. Why did you never use modern irrigation technologies? (Can you give us three main reasons) – Only for farmers in Category D

b. Why did you stop using modern irrigation technologies? (Can you give us three main reasons) – Only for farmers in Category C

c. Instead of modern irrigation technologies, what irrigation methods do you prefer? For Rabi? For Kharif?

d. Are there factors that would help you to start using modern irrigation technologies? (Select all that apply)
   1. Government support – specify

2. Financial support – specify
3. Knowledge and informational support – specify
4. Agricultural support – specify
5. Irrigation support - specify
6. Social support - specify
7. Other – specify

Appendix 5: Survey Participant Oral Consent Form

Survey Participant Oral Consent Form

Dear Respondent,

Thank you for agreeing to take part in this survey today. The Water and Land Management Institute (WALMI), Bhopal wishes to conduct a survey among Water-user Association members in districts where the Madhya Pradesh Water Sector Restructuring project was implemented and districts that did not participate in the project. This survey is part of a University of Oxford study that is helping Madhya Pradesh to understand the impacts of the MPWSRP from the perspective of farmers. The aim of the survey is to better understand the quality of irrigation services after closure of the project, impacts felt by farmers in their agricultural production and learn about their household characteristics.

I am here as a representative of the Water and Land Management Institute and we are helping to facilitate the survey on behalf of University of Oxford. I would like to ask you some basic questions about your farming and irrigation practices as well as some background on your household situation. The information you provide will be kept confidential and thus will not be revealed to anyone. We will ensure that your responses remain anonymous and will not be used by WALMI, Madhya Pradesh government or any other body other than as information for research purposes for the University of Oxford study.

Having heard the summary of the survey and its purpose, do you give oral consent to continue with the interview (to be filled by enumerator)?

Yes ☐ No ☐

Section below to be filled by enumerator:

Name of Respondent: _____

Date: _____

Tel: _____