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Institutional innovation in groundwater governance in Odisha (India):

A numerical simulation in water user association (WUA)

DISSERTATION

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Submitted by

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DECLARATION

According to the §17 of the Doctoral Examinations Regulations of the Faculty 09, from July 7th 2004, last changed on May 29th 2019

I declare: this dissertation is a work of my own, written without any illegitimate help by any third party and only with materials indicated in the dissertation. I have indicated in the text where I have used texts from already published sources, either word for word or in substance, and where I have made statements based on oral information given to me. At any time during the investigations carried out by me and described in the dissertation, I followed the principles of good scientific practice as defined in the "statutes of the Justus-Liebig University Giessen for the safeguarding of the good scientific practice".

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Date Applicant

Preface

In this study, I enquired the scope of cooperation in water resource governance that has potential to enhance net farm income by reducing the cost of water. Water user association (WUA) on groundwater is a government-subsidised cooperative model where farmers make collective decisions regarding water distribution. Many times, due to improper management of the groundwater resource system and its physical structure, cooperation collapsed. Moreover, subsidized irrigation water exaggerated water extraction, and as a result, the water table declined beyond the bottom of the well, threatening the sustainability of the WUA.

In this study, I described diversity of agricultural production systems (APS) under similar community irrigation distribution systems. From diverse APS, I developed distinct farm types and substantiated them with theoretical viewpoints and empirical data. I further maximized net return of a farm by adopting cost effective cropping patterns. To maximize water conservation in a community irrigation distribution system, an incentive scheme in a principal-agent (P-A) mode is devised that features a cooperative model. The P-A model results indicated that economic incentives offered for water saving from the WUA motivated farmers to adopt water saving activities at the farm level. In addition, WUA achieved maximum total water savings by reducing pumping operation. However, the impact of economic incentives for water saving differs by farm type. Therefore, the study recommends that a WUA should amend its water distribution institutions to encourage adoption of water-saving cropping patterns by member farmers by advancing multiple fixed and variable incentives.

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List of Abbreviations

AHC:	Agglomerative Hierarchical Clustering
APS:	Agricultural Production System
bcm:	billion cubic meters
CIDA:	Community Irrigation Distribution Arrangement
CTW:	Cluster Tube Well
FGD:	Focus Group Discussion
FPO:	Farmer Producer Organization
GAMS:	General Algebraic Modelling Software
GCA:	Gross Cropped Area
GDP:	Gross Domestic Product
GES:	Groundwater Extraction Structure
HDIAM:	Highly Diversified Irrigated Agriculture for Direct Market Supply
HWI:	High Water-Intensive
ICA:	Irrigation Command Area
ICRIER:	Indian Council for Research on International Economics
LDIACM:	Least Diversified Irrigated Agriculture For Contacted Market Supply
LULCC:	Land Use and Land Cover Change
LP:	Linear Programming
LPS:	Litre per second
LWI:	Low Water-Intensive
MCA:	Multiple Correspondence Analysis
MDLIAM :	Moderately Diversified Limited Irrigated Agriculture For Direct Market Supply
NABARD:	National Bank for Agriculture and Rural Development
NGO:	Non-Government Organizations
NIA:	Net Irrigated Area
OLIC:	Odisha Lift Irrigation Corporation Limited
PIM:	Participatory Irrigation Management
PRA:	Participatory Rural Appraisal
SRI:	System of Rice Intensification
STW:	Shallow Tube Well
tgm:	total gross margin
WUA:	Water User Association

Summary

Technological advances during early 1970s in the form of green revolution promoted adoption of water-intensive cropping activities that explored groundwater through millions of small-scale groundwater extraction structures (GESs) and enabled India self-sufficient in foodgrain production. However, uncontrolled groundwater extraction and inefficient distribution led to gradual depletion of groundwater table. It increased water extraction costs and reduced net farm income from irrigated agriculture. As a regulatory measure, in Odisha, the stage government promoted installation of community tube wells and formed the Water User Association (WUA) for irrigation water distribution. During 2001, *Pani Panchayat* (PP) Act 2001 was enacted to strengthen, restructure, and redesign the institutions for water sharing in a WUA. However, many WUA collapsed within a decade or two due to improper maintenance of the physical structure and disputes over water distribution. In this light, this research is entailed to enquire how can a farmer optimise land-based water-saving activities, and how does an individual farmer's farm-level decision exaggerate a well scale water extraction?

A primary field survey was conducted in fifteen villages from Cuttack, Jagatsinghpur, and Ganjam districts of Odisha, and 53 farms were chosen to elucidate the irrigation requirements of a wide range of land-based production during Nov 2018-April 2019.

Multiple correspondence analysis (MCA) was employed to group diverse agricultural production systems (APS) that evolved under different water distribution systems at the village level. MCA grouped these APS into three major farm types i.e. (i) Highly diversified irrigated agriculture for direct market supply (HDIAM) farms, that were predominated by marginal and small farmers (operated on < 2 ha of land), who adopted maximum crop diversification, and engaged family members in production activities; (ii) Moderately diversified limited irrigated agriculture for direct market supply (MDLIAM) farms, that were semi-subsistent, adopted rainy season rice followed by *Vigna radiata* (White Lentil) or *Vigna mungo* (Red Lentil), exchange family labourers with neighbouring farms for many farming operations, and sold outputs to a nearby market; and (iii) Least diversified irrigated agriculture for contacted market supply (LDIACM) farms, that were small and medium sized, where specialised farming of rice or sugarcane was practised with a contracted sale agreement.

To enquire about the scope of farm level maximum water saving, their total gross margins (*tgm*) were optimized by employing a linear program (LP) that promoted adoption of different water saving activities in a cropping system. The simulation of farm level *tgm* with increased water price under zero water procurement cost promoted adoption of water-intensive cropping system across the farms. However, marginal farms accrued higher marginal benefits per unit cubic meter of additional water, while large farms had to forgo fifty percent of their *tgm*, in

comparison with their status quo. Under unlimited water supply with no scope for inter-farm water exchange simulation, *tgm* of every farm reduced. The HDIAM farms were able to harness higher *tgm*/ha by engaging family labourers that reduced production cost, while MDLIAM and LDIACM farms were limited in this aspect and accrued lesser *tgm*/ha.

Further, to know the group dynamics for water saving of WUA farmers, an incentive scheme was adopted in a principal agent (P-A) model. In the initial run, when all the farmers were assumed to be equally interested in saving water, the model predicted an annual water savings of 98.09 per cent by adopting the water-saving scheme. When the model was simulated with an increase in water price from INR 1.50 to 5.0 per cubic meter, it did not increase water saving in the same proportion for all the farms, as many farm plots were already under water saving activities or remained uncultivated. During the numerical simulation, it was found that WUA had a higher bargaining power to decide the revenue share in order to convince farmers to participate in the contract scheme. A modest water price and restriction in water transfer influenced HDIAM farms to save 86.35 percent of water. However, any further increase in water price did not increase water saving because of their limited resources endowment and meagre scale of operation. LDIACM farms continued to prefer perennial crops such as sugarcane that reduced scope for water saving.

Therefore, advocating a uniform incentive scheme was not sufficient to attract different farmers to conserve water. Hence, water pricing mechanisms should be combined with volumetric restrictions and other economic incentives. Further, a WUA should amend existing institutions for water sharing to promote water-saving cropping patterns by advancing multiple fixed and variable incentives to the members in a contract scheme.

Zusammenfassung

Technologische Fortschritte in den frühen 1970er-Jahren in Form der grünen Revolution förderten die Einführung wasserintensiver Anbauaktivitäten, die das Grundwasser durch Millionen von kleinen Grundwassergewinnungsanlagen (GESs) erschlossen und Indien ermöglichten, sich selbst mit der Produktion von Nahrungsmitteln zu versorgen. Jedoch führten die unkontrollierte Grundwasserentnahme und ineffiziente Verteilung zu einer allmählichen Absenkung des Grundwasserspiegels. Dadurch stiegen die Kosten für die Wasserentnahme und das Nettoeinkommen der landwirtschaftlichen Betriebe aus der bewässerten Landwirtschaft sank. Als Regulierungsmaßnahme förderte die Regierung in Odisha die Installation von Gemeinschaftbrunnen und gründete die Water User Association (WUA) für die Verteilung von Bewässerungswasser. Im Jahr 2001 wurde der *Pani Panchayat* (PP) Act 2001 erlassen, um die Institutionen für die gemeinsame Nutzung von Wasser in einer WUA zu stärken, umzustrukturieren und neu zu gestalten. Viele WUA brachen jedoch innerhalb von ein oder zwei Jahrzehnten aufgrund unsachgemäßer Instandhaltung der physischen Struktur und Streitigkeiten über die Wasserverteilung zusammen. Vor diesem Hintergrund wird in dieser Studie untersucht, wie Landwirte ihre wassersparenden Aktivitäten auf dem Land optimieren können und wie die Entscheidung eines einzelnen Landwirts auf Betriebsebene die Wasserentnahme in einem Brunnen übersteigt.

Eine primäre Felduntersuchung wurde in fünfzehn Dörfern aus den Distrikten Cuttack, Jagatsinghpur und Ganjam in Odisha durchgeführt, und 53 Farmen wurden ausgewählt, um den Bewässerungsbedarf einer breiten Palette von landgestützten Produktionen zwischen November 2018 und April 2019 zu ermitteln. Zur Gruppierung verschiedener landwirtschaftlicher Produktionssysteme (APS), die unter verschiedenen Wasser-Verteilungssystemen auf Dorfebene entstanden sind, wurde eine Multiple-Korrespondenzanalyse (MCA) verwendet. Die MCA gruppierte diese APS in drei Hauptbetriebstypen: i) Hochdiversifizierte bewässerte Landwirtschaftsbetriebe für die Direktvermarktung (HDIAM), die überwiegend von marginalen und kleinen Landwirten (mit einer Fläche von weniger als 2 ha) bewirtschaftet werden, die eine maximale Diversifizierung der Anbauprodukte anstreben und Familienmitglieder in die Produktion einbeziehen;; ii) Mäßig diversifizierte Betriebe mit begrenzter Bewässerungslandwirtschaft für die Direktvermarktung (MDLIAM), die semi-Subsistenz waren, in der Regenzeit Reis anbauten, gefolgt von *Vigna radiata* (White Lentil) oder *Vigna mung*o (Red Lentil), für viele landwirtschaftliche Tätigkeiten Familienarbeiter mit benachbarten Betrieben austauschten und ihre Erzeugnisse auf einem nahe gelegenen Markt verkauften; und iii) am wenigsten diversifizierte Betriebe mit Bewässerungslandwirtschaft für die Direktvermarktung (LDIACM), die klein und mittelgroß waren und sich auf den Anbau von Reis oder Zuckerrohr spezialisiert hatten, wobei der Verkauf vertraglich geregelt war.

Um nach dem Umfang der maximalen Wassereinsparung auf Betriebsebene zu ermitteln, wurden die Gesamtbruttomargen (tgm) durch den Einsatz eines linearen Programms (LP) optimiert, das die Einführung verschiedener wassersparender Aktivitäten in einem Anbausystem förderte. Die Simulation der tgm auf Betriebsebene mit erhöhtem Wasserpreis bei Wasserbezugskosten von Null förderte die Einführung eines wasserintensiven Anbausystems in allen Betrieben. Allerdings erzielten marginales Ackerland jedoch höhere Grenzvorteile pro Kubikmeter zusätzliches Wasser, während große Betriebe im Vergleich zu ihrem Status quo auf fünfzig Prozent ihrer tgm verzichten mussten. Bei einer unbegrenzten Wasserversorgung ohne die Möglichkeit eines Wasseraustauschs zwischen den Betrieben sank die tgm aller Betriebe. Die HDIAM-Betriebe konnten höhere tgm/ha durch den Einsatz von Familienarbeitern zur Kostensenkung erzielen, während die MDLIAM- und LDIACM-Betriebe in dieser Hinsicht begrenzt waren und geringere tgm/ha erwirtschafteten.

Um die Gruppendynamik für die Wassereinsparung von WUA-Landwirten zu verstehen, wurde ein Anreizsystem in einem Principal Agent (P-A) -Modell eingeführt. Im ersten Durchlauf, bei dem davon ausgegangen wurde, dass alle Betriebe gleichermaßen daran interessiert sind, Wasser zu sparen, prognostizierte das Modell eine jährliche Wassereinsparung von 98,09 Prozent durch die Einführung des Wassersparprogramms. Als das Modell mit einer Erhöhung des Wasserpreises von INR 1,50 auf 5,0 pro Kubikmeter simuliert wurde, erhöhte sich die Wassereinsparung nicht bei allen Betrieben im gleichen Maße, da viele Parzellen bereits wassersparend bewirtschaftet wurden oder unbewirtschaftet blieben. Bei der numerischen Simulation wurde festgestellt, dass die WUA eine höhere Verhandlungsmacht bei der Festlegung der Umsatzbeteiligung hatte, um die Landwirte von der Teilnahme an dem Vertragssystem zu überzeugen. Ein bescheidener Wasserpreis und Einschränkungen beim Wassertransfer haben dazu geführt, das HDIAM-Betriebe, 86,35 Prozent Wasser einsparen konnten. Allerdings hat eine weitere Erhöhung des Wasserpreises aufgrund ihrer begrenzten Ressourcenausstattung und ihrer geringen Betriebsgröße keine zusätzlichen Wassersparnisse gebracht. LDIACM-Betriebe bevorzugten weiterhin mehrjährige Kulturen wie Zuckerrohr, die den Spielraum für Wassereinsparungen einschränkte.

Daher reichte es nicht aus, für alle Landwirte eine einheitliche Anreizregelung zu fordern, u Wasser zu sparen. Stattdessen sollten Mechanismen zur Wasserpreisbildung mit volumetrischen Beschränkungen und anderen wirtschaftlichen Anreizen kombiniert werden. Darüber hinaus sollte eine WUA vorhandene Institutionen für die Wasserverteilung überarbeiten, um wassersparende Anbaupläne zu fördern, indem den Mitgliedern eines Vertragsprogramms mehrere feste und variable Anreize geboten werden.

CHAPTER 1: INTRODUCTION

1. Introduction to irrigated agriculture in India

1.1. Irrigation network expansion and agricultural diversification

Agriculture has experienced rapid growth in many agrarian economies during the past few decades, mainly due to the expansion of irrigation networks. Globally, freshwater used for agricultural purposes amounted to 2767.15 billion cubic meters (bcm) in 2017, which accounted for 71.3 per cent of freshwater abstraction from rivers, lakes, and aquifers (World Bank, 2021). However, the share of groundwater has grown exponentially when disaggregated by source. Globally, two-thirds of groundwater is extracted from Asian countries, including India, China, Pakistan, Iran and Bangladesh (Giordano, 2009).

Irrigated agriculture in India withdrew annually 446 bcm of freshwater, contributing 21.16 percentage to the global fresh water extraction (World Bank, 2021). A joint study by the National Bank for Agriculture and Rural Development (NABARD) and the Indian Council for Research on International Economics (ICRIER) reported that Indian agriculture consumed 78 per cent of fresh water during 2017-18 (B. R. Sharma et al., 2018).

During 1970s, the Indian green revolution expanded the rice and wheat acreage with supplemental irrigation water. Simultaneously, groundwater irrigation was explored across the country in connotation with innovative groundwater extraction structure (GES) (T. Shah, 2009). It further intensified the wheat area in northern and rice area in eastern India. During 2018-19, rice and wheat occupied 44.16 and 29.32 million hectares of arable land; respectively, it constitutes 23.01 and 15.28 percentages of the gross cropped area (GCA) of which 60.1% and 94.2 % are irrigated (GoI, 2021). Sharma (2018) reported that rice, wheat, and sugarcane are the three “water guzzler” crops that occupied 41 per cent of the GCA and consumed 80 per cent of the irrigation water. The public procurement policies of these ‘water guzzler” crops coupled with “*top-down, persuasive and paternalistic technology transfer*” for groundwater extraction further jeopardized the scarce groundwater resource base (M. Shah, Vijayshankar, & Harris, 2021).

1.2. Increased emphasis on groundwater irrigation

With the increasing emphasis on groundwater sources, agriculture production system in India shifted its focus from monsoon dependent agriculture to irrigated farming system. However, more than 60 per cent of the total arable land is still rain-fed. Increasing instance of erratic rainfall coupled with prolonged drought in rain-fed and irrigated areas negatively affected rural India (GoI, 2021). Public and private excavation of groundwater through many GES, has resulted in significant groundwater depletion in several parts of India (Himanshu, 2011a, 2011b). Especially in the deep alluvial region of north India and alluvial regions in eastern India, groundwater becomes the primary source of irrigation for year-round agriculture (T. Shah, 2009). In the hard rock zones of Peninsular India, the deepening of GES has already posed threats to farmers in terms of higher marginal cost coupled with increasing probabilities of tube well failure (Chandrakanth & Arun, 1997).

1.3. Is community irrigation distribution system a panacea?

The irrigation water requirement for various land-based activities evolved different types of GES since the year 2000. In figure 1.1 it can be found that groundwater exploration since 1970 has overtaken all other sources of irrigation. Canal irrigated area also increased with the increase in canal networks during the same refence period. However, since the year 2000, erratic rainfall coupled with poor maintenance of canal network encouraged farmers to seek alternate sources of irrigation.

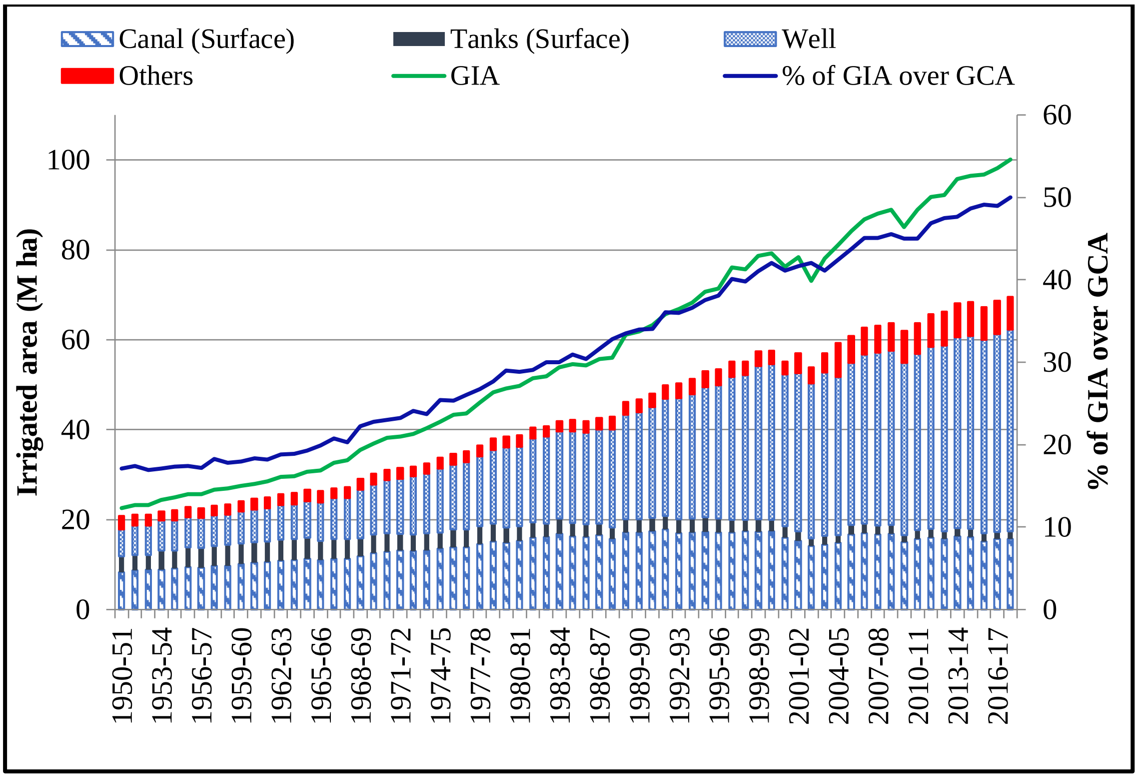


Figure 1.1 Source wise gross irrigated area in India during 1950-51 to 2017-18.

Source: Ministry of Agriculture, Government of India, 2022.

In the eastern parts of India, majority of the farmers are economically challenged and poorly resourced to own a GES. To sustain agriculture from recurring biotic and abiotic stress, such as prolonged dry spell during rainy season, drought, or flood, public policy brought-in the panacea of subsidized GES installation at this juncture.

In order to promote community irrigation distribution arrangement (CIDA) in GES management, government of Odisha started a subsidy program in 1980s. These community GES are owned and managed by farmer-beneficiaries and after 2002, they are registered under the *Pani Panchayat* act 2002 (a Hindi word for water user association or WUA). Nevertheless, individually owned, and managed GES installed by private investment or government subsidy schemes continued to extract and irrigate respective irrigation command areas. As of 2016, groundwater irrigation sources served diversified agriculture that enhanced the gross margin of farming families and improved their livelihood (T. Shah et al., 2016).

In order to ensure a competitive water price for beneficiaries, CIDA always aims to minimize the current cost of water procurement and fulfils concurrent water demand. Private GES owners also attempt to meet short-term irrigation water demand in their designated irrigation command area (ICA) (Himanshu, 2011a; Srinivasan & Kulkarni, 2014). Researchers have found that assured irrigation enabled farmers to adopt high water-intensity production activities, such as switching rice-fallow fields with perennial sugarcane (Ghosh et al., 2006; Ghosh, Verma, Panda, Nanda, & Kumar, 2012). Irrigation water provision at a subsidised rate reduced the marginal cost of water. This, in turn, reduced the total cost of production and triggered escalation in water extraction. A WUA beneficiary farmer eventually realized incremental net benefit, either from existing irrigated cropping activities or by adopting any other remunerative irrigation intensive crop. (Quintana Ashwell, Peterson, & Hendricks, 2018; Ward, 2010).

1.4. Water user association (WUA) in the groundwater distribution system

WUA on groundwater (hereafter, a groundwater WUA is indicated as WUA) is a special form of irrigation governance. As a medium-term goal, member farmers tend to maximize their net present income from water trade while expanding the ICA to reduce the marginal cost of water. The expansion of the ICA, however, will increase water extraction. This is directly proportional to pumping hours. Consequently, the energy cost of lifting water and the pump operation cost will rise, ultimately increasing the marginal cost of water procurement. Thus, the WUA must balance pumping hours and water extraction volumes. Secondly, any expansion of WUA's delineated area leads to an increase in the irrigated area, and in most cases, new memberships result. However, with the expansion of ICA, additional monitoring costs in water extraction, water distribution, and related dispute settlements, water fee collection, water pilferage activity, and other associated costs (hereafter, termed as transaction costs), take place. Therefore, an increase in ICA needs to be balanced with the costs associated with groundwater extraction and distribution.

1.5. Is the present water extraction structure sustainable?

From the viewpoint of groundwater hydrology, when water extraction exceeds recharge for an extended period, a decline in the groundwater table is observed. Studies on uncontrolled and myopic extraction of groundwater from several south Indian states reveal a drastic reduction in groundwater tables, and premature well failure becomes widespread (Chaitra & Chandrakanth, 2005; Chandrakanth & Arun, 1997; Halanaik Diwakara & M. G. Chandrakanth, 2007; Steinhübel, Wegmann, & Mußhoff, 2020). With increasing drought and prolonged dry spells, the natural groundwater recharge has also been reduced in many alluvial aquifers in eastern India (Fishman, Devineni, & Raman, 2015). Thus, any myopic extraction of groundwater by increased hours of pump operation will ultimately endanger the ecologies of the retention system of the WUA wells. This may paralyze the diversified irrigated agriculture.

Scholars have reported that premature drying up of wells is due to increased water extraction to meet mounting water demand. Accordingly, this is also at the vagaries of nature (Steinhübel et al., 2020). Causes of such premature well failure is primarily due to sand penetration under immense suction created into the bore casing. Such distortions have caused irreversible damage to the entire water extraction structure. In response to that, respective state governments have stepped in with institutional innovations that include: (1) strict norms to combat well interferences and promote low water-intensive (LWI) crop cultivation, (2) adoption of water-saving technologies, such as system of rice intensification (SRI) method of rice cultivation, (3) irrigation through a drip system, (4) crop insurance to avoid financial loss from crop failure, (5) groundwater mapping for installation of new wells, (6) well recharge structure, (7) subsidised electricity, and very recently, and (7) solar-powered irrigation structures (Halanaik Diwakara & M. G. Chandrakanth, 2007; H Diwakara & M.G. Chandrakanth, 2007; T. Shah et al., 2016).

1.6. Mechanism to reverse uncontrolled groundwater extraction

Scholars have cited multi-scale and multidisciplinary solutions to its spatial and temporal scarcity with growing groundwater management concerns. Some solutions are locally devised through water users, and some are by an external body, such as the state government, through subsidies (Allen & Gisser, 1984; Amjath-Babu, 2009; Blakeslee, Fishman, & Srinivasan, 2020; Halanaik Diwakara & M. G. Chandrakanth, 2007; Feinerman & Knapp, 1983; Fishman et al., 2015; Gisser & Sanchez, 1980; Hansen, Jensen, & Amundsen, 2014; Laukkanen & Koundouri, 2006; Lopez-Gunn, 2003; Maheshwari et al., 2014; Meinzen-Dick et al., 2018; Muddu, Javeed, Bandyopadhyay, Mangiarotti, & Mazzega, 2011; Nibbering, 1997; Rouillard & Rinaudo, 2020; Taher, Bruns, Bamaga, Al-Weshali, & van Steenbergen, 2012; Woldewahid, Gebremedhin, Berhe, & Dirk, 2011; Yashodha, 2017). The state government offered subsidy packages for drilling a well to mitigate irrigation water scarcity. However, water appropriation was left to the users themselves (Ostrom, 2000). One such arrangement is participatory irrigation management. In this arrangement, a farmers' organization is assigned the responsibility of taking care of the water harnessing structure by forming a WUA. As a statutory body, WUA, , takes care of the physical water distribution and developed a sharing arrangement among the users in terms of operational costs, perceived benefits, and other 'transaction costs' (Abdullaev, Kazbekov, Manthritilake, & Jumaboev, 2010; Ghosh, Kumar, Nanda, & Anand, 2010; Nagrah, Chaudhry, & Giordano, 2016; Rouillard & Rinaudo, 2020; Wegerich, 2008).

With growing water demands for all year agriculture, subsidised groundwater distributed by WUAs gained immediate popularity that fulfilled those needs. However, it attracted several critics. One of the critics follow Hardin's proposal of a 'Tragedy of Commons' was further backed by Ostrom (2000), who emphasizes 'self-organization'. In Indian context, a farmer's family first tries to fulfil its objective of subsistence, subsequently marketing the surplus for meeting other household demands. While groundwater served as the only source of irrigation to fulfil the farmer's first objective, the lesser marginal benefit of the family labour engagement in the year-round farm operations negatively influences crop diversification. As a result, many farm families sourced their household needs from various non-farm wage paying activities. Eventually, irrigated agriculture turned into specialized farming (Bennett, Bending, Chandler, Hilton, & Mills, 2012; Danso, Jeffrey, Dridi, & Veeman, 2021; Grades, 2008; Mellaku, Reynolds, & Woldeamanuel, 2018; Palash, 2015; Steward et al., 2009; Toorop et al., 2020).

On the other hand, with the increasing marketing opportunities, the demand for year-round seasonal vegetables has turned land-based production to diversification (Woldewahid et al., 2011). This diversity over space and time is further influenced by water provision for different crop growing periods (Danso et al., 2021). Finally, the water provisioning made through a WUA under the defined institutional arrangements determined farm-level cropping decisions. These decisions are also observed at a village scale (Maheshwari et al., 2014; Nguyen, Grote, & Nguyen, 2019).

1.7. The aim, research question and objectives

This research aims to develop a cost-sharing regulation to minimize the water procurement cost and optimal allocation in a teamwork framework. The research raised the following research questions.

i. How can a farmer optimize land-based water-saving activities?

ii. How does an individual farmer's farm-level decision exaggerate a well scale water extraction?

Following broad research objectives were developed to answer the above questions.

i. To classify the diverse farming systems into homogeneous types,

ii. To optimize farm-level land-based activities, and

iii. To develop a cooperation model in water distribution by linking farm-level decisions at a well level.

It was claimed that a farmer maximizes farm-level gross margin by adopting a water-intensive but labour-saving activity.

1.8. The methodological framework in brief

Three coastal districts from Odisha state of India were chosen for the primary field survey. From the existing farming systems, a typology of farms was developed based on the distinctive characteristics of each one. The identified farm types were then linked to developing optimal farm-level land-based activities in a linear program. I discussed farm-level activities under different water-sharing arrangements and their application to fulfil the objectives. Then, I explained general economic considerations of farms in which the nature of different agricultural production system is discussed. Following that, a linear relationship between factors of production and cropping pattern is discussed. By observing a stepwise function in a linear programming model, shadow price of water was estimated. Cost functions are then derived from these estimates. In the next chapter, a principal-agent model was used to test collection water saving nature of the farmers and were provided incentives to comply with a cooperative WUA .

1.9. Analytical procedure

An iterative process from the plot to the farm was performed to estimate the impact of plot-level land-based production decisions of a farm. I used endogenous optimal cropping decisions at the plot level to achieve this. In the second step, a backward iteration from the farm level to the plot level was used for optimal crop choice. In the third step, plot-level optimal cropping decisions that maximize the gross margin, subject to the water cost, are used to determine the farm-level cropping decisions. In the fourth step, the farm-level optimal cropping decision is utilized exogenously to maximize water-efficient crop acreage at the farm level, subject to the available farm household labourers and the endogenous water availability. At the fifth stage, the water-saving activities of a farm are endogenously employed to maximize the delineated irrigated area of a well. The optimized well area under water saving is used to calibrate the farm-level decision of cost minimization to determine the area under water-saving crops. I performed it simultaneously at the plot level to develop optimal cropping decision at plot level, subject to water availability at the farm level. In the next stage, the farm-level optimized area under the water-saving crop combination is exogenously used to determine the well-delineated area, subject to the initial number of farms under the well ICA. Finally, the optimized area of a well was utilized to determine optimal cropping pattern.

The methodological framework of the study is presented in Figure 1.2. I considered farm plot as a lowest production unit where a farmer takes agro-economic decision. With the advent of irrigation technology many farm plots adopted irrigation intensive cropping activities. The aggregate economic decision at the farm level results transformation of a water saving farm to a water intensive one. Consequently, on farm scale it increased annual water demand, that resulted increase in cost of production. At the well scale, an increase in volume of water extraction directly increased cost of water extraction in the economic domain. A higher volume of water demand at the ecological domain resulted into higher proportion of high water intensive (HWI) farms at the well scale that recurrently feeds back into the loop of water intensive cropping activities at the farm scale. Therefore, a cyclical path of increased water demand from irrigation intensive cropping activities creates a negative externality at the social domain. At the well scale, many farms adopted irrigation intensive specialized cropping activities that previously balanced with LWI and HWI cropping. Due to increase in irrigation intensive specialized farming, many family members searched for non-farm wage payment activities and seasonally emigrate to a distant place. Eventually, that created labour scarcity at the village level , that many a times compelled a diversified farm owner to adopt specialized cropping activities.

The economic instrument is introduced at the WUA scale, that promoted adoption of LWI cropping activities at the plot level. It generated incremental net return for a farmer and was awarded with a fixed initial incentive, and a variable incentive that is directly propotional to farm level aggregate volume of water saving. The third incentive is a bonus, that is paid for encouraging neighbouring farmer to adopt the incentive scheme offered by a WUA. This intervention further impact at the well scale in the ecological domain by an aggregate decline in water demand and conserved groundwater. In the economic domain this aggregate water saving reduced the cost of water procurement and that also reduced cost of production at the farm scale. The model promoted crop diversification that invariably increased scope of household labour engagement, implying increased labour productivity.

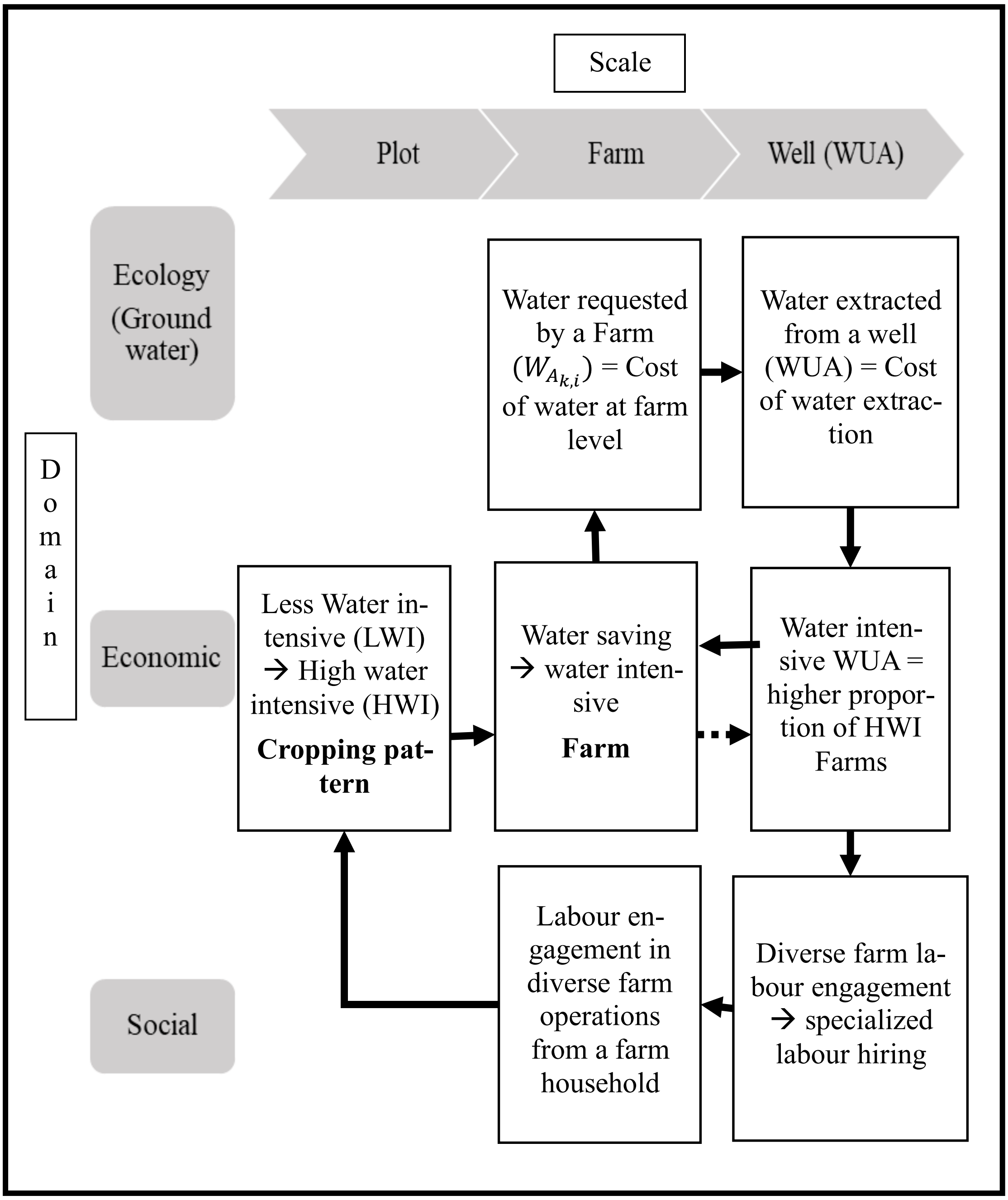


Figure 1.2: Methodological framework

Source: Adapted from Eigner, A. (2017)

1.10. Study structure

Chapter one – A brief introduction to the case study, problem statement and objectives are presented in introduction chapter.

Chapter two – The research design and data collection procedure is presented in this chapter. Further, the agro-economic and socio- cultural attributes of the study districts are narrated with descriptive statistics.

Chapter three –In the study area, I observed diversities in land-based production decision in natural, social, economic and market dimensions to uphold different farming systems, that are unique on their own. A meaningful classification of diverse farms into most similar groups was developed that helped to design appropriate policies to realize the best outcome. The existing pool of farm typology methods were reviewed, and a most suitable method was utilized to develop the farm types. The characteristics of these farm types were later analysed independently.

Chapter four – Upon understanding the farm characteristics, a linear programming model was used to show plot level decision-making and its impact on the entire farm, subject to its farm and well-level capacities. The farm-level capacities complement farm family labourers and animal power, while the well-level capacity is complemented by its seasonal water availability. Within the ecological domain, the optimal water extraction at a well scale is modelled to optimize the area under water-saving crops, subject to its water provision for different farms. A farmer’s decision making on a spatial scale is characterized by cropping pattern change at the plot level and participation in the incentive scheme for sharing the cost of water procurement.

Chapter five- In this chapter I modelled farmers' collective action in water saving as a group and subgroups in a principal-agent model. Farmers adopted water saving activities to reduce water demand and received incentives from the principal. In addition, possible changes in water saving due to an increase in the cost of water are described.

Chapter six – In this chapter, I conclude that the remunerative irrigated agriculture under the WUA is not consistent with its sustainable water extraction. Therefore, a balance between its acreage and water extraction should be maintained.

CHAPTER 2: RESEARCH DESIGN, DATA COLLECTION AND DESCRIPTIVE STATISTICS

2. Research design, data collection and descriptive statistics

2.1. Research site

The coastal region of Odisha is comprised of ten districts, of which Cuttack, Jagatsinghpur, and parts of Ganjam are located in the alluvial aquifers of *Mahanadi* and *Rusikulya* rivers. In figure 2.1 it can observed that, the pale-yellow coloured areas are indicated with alluvial aquifer areas. In these areas Odisha Lift Irrigation Corporation Ltd. (OLIC) and other government entities have been promoting installation of medium-deep tube wells and WUA formation since the 1970s. Apart from water distribution among the member farmers, a WUA is also responsible for improving water use efficiency by increasing the area under low water intensive (LWI) activities and crop diversification (Ghosh et al., 2006; Ghosh et al., 2010).

WUAs are mostly developed in the coastal Odisha districts where well discharge is greater than 15 litres per second (LPS) (figure 2.1). With an average annual rainfall of 1350 mm, the southwest monsoon used to recharge the alluvial aquifers. Due to low water extraction costs, farmers have been able to harvest maximum revenue from water-intensive crops.

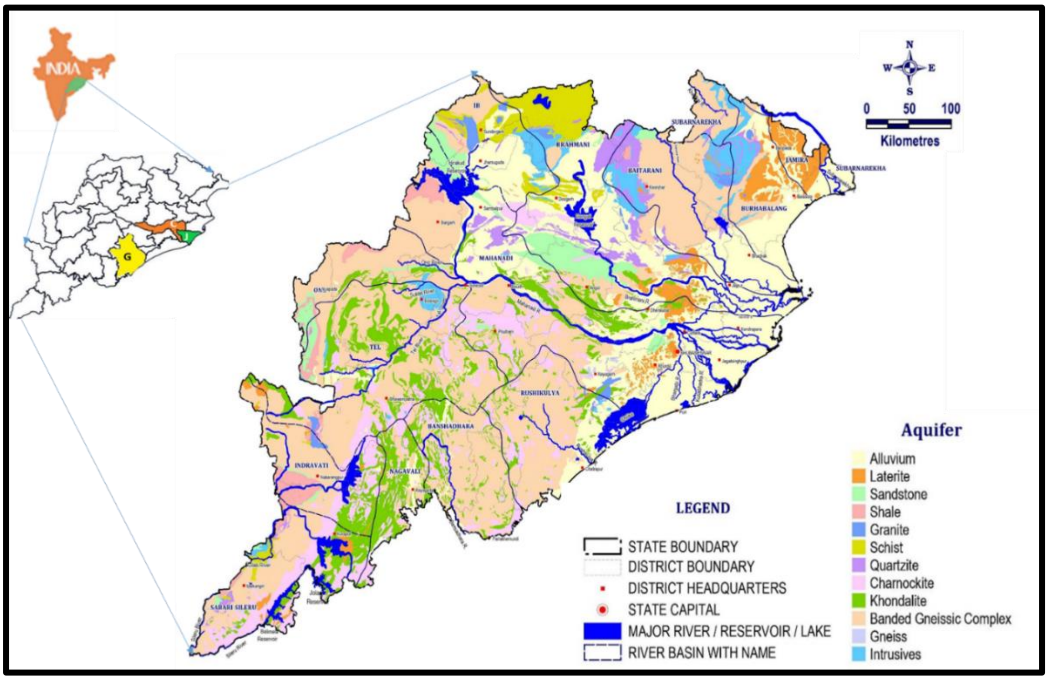


Figure 2.1 Alluvial aquifers (marked yellow) of Odisha state

Source: Central Groundwater Board, 2020.

During the month of April and May 2018 a preparatory fieldwork was conducted in the costal districts of Odisha. In Cuttack, Jagatsinghpur and Ganjam districts, irrigation distribution systems ranged from government sponsored WUA to, privately-owned tube wells, where wide range of cropping activities are adopted. In figure 2.2, the location of the study villages is presented. The Cuttack and Jagatsinghpur districts are adjacent, and the groundwater hydrology is comprised of alluvial aquifers in the Mahanadi River basin. Since the 1970s, in these two districts, state government has been promoting WUA formation in alluvial aquifers and provided subsidized community tube wells along with water distribution system. The Ganjam district is located in the southeast part of the state in the *Rushikulya* river basin alluvial aquifer, where WUAs also formed during the same reference period. These three districts produce 40 per cent of the seasonal and non-seasonal vegetables and 30 per cent of rice (Government of Odisha, 2020). Villages (indicated with red dots on the map) with relatively greater concentration of WUA formation as well as other forms of CIDA i.e. self-initiated community wells and cluster tube wells (CTW) are finally chosen for the primary fieldwork.

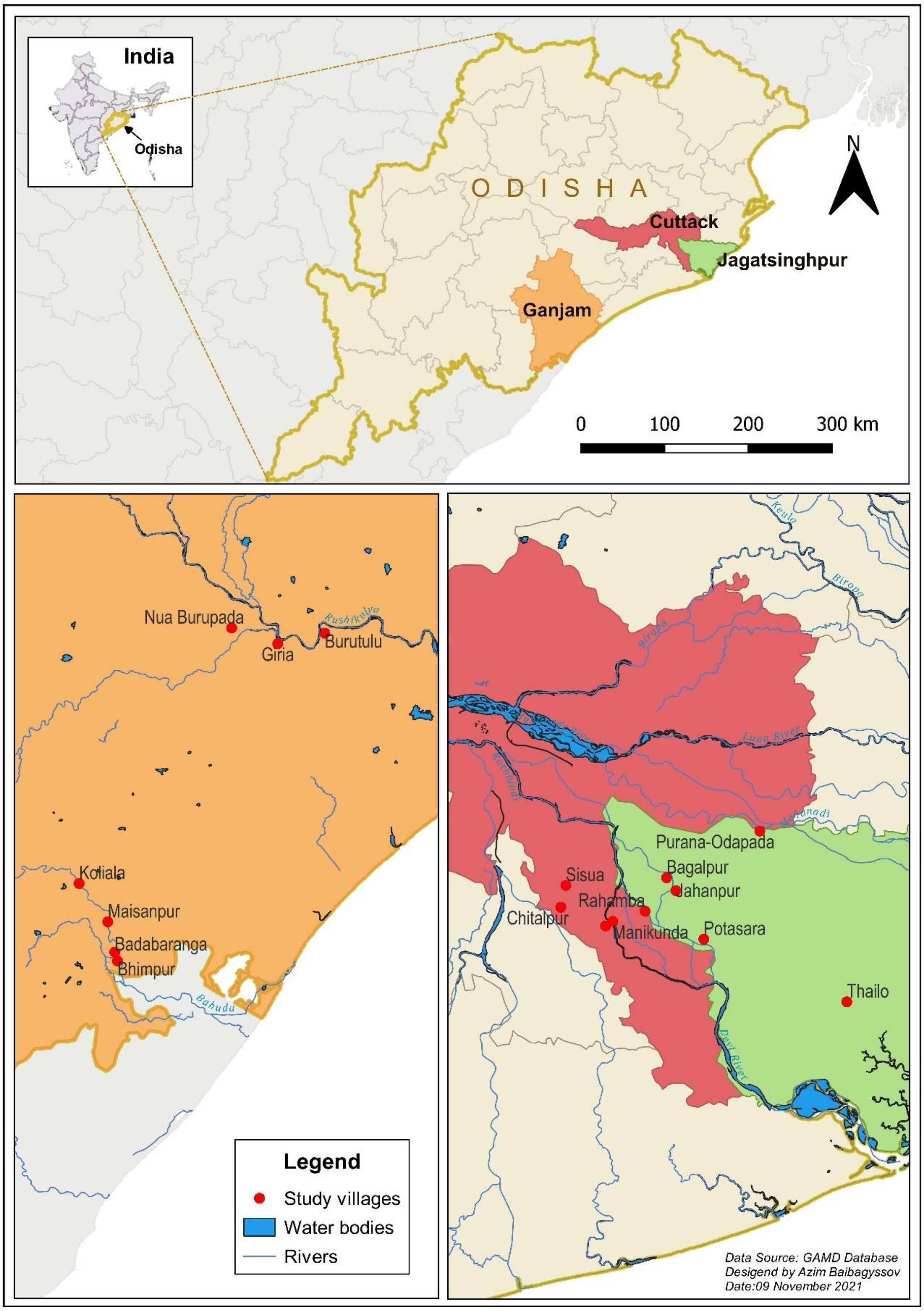


Figure 2.2 Map of the study area

Source: Prepared in Q GIS

2.1.1. *Irrigation distribution system in the study area*

In table 2.1, the district wise irrigation coverage is presented. The area coverage through major and medium surface irrigation network remained unchanged in recent decades. However, regional canal irrigation network i.e. minor flow irrigation network expanded marginally. In contrast, lift irrigation coverage increased by twofold over the period of 20 years from the agricultural year 2000-01.

Table 2.1 Source-wise irrigated area in the survey districts (in thousand ha)

District	Year	Major and medium surface irrigation		Minor flow irrigation		Minor Lift irrigation		Other sources of irrigation	
		Kharif	*Rabi*	*Kharif*	*Rabi*	*Kharif*	*Rabi*	*Kharif*	*Rabi*
Cuttack	2000-01	87.3	53.7	17.0	3.4	20.1	12.1	31.9	19.8
	2004-05	89.1	54.7	19.2	3.4	21.8	13.1	31.9	31.2
	2009-10	89.1	54.7	21.2	3.5	27.7	16.0	25.1	32.3
	2014-15	89.1	54.7	24.5	3.8	32.7	18.2	32.0	31.3
	2017-18	89.1	54.7	29.1	4.3	37.0	20.4	34.1	31.0
Ganjam	2000-01	122.8	8.9	97.9	6.8	23.1	13.9	30.1	22.7
	2004-05	128.1	13.7	13.7	6.8	23.9	14.3	30.1	22.7
	2009-10	132.2	13.9	105.4	7.0	28.4	16.7	36.8	24.3
	2014-15	132.7	13.9	110.0	7.4	34.6	19.3	37.7	29.8
	2017-18	132.7	13.9	118.0	8.2	39.9	22.0	38.7	29.6
Jagatsinghpur	2000-01	30.5	17.2	-	-	8.1	4.9	12.4	7.2
	2004-05	34.8	17.2	-	-	8.5	5.1	13.9	8.4
	2009-10	34.8	17.2	-	-	11.8	6.1	25.8	13.5
	2014-15	34.8	17.2	-	-	12.4	6.5	32.6	32.0
	2017-18	34.8	17.1	-	-	14.9	7.9	33.7	31.7
Odisha state total	2000-01	1176.1	499.8	450.4	70.0	355.9	201.6	557.9	308.0
	2004-05	1238.2	563.2	497.5	71.4	364.3	218.6	565.0	413.1
	2009-10	1322.0	601.6	551.1	74.4	492.9	277.0	596.2	523.8
	2014-15	1390.6	636.9	615.0	78.9	794.2	389.6	677.2	597.1
	2017-18	1425.6	652.4	704.2	89.7	NA	NA	758.9	592.8

Note: NA- values are not available.
Source: 5th Census of Minor Irrigation Schemes Report, (GoI, 2017)

In addition, inadequate surface irrigation supply during the *rabi* season is mainly met with localized lift irrigation provisioning. Meanwhile, coastal Odisha has been experiencing major climatic shocks since the year 2000-01, ranging from cyclonic storms, droughts, prolonged periods of dry weather, followed by heavy rains and flooding. Due to such periodic events in the *kharif* season, farmers were left with no choice but to generate income only during the *rabi* season. The lift irrigation system eventually proved to be the only source of irrigation that could sustain agriculture.

At the village level, differences in farm-level decision-making stimulates diverse area allocation under similar crops. Irrigation infrastructure has made farm-level crop choice even wider, and consequently, the choice to adopt a diversified or specialized farming system easier, in comparison with those who remain deprived of it. Statistics on district-level crop acreages reveal that crops grown under unirrigated conditions were either brought under irrigation provision or replaced by a more profitable irrigation intensive crop. Consequently, irrigation from groundwater WUAs widened the window of crop diversification and also escalated the acreage under high water intensive (HWI) crops. However, this led to a variety of negative externalities, including myopic extraction, inefficient irrigation distribution, and non-cooperative water sharing among member farmers. While conducting the preliminary fieldwork for this study, it was observed that the WUA operations in these three districts had varying capacities and different scales. The crop acreages during 2000-01 to 2017-18 along with their irrigation coverages is presented in tables 2.2 for the *kharif*, and table 2.3 for the *rabi*.

It can be observed that during *kharif* maximum area different crops was under irrigation coverages in all three districts. The same is also apparent at the state level. It indicates that irrigation is inevitable in all types of farming activities. Since the year 2000, frequent drought and prolonged dry spells, followed by floods, have narrowed down the scope of monsoon dependent farming among smallholders in Odisha and increased overreliance on diverse irrigation sources (Gemma & Tsur, 2007; Govt. of Odisha, 2018; Government of Odisha, 2020).

Table 2.2 shows that irrigation in previously unirrigated areas has increased over time. As a result, rainfed farming appears to have declined in recent years. In the state, the number of vegetables cultivated under irrigation has risen. At the district level, the effect of climatic aberrations is prominent, and this has caused changes in the acreage under vegetables, oilseeds, and pulses. There has been an increase in irrigated land area, indicating greater reliance on irrigated farming during the *kharif* season.

In the *rabi* season, the vast majority of crops are irrigated. However, the acreage of irrigated *rabi* rice declined (Table 2.3). Conversely, the area irrigated with pulses and oilseeds increased within the district. In the same way, the gross cropped area and the acreage under irrigation increased as well. The interesting thing to note is that vegetables have replaced cereals in all the districts over the decades.

Moreover, sugarcane acreage declined at the aggregate level. However, the acreage has remained constant or has increased only with adequate irrigation at the district level. It is worth mentioning that farmers could continue farming sugarcane due to the contract sales agreement.

Table 2.2 Area under major crops grown in *kharif* season in the study districts (in thousand ha)

Dist.	Year	Rice	Total cereals	Total pulses	Total oil seeds	Total vegetables	Total spices	Total cropped area
Cuttack	2000-01	153 (55.3)	156.2 (54.2)	4.1 (NA)	1.1 (-)	2.4 (100)	3.2 (14.1)	169.8 (51.9)
	2004-05	142 (63.3)	144 (62.6)	1.8 (68.9)	1.7 (91.1)	10.4 (80.0)	2.6 (-)	161.8 (63.8)
	2009-10	138 (64.0)	139.7 (63.3)	2.8 (NA)	1.7 (-)	10.3 (61.7)	2.7 (56.2)	158.3 (61.4)
	2014-15	121 (73.9)	121.7 (73.6)	1.5 (-)	1.3 (-)	3.4 (100)	2.8 (-)	132 (73.5)
	2017-18	109 (72.1)	109.6 (72.0)	0.9 (-)	0.8 (-)	2.6 (87.7)	2.8 (100)	117.7 (72.2)
Ganjam	2000-01	276 (76.0)	332.9 (63.0)	33.2 (NA)	30.8 (NA)	15 (100)	5.9 (NA)	424.4 (53.0)
	2004-05	259 (79.3)	313 (69.3)	32.6 (9.7)	25.1 (8.7)	20.2 (81.3)	1.5 (-)	397.9 (60.1)
	2009-10	277 (66.0)	331 (61.7)	39.7 (18.7)	22.2 (19.9)	25 (83.9)	2.1 (52.6)	423.9 (56.2)
	2014-15	264 (86.9)	321.1 (78.1)	39.1 (NA)	23.7 (26.0)	13.7 (100)	2.6 (NA)	403.2 (67.7)
	2017-18	205 (89.3)	239.8 (84.8)	43.3 (5.0)	23.3 (13.7)	13.9 (50.9)	2.7 (100)	325.4 (67.1)
Jagatsinghpur	2000-01	92 (55.4)	92.5 (55.1)	0.4 (4.5)	0.3 (-)	1.1 (100)	0.9 (-)	95.3 (54.8)
	2004-05	96 (56.5)	96.3 (56.5)	0.2 (-)	0	10.2 (4.1)	1.1 (NA)	107.9 (50.9)
	2009-10	82 (79.1)	82.1 (79.0)	0.3 (-)	0	7.6 (93.7)	2.1 (33.2)	92.3 (105.4)
	2014-15	84 (88.9)	84 (88.9)	0.2 (-)	0	2.9 (100)	1.8 (NA)	89 (89.3)
	2017-18	78 (87.9)	78 (87.9)	0.1 (-)	0	2.6 (96.2)	1.8 (66.3)	82.6 (87.5)
Odisha total	2000-01	4227 (34.8)	4639.9 (32.0)	541.3 (2.0)	381 (2.4)	163.5 (42.0)	78 (19.0)	5891.8 (27)
	2004-05	4199 (38.6)	4603.1 (35.9)	594.4 (5.3)	450.8 (5.5)	289 (42.4)	73.8 (NA)	6102 (30.2)
	2009-10	4100 (42.2)	4527 (39.3)	750.7 (6.0)	398.9 (4.5)	304.7 (62.2)	74.6 (25.9)	6143.7 (33.5)
	2014-15	3865 (46.7)	4318.3 (43.2)	712.6 (7.4)	326 (11.9)	278 (100)	78.9 (NA)	5865.7 (39.7)
	2017-18	3544.5 (53.9)	3921.1 (50.2)	708.1 (5.6)	286.5 (9.1)	275.7 (62.4)	76.7 (36.6)	5428.3 (41.2)

Note. Figures in parentheses are percentage areas irrigated to their respective cultivated area.
NA- values are not available, (-)- values are less than 0.001 percent position.
Source: 5th Census of Minor Irrigation Schemes Report, (GoI, 2017)

Table 2.3 Area under major crops grown in *rabi* season in the study districts (in thousand ha)

Dist.	**Year**	**Rice**	**Total Cereals**	**Total pulses**	**Total oil seeds**	**Total vegetables**	**Total spices**	**Sugarcane**	**Total cropped area**
Cuttack	2000-01	3.3 (100)	3.9 (100)	54.4 (7.5)	9.2 (11.1)	8.8 (100)	2.1 (100)	2.2 (100)	80.7 (27.5)
	2004-05	5.4 (100)	6 (100)	97.4 (10.6)	13.4 (46.3)	14.2 (100)	4.5 (100)	5.4 (100)	141 (33.2)
	2009-10	3.3 (100)	3.9 (100)	110.9 (12.7)	13.5 (71.4)	16.5 (100)	4.3 (100)	2.4 (100)	151.5 (33.6)
	2014-15	1.3 (100)	1.8 (100)	96.4 (23.3)	11.9 (13.9)	21.1 (100)	4.6 (100)	3.3 (100)	139.2 (39.5)
	2017-18	0.4 (100)	0.8 (100)	85.4 (8.7)	9.0 (88.6)	21.1 (100)	4.5 (92.5)	3.3 (100)	116 (38.6)
Ganjam	2000-01	1.4 (100)	3.8 (98.1)	120.1 (NA)	13 (41.5)	7.5 (100)	1.3 (100)	2.5 (100)	148 (13.7)
	2004-05	0.8 (100)	4.3 (100)	148.2 (3.4)	24.6 (39.4)	26.1 (69.3)	3.7 (100)	2.5 (100)	209.2 (20.6)
	2009-10	1.3 (100)	4.9 (100)	207.5 (0.4)	22.3 (56.5)	23.8 (96.5)	3.1 (100)	3.4 (100)	265 (18.1)
	2014-15	0.6 (100)	3.9 (100)	217.5 (1.5)	32.7 (49.4)	19.9 (100)	4.5 (100)	2.9 (100)	281.4 (18)
	2017-18	NA	2.5 (100)	146.3 (8.7)	19.3 (51.1)	18.7 (99.2)	4.1 (91.5)	2.1 (100)	193 (25.7)
Jagatsinghpur	2000-01	2.6 (100)	2.7 (100)	33.6 (17.1)	14.9 (0.9)	3.2 (36)	0.4 (100)	0.3 (100)	55.1 (19)
	2004-05	1.5 (99)	1.7 (96)	46.3 (5.2)	11.7 (6.1)	10 (72.8)	4.4 (100)	1.0 (100)	75.1 (21)
	2009-10	0.9 (100)	1.1 (100)	50.8 (26.5)	11.6 (28.6)	13.4 (100)	3.3 (100)	0.6 (100)	80.8 (43.5)
	2014-15	1.4 (100)	1.6 (100)	55.7 (0.8)	10.1 (5.6)	14.3 (100)	3.9 (100)	0.8 (100)	86.3 (25)
	2017-18	0.9 (100)	1.1 (100)	63.8 (24.8)	9.5 (87.7)	14.6 (96.4)	4.1 (92.3)	1.3 (100)	94.3 (47.5)

Dist.	Year	Rice	Total Cereals	Total pulses	Total oil seeds	Total vegetables	Total spices	Sugarcane	Total cropped area
Odisha state total	2000-01	206.7 (100)	232.7 (99.2)	848.7 (6.2)	322.9 (13.6)	192.7 (73.2)	51.4 (68.2)	31.4 (100)	1683.2 (31.8)
	2004-05	292.8 (100)	322.2 (99.4)	1056.5 (10.0)	390.1 (25.9)	362.9 (64.5)	72 (100)	33.8 (100)	2242.2 (37.7)
	2009-10	264.8 (100)	300.9 (100)	1341.3 (8.2)	398.4 (32.8)	398.5 (81.6)	73.2 (100)	36.9 (100)	2552.6 (38.4)
	2014-15	301.3 (100)	333.5 (100)	1368.1 (10.6)	415.6 (34.2)	390.4 (100)	87.9 (100)	34.1 (100)	2631.3 (43.1)
	2017-18	221.9 (100)	246.7 (100)	1339.3 (19.9)	316.9 (59.9)	375.9 (100)	84.9 (87.1)	27 (100)	2390.9 (49.4)

Note. Figures in parentheses are percentage areas irrigated to their respective cultivated area.
NA- values are not available.
Source: 5th Census of Minor Irrigation Schemes Report, (GoI, 2017)

2.1.2. Types of irrigation distribution arrangements and institutional diversities

Table 2.2 shows that privately organized and government-sponsored lift irrigation systems started gaining importance in previously traditional rainfed farming systems and subsequently realized a miracle production boom. Government subsidies helped the capital-deprived smallholders to adopt the localized lift irrigation system. The evolution of irrigation distribution can be divided into five phases: background, initiation, expansion, restructure, and regrowth.

2.1.2.1. Background

Prior to 1960, irrigation was primarily provided through a government-owned canal irrigation network under which the cost of irrigation was heavily subsidized. In addition, traditional water harvesting structures such as ditches, creaks, village ponds, and a few surface and groundwater lifts played an important role in irrigation. During that period, most crops were traditional rice, jute, millets, pulses, and oilseeds. Only a few wealthy farmers had made the decision to drill their own tube well since the groundwater extraction structures (GES) was not subsidised by the government or non-governmental organizations (NGO). In this context, it is important to note that the village communities maintained the water harvesting structures for domestic and agricultural use.

Meanwhile, the government invested heavily in combating periodic disasters such as floods and constructed medium to large sized check dams and barrages. At the end of the 1960's, the Indian Green Revolution realized that the provision of assured irrigation was crucial for the ultimate success of dwarf rice farming. Despite traditional open wells continuing to serve a limited number of irrigation requirements, government subsidy schemes enabled groundwater exploration for the first time (M. Shah et al., 2021; T. Shah, 2009).

2.1.2.2. Initiation

The government of Odisha offered a 90 per cent financial subsidy in order to promote groundwater extraction technologies. Because of this, poor, capital-deprived smallholders were able to realize incremental net returns by increasing their net irrigated area (NIA). During the early 1960s, the water resource department established farmer organizations to increase groundwater usage. An official from the department of water resources was also a member of the farmers' organization (FO). WUA formation on the lift irrigation task was given to an independent organization, known as Odisha Lift Irrigation Corporation (OLIC), which served as a subsidiary organization of the Ministry of Water Resources in Odisha during the year 1973. OLIC specialized in the provision of a full range of administrative services, including the selection of the site for WUA formation at the village level, development of a proposal for a WUA well installation along with water distribution channels, legal clearance from the land administration, and formation of the WUA (Shah, 2009).

2.1.2.3. Expansion

The OLIC officials were also responsible for the operation and maintenance of the WUA, which included the determination of crop-based water costs and the collection of water revenue. A rapid increase in WUA formation was noted in the 1980s with the assistance of various sources, such as state and central government budgetary allocations, the NABARD, the KfW bank based in Germany, and the World Bank. Consequently, the gross irrigated area had increased many folds within a decade. Most of the additional acreage was derived from the tail end of the canal command area and rainfed farmlands.

Public policies have also extended the capital subsidy to owning a water extraction structure and water-lifting pump powered by diesel or electricity. To qualify for a subsidy, arable land had to be outside the area commanded by a canal. In the 1990s, subsidised electricity also encouraged the development of privately owned tube wells. This eventually resulted in a significant expansion of irrigated agriculture. During this period, individual farmers who had been granted government subsidies began selling water to neighbouring farms. In contrast to Karnataka's system of water trading, water transactions used to take place among any neighbouring farms, regardless of clan, family or close friends (Patil, 2015).

2.1.2.4. Restructure

From 1990 to 2000, many WUA wells began to experience dysfunction, either because of well maturation or prematurity defunct. Due to a lack of funds, public rehabilitation of these projects was limited, leaving farmer members with no choice but to adopt rainfed agriculture. Only a few WUAs have managed to restore their wells, but the majority of them remained dysfunctional. However, government policies have generally promoted individual ownership and management of wells. At the same time, privately invested wells received subsidised electricity to power their irrigation pumps. The individually owned GES provided irrigation services at a monopolistic price to their neighbouring farms for the next ten to twelve years.

In the year 2002, the Odisha state government enacted the *Pani Panchayat* (PP) Act, which is a Hindi word that means a water user's association (Ghosh et al., 2006; Govt. of Odisha, 2002; Pati, 2010). As a result, the ownership and maintenance of all WUA were transferred to the farmers' organization (FO). Under the new act, farmers were obliged to develop a crop calendar, a water distribution roaster, a water cost collection plan, and maintenance of their irrigation lifting and distribution systems. The new legislation had multiple impacts on the farmers regarding the survival of the WUA.

The primary objectives of the Odisha PP Act of 2002 (Govt. of Odisha, 2002) are outlined below.

1. To promote and secure the distribution of water among its users,
2. Adequate maintenance of the irrigation system,
3. Efficient and economical utilisation of water to optimise agricultural production,
4. To protect the environment and to ensure ecological balance by involving the farmers, and

5. To inculcate a sense of ownership of the irrigation system following the water budget and the operational plan.

Some of the essential functions of the PP objectives are mentioned below.

1. To prepare a cropping programme suitable for the soil and agro-climatic condition with due regard to crop diversification.
2. To prepare a plan for the maintenance of irrigation systems in the area of its operation at the end of each crop season and carry out the maintenance works of both distributary system in its area of operation, with the funds of the PP from time to time.
3. To manage the lift irrigation points as may be handed over to the farmers' organisation through a mutual agreement between two parties, as may be prescribed.
4. To regulate the use of water among the various pipe outlets under its area of operation according to the *warabandi* (a Hindi word for rotational distribution) schedule of the system.
5. To promote economy in the use of water allocated
6. To assist the revenue department in the preparation of demand and collection of water rates
7. To collect fees from the water users of the lift irrigation points, for payment of energy charges, for repair, maintenance of machinery and distribution system, and future replacement of machines.
8. To resolve the disputes, if any, between the members and water users in its area of operation and others.

The PP act 2002 do not specify groundwater management regulation except the periodic payment of electrical costs to the electricity provider. The subsequent amendments do not identify explicit provisions for the conservation of groundwater ecology or its optimum utilization. Currently, many groundwater user associations have established institutions to ensure dispute-free distribution of water. However, regulations on benefit sharing apart from water distribution is not apparent in PP act. In this connection, a WUA also devise regulations for sharing benefits and are vary by GWUAs. This further motivated me to classify the villages into similar ones to understand the diversities in water sharing institutes.

2.1.2.5. Regrowth

Some farmers also spontaneously explore groundwater through their own private investments despite various public policies, in order to provide vital irrigation services. In the restructuring phase, many privately managed irrigation groups formed a subgroup of a dysfunctional WUA to provide irrigation service to their farms. Nevertheless, the energy cost for these wells is not subsidised. In 2010, OLIC realized that a standard norm of 20 hectares for a WUA would not be feasible for many villages. In response to this, OLIC has established a cluster tube well program (CTW) which is more compact in scope than a WUA. As part of this program, five to fifteen pumps are connected to a dedicated power source, and farmers irrigate their respective farm plots with land owned by other neighbouring farmers. OLIC also ensures that the pumps cover up to five hectares of arable land and that the cost of irrigation is shared with neighbouring farmers.

2.2. Survey design and data

The preparatory visit during April-May 2018, enabled me to select the study villages from the blocks[1]. I obtained a list of WUAs from OLIC administrative office at Bhubaneswar, to identify them. The villages were selected using the stratified purposive sampling technique. As a part of the sampling procedure, diversity was examined at the block, village, and WUA levels. For the final primary survey, 33 WUAs were selected from 15 villages. Surveys were conducted in conjunction with Participatory Rural Appraisals (PRA).

PRA was accomplished in two stages. In the first stage, a transaction walk was conducted, and then prepared a resource map by the respondent farmers, and a timeline of technological interventions in the village. In this stage, I collected information on village level natural resources, including arable land, irrigation sources and their respective coverage, farming systems, demography, rate of technological adoption in agricultural production activities, and communication networks to the nearest market. In the second phase, a focus group discussion (FGD) was conducted with WUA members and non-member neighbouring farmers in each village. In FGD I obtained information on existing irrigation systems and their associated rules and regulations in agriculture production (figure 2.3). Additionally, a key informant interview was conducted to triangulate the information obtained during the first and second phases. However, the lack of written records of activities from many WUAs at the time of their establishment limited the availability of data. However, it was subsequently triangulated using information gathered from village elder farmers.

1 A block is an administrative unit that is composed of a group of villages, and a group of block compose a district.

Figure 2.3 Resource map and seasonal calendar preparation at a FGD with WUA members from Giria village

Source: Authors own fieldwork photo.

Farmers in the surveyed villages enjoyed an added advantage from subsidised irrigation and cultivated many remunerative crops. From these villages, I chose 53 representative farms who benefited from any of the subsidized groundwater irrigation distribution system, in partial or full.

Upon enquiry to the Odisha Lift Irrigation Corporation Ltd. (OLIC) executives shared a list of members farmers of the selected villages . With the help of that respondents were randomly chosen and interviewed using a pre-tested structured questionnaire designed to elicit information on land use and land cover change (LULCC), irrigation provision and its use for plot-specific activities, irrigation distribution system, and crop product sale decisions during the 2018-19 cropping season. The primary database is comprising of respondent farmers' recall data for the *kharif* season 2018-19. However, enumerators triangulated the information since they were physically present on the farms during the *rabi* 2018-19.

2.2.1. *Salient characteristics of the study area*

a. *Demography*

During 2011 census, the population of Cuttack and Jagatsinghpur districts was 2.62 million and 1.14 million, constituting 6.25% and 2.51% of the state's population, respectively. The female population was 940 and 968 per 1000 males in respective districts. There were 48 and 52 per cent of the working population in the corresponding districts, of which the majority worked in agriculture and related activities (Table 2.4).

Table 2.4 Demographic information of the sample districts

Particulars	Cuttack	Jagatsinghpur	Ganjam
1. Population (M)	2.62	1.14	3.53
2. Male (M)	1.35	0.58	1.78
3. Female (M)	1.27	0.56	1.74
4. Literacy rate (Percentage)	85.50	86.59	71.09
5. Rural population (M)	18.88 (72%)	10.21 (90%)	2.76 (78%)
6. Rural male (M)	0.97	0.52	1.38
7. Rural female (M)	0.92	0.50	1.38

Note: Figure in parentheses is the percentage of the total population
Source: District statistical handbook of Cuttack and Jagatsinghpur, 2019.

b. *Location and physical characteristics*

Cuttack and Jagatsinghpur districts are geographically adjacent and share the administrative boundary of Cuttack districts' *Kantapada* block and *Biridi* block of Jagatsinghpur. The Ganjam district is located in the southern region of the state, bordering Andhra Pradesh state (refer to figure 2.2). Cuttack, Jagatsinghpur, and Ganjam districts cover 393, 167, and 821 thousand hectares of administrative delineated area, respectively. The three districts, respectively, consist of fourteen, eight, and twenty-two community development blocks; 373, 194, and 475 *Gram Panchayats* (an administrative unit below a block that is constituted with many adjacent villages); and 1950, 1320, and 3250 inhabited villages (Table 2.5).

c. Climate, Rainfall and Natural endowment:

The three cropping seasons in the state are *kharif* (June-September), *rabi* (October-January) and summer (February-May). Southwest monsoons begin in June and last until the end of September. In the 2018-19 agricultural year, the average annual rain-fall in Cuttack, Jagatsinghpur and Ganjam was 1440 mm, 1514 mm, and 1373 mm, respectively. A decadal distribution of rainfall patterns indicates that rainfall patterns have been irregular over the last couple of years, causing prolonged droughts fol-lowed by heavy rains that have adversely affected crop growth (Govt. of Odisha, 2018). These districts experienced temperatures ranging from 10 to 38 C. The soils are alluvial in nature, shallow in depth, and well-drained, containing some areas of red and lateritic soils (Govt.ofOdisha, 2018).

d. Land Utilization

In table 2.5, a summary of the land utilization pattern in the study area blocks during 2017-18 is presented. In comparison with the state average of 43.7 percentage (15424 thousand ha of total geographic area), there were relatively more lands allocated to agricultural activities in the study blocks. Forested areas constituted to occupy a very small proportion of the total geographical area, except Patrapur block, while most of the land was devoted to agriculture.

Table 2.5 Land utilization pattern by blocks in the study districts (in ha)

Particulars	Cuttack	Jagatsinghpur				Ganjam			
	Kantapada	*Baliku-da*	*Biridi*	*Jagatsinghpur block*	*Raghunathpur*	*Hin-jilikatu*	*Purushotyampur*	*Chikiti*	*Pa-trapur*
1. Forest	32 (0.3)	1412 (4.7)	-	-	38 (0.001) -	51 (0.3)	2146 (8.7)	2290 (10.9)	11365 (31.7)
2. Land put to Non-agricultural use	2623 (22.2)	6665 (22.2)	2533 (23.4)	3602 (21.4)	2914 (2.9)	2460 (15.7)	2826 (11.5)	6085 (28.8)	2251 (6.3)
3. Barren & Non-cultivable land	31 (0.3)	63 (0.2)	-	-	-	1093 (7)	1312 (5.3)	324 (1.5)	412 (1.1)
4. Permanent Pastures & other grazing land	444 (3.8)	2963 (9.9)	280 (2.6)	592 (3.5)	458 (0.5)	171 (1.1)	506 (2.1)	388 (1.8)	548 (1.5)
5. Land under misc. tree crop& groves not included net area sown	157 (1.3)	332 (1.1)	185 (1.7)	472 (2.8)	521 (0.5)	214 (1.4)	427 (1.7)	489 (2.3)	270 (0.8)
6. Cultivable Waste	186 (1.6)	179 (0.6)	122 (1.1)	322 (1.9)	209 (0.2)	55 (0.4)	511 (2.1)	358 (1.7)	1722 (4.8)
7. Old fallows	834 (7.1)	1128 (3.8)	520 (4.8)	167 (1.0)	542 (0.5)	319 (2)	61 (0.2)	282 (1.3)	3314 (9.2)
8. Current Fallows	412 (3.5)	1573 (5.2)	597 (5.5)	492 (2.9)	433 (0.4)	434 (2.8)	2734 (11.1)	430 (2)	2253 (6.3)
9. Net Area sown	7098 (60.1)	15742 (52.4)	6581 (60.8)	11161 (66.4)	96107 (94.9)	10835 (69.3)	14036 (57.2)	10452 (49.5)	13696 (38.2)
10. Total Geographical Area	11817	30057	10818	16808	101222	15632	24559	21098	35831

Note: Figures in parentheses are percentage to total geographic area of respective blocks

Source: District statistical handbook of Cuttack, Jagatsinghpur and Ganjam, 2018.

In table 2.6, source-wise irrigation coverage in the study area is presented It was found that, government canal irrigation network occupied majority of the total irrigated area, followed by private groundwater lift irrigation and then government lift irrigation systems. In Cuttack district, Kantapada block owned 6.8 per cent of total irrigated area. Interestingly, the privately owned groundwater extraction structures irrigated twice the area of government subsidised structures. This is almost similar in other sample blocks of Jagatsinghpur and Ganjam districts. It indicates that, to avoid any production loss due to erratic rainfall, farmers owned different types of GES as a mitigation strategy. Overall, the trend in source-wise irrigated area indicate that a larger proportion of area is increasingly irrigated by groundwater sources (Govt.of Odisha, 2018).

Table 2.6 Source wise irrigation in sample districts (in ha.)

District/ Blocks	Canal	Groundwater lift (Govt.)	Groundwater lift (Pvt.)	Dug Well & other source	Total
A. Cuttack district Total	**79711**	**33923**	**31820**	**20910**	**182678**
1. *Kantapada block*	8415 (10.6)	1093 (3.2)	2741 (8.6)	229 (1.1)	12478 (6.8)
B. Jagatsinghpur district Total	**59808**	**8373**	**11180**	**1920**	**81281**
2. *Jagatsinghpur block*	11558 (19.3)	688 (8.2)	1651 (14.8)	260 (13.5)	14157 (17.4)
3. *Raghunathpur block*	6696 (11.2)	726 (8.7)	447 (4.0)	54 (2.8)	7923 (9.7)
4. *Balikuda block*	10272 (17.2)	1104 (13.2)	2312 (20.7)	239 (12.4)	13927 (17.1)
5. *Biridi block*	6502 (10.9)	819 (9.8)	603 (5.4)	177 (9.2)	8101 (10)
C. Ganjam district total	**217047**	**17283**	**8548**	**23041**	**265919**
1. Hinjilikatu block	14789 (6.8)	954 (5.5)	107 (1.3)	1081 (4.7)	16931 (6.4)
2. Purushotyampur 3. block	8445 (3.9)	1939 (11.2)	295 (3.5)	1708 (7.4)	12387 (4.7)
4. Chikiti block	9327 (4.3)	1096 (6.3)	317 (3.7)	960 (4.2)	11700 (4.4)
5. Patrapur block	14655 (6.8)	632 (3.7)	332 (3.9)	689 (3)	16308 (6.1)

Note: Figures in parentheses are percentages to the respective district acreage total.

Source: District statistical handbook of Cuttack, Jagatsinghpur and Ganjam, 2018.

e. Cropping pattern

During 2017-18, in kharif season, rice accounted for the majority of the acreage, followed by vegetables and other seasonal and perennial crops. In the *Rabi* season, rice dominates in the Kantapada block, followed by pulses and seasonal vegetables. A variety of crops were grown in the blocks of Jagatsinghpur, including irrigated rice, rainfed pulses, and seasonal vegetables (table 2.7). Sugarcane accounted for a significant area in all the blocks and was primarily irrigated. *Kharif* rice dominates the seasonal acreage in the blocks of the Ganjam district.

In *rabi* season, soon after rice is harvested, green gram and black gram beans dominated in the cropping pattern(table 2.8). In many other farm plots groundnut and sesame is cultivated as a second crop. A variety of seasonal vegetables are also grown in all the blocks to a varying extent. Farmers sold vegetables at a remunerative price at the secondary market. The block level crop acreages and its seasonal variability reflects significant role of irrigation, especially in the *rabi* (post rainy season) for rice and seasonal vegetable cultivation. However, there exists no published database on village level water sharing methods and associated agricultural production systems. Therefore, an investigation was made at the village level to understand the diversity in agricultural production system. I used this information to develop a meaningful cluster of villages that are distinct in terms of water use, crop production activities and other social dimensions, and is discussed in the next chapter.

Table 2.7 Block wise gross cropped area under different crops during 2017-18 in *kharif* season (in ha)

Crops	**Cuttack**	**Jagatsinghpur**				**Ganjam**			
	Kantapada	Jagatsinghpur	Raghunathpur	Balikuda	Biridi	Hinjilikatu	Purusho tyampur	Chikiti	Patrapur
1. Rice	5520	11135	6902	13260	5940	12110	9740	9760	10110
2. Maize	19	5	4	6	4	395	235	390	770
3. Finger millet	0	0	0	0	0	425	310	0	1800
4. Small millets	0	0	0	0	0	0	0	150	200
5. Green gram	0	0	0	0	0	80	170	100	100
6. Black gram	0	6	5	5	5	125	170	615	770
7. Red gram	5	1	0	1	1	550	348	550	850
8. Other pulses	0	0	0	0	0	500	202	400	700
9. Ground nut	0	0	0	0	0	75	150	120	500
10. Sesame	0	0	0	0	0	215	100	510	350
11. Castor	5	0	0	0	0	20	0	40	100
12. Cotton	0	0	0	0	0	0	0	10	50
13. Chili	98	173	79	289	61	200	105	60	50
14. Cow pea	0	9	2	3	2	0	0	0	0
15. Total vegetables	1845	2889	643	2415	1687	5125	2835	1870	2525
16. Turmeric	10	44	13	12	51	0	0	0	0
17. Ginger	10	52	41	50	60	0	0	0	0
18. Sweet potato	0	9	4	9	9	0	115	0	100
19. Mesta	0	0	0	0	0	80	20	0	0
20. Sun hemp	0	0	0	0	0	100	115	0	0
21. Sugarcane	495	72	302	13	318	0	144	0	0
***Kharif* (2016-17) total**	**8007**	**14395**	**7995**	**16063**	**8138**	**20000**	**14759**	**14575**	**18975**

Source: District statistical handbook of Cuttack, Jagatsinghpur and Ganjam, 2018.

Table 2.8 Block wise gross cropped area under different crops during 2016-17 in *rabi* season (in ha)

Crops	**Cuttack**	**Jagatsinghpur**				**Ganjam**			
	Kantapada	Jagatsinghpur	Raghunathpur	Balikuda	Biridi	Hinjilikatu	Purushotyampur	Chikiti	Patrapur
1. Rice	5240	16	38	10	10	12110	9740	9760	10110
2. Wheat	0	0	0	0	0	5	0	0	1061
3. Maize	10	17	16	15	15	50	50	70	50
4. Finger millet	0	0	0	0	0	20	0	60	75
5. Total cereals	**5250**	**33**	**54**	**25**	**25**	**12185**	**9790**	**9890**	**11296**
6. Gram	4	3	2	3	4	25	22	50	25
7. Green gram	2035	6771	3508	8732	3357	2192	3661	3000	1489
8. Black gram	1505	2296	1572	774	1083	985	750	950	850
9. Horse gram	805	62	122	463	541	560	220	500	300
10. Field pea	0	0	0	0	0	80	65	75	55
11. Cow pea	40	25	25	20	50	30	30	40	30
12. Other pulses	31	16	7	9	8	280	207	385	219
13. Total pulses	**4420**	**9173**	**5236**	**10001**	**5043**	**4152**	**4955**	**5000**	**2968**
14. Ground nut	290	249	48	9	47	975	120	230	600
15. Sesame	31	4	3	26	22	430	313	925	880
16. Castor	0	0	0	0	0	0	0	50	10
17. Sunflower	14	23	26	52	27	50	31	479	471
18. Mustard	40	29	31	72	30	0	0	120	135
19. Total oilseed	**375**	**305**	**108**	**159**	**126**	**126**	**464**	**1804**	**2096**
20. Sweet potato	10	4	4	9	5	20	0	30	35
21. Potato	407	198	91	59	90	0	15	20	7
22. Onion	46	88	29	29	22	15	20	50	30

Crops	**Cuttack**	**Jagatsinghpur**				**Ganjam**			
	Kantapada	Jagatsinghpur	Raghunathpur	Balikuda	Biridi	Hinjilikatu	Purushotyampur	Chikiti	Patrapur
23. Field pea	21	5	6	11	13	0	0	0	0
24. Other Veg.	1412	4199	1741	4241	2108	575	845	558	320
25. Total vegetables	**1896**	**4494**	**1871**	**4349**	**2238**	**610**	**880**	**658**	**392**
26. Chili	140	126	240	932	256	692	267	401	261
27. Coriander	26	30	70	60	50	35	20	40	15
28. Garlic	23	18	4	36	16	175	20	20	19
29. Total spices	189	174	314	1028	322	705	250	320	234
30. Sugar cane	495	68	312	9	285	680	123	0	0
***Rabi* (2016-17) season**	12814	14421	8209	16599	8361	19360	16769	18133	17281
GCA	**20821**	**28816**	**16204**	**32662**	**16499**	**39360**	**31528**	**32708**	**36256**

Source: District statistical handbook of Cuttack, Jagatsinghpur and Ganjam, 2018.

f. Household characteristics

This section describes the general characteristics of the study area villages. In addition, it provides an understanding of the socio-cultural-economic background of the study area. Table 2.9 summarizes the demographic characteristics of the villages. The majority of the farmers are engaged in crop cultivation throughout the year. Within the Kantapada block, there are 40, 67, 48, 120, and 120 households representing all social classes. The results of the focus group discussion indicate that the majority of farmers are from the *Behera* tribe. Together with family members, they pursue agricultural activities, and some own a dairy farm, which consisted of indigenous as well as mixed-breed cows, goats, and sheep.

A striking characteristic of these households was that only the male members contributed to the agricultural operations at the main field. Farm women engage themselves in homestead kitchen garden rearing, livestock and bird rearing, and post-harvest operations such as sorting of the vegetables, packing them in sacks and help men to keep ready for dispatching to the market, apart from their day-to-day household activities. They hired casual labourers particularly during the sowing or planting of rice seedlings in *kharif* and *rabi*. In the villages of Jagatsinghpur district, it was observed that there are wide variations in terms of employment. Purana-Odapada and Kamalpur villages had a relatively high proportion of agricultural labourers compared to Bagalpur, Patasara, and Thailo villages. Most of the inhabitants of these villages belong to upper castes. In addition, women from these families do not engage in main field agricultural operations. Regardless of gender, the literacy level of the village indicates that it has a high level of education. This implies that farmers may communicate with government officials regarding any agricultural and rural development policies.

Table 2.9 Demographic information of the sample villages

Particulars	**District**: Cuttack					Jagatsinghpur					Ganjam				
	Block: Kantapada					Biridi		Jagatsinghpur Block	Raghunathpur	Balikuda	Chikiti	Hinjilicut		Patrapur	
	Vill: Chitalpur	Olarpur	Chheda	Manikunda	Rahambha	Bagalpur	Kamalpur	Patasara	Purana-Odapada	Thailo	Nua Maisanpur	Giria	Nua Burupada	Koliala	Badabaranga
1. Rural population	1107	1214	867	1265	2191	2487	2146	1303	2454	894	1927	1640	929	1191	1253
2. Total household	40	67	48	120	120	135	121	279	574	38	449	345	244	272	279
3. Rural male	578	626	446	637	1135	1264	1106	677	1277	443	954	818	405	545	624
4. Rural female	529	588	421	628	1056	1223	1040	626	1177	451	973	822	524	646	629
5. Rural literacy rate (%)	85.61	85.48	97.53	73.99	81.41	84.47	84.55	87.09	84.21	84.44	65.12	64.26	50.92	50.12	66.9
6. Working population	410	369	410	552	1138	938	883	543	1043	296	721	1011	440	568	531
7. Agricultural labour	8	20	9	66	254	224	151	88	398	42	201	121	89	23	161

Particulars	**District**: Cuttack					Jagatsinghpur					Ganjam				
	Block: Kantapada					Biridi		Jagatsinghpur Block	Raghunathpur	Balikuda	Chikiti	Hinjilicut		Patrapur	
	Vill: Chitalpur	Olarpur	Chheda	Manikunda	Rahambha	Bagalpur	Kamalpur	Patasara	Purana-Odapada	Thailo	Nua Maisanpur	Giria	Nua Burupada	Koliala	Badabaranga
8. Avg. landholding/ HH (acre)	1.95	1.92	2.11	1.68	3.32	4.65	2.23	2.44	2.04	2.87	2.96	0.60	3.22	1.11	2.54
9. Average no. of parcels	5	4	3	4	2	2	3	4	5	3	3	5	4	3	3
10. Avg. cattle ownership	3.6	2.8	2.2	3.4	1.8	2.2	2.8	2.9	4.6	2.2	3.2	3.5	2.2	3.8	3.1
11. Ownership of medium to large farm machines / HH	0.14	0.10	0.15	0.18	0.08	0.10	0.11	0.07	0.06	0.06	0.24	0.02	0.01	0.01	0.11

Source: Census of India, 2011

Additionally, the study examined the relationship between educational attainment and social background (caste) of the farmers and their participation in irrigation distribution systems. Farmers from socially disadvantaged areas were more likely to join a WUA. In spite of their limited educational attainment, they took the rational decision concerning crop selection, a decision that is generally determined by crop water requirements.

g. Landholding

Within the sampled villages, the average size of a farm was almost similar. Moreover, it was found that the average size of the landholding per farm household in the villages of Cuttack district ranged from 1.6 acres in Manikunda to 3.3 acres in Rahambha. It is interesting to note that Chitalpur and Olarpur villages have a higher proportion of land under irrigation compared to other villages. Observations on the field also indicate that farmers owned farms on different parcels, and this affected the crop choice decisions. Typically, a farmer grows a wide range of cash crops in their farm plots closest to their residence because of their constant supervision of crops. If a farmer is cultivating a distant plot, despite having guaranteed irrigation from a WUA or other source, he usually consults a neighbour in advance. the research primarily focused on land diversification in terms of cropping activity. Spatial variation in cropping activities influenced the development of village typologies.

h. Livestock and farm machinery

In Kantapada block, farmers practised a mixed to a specialized farming system where livestock played a significant role. The local dairy industry supported the production of milk from indigenous and crossbred cows. The use of cow dung is one of the best ways to provide organic matter, and it has historically been used to maintain soil structure and nutrient levels.

The increased use of machines for various farm operations has reduced the use of bullock pairs for land preparation or transportation. It is noteworthy that the Behera cast dominant villages own a greater proportion of cattle. Many villages also raise small ruminants along with poultry, although their numbers are limited.

At the village level it was observed that tractor-drawn implements were primarily used for rice and sugarcane sowing and for harvesting operations. For instance, in Chitalpur village, the average number of households with medium and large sized machineries such as power tillers and tractors was 0.14, implying that one machine was owned/shared by seven farm households. Despite this, there are many operations that required human labour, such as the making of ridge and furrows, intercultural operations, weeding, and harvesting of vegetables, pulses, and oilseeds. Considering the economic scarcity of labour, farm mechanization has been a new approach to raising the sugarcane bed and to harvesting it. Weeding is accomplished with power weeders.

2.2.2. Existing irrigation distribution arrangements

The selection of villages were based on prevailing representative irrigation distribution arrangements as outlined in the sampling procedure. During the transaction walk It was observed that different irrigation systems were used for different purposes. Detailed information was recorded on the year of establishment, initial delineated area and current coverage area, membership, authority, and institutions involved in sharing irrigation. During the FGD, the given information was cross-checked, followed by the classification of the irrigation distribution arrangements into six different categories. I identified major irrigation distribution systems, namely: individual wells financed by private investors (IW-P), individual wells financed by the government (IW-G), community tube wells installed with government support and managed by farmers' organizations (WUA), cluster tube wells (CTW) that were individually owned, and a group of seven to ten farmers who take advantage of government subsidised electricity from a dedicated power sub-station. Furthermore, field observations also indicated that canal irrigation networks were responsible for providing irrigation during the *kharif* season. Nevertheless, due to its location at the tail end of the region and unreliable water supply, farmers relied on local water bodies, such as village ponds and groundwater supplies.

CHAPTER 3: FARM TYPOLOGY IN THE COASTAL AQUIFERS OF ODISHA

3. Farm typology in the coastal aquifers of Odisha

3.1. Existing irrigation distribution systems in Odisha

With increasing instances of drought and prolonged dry spells, divergent land-based production activities have been observed in India (Blakeslee et al., 2020; Fishman et al., 2015). Flow or surface irrigation networks dominated irrigation in Odisha, providing water primarily in the *kharif* (rainy) season to support *kharif* rice. Over the past three decades, Odisha experienced a variety of biotic and abiotic shocks, that includes severe droughts, prolonged dry spells, followed by heavy rains, and floods alternately. Therefore, irrigation became necessary for agriculture regardless of seasonal rainfall. The surface irrigation system primarily provides irrigation during the *kharif* season. Minor lifts (rivers and groundwater lifts) and other sources of irrigation (farm ponds, open wells and dug wells) complement the farm-level irrigation requirements, especially in the *rabi* (post-rainy) season (Behura, Haldar, & Pal, 2018; Ghosh et al., 2012; Govt. of Odisha, 2018; Pati, 2010).

Until the year 2000, state water resource department owned and managed the irrigation provisioning system. However, increasing number of member beneficiaries attracted different issues related to water distribution. Ensuing these problems, state government introduced the PP Act 2001 and transferred irrigation management to the farmers' organization . Despite its local management, there were mismatches in the delivery of water by the state authority during the *kharif* season. As a result, farmers began exploring other irrigation methods, such as individual groundwater lifts and other sources. For instance, a small-scale lift-irrigation system is owned and managed by few farms or a small group of farmers who may not belong to any major irrigation system. Researchers claim that farmers' participation in managing these small-scale lift irrigation systems in regard to (i) water distribution, (ii) maintenance of physical infrastructure, (iii) crop planning, (iv) determination of water cost, (v) energy cost collection, (vi) periodic payments, and others are higher than their participation in surface irrigation. Groundwater (lift) irrigation enables round-the-year irrigation, allowing for a wide range of farming systems, from diversified to specialized irrigation intensive ones (Ghosh et al., 2006). In addition to that, small-scale groundwater irrigation sources became crucial to facilitate irrigation for agricultural purposes mostly at the tail end of the canal command areas. Eventually, this improved food production and helped restore smallholder farming (Feinerman & Knapp, 1983; Gandhi, Johnson, Neog, & Jain, 2020; Nagrah et al., 2016).

In many parts of peninsular India, irrigation systems are owned by individuals and managed by groups, in which clan membership is most prevalent (Patil, 2015). Along with individual ownership and management, joint public and private investments were also used to create community irrigation distribution arrangement (CIDA) to meet irrigation needs at varied scales.

The CIDA organized thousands of smallholders to enhance their farming systems under climatic and non-climatic extreme events. A CIDA adhere to specific rules and regulations (henceforth, institutions) to allocate irrigation water among the member farmers and determines cost of water. Furthermore, a CIDA also develops institutions for physical infrastructure maintenance, crop planning, and dispute settlement (Ghosh et al., 2010; Kolavalli & Brewer, 1999; Zhang, Heerink, Dries, & Shi, 2013).

3.2. Irrigation distribution through a WUA

Since the 1960s, public policies have supported groundwater exploration to supplement irrigation for non-canal irrigation recipients. In Odisha, a community tube well distributed irrigation up to 20 hectares on average. As a result, beneficiary farmers have adopted diverse land use practice to maximize their net farm income. As of the year 2017, 4774 WUA have provided irrigation to 246,860 farmers in Odisha (http://dowrodisha.gov.in/DIP/DIPIndex.htm). Some WUAs have adhered to statutory regulations regarding crop choice, while others have developed farming systems based on water availability. With the help of these government-funded projects, farmers can now choose the most suitable farming systems. Together, these farm-level heterogeneous decisions typify the village as well as block level farming.

3.3. The diversity of land-based production methods in various irrigation distribution systems

Researchers have shown that family labour, natural resource endowments, socio-cultural preferences, membership to an irrigation distribution system, and the market collectively determine the farming system (Köbrich, Rehman, & Khan, 2003; Valbuena, Verburg, & Bregt, 2008). Diverse farming systems emerged under similar types of irrigation, eventually as sharing systems. Among its many determinants, water access and its governing institutions directly affect marginal and smallholders' farming systems (Alvarez et al., 2018).

Smallholders of Odisha have adopted different cropping patterns in spite of similar irrigation distribution system. In all these irrigation systems, institutions in water sharing are either locally devised or state enforced. WUAs often modifies state prescriptions according to local requirements, such as, adoption of high water intensive (HWI) cropping patter instead of water saving activities (Ghosh et al., 2006; Mosse, 2003; Shiferaw, Reddy, & Wani, 2008). Diversity in water-sharing institutions and their impact on agricultural production systems, however, have seldom been examined. Scholars have further argued that water-sharing institutions, in most cases, are inappropriate and eventually become obsolete (Aarnoudse, Qu, Bluemling, & Herzfeld, 2017).

However, these differences are not apparent from the available district-level secondary statistics. Thus, policymakers have less opportunity to examine actual farming practices and their divergent patterns (Ghosh et al., 2006; Ghosh et al., 2010). Consequently, any policy prescription, such as formation of a farmer-producer organizations (FPOs), crop insurance benefits or crop development trials may go awry.

Many farmers from Odisha collectivized their production unit to form an FPO and accrued benefits from economies of scale at both forward and backward ends of the value chain. Furthermore, inter-farm variation is a result of the individual farm households' resource endowments. Nonetheless, these WUAs developed additional institutions in addition to the PP act for irrigation water distribution (Alvarez et al., 2018; Andersen, Elbersen, Godeschalk, & Verhoog, 2007). Hence, the study attempted to answer the question of why certain water-sharing institutions develop under similar agricultural production systems.

The study aimed to understand and analyse the heterogeneity of water-sharing systems at the farm and community level and to develop an explanation of its variability. Further the study investigated the extent to which a given agricultural production condition was intensive or diversified in relation to the water-sharing institutions.

3.4. Research objective

In this chapter I identified distinct agricultural production systems from existing diverse agricultural production in WUA farms at the village scale by characterizing their physical, operational, institutional, technological, and economic attributes.

3.5. Hypothesis

As a reference, I hypothesised that a WUA function as a participatory collective decision-making body. The dominant agricultural production practices in the villages are mostly diverse with the advent of subsidised community irrigation water.

3.6. Theoretical background

3.6.1. Theories of institutional change

In light of the invisible nature of mobility, scholars support fine tuning of groundwater management institutes from the existing PP act 2002. North (1990) defined institutions as the “rules of the game in a society or, more formally, are the humanly devised constraints that shape human interaction.” He further claimed institutions “structure incentives in human exchange, whether political, social, or economic.”. Institutions in groundwater resource management also evolved over time and that also vary over space. These institutions function as life and blood in a skeleton of organizational structure. Hence, institutions can be regarded as a software that function on a hardware, in this case it is organisation. Policymakers have been keen to study usefulness of different institutions for better management of groundwater under increasing instance of risk, especially in developing nations (Meinzen-Dick et al., 2018; Robert et al., 2017).

Marx and Weber offered two different perspectives on institutional change. Marx proposed that organisations change their institutions with the evolution of technology, while Webber claimed that it should be other way around (North, 1990). WUA formation in the context of irrigation provision is an organisational manoeuvre that establishes new institutions in the rural setting. Further, to understand the evolution of institutions, would like to draw Ostrom’s evolutionary theory (2014; 1990) and a case study from Nepal done by Varughese & Ostrom (2001). According to her, biological evolution, such as on the agronomic front, has a greater effect on institutional evolution. In her analysis, membership, water-sharing regulations, and cost-sharing mechanisms are described as ‘phenotypic structures’. On the other hand, the set of embedded instructions included in production is determined by both the biophysical and cultural structure of a community, which she called ‘genotypic structure’.

To understand and measure the impact of any biotic and abiotic stress in a static period (during 2018-19 agricultural year), I narrated complexities of the agricultural production system (APS). APS consists of crop production, livestock rearing, household economic attributes, and market accessibility, which influence production sustainability (Walters et al., 2016). Recently, researchers have attempted to attribute the APS as a proxy measure to capture the evolution of irrigation arrangements. I, therefore, attributed variations in APS under different CIDAs. It appears, however, that the effect of incentives for collective action in a CIDA depends on the resource characteristics of a CIDA, including the irrigation command area (ICA), physical infrastructure status, property rights enforcement, and market proximity (Araral, 2009).

By using the typology, I explained such embedded variation in institutions by disentangling the characteristics of production systems. In support of the explanations, I would like to refer to the theories of institutional evolution, discussed by Hamidov (2015; 2015). He narrated that many institutions co-evolve to govern a resource system exclusively under cooperation. Whereas a pre-existing trend in resource appropriation many a times influence production decisions, which can be termed as institutional path dependencies. However, technological innovation in resource appropriation and improvement in market accessibility potentially encouraged such production system that followed decision by majority, is termed as institutional mono-cropping. With this theoretical background I now proceed to understand the data and analytics.

3.7. Data and analytical techniques employed

In this study, a multivariate statistical method and cluster analysis were used to establish a farm typology representing different agricultural production systems and compare their institutional arrangements at a regional scale (Valbuena et al., 2008). In the Indian context, Robert et al. (2017) developed a typology of farming systems that explains farmers' adoption decisions in irrigation farming and the inherent dynamics in a changing socio-economic-agronomic environment. Due to the small sample size, I used this concept with caution to characterize the WUAs related to villages. Using this approach, I will explain the differences in existing water-sharing institutions.

3.7.1. Cluster analysis

For the development of a meaningful classification of the farming systems, a mixed method of research was adapted from Robert et al. (2017). At first, nine dimensions of farm characteristics and farming practices are identified, viz. land resource, crop characteristics, farm structure, farm practices, irrigation provision as a regulation, market and marketing process, farm economic performances and social composition. To obtain information on the above farm characteristics, focus group discussions (FGD) were in fifteen villages and inputted data in a matrix format with common characteristics on the left side and their responses in the right side. Villages were considered by spatialized indicators to examine the variability and spatial pattern in each dimension. The qualitative variables were converted into quantitative ones using meaningful logical transformation method and an analysis of variance was used to compare the villages (ANOVA) . The independence of qualitative variables was tested by chi-square tests at a level of confidence of 95 per cent.

The variables along with their definitions used for the farm typology are presented it in Table 3.1 by the dimensions of the farm characteristics. A farm’s land resource characteristics is attributed by its soil type, that is the primary criteria for crop choice. In the surveyed villages different types of soils were found (variable code soilLand)

and their e proportionate area under different irrigation system is captured with the variable (variable code irrgLand). Further, elevation of a farmland (variable code ElvLand), and its gradient is captured, and their variability is converted in Likert scale. To observe the impact of a distant farm on crop choice, I considered its distance measured in kilometre from the village centre (variable code distLand). To measure the impact of a large water body or any natural ecosystem near to a farm plot, distance among them is added as another variable. However, to distinguish the influence of a large wate body or river or streams to a farm plot on its cropping decision I included it separately from ecosystem variable and measured them with dichotomous responses.

The crop characteristics dimension captures absolute acreage under different cropping activities and any area reallocation by crop replacement, is also captured. The farm structure dimension captured variability of the farms by their draft and machine power ownership (variable AniPower and mpower). To obtain a single value of livestock ownership, small ruminants were standardized into large ruminant by following methodology of Jakkula et al. (2018) and Rahaman (2015). Silimarly, differnet machine power used in the farming operations are also converted into a standard machine machine.

I found five distinct cropping pattern during the field survey d indexed them as CS1 toCS5. The irrigation provision from eight different sources are considered in this study, whereas no irrigation provision is appended as a ninth option.

As an overarching variable, cost of irrigation and adoption level of WUA institutions are added. Market research scientists claimed that similar farming systems are also influenced by the market proximity as well as the market structure (Charyulu, Thu, & Oo, 2019; Ichinose et al., 2020; Selviaridis & Wynstra, 2015; Ward, 2010). Hence, vicinity of a market from a village centre in kilometres is included as a market dimension .

To rule out the scale economics, I considered economics performance of a farm by including per hectare cost of production and returns in an interval scale. Further, the income earned from non-farm activities, its area was also included to know its impact on farming decisions.

I also included the social composition of the farm owners through three variables by their heterogeneity in social class, previous knowledge in water sharing and their level of awareness on concern and measures on decline in water table.

In table 3.1, the variables are presented by an alpha numeric symbol. These variable attributions are necessary for distinguishing their location in a two-dimensional visual presentation, such as factor map and distribution of farm types of MCA, that is presented in the result section.

In the second step, multiple correspondence analysis (MCA) and Agglomerative Hierarchical Clustering (AHC) algorithms were adapted from Robert et al. (2017). This served as a basis to develop meaningful farm typologies of distinguishable agriculture production systems at the village level.

Table 3.1 Definition of the variables used for cluster analysis

Category	Code	Definitions	Class	Abbre-viation
A. Land resource	distLand	Distance of the land from the house (ratio scale: in kilometre)	the numeric value in kilo-metre	D1
	Elvland	Land elevation (ordi-nal scale)	1=Upland(bunded),	E1
			2=Upland(un-bunded),	E2
			3=Medium,	E3
			4=Lowland,	E4
			5=Very lowland	E5
	grdLand	Land gradient (ordinal scale)	1= nearly flat (< 5 degree),	G1
			2=moderately sloppy (5-10 degree),	G2
			3=very sloppy (10-15 de-grees)	G3
	irrgLand	Distance of irrigation point from each farm plot (ratio scale)	numeric vale in meter	P1
	soilLand	Soil type (ordinal scale)	1=Clay	O1
			2=Clay loam	O2
			3=Sandy clay loam	O3
			4=Sandy loam	O4
			5=Loamy sand	O5
			6=Loam	O6
			7=Sandy	O7
	ecosLand	Vicinity to any natural ecosystem such as for-est (ordinal scale)	1= yes, 2=no	F1
	wetland	Vicinity of large water body/surface irrigation channel/river to the farm plot (ordinal scale)	1= yes, 2=no	R1
B. Crop characteris-tics	totar-eaCrop	Total cropped area	numeric value in acres	C1
	ir-rgareaCr op	Irrigated area	numeric value in acres	C2
	irrgCrops	Crops under the irri-gated area	numeric value in acres	C3

Category	Code	Definitions	Class	Abbre-viation
	unirrgCrop	Crops under the un-irrigated area	numeric value in acres	C4
	repld-Crop	Crop replaced with low water-intensive during last five years	1= yes, 2=no	C5
	repl-dareaCrop	Replaced crop acreage	numeric value in acres	C6
C. Farm structure	AnPower	number of livestock on the farm (oxen, bull, buffalo, cow) = 1, (sheep, goat) = 0.2	none	A1
			1 to 2	A2
			>2	A3
	mpower	No. of farm machines (tractor and tractor-drawn implements) = 1, (power tiller and drawn imple-ments)=0.5, other small machinery (power sprayer, power weeder, motor-operated reaper, etc)=0.2 Human oper-ated machines (manu-al/ k-s sprayer, rotary paddy weeder, fruit plucker)=0.1	1.0 to 2.0	FM1
			0.8 to 1.0	FM2
			0.5 to 0.8	FM3
			0.3 to 0.5	FM4
			<0.3	FM5
			none	FM6
	cropsys	cropping system fol-lowed during 2018-19	rainfed, only cash crops	CS1
			rainfed, cash and subsist-ence crops	CS2
D. Farm prac-tices			irrigated, only cash crops	CS3
			irrigated and rainfed, only cash crops	CS4
			irrigated and rainfed, cash and subsistence crops	CS5
E. Irriga-tion provi-sion	sourIrrg	Irrigation source	1=Community T/W (GSP)	S1
			2= Cluster T/W (CTW)	S2
			3=Joint invested pvt. T/W (JWE)	S3

Category	Code	Definitions	Class	Abbre-viation
			4= Own private T/W	S4
			5=Dugwell	S5
			6=Canal	S6
			7=River lift	S7
			8=Pond	S8
			9= Un irrigated	S9
F. Irrigation distribu-tion regulations	costIrrg	Irrigation cost	1= per hour	I1
			2= per acre	I2
			3=per acre for a crop season	I3
	instLevel	level of *pani pancha-yat* institutions fol-lowed	1= all	IL1
			2 = many	IL2
			3 = few	IL3
G. Market	villMar-ket	Vicinity to a village market	1= yes, 2=no	M1
	distvillm arket	Distance to the village market	numeric value in kilometre	M2
	town-Market	Vicinity to a town market	1= yes, 2=no	M3
	disttown Market	Distance to a town market	numeric value in kilometre	M4
	city-Market	Vicinity to a City mar-ket	1= yes, 2=no	M5
	distcity-Market	Distance to the City market	numeric value in kilometre	M6
	meth-Market	Marketing method	1= self, 2=village trader, 3= external trader	M7
	con-trMarket	Contract farming: with trader	1= with trader, 2= with company, 3=no contract	M8
H. Farm economic per-formance	costInput 2018K	cost of *kharif* crops per ha during 2018	< INR 10000	ECK1
			INR 10000 -30,000	ECK2
			INR 30,000-60,000	ECK3
			> INR 60,000	ECK4
	costInput 2018R	cost of *rabi* crops per ha during 2019	< INR 10000	ECR1
			INR 10000 -30,000	ECR2
			INR 30,000-60,000	ECR3
			> INR 60,000	ECR4

Category	Code	Definitions	Class	Abbre-viation
	in-comeK2018	net income from per ha *kharif* crops sale in 2018	< INR 20,000	EIK1
			INR 20,000 -50,000	EIK2
			INR 50,000- 100,000	EIK3
			INR > 100,000	EIK4
	incom-eR2019	net income from per ha *rabi* crops sale in 2019	< INR 20,000	EIR1
			INR 20,000 -50,000	EIR2
			INR 50,000- 100,000	EIR3
			INR > 100,000	EIR4
	non-farmInc	annual income earned from non-farm activi-ties by the household member during 2018-19	INR < 100,000	EIN1
			INR 100,000-250,000	EIN2
			INR > 250,000	EIN3
I. Social composition	socmphetero	heterogeneity in social class of farmer mem-bers	1.0 = nearly homogeneous, 0.5 = mixed, 0.1= nearly heterogeneous	SC1
	socmp-know	use of previous water-sharing knowledge in present WUA	1.0= to a greater extent, 0.5= many a times, 0.1= to a lesser extent	SC2
	scomp-concer	concern and measures over water table deple-tion	1=very much, 0.5= to some extent, 0.1= to a few extent	SC3

Source: Authors own

3.8. Results and discussion

3.8.1. Cluster analysis to identify the types of farms in coastal Odisha

The present study identified 33 qualitative and quantitative variables related to land resources, crop characteristics, farm structure, farm practices, irrigation provision and sharing, farm economic performances, and market participation, and social composition of the farmers. However, social composition variables had a lower weight than other variables and were therefore considered complementary. I presented the category-wise variable attribution in table 3.1. To perform the multiple correspondence analysis (MCA), XLSTAT trial version add-ins in MS Excel was used. Based on the AHC algorithm, the highest jumps were divided into three agricultural production systems. This typology describes the heterogeneity of coastal alluvial aquifers in Odisha.

The first two components of the MCA explain 21.25 percentage of the total variability in the village level heterogeneity (Figure 3.1). In addition to that, the third and fourth components explain 8.98 and 8.42 percentage of variability in the village heterogeneity respectively (Table 3.2).

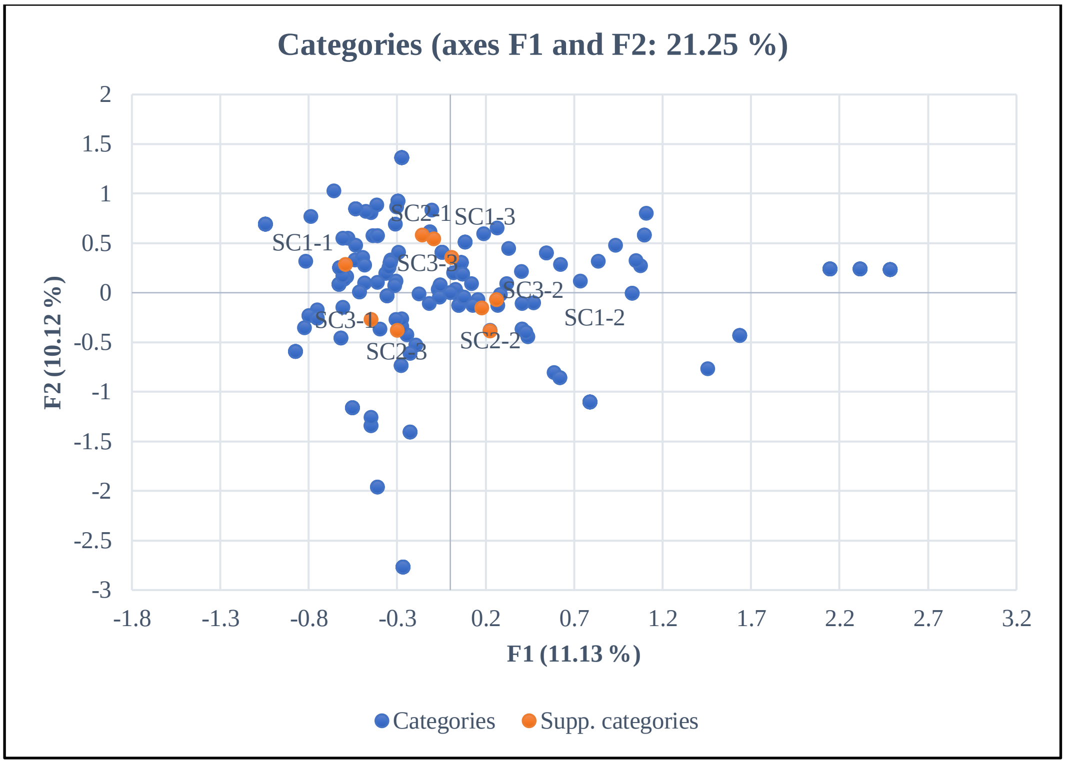


Figure 3.1 Factor map

Source: Authors own, result of the MCA analysis.

In the first axis, I distinguished (1) villages owning WUA as well as privately owned irrigation wells supporting irrigated agriculture, such as sugarcane; in addition, they received relatively higher amounts of non-farm incomes; with (2) villages owning farms that operate under irrigated and rainfed condition with relatively little scope to supplement farm family income with non-farm incomes.

The second axis differentiates (1) villages owns large farms (C1) that produce fewer crops, that are under irrigation (C4) and that have multiple sources of irrigation (S1 - S9); with (2) small and marginal farms, which cultivate diversified crops in many parcels and often obtain irrigation water from nearby water bodies, usually ditches or annual streams.

Table 3.2 Eigen values of each factor component

Particulars	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
Eigenvalue	0.34	0.31	0.28	0.26	0.24	0.23	0.21	0.20	0.19	0.18	0.17	0.16	0.15	0.14
Variability (%)	11.13	10.12	8.98	8.42	7.82	7.49	6.89	6.56	6.11	5.95	5.60	5.37	4.89	4.66
Cumulative %	11.13	21.25	30.22	38.64	46.46	53.95	60.84	67.41	73.52	79.47	85.07	90.45	95.34	100.00

Source: Authors own, result of the MCA analysis.

By performing multiple correspondence analyses on the dataset, the number of dimensions was reduced by scaling down to the first six components that collectively explain 53.94 per cent of the total variations (figure 3.2). Furthermore, these components are used as inputs to develop the Agglomerative Hierarchical Clustering algorithm (AHC), and I present it in figure 3.3.

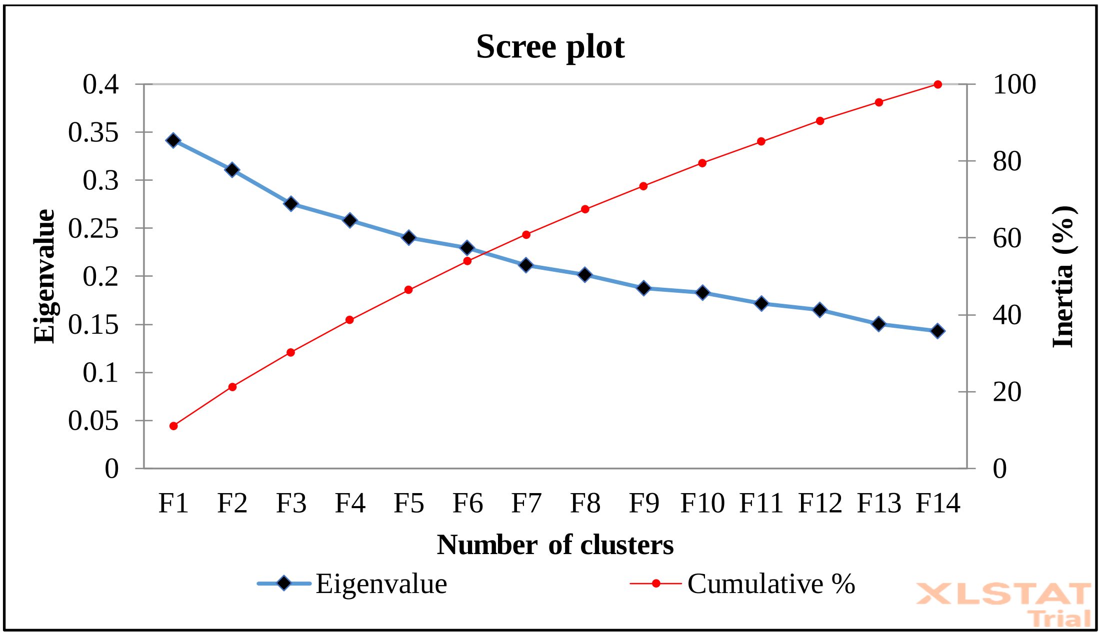


Figure 3.2 Scree plot of inertia gain
Source: Authors own, result of the MCA analysis.

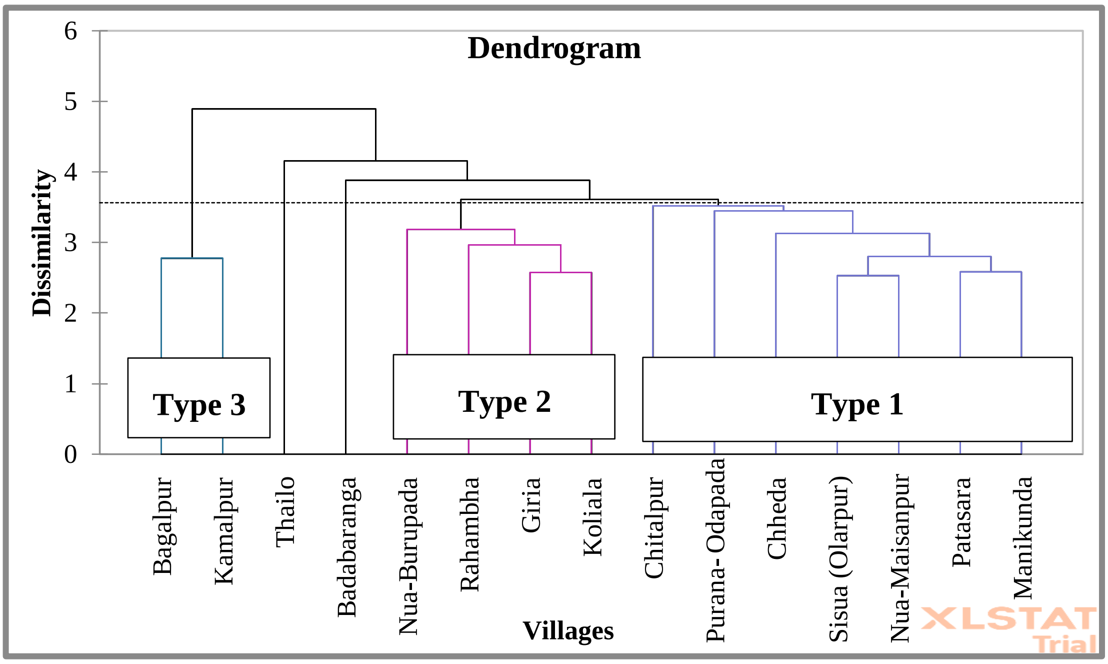


Figure 3.3 Dendogram of villages from Agglomerative Hierarchical Clustering on first 57 components of the multiple correspondence analysis (MCA).

Source: Authors own, result of the MCA analysis.

Using the gain of inertia between clusters with maximum jumps farm types are identified. Based on findings, three meaningful farm types are identified, which are distinctly projected on the first plane of MCA (figures 3.4 and 3.5). It can be observed that marginal and small subsistence farms (up to 2 hectares) are most frequent in the first farm type, whereas type three villages consist of small and medium (up to 5 hectares) specialized farms. Here, the intention is not to establish any causal relationship among farm size and village type, rather to understand exiting diversities in different dimensions. In the following subsection, the predominant characteristics of these farm types is summarized.

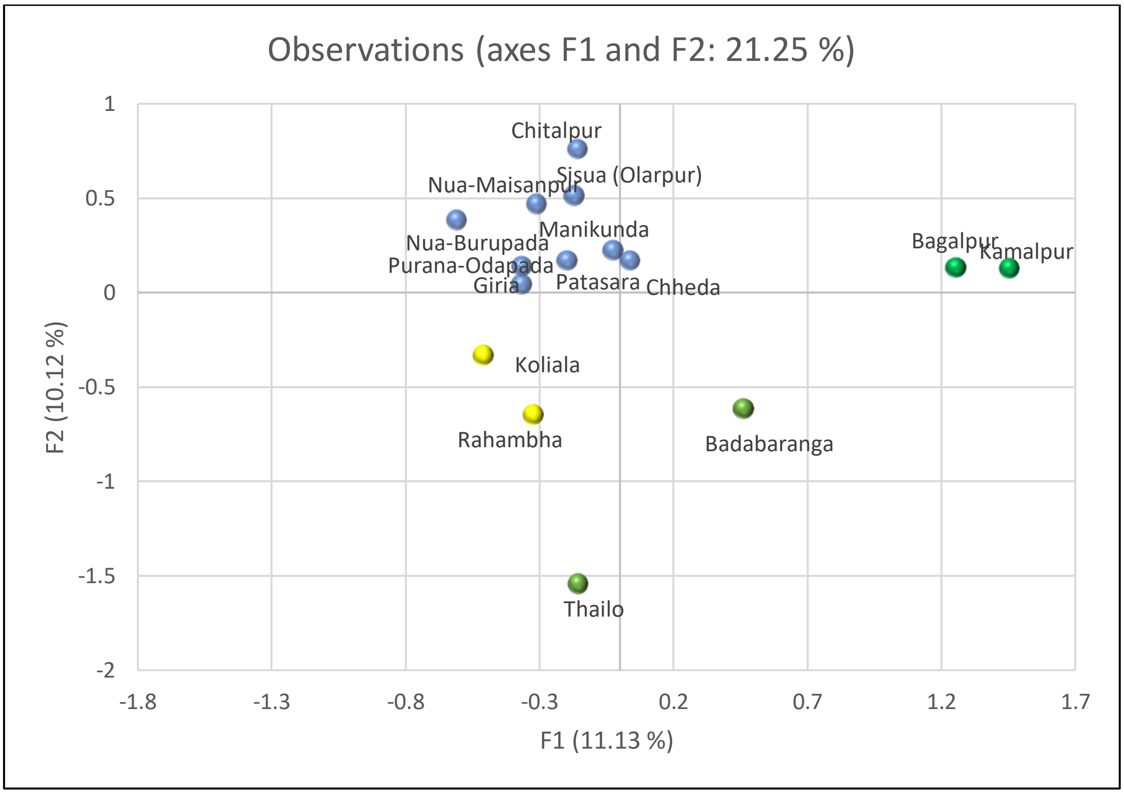


Figure 3.4. Distribution of farm types on the first plane of MCA
Source: Authors own, result of the MCA analysis.

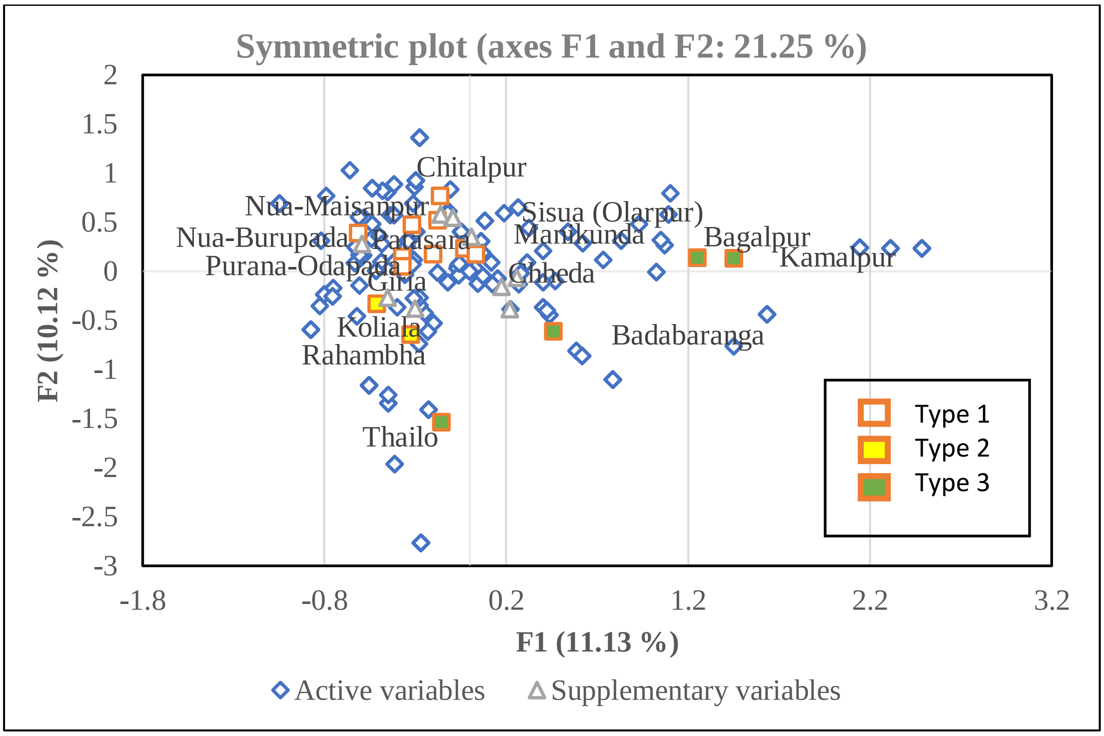


Figure 3.5 Three farm types projected on two dimensions of MCA.
Source: Authors own, result of the MCA analysis.

a. *Type one: Highly diversified irrigated agriculture for direct market supply (HDIAM)*

The first type of agricultural production condition is observed in villages where marginal and small subsistence farms (up to two hectares) predominate. At the beginning of the agricultural year (usually on the 14th or 15th of April, which is the regional new year, on the first day of *Baisakh* month), the cropping plan is elaborated by all members in a detailed discussion. Traditionally, crop rotation is carried out to maintain soil productivity. This crop plan is based on plot elevations and soil characteristics of plots. I found that, the crop plan is highly dependent on the WUA irrigation source distributed through *warabandi* (a Hindi term meaning a system of alternate distribution of water to users) and the crop water requirements. All-round farm activities were carried out by family members, while family women participated mostly in postharvest processing such as sorting and bagging of vegetables, drying and de-husking of beans, pea nut and cattle rearing. During the onset of rainy season, the first preparatory tillage operations are performed collectively using tractor-drawn equipment. For intercultural operations, farmers use animal traction. Most of the farm outputs, such as vegetables, rice, pulses, and oilseeds, were used at home, and the surplus was sold in the market for livelihood.

To understand the water-sharing arrangements made through WUAs and other privately-owned wells, I prepared irrigation water sharing map at the village level. In figure 3.6 I present water sharing system of *Sisua* village to represent first farm type. The river, *Prachi*, on the south, provided irrigation water until 1960s and caused flash flood during rainy season. At present, check dams constructed on the head region regulates water flow. From the geo-hydrological perspective, river base flow recharges the village level groundwater aquifer and helped to drill a shallow or medium deep tube well. I illustrate the delineated boundaries of the irrigation command area in *Sisua* village with the dotted lines. The area served by WUA in this village is more extensive than that of the other sources. Interestingly, the WUA delineated areas are adjacent to a privately owned well and sometimes enclaved a pre-existing private well delineated area. On the northwest part of the village, it can be observe that, WUA well formed during 1980s led to termination of an adjacent private well (dotted line indicating the delineated area with dysfunctional well at the centre). The underground water distribution pipeline is indicated by a black line and water is distribution from water outlets. It is important to mention here that government subsidy scheme cover the cost of drilling a well, pump installation, laying down of water distribution pipes and construction of water outlets. In contrast to the north side of the village, the southeast part of the village is populated with various types of irrigation sources, privately owned tube well, river lift cluster tube well, groundwater cluster tube well and an WUA as well. I observed great crop diversification with seasonal vegetables, sugarcane, pulse crops and traditional rice as well. Further it was found that, WUA many a times shared water with non-members during summer at a pre-agreed cost which is mostly higher than a WUA water cost, but far less than a private water seller. During FGD, farmers revealed their consensus on their preference to WUA over any other private water sources. They characterized WUA with timely water delivery, freedom to crop choice, urgent water delivery during prolonged dry spell, relatively cheap water price than private water seller and a social we-feeling. Farmers from these villages market multiple farm products, in particular seasonal vegetables, through village roads connected to the road leading to Bhubaneswar, the state capital market.

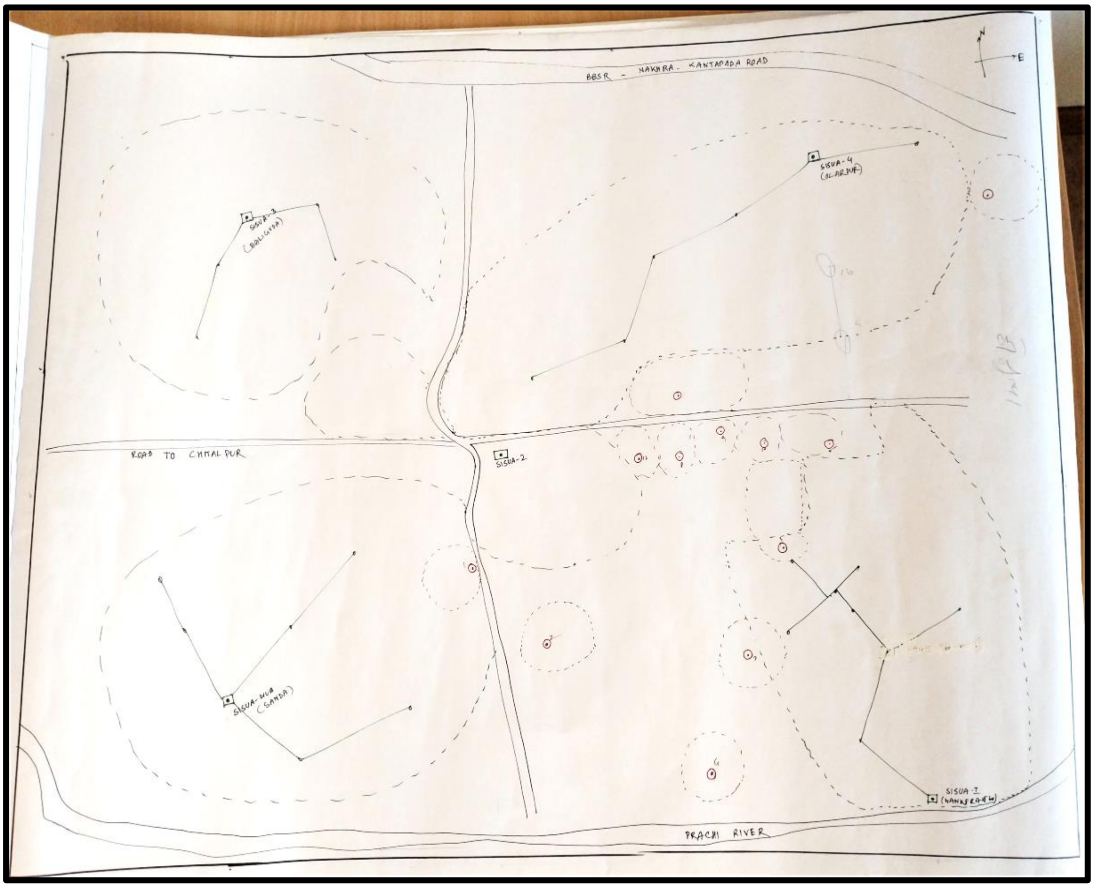


Figure 3.6 Sisua village map showing WUA and private wells with their respective irrigation command area delineated by dotted lines

Source: Authors own, developed during FGD.

b. *Type two: Moderately diversified limited irrigated agriculture for direct market supply (MDLIAM)*

The second type of production system is semi-subsistence in nature. The medium elevation plots with sandy loam soils are used to grow seasonal vegetables, while the low elevation plots with clay or clay loam soils are planted with rice or sugarcane. The villages are situated on the riverbank and syphon river water through the river lift

WUA or from privately owned wells. In addition to the WUA delineated area, there are several privately owned wells and irrigation canals. Through FGD and expert interview, I came to know that canal irrigation provides irrigation only during *kharif*. In these villages, the water distribution and cropping plans of the WUA are inadequately implemented as per the PP Act, leading to frequent disputes between the members and the adjoining farm owners who are not members. In terms of farm family member engagement in production activities, they are similar to the first type of farm. On the one hand, labour sharing among neighbour farms while performing intercultural and fruit plucking/harvesting activities have a positive impact on reducing production costs.

The water sharing system of Giria village of Ganjam district is presented in figure 3.7, as a representative of type two villages. On the north side of the village *Rushikulya* river is flowing from west to east. Since the 1980s because canal irrigation failed to provide irrigation during the critical stages of crop growth in *kharif*, farmers started installing private tube wells. On the northwest side, many private water sellers expanded their water trading business since then and are continuing at a competitive water price. During the period of 1995 to 2000, two river lift irrigation projects began providing irrigation services from the *Rushikulya* river to complement increased need of water during *rabi* and summer season. However, frequent dispute over water distribution among large number of members resulted into dysfunctional of many RLWUA. From the figure 3.7, one can observe that the delineated are of RLWUA catered irrigation on northeast and north-western parts that supported rice+ green gram/ black cropping pattern. On the central part of the village map, an irrigation canal is still supporting irrigation need, but only during *kharif*. On the west side of the village, farmlands are newly irrigated with two WUA and their delineated area is adjacent to each other. During 2012 and 2016 two WUA are formed in order to provide irrigation for the vegetables in the *rabi* season, and later, sugarcane replaced many seasonal crops. From the perspective of PP Act institutions, wide adoption of Sugarcane on annual crop plots may reflect its inappropriate implementation. However, it was found that, most of the farm plots are of clay soil, and water submergence during *kharif* and *rabi* left with limited opportunity to adopt diverse cropping pattern to enhance net farm income. In an FGD, farmers conveyed that, after WUA formation, private water sells do consider concurrent WUA water prices, and in many instances, offer a competitive water price and additional supervision for seamless water distribution to the water buyers. Proximity to a daily vegetable market encouraged farmers to cultivated various seasonal vegetables and in the off- season, that enhanced net return.

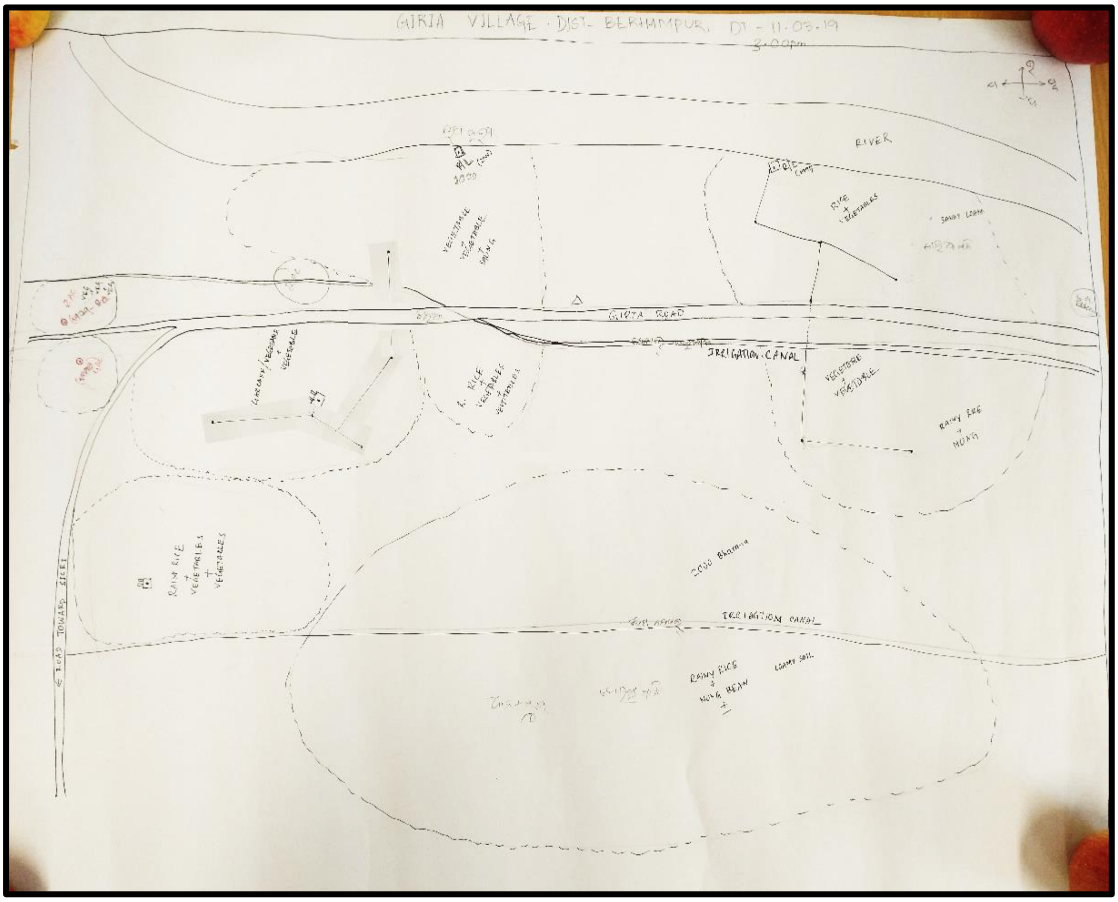


Figure 3.7 Giria village map showing WUA and Pvt Wells with their respective irrigation command area delineated by a dotted line

Source: Authors own, developed during FGD.

c. *Type three: Least diversified irrigated agriculture for contacted market supply (LDIACM)*

In type three, small to medium sized farms (between two and five hectares) are predominant. Farming systems in these villages are specialized in nature. A collective decision-making process is seldom taken among the farmers in crop planning and irrigation water distribution. Water distribution depends largely on the decision of the WUA president. In figure 3.8, I present the irrigation water sharing system of Bagalpur cluster villages. From the village map, one can observe that on the east side, *Gelapur*, *Balapur*, *Samsidhhpur* and other four hamlets are situated on the *Biluakhai* riverbank. Majority of the farmlands are in low and medium elevation are composed with clay and clay loam soils. Farm family members are mostly from the upper caste and are engaged in many salaried services or in business as a primary occupation. From FGD, it was found that, many farm families do not have sufficient family members to contribute to seasonal farm operation. Therefore, vegetable cultivation is very much limited in these villages. Since the year 1995, sugar factories extended contract sale agreement of sugarcane and facilitated with installation of private tube wells operated by diesel pumps. This resulted in the expansion of sugarcane production. Though sugarcane-based cropping system helped farmers to reduce multiple negotiations among member farmers regarding irrigation water distribution, but do not comply with the core regulations of the PP Act 2002.

On the east side of the map, red circles, and the dotted line around them indicates privately owned well delineated areas, their close proximity indicated frequent dispute over water extraction especially during summer months, however, are not in use after formation of WUA. On the central and west side of the village map one can find that many WUA delineated areas are adjacent to each other. There are many private tubewell points are still visible but are not functional due to the affordable irrigation water from WUA and increase in diesel price. It was observed that during *kharif* and *rabi*, a large proportion of marginal and small farmers engage in sugarcane farming and pull many farm operations such as preparatory tillage, sowing of sugarcane sets, earthing up and furrow making and harvesting. It indicates that marginal and small farmers also gained efficiency in sugarcane farming and managed to perform collective farming. However it contradict with the principles of the PP act, that promotes diversified usage of irrigation water for land-based activities. This finding partially negate the inefficiency-specialization claim of Manjunatha et al. (2013), however it requires to be statistically tested and validated.

On one third of farmland *kharif* rice followed by green gram/black gram is cultivated for household consumption and are also marketed at variable proportion. Most of the farming activities are conducted with tractor-mounted implements and to a certain extent by hired labourers.

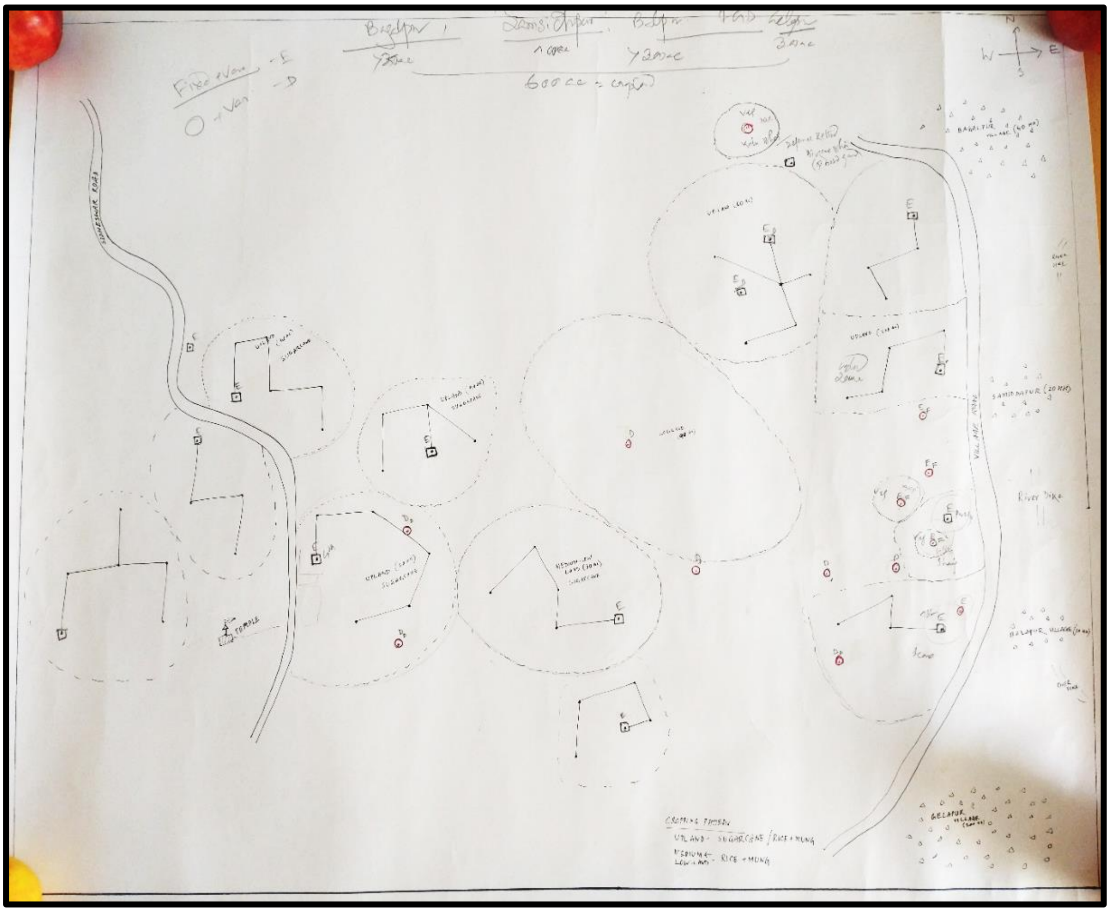


Figure 3.8 Bagalpur cluster village map showing WUA and Pvt Wells with their respective irrigation command area delineated by a dotted line

Source: Authors own, developed during FGD.

3.9. Discussion: Typology of prevailing institutions in WUAs

In Odisha, a water user association (WUA) is formed parallel to a subsidy scheme, and its management is performed by village level farmer's organizations. I developed a typology of agricultural production systems in the study area villages. I used stratified sampling to achieve comparable agro-climatic and socio-economic conditions for the selection of the study villages. In these villages, irrigation distribution is mostly performed with groundwater sources such as WUA, privately owned tube wells and many of them received subsidy to install the bore and for a pump set. In the survey, I the censorship bias was avoided by selecting villages with non-functioning WUAs and maximum diversity for agricultural production (Araral, 2009).

To strengthen the discussion a meaningful relationship with the theories of intuitional evolution and the typology is discussed below (table 3.3). The study revealed that, state government extended up to 90 percent subsidy for a groundwater WUA formation. Therefore, any productivity enhancement due to WUA formation is clear indication of the return on investment.

Table 3.3 Theories of institutional evolution favouring farm types

Theories	Typology
1. Co-evolution in co-operation	First type: Marginal and small (up to 2 ha) subsistence farm villages
2. Path dependencies	Second farm type: Semi-subsistence productivist (2-4 ha) villages
3. Institutional mono-cropping 4. Path dependencies	Third farm type: Small and medium (2-5 ha) specialized villages

Source: Adapted from Hamidov (2015; 2015)

The study found that, village in the first farm type adopted a diversified production system and explored a wide range of marketing opportunities. The embedded regulation in these WUAs, such as crop choice, reflects the high degree of reciprocity between members as well as neighbouring farm owners. In contrast, farmers from other farm type take independent decision or followed the prevailing trend in crop selection.

Therefore, villages from the first farm type were able to determine the possible market opportunities so that seasonal cropping activities could be planned accordingly in order to maximize net benefit. Further, these WUAs devised a next level of institutional precision in terms of plot-specific cropping patterns. On an upland plot, for example, farmers would plant rice in the rainy season, followed by the green gram or horse gram in the post-rainy season, and finally irrigated green gram in the summer. March and Olsen(1989) refers to this as co-evolution in cooperation, which is an example of embedded institutions. There was a proliferation of correct interpretations of the irrigation institutions among non-members who owned farm plots in the surrounding areas of WUA. Thus, farm plots in the peripheral regions adopted a synchronized cropping pattern that enabled them to access WUA water during the time of dire need and harnessed the margin by following member farmers' marketing decisions. As a result, pumping operation in these villages are relatively less than other farm type villages and it indicates an efficiency over water distribution.

With respect to the second farm type, farms in these villages shifted to sugarcane from pre-existing rice-green gram cropping pattern because irrigation provision and contractual buy back agreement supported this decision. These villages are termed as semi-subsistence productivist, where a limited number of farm plots cultivated vegetables on their homestead garden by availing groundwater irrigation. In spite of irrigation provision, farms in these villages are very slow to adopt vegetable-based cropping pattern because of path dependencies to rice-green gram or sugarcane.

Villages from the third farm type has adopted a specialized production system, which can be explained by the effect of institutional mono-cropping, and I refer it as a "lock-in" situation. However, marginal farmers, who followed the prevailing trend did diversify vegetable farming on their small homestead gardens. Any expansion of these vegetable plots to the main field is subject to irrigation availability, although path dependence in sugarcane farming impedes such expansion.

In addition to these three farm types, another two villages are grouped into a fourth type of production system. Typically, these villages consist of self-initiated farms where irrigation distribution is privately organized, and diversification is undertaken to the maximum extent possible with limited irrigation facilities.

As a result, the study found that the role of WUAs in collective decision-making about groundwater use is most pronounced among villages whose agricultural productivity is characterized by labour-intensive, semi-subsistence farming with a wide array of crop choice. WUA played a limited role in the villages with highly commercialized agriculture and mono cropping.

3.10. Concluding remarks

Irrigation distribution arrangements differed according to their preferences. Highly diversified irrigated agriculture for direct market supply (HDIAM) and moderately diversified limited irrigated agriculture for direct market supply (MDLIAM) villages are unique in terms of their diversity of irrigated agriculture due to the market proximity MDLIAM villages practiced sugarcane-based specialized farming, however a contract agreement was inevitably required. It is evident that, whether or not a groundwater WUA functions as a participatory decision-making body, that influenced both crop productivity and labour engagement in regard to irrigation water. In those villages where labour-intensive, semi-subsistence agriculture is predominant with greater crop diversification, collective decision making on groundwater usage is most prevalent. On the other hand, villages that are characterized by highly commercialized farming and monoculture, the role of WUAs is limited. Overall, the identified typology of WUAs provides an array of compositional diversity that is used to describe either permitted or prohibited activities. This helped me to understand how a state government subsidized WUA function . The typology developed in this section are further used as a boundary criterion when simulating various degrees of precision at the village and WUA scales to observe optimized land use pattern in relation to the organizational dimensions.

CHAPTER 4: OPTIMIZATION OF LAND-BASED WATER-SAVING ACTIVITIES

4. Optimization of land-based water-saving activities

4.1. Overview of the complex agricultural production system

In light of the heterogeneity in farm production, the study identified three distinct types of farms at village scale. Across all farm types, the villages are composed of sample farms, where land-based production activities are carried out with similar diversity. The concern is rather at the farm level, where heterogeneity lies in the farm characteristics, the farm-level resource constraints, and the farm family labour resources relevant to agricultural production. To ensure year-round net income flow from agricultural production activities, a farm utilizes all these resources. In order to achieve sustainable resource use and maximize output, I examined complex agricultural production system from various perspectives. Scholars investigated the use of resources and its efficiency, and have identified the connections between social, economic, and political factors (Behura et al., 2018; Bozorgi, Moein, Nejadkoorki, & Toosi, 2020; McGinnis & Ostrom, 2014; Smith, 2002; Walters et al., 2016). The irrigation water use and policy prescription for its distribution by state government, and its adoption at varied level is discussed in the previous chapter. Furthermore, differences in methods of water distribution adapted at different agricultural production systems are also discussed. The differences in scale of irrigation distribution system and effects of institutional arrangements at the farm level are also discussed.

4.2. Why are smallholders' decisions in land-based activities important?

Smallholders who operate in marginal (less than one ha) and small farm (one to two ha) parcels are usually constrained by limited farm and family resources. Therefore, they make land-use decisions to maximize farm family income. In the year 2000, the World Food Program Census of Agriculture reported that Asia and the Pacific have the smallest average agricultural holdings (FAO, 2010). It has been reported that farmers in Asia cultivate just one hectare of land compared to 114 FAO member countries (FAO, 2021).

In India, smallholders constitute 82 per cent of all farmers, and they own 47,3 per cent of the arable land. During 2018-19, Indian agriculture contributed 17.32 per cent of the country's gross domestic product (GDP) of which more than 60 per cent came from irrigated farms. Commercialization in agriculture has significantly impacted over the past two decades, and farm mechanization has been the driving force. Moreover, smallholders adopted different levels of mechanization to sustain their farming (GoI, 2021).

I discussed in the third chapter that irrigation water provisioning is made by varying degrees of mechanization, depending on the activities and scale of operation. Many smallholder farmers face difficulties in adopting modern irrigation technology such as drip irrigation and sprinkler irrigation, despite their efficiency. Therefore, irrigation technologies available on a farm complement crop production decision in order to maximize total gross margin. Since crop returns are largely determined by nature and market dynamics, a farmer should always try to minimize production costs. Thankfully, many public policies aimed to reduce such arbitrary natural impacts on agriculture by providing subsidized irrigation, quality seed material, plant nutrients, etc. On the other hand, farmers also benefitted from the minimum support prices for different farm outputs (Hansen et al., 2014; T. Shah et al., 2016).

4.3. How to achieve optimal land use planning?

Researchers have emphasized the relevance of mathematical models in the study of human-environment interactions so as to optimise farmers' decisions regarding the allocation of resources (Berkes, Colding, & Folke, 2003). Mathematical programming methods are utilized to simulate farmers' decision-making at the farm level, which can also be up scaled at the landscape level. By considering the optimal combination of a set of variables subject to linear inequalities and equality, a simple linear programming (LP) model optimizes the objective function of a farm (Panik, 2019). LP is widely used to optimize land-use decisions for smallholders' crop production, indicating opportunities for improving resource efficiency and profitability (Delgado-Matas & Pukkala, 2014; Mellaku et al., 2018). However, the focus of the study is to know the optimal combination of cropping activities and the role of water-saving methods that reduce production costs. In this context, the research asked, “how can a farmer optimize land-based water-saving activities?” In order to address this issue, following two-fold research objective are developed.

4.4. Research objectives

a. To maximize farm level gross margin by using optimal farm-level land-based production activities under variable level of water use
b. To estimate farm level shadow price functions of water.
c.

To accomplish the above objective, I first describe the present cropping pattern and cropping system at farm level. After that, I estimated the optimal cropland use, annual crop production and net return. Finally, I simulate the impact of different water-saving plans on the sustainability of smallholders' agriculture.

I hypothesized that farmers were sub-optimal with respect to irrigation water use for crop production. Hence, an increased acreage devoted to water-saving practices will lower overall cost of production. In addition, it is claimed that a farmer maximizes plot level gross margin by employing a labour-saving but water-intensive activity in his farm level annual cropping pattern. Therefore, a water-saving crop if succeed with a water-intensive crop at the plot level, it fulfils the total water budget at the farm level.

4.5. Theory: General economic considerations of farms

A common understanding of the production decision of a firm is that it is dependent on the product type and market structure. In agricultural production process, it is observed that, the level of output of a product is determined by the various combination of input use. A firm will only produce a certain amount of a product when profit from its sale is comparatively higher than other possible products using the available resource (Alston, Norton, & Pardey, 1995). In a pure competitive market, numerous firms producing similar products do not influence the market price, and therefore, the profit margin is determined by each firm's efficiency. As a result, a rational producer will seek to minimize its cost of production by maintaining its output at a constant level. Ceteris paribus, an increase in total output can also result in an increase in gross margin and therefore maximize profit. In order to maximize its net return or profit, a producer employs the lowest cost in the production process and wishes to gain the maximum output. The production decision is taken as a result of farm-level resource constraints that are simultaneously met to maximize the net profit of a firm (Debertin, 2012).

Based on an understanding of the complex nature of the production process, a linear programming (LP) model is utilized to optimize a linear objective function with linear equality and inequality constraints. Farms make different crop production decisions at different levels of resource endowment because of their heterogeneity. It has been suggested that linear programming is an effective method to combine the factors of production to produce an optimal net return (Palash, 2015). The application of LP in agricultural economics ranges from the general optimization of scarce resources to the mixed cropping type of farming decisions (Bare, 1989).

4.6. Data and methodology

4.6.1. Heterogeneous farms under similar water-sharing systems in Odisha

Small and marginal farmers engage in a variety of farming activities in coastal Odisha. The farms maximize their net farm income by using irrigation water sourced from diverse sharing arrangements. Natural and biotic hazards such as cyclonic storms, pest attacks on green gram and maize, and unfavourable market mechanisms have triggered farmers' goals of minimizing the cost of production and then maximizing net farm income.

In Table 4.1, I present a brief description of an average rural farm household. An average farm household is mostly male headed with average membership of 6.2. Besides the husband and wife, elders also lived in the same home with one or two children. Therefore, a typical household takes care of the elderly and children who may not necessarily contribute to the varied agriculture activities that are carried out throughout the year. A rural household has, on average, 3.2 male members, indicating that siblings stay together with their family members.

Table 4.1 Socioeconomic characteristics of an average surveyed household

Sl. No.	Parameter			Mean (Std. Dev.)
1.	Yrs. of farming experiences			23.1 (13.6)
2.	Males in a household			3.2 (1.7)
3.	Females in a household			3.0 (1.5)
4.	Married household member			3.8 (1.9)
5.	Not a married household member			2.3 (1.4)
6.	Age of respondent (in years)			50.3 (11.0)
7.	Age of household members	Male	Below 18 years	10.1 (4.9)
8.			Between 18 to 60 years	39.8 (8)
9.			Above 60 years	68.9 (9)
10.		Female	Below 18 years	9.3 (4.8)
11.			Between 18 to 60 years	38.0 (7.4)
12.			Above 60 years	69.5 (6.9)
13.	Years of education of the respondent			8.0 (3.7)
14.	Schooling	Attained primary school		1.9 (1.1)
15.		Attained middle school		3.4 (2)
16.		Attained high school		1.7 (1.2)
17.		Graduate and higher educated		1.8 (1.2)
18.	Occupational status	Farming		1.8 (1.0)
19.		Salaried job		1.4 (0.9)
20.		Services		1.3 (0.6)
21.		Business		1.1 (0.3)
22.		Agricultural labour		1.8 (0.5)
23.		Household job		2.0 (0.9)
24.		Student		2.0 (1.0)
25.		Other activities		1.3 (0.5)

Source: Authors own survey, 2018-19.

The average age of the household heads I interviewed was 50.3 years, and the standard deviation was 11 years. It indicates that the surveyed respondents are mainly middle to upper middle aged. In this study, the large pool of respondents provided valuable information on irrigated agriculture and on the evolution of irrigation distribution systems. To understand the family composition, I classified them based on their age and education level. Males and females in the working group, on average, are 39.9 years old and are mainly farmers by tradition. Elderly family members are mostly 70 and older. As a result, their contribution to farming is limited. In addition to this, the occupation status of all family members reveals that on average 1.8 members of the family are engaged in farming activities and the same number of members are also employed in many off-farm wage-earning activities. Besides farming, some household members also worked in salaried jobs, small businesses, and other non-farm activities.

4.6.2. Water procurement systems in the study area

The surveyed villages are selected based on their diversity of water procurement systems. It is important to point out that the scale of operation of each water-sharing system depends on the capacity of the pump installed at the well. A pump is designed to extract maximum amount of water based on the capacity of the well. The size of the water procurement system is also directly related to the number of farmers who participate in the program. Due to the scattered nature of farm parcels, many of the farmers source water from more than one water procurement system. In spite of that, many farm plots remain inaccessible to any irrigation system, leaving rainfed farming as the only option available. In table 4.2, the average number of beneficiaries are presented in different water procurement systems and well ownership. Traditionally, a farmer dig an open well on the farmland to irrigate plots. The operational area is small, and irrigation is rarely shared with others. Many farmers also installed a shallow or deep tube wells either with own finance or availed a government subsidy.

Table 4.2 Average number of beneficiaries by different water distribution systems in the study area

Irrigation distribution system	Well ownership/ Membership				
	Household	Jointly with others	Private farmers association	WUA	Private water seller
1. Cluster T/W (CTW)	5.5	7.5	-	-	-
2. Deep T/W (DTW)	2.0	-	-	-	-
3. Dug Well (DW)	1.0	-	-	20.0	15.0
4. Groundwater + River lift	-	-	-	30.0	-
5. Shallow T/W (STW)	17.3	4.8	4.0	-	2.7
6. Community wells (STW or Medium deep T/W)	-	-	-	26.8	-
Overall	**6.9**	**4.8**	**4.0**	**26.1**	**5.8**

Source: Authors own survey, 2018-19.

In the study area, OLIC helped farmers to form cluster tube well, in which five to seven farmers share irrigation water from a shallow or medium deep tube well. In this case, farmers collectively deposit 20 percentage of the total investment cost and share the ownership of the irrigation well, pumping device, electricity supply unit and water distribution pipes. The state government subsidy schemes also supported installation of shallow tube wells, where irrigation water is distributed through pipes up to 17 farmlands. A WUA on the other hand share water to on an average of 27 farmers. In some villages, a WUA complemented irrigation water needs from river-lift projects apart from their groundwater sources. It implies that farmers try to minimize the risk of water shortage by sourcing water from multiple water sources. In addition to the subsidised water procurement system, private water sellers also shared water with neighbour farms at an agreed rate since they installed tube wells on their farms. Thus, from the dimension of well ownership, it can understood that except WUA, all other Irrigation distribution system is initially owned by a household, and later neighbour farmer pooled their investment to share the ownership of either a shallow tube well (STW) or a cluster tube well (CTW). It was also found that an individual farmer installed a STW or dug well and sold water to a neighbour farm. In the previous chapter the functioning of a private water seller, importantly water-procurement and distribution system between the year 2000 and 2010 and reaped maximum profits from water trading.

In table 4.3 the proportionate ownership of water distribution system is presented in the study area. From the table one can find that individual households owned 21.7 percent of STW followed by 3.3 percentage each of CTW and Deep TW, and 1.7 percentage of DW.

Table 4.3 Water distribution systems by ownership in the study area (in percentage)

Irrigation distribution systems	**Ownership/ Membership**				
	Household	Jointly with others	Farmers association	WUA	Pvt. water seller
1. Cluster T/W (CTW)	3.3	6.7	-	-	-
2. Deep T/W (DTW)	3.3	-	-	-	-
3. Dug Well (DW)	1.7	-	-	3.3	1.7
4. Groundwater + River lift	-	-	-	1.7	-
5. Shallow T/W (STW)	21.7	6.7	3.3	-	13.3
6. Community wells (STW or Medium deep T/W)	-	-	-	33.3	-
Overall	**30.0**	**13.3**	**3.3**	**38.3**	**15.0**

Source: Authors own survey, 2018-19.

Further, it was found that, many households jointly owned CTW and STW by 6.7 percentage respectively. Water user associations on the other hand owned 38.3 percent of community STW or medium deep tube wells and 3.3 percent of dug wells. Large and deep dug wells were excavated during 1970s to complement pre-existing canal irrigation network in Ganjam district. Private water sellers also owned 13.3. percentage of STW and 1.7 percentage of DW and provided irrigation water to the neighbouring farmers. In the study, the sample respondents represent all of these water procurement systems and enriched the discussion.

In the section 3.8.1, farm types are presented, and water procurement system of representative villages are described from each farm types. In the following section, I discuss representative WUA from those villages. For that, the study present the existing cropping pattern and water distribution mechanism in and around a WUA.

4.6.3. Cropping pattern followed by the different WUAs in the identified farm types

a. A representative WUA from Chitalpur village from the highly diversified irrigated agriculture for direct market supply (HDIAM) villages

Farmers used irrigation sourced from diverse water procurement systems to adopt plot-specific crop enterprises in various seasons. Water supply from a WUA supported the cultivation of annual and perennial crops throughout the year. In section 3.8.1, farm types and WUA organization at the village-level and water sharing system are presented.

In figure 4.1, a GIS map of a representative WUA from Chitalpur village of Cuttack District is presented, which is classified as a HDIAM village. The WUA irrigation command in delineated by a yellow dotted line. On the map, one can visually distinguish the farm plots inside the delineated WUA area based on their size and colour of the farm plots. A red square indicates the WUA well point, and a red circle indicates a private well point on the edge of the irrigation command area.

Figure 4.1 Map of a representative WUA from Chitalpur village from Kantapada block of Cuttack district, Odisha.
Source: Google earth, accessed on 13.06.2019.

To understand the cropping patterns at the WUA level, a plot specific cropping map was developed during the focus group discussion, and it in presented in figure 4.2. From the figure one can observe that farmers grew diverse crops depending on their plot elevation during the 2018-19 *rabi* season. While developing the cropping map, farmers shared that the crop choice is often plot specific that attributes with soil type, plot elevation and its gradient, and vicinity to a water outlet. Hereinafter it is as a *suitability constraint*, and it is further utilized in the linear programming. Summer rice was cultivated in a few lowland plots following the *kharif* rice and sugarcane was cultivated in others. In the medium elevation plots, seasonal vegetables were cultivated after the early *rabi* vegetable crop and farmers reported that they had planned to grow summer vegetables in these plots.

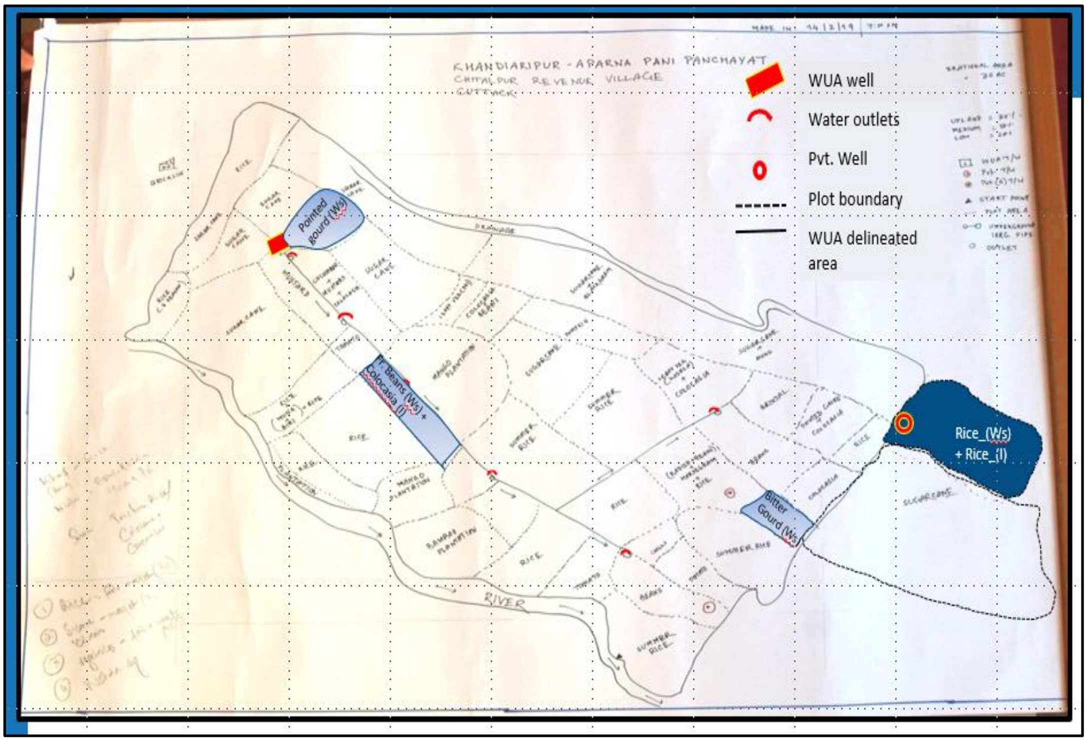


Figure 4.2 Plot specific crop choice in a representative WUA from Kantapada block of Cuttack district

Source: Fieldwork outcome from focus group discussion, dated 14.02.2019.

The upland plots were planted with perennial vegetables such as pointed gourds. The suitability constraints are further influenced by some social variables. To avoid conflict with neighbour farm plot owners, farmers cultivate similar types of crops and often pool initial operations for land preparation to reduce operation costs. From the figure 4.1 and 4.2, one can find that that *Prachi* River is flowing from the west to the south. However, its water flow has reduced over time due to construction of many check dams on upstream. On the other hand, many individual and community river lift projects drilled on the riverbed to pump out water, has reduced surface water flow, except in the rainy season.

To identify a farm, I assigned it an anonymous six-digit identification number (ID). The last two digits from right represent a farm, the next two digits represent a village, and the first two digits represent a district. Additionally, each farm plot was assigned an alphanumeric identification code. For example, farm plot ID 111112 represents a farm in Chitalpur village (12) in Kantapada block (11) from Cuttack district (11). Further, the cropping patterns of Cuttack, Ganjam, and Jagatsinghpur districts are represented by farms 111112, 311115, and 211114 respectively.

On figure 4.1 and 4.2, I present plot specific cropping of a respondent farmer (respondent ID 111112). The farmer owned four farm plots. One farm plot is located on the northwest corner on the map and is very near to the WUA well where a watering point exists. The second and third plots are on west central and east central part of the map and received water from the watering points by making earthen channels to the plots. The fourth plot is situated on the northeast side of the map, and it is just outside of the WUA delineated area. Interestingly, there exists a privately-owned tube well and the representative farmer source water from that tube well to cultivated summer rice during post rainy season.

In figure 4.2, the cropping pattern followed by that farmer during 2018-19 is presented. The red square on the northwest side indicates the location of the WUA well. A straight line that passes through the middle of the delineated area started from the red square and connecting other five semi circles (in red colour) demarcates the underground waterpipe that conveyed water from well to different water outlets. From each water outlets, farmers conveyed water to their farm plots by making earthen channels. It can observed that farm plots alongside the conveyed pipe and near to the water outlets are under seasonal vegetables. As one move away from the water conveyed pipeline, the plot elevation decreases. It was found that sugarcane or rice was mostly cultivated on the low-lying plots, and they are mostly on the periphery of the WUA delineated area.

From figure 4.2, one can further observe that the representative farmer cultivated pointed gourd (*trichosanthes dioica*) during rabi season which fruits throughout summer and rainy season until the November. On the central part of the map, the farmer cultivated French beans (*Phaseolus vulgaris*) during post rainy season and started planting *Arbi* (*Colocasia esculenta*) which takes two consecutive season and requires frequent irrigation in alternate days. On the northeast side of the delineated area, he cultivated bitter gourd (*Momordica charantia*) on his farm plot. His farm plot is on the edge of the WUA delineated area, and he often realize water scarcity during summer months because ten other farm plots are provided water from the last water outlet. The respondent farmer shared that bitter gourd requires less water in comparison with other perennial crops during the summer season. On the fourth farm plot, that is situated outside of the WUA delineated area he preferred to cultivate rice during rainy as well as post rainy season and sourced irrigation water from the private tube well. The farmer expressed that cost of irrigation water from private water seller was more or less same with the WUA. This indicates cooperative nature of private water seller to the water buyers.

b. *A representative WUA from Giria village from the moderately diversified limited irrigated agriculture for direct market supply (MDLIAM) villages.*

The MDLIAM farms are usually located on the banks of a river, and they source water from multiple irrigation sources, such as, a river lift WUA, a groundwater WUA, a privately invested tube well and pre-existing canal irrigation networks. Figure 4.3 shows a GIS map of a representative WUA from Hinjilicut block in Ganjam district. This WUA borders a nearby groundwater WUA and a river lift WUA. Farm plot owners along the edge of the irrigation command area (ICA) stated that they frequently disagreed with neighbouring owners from other water sharing systems about crop choice. From figure 4.3, one can find that farm plots are of different size, and many are grey to pale yellow, when a few are dark green. During the survey period, sugarcane and peanut harvesting were taking place.

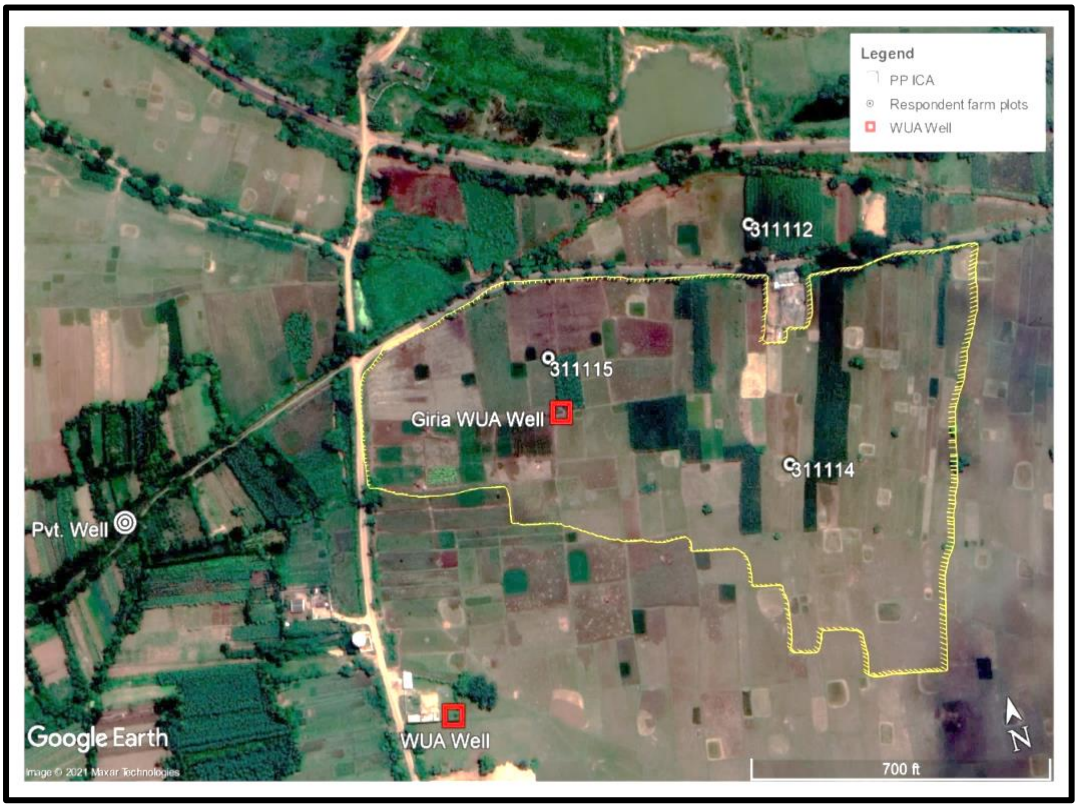


Figure 4.3 Map of a representative WUA from Giria village from Hinjilicut block of Ganjam district, Odisha

Source: Google earth, accessed on 10.06.2019.

To know the dynamics of cropping and their determinants, I conducted two rounds of focus group discussion (FGD), of which first one was near to the WUA well point and the second one was at the village centre. I developed a cropping map of the same WUA with the help of member farmers that I present in figure 4.4. on the west central part of the map, one can find the red square, indicating the WUA well and a block continuous line connecting seven semi circles towards east and northside of the map. I found that most of the farm plots were very small in size, and an average plot sized 0.04 ha. However, farmers performed collective tillage activities by using tractor drawn implements. For other plot level operations, they used small machines such as power tiller, rotary paddy weeder, and power sprayer. A few farmers also used animal traction for intercultural operation, especially for sowing groundnut.

The farm plots near to the watering points were planted with either sugarcane or seasonal vegetables. As one can see on figure 4.3, just outside of the WUA delineated area, the farm plots with dotted lines indicate neighbour farms to where irrigation water is provided under a temporary contract from the WUA. It can be observed that the respondent farmers (ID no. 311115) further subdivided his farm plot into three subplots. On two subplots he cultivated rainy rice followed by green gram, and on another subplot, he cultivated rainy rice followed by peanut. Interestingly, one can observe that sugarcane is cultivated on the west side of the WUA, and they are the neighbouring farm plots to the respondent farmer. On the central and east side of the WUA delineated area farm plots are under rainy rice followed by green gram or black gram or seasonal vegetables. During the field survey it can be observed that many farmers cultivated seasonal vegetables such as aubergine, okra, tomato, cauliflower, and other seasonal vegetables.

On the southwest side of the WUA in figure 4.3, one can visualize that there are many green patches that are outside of the WUA delineated area and there exists another WUA well. It can be found that the surveyed WUA is bordering with an another WUA on the southwest side. However, there are many farm plots that lies outside of the WUA delineated area, but not the part of adjacent WUA. In general, these farm plots borrow irrigation water from the interviewed WUA at a variable cost. Interestingly, farmers cultivated rainy rice followed by green gram, that are similar with respect to the neighbouring farm plots to avoid disputes over water distribution (figure 4.4).

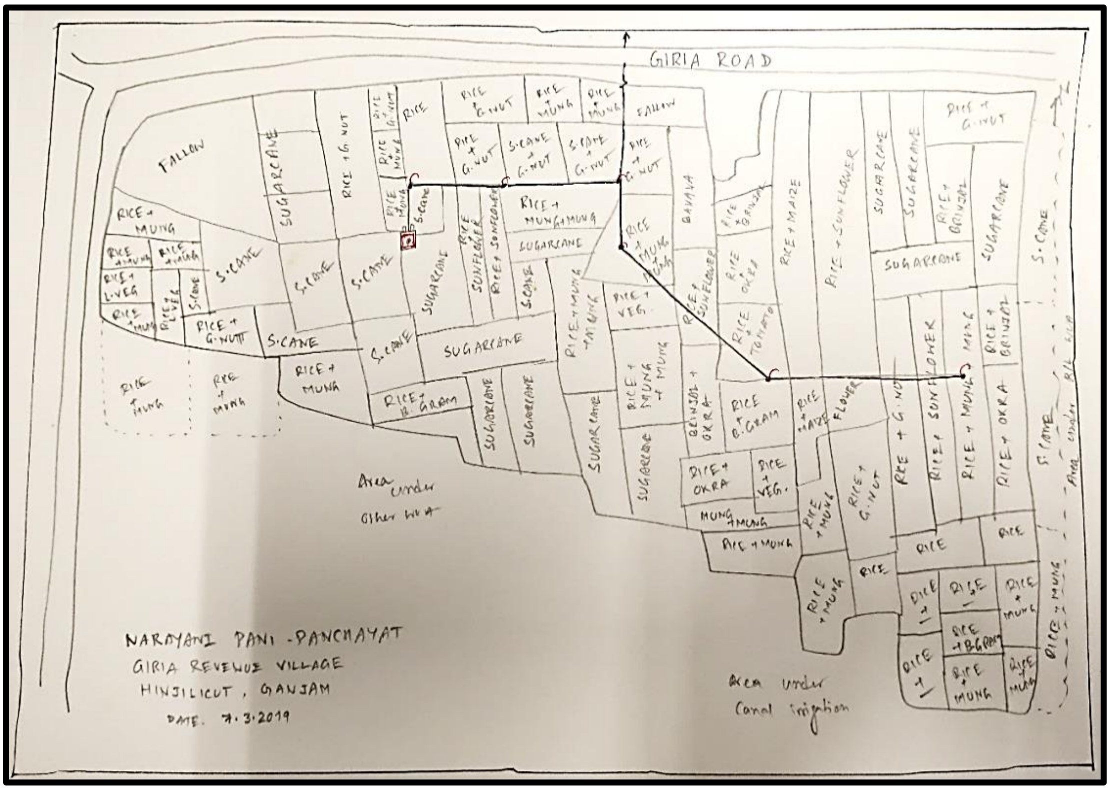


Figure 4.4 Plot specific crop choice in a representative WUA from Giria village of Hinjilicut block of Ganjam district

Source: Fieldwork outcome from focus group discussion, dated 07.03.2019

c. *A representative WUA from Bagalpur village from the least diversified irrigated agriculture for contacted market supply (LDIACM) villages.*

In section 3.8.1.c, I described the LDIACM villages where rainy rice is followed by green gram, and many farm plots are under sugarcane. On the central part of figure 4.5 one can find a representative WUA, named as *Balapur* WUA 3 from Bagalpur village in Jagatsinghpur block. The GIS mapping clearly distinguishes the mono-cropped sugarcane plots that are dark green in colour from the recently harvested rice plots in pale yellow. From the figure 4.5 one can find that *Balapur* WUA 3 delineated area is bordering with the *Balapur* WUA 8 delineated area on the west side. During past seven years ten groundwater WUAs are formed. However, three of them are dysfunctional due to conflict of interest among the members. WUAs often follow similar cropping patterns. In figure 4.5 I indicate farm plots of the representative farmer (ID 211113), and they are under two neighbouring WUA.

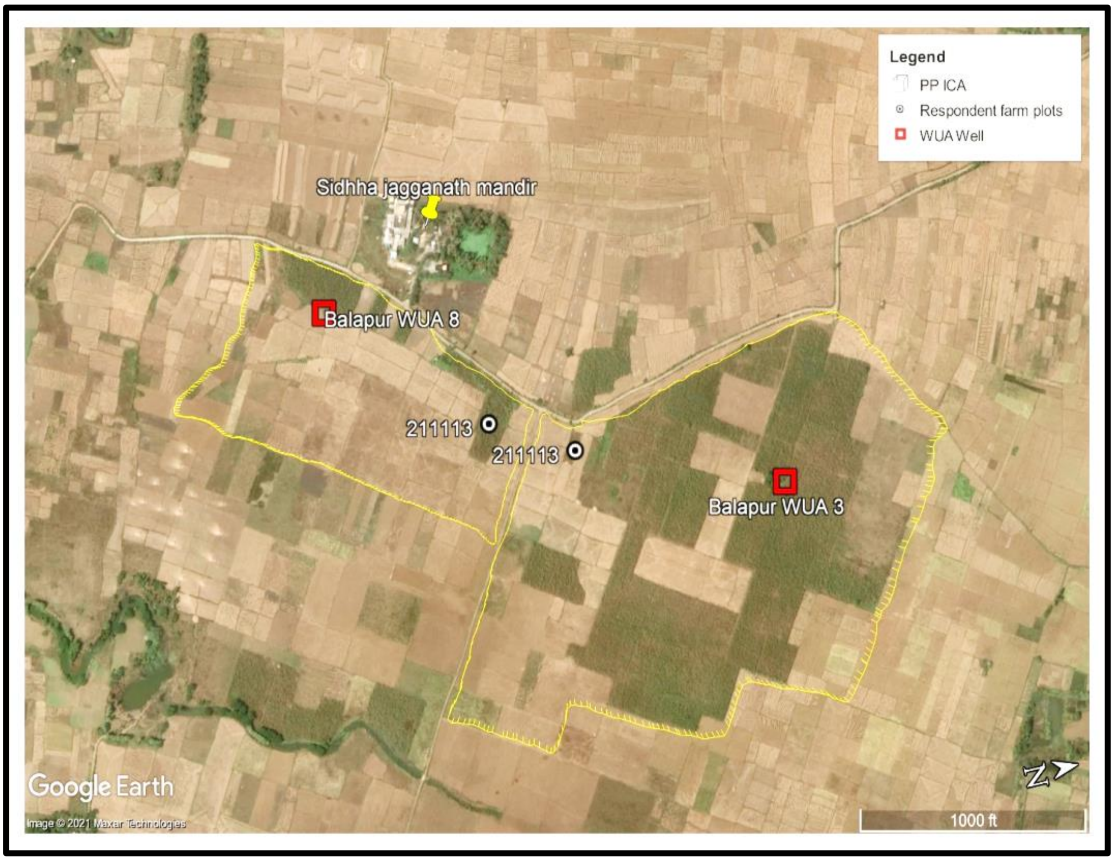


Figure 4.5 Map of a representative WUA from Bagalpur village from Jagatsinghpur block in Jagatsinghpur district.

Source: Google earth, accessed on 10.06.2019.

The cropping pattern of *Balapur* WUA 3 was peppered from two rounds of FGD and is present in figure 4.6. The dark black line drawn in the centre of the WUA map indicates the underground irrigation pipes that distributes water through six water outlets, market by a red semi-circle. Farm plots near to the water outlets are mostly under sugarcane (dark green patches in figure 4.5) and they border with each other. Rainy rice followed by mung beans are cultivated on farm plots around the WUA edge. From the figure 4.5 one can further imply that farm plots outside of the representative

WUA also followed similar cropping pattern. In these village, most of the family members are either engaged in salaried job or perform business activities, that created scarcity of family labourer for farm activities. However, a few farmers cultivated vegetables on their homestead garden for family consumption and a very few amounts is sold to a nearby market. Villagers sourced grocery items from nearby markets, and vegetables from village level weekly markets.

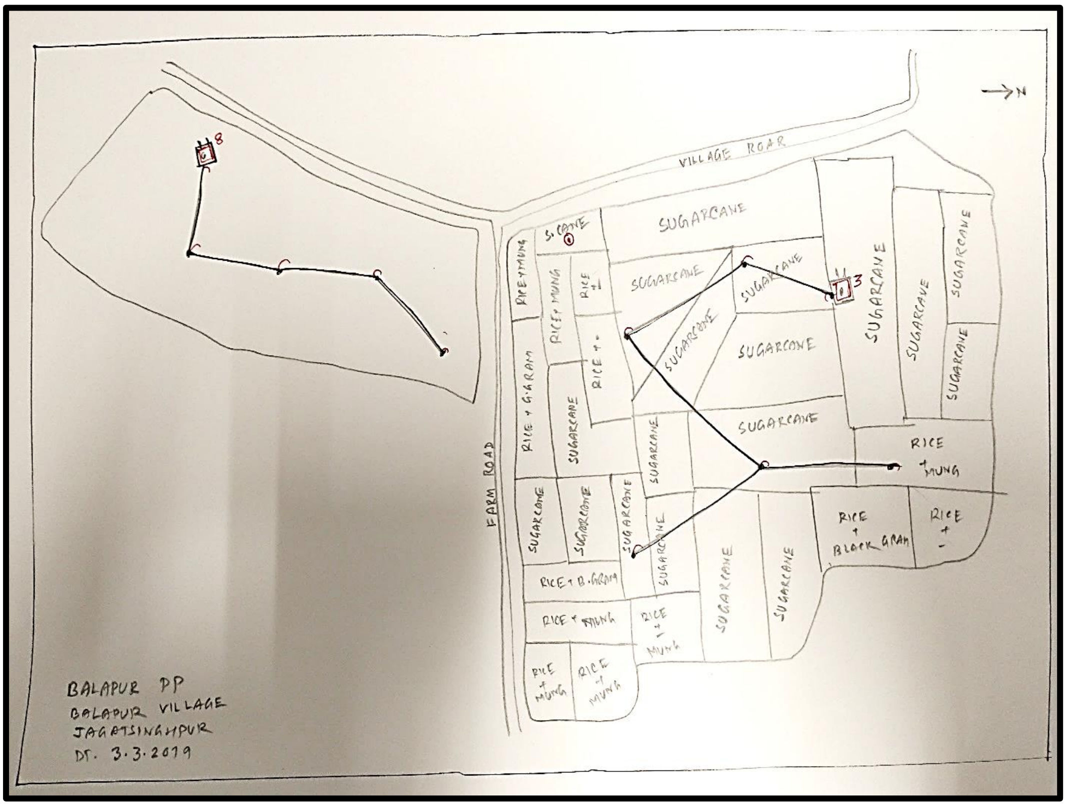


Figure 4.6 Plot specific crop choice in a representative WUA from Bagalpur village in Jagatsinghpur district.

Source: Fieldwork outcome from focus group discussion, dated 03.03.2019

Now, in the following section, the land use pattern is described by farm type and blocks for the representative farms. Further, the scope of water saving is investigated and the viability of an incentive schemes for water saving is tested.

4.6.4. Cropping pattern followed by the respondent farmers

The cropping pattern followed by the farmers is presented in table 4.4. A cropping pattern is understood as the "yearly sequence and spatial arrangement of crops or crops and fallow on a given area" (Andrews & Kassam, 1976). The intensity of water consumption is indicated in parentheses as "w" for water-saving crops and "i" for water-intensive crops. The respondent farmers cultivated annual crops on 87.5 percent of their farmland and remaining area is under perennials, such as sugarcane, lemon, and other non-food crops.

The water-saving seasonal vegetables were most preferred by the sample respondents and constituted 16.64 percent of farmland. Interestingly, vegetables were grown three times in a row on 7.1 percent of farmlands. During the *kharif* season, cauliflower (w), cabbage (w), tomato (w), and chilli (w) were grown as off-season vegetables to fetch a remunerative price. In the *rabi*, these were followed by cluster bean (w), cowpea (w), cucumber (w), pumpkin (w), potato (w), ridge gourd (w), bitter gourd (w), and pointed gourd (w). Most of these crops were grown on a medium elevation farm plot with assured irrigation. Farmers maintained a slope of two to five degrees in order to drain excess rainwater to prevent plants from drowning.

Table 4.4 Cropping pattern followed by the respondent farmers

Crop type	**Cropping pattern**	**Area (ha)**
A. Seasonal	1. Rainy Rice (w)-Pulses (w)	19.01 (24.0)
	2. Rainy Rice (w)-Fallow	12.33 (15.6)
	3. Pulse(w)	6.23 (7.9)
	4. Vegetable (w)	5.54 (7.0)
	5. Vegetable (w)-Vegetable (w)	4.24 (5.4)
	6. Rainy Rice (w)- Vegetables (w)	3.48 (4.4)
	7. Rainy Rice (w)-Post rainy Rice (i)	3.29 (4.2)
	8. Rainy Rice (w)-Oilseed (w)	3.28 (4.1)
	9. Vegetable (w)-Vegetable (w)-Vegetable (w)	1.49 (1.9)
	10. Others (w)	0.8 (1.0)
	11. Rainy Rice (w)-Pulses (w)-Pulses (w)	0.8 (1.0)
	12. Vegetable (w)-Pulse (w)	0.69 (0.9)
	13. Rice (w)- Vegetables (i)	0.66 (0.8)
	14. Vegetable (w)-Vegetable (i)	0.58 (0.7)
	15. Post rainy Rice (i)	0.56 (0.7)
	16. Vegetable (i)	0.5 (0.6)
	17. Pulse(w)-Pulse(w)	0.26 (0.3)
	18. Oilseed (w)	0.17 (0.2)
	19. Vegetable (w)-Vegetable (w)-Vegetable (i)	0.06 (0.1)
	20. Vegetables (w)	0.060.1)
B. Perennial	21. Sugarcane (i)	11.89 (15.0)
	22. Lemon(w)	1.12 (1.4)
	23. Essential Oil grass (w)	1.7 (2.1)
	24. Other perennials (w)	0.21 (0.3)
	25. Other perennials (i)	0.13 (0.2)
	a. Gross Cropped area	**79.06 (100)**

Note: Figures in parentheses are percentages to the gross-cropped are (GCA).
i and w in parentheses indicate irrigated and water-saving cropping patterns respectively.
Source: Authors own survey, 2018-19

Rice is traditionally grown as the first crop after the onset of the monsoon in June. In the surveyed farms, rainy-season rice occupied 54.19 percent of the total arable land and was followed by vegetables, pulses, or oilseed crops, which occupied 30.52 percent. It was common to plant pulse crops, such as green gram (*Vigna radiata*) and black gram (*Vigna mungo*) as a second crop after rainy season rice during the *rabi* season. A large majority of low-lying farm plots are cultivated in these ways. Due to prolonged submergence or flood incidence in the *kharif* season, pulses are grown in the *rabi* season on lowlands under residual moisture that enriches the soil with nitrogen. Following *kharif* rice, oil seeds such as mustard, peanut, sesame, and sunflower are grown on upland and medium-sized farm plots, either with supplemental irrigation or residual moisture. Perennial crops, such as sugarcane are cultivated primarily in low and medium-lying plots during the post-rainy season and are irrigated. Several other farmers replaced rice on their medium-elevation farms with lemon and essential oil grass, because of their substantial less water and labour requirement than rice. It was that markets and marketing opportunities for the output, timely availability of quality seeds, seamless credit facilities and risk bearing ability other than irrigation water and family labour availability influenced the decision on plot level cropping patterns. The scope of study is limited to farm-level factors of production, such as the size of the farmland, availability of family labour, and farm's ability to hire casual or contractual labourers for various farm operations. The model incorporated the above-mentioned constraints into a linear program to maximize the farm's profits.

4.7. Methodology: Linear Programming in a Farm Model

Two integrated steps are used to model the economic decision at the farm level. A farm's diverse decision-making process is the starting point in terms of methodological analysis. Farm owners optimize the plot level gross margin based on the available resources, such as plot area, by choosing the most suitable cropping pattern. In contrast, the amount of labour supplied by a farm family (a farm-scale variable) also influences the decision making at the plot level. Additionally, some activities are carried out by casual workers to fulfil the farm-scale labour demand.

A farm is dependent on the total amount of water available to it, that is the well level variable for us. Therefore, the water demand at the farm level must always be adjusted to the total crop water demand and should be lower than the average water availability at the well level. A farm owner usually tries to optimize the gross margin with all these constraints, and by doing so, this study optimized the gross margin at the well scale.

In order to optimize the net farm income, a simple linear programming model is used that optimizes a linear objective function subject to linear inequality and equality constraints (Panik, 2019). For a farm whose goal is to maximize its gross margin, the profit function (π) is written as follows:

$$\text{maximize} \quad \pi = c^T x$$

$$\text{subject to} \quad Ax \leq b$$

$$x \geq 0$$

Here, x represents the vector of variables, and in this case, it is the level of land use activity, is ‘unknown’ to us. c and b are vectors of coefficients and here, they represent the gross margin of one unit of activity, and the level of resource endowments, respectively, is known to us. A is the matrix of coefficients, that is, the demand of resources used to produce one unit of activity (is known to us), and T refers to the matrix transpose.

I used GAMS[2] software to maximize the net margin of a farm subject to its resource constraints. Using matrix algebra, the components of the optimization problem is summarized as ‘sets’.

2 General Algebraic Modelling Software

4.7.1. A linear farm model: iteration procedure

Farm is the lowest level of the decision-making system in this study. Farmers are assumed to make economic decisions about cropping activity in different plots throughout the year. Cropping decisions are plot-specific because of the different land elevations: upland, medium, and lowland. It is considered as the first constraint for a farmer; therefore I referred it as the *suitability constraint*. Then, the total area of a farm is optimally allocated to the cropping activities that generate the highest gross margin. A farmer tries to generate a maximum marginal return by using additional water and aiming to replace the family labourers to some extent. Consequently, a farmer face the second level of constraint on his farm with the availability of family labour resources, animal power resources, and working capital to pay the factors of production. For the LP, it was assumed that farmers sourced irrigation water primarily from groundwater. As a member of an irrigation distribution system, a farmer distributes water to each plot by *warabandi* (a Hindi term for rotational water distribution method). Thus, the third level of constraint at the well level can also be considered the total volume of water extracted, that was used to maximize a farm's gross margin.

The study used agro-economic information from 54 farms located in 15 villages that represent 33 different community water-sharing systems. I compared the survey period net margins realized during 2018-19 to the various simulations for different farm types. The first stage of modelling assumes that all farms are independent of each other in terms of water sharing, which means they must source their own water. The farm plots in the various farms also have the same probability of achieving any cropping activity in the modelling iterations.

As a part of the optimization process, it was assumed that a plot could accommodate more than one activity by dividing it into multiple subplots, and the same is already shown in *Giria* village (see section 4.6.3.b). Further it was assumed that it is not necessary to utilize the entire farm area to obtain the optimal net return. By maximizing the gross margin at each farm, the model allocates activities to different plots and utilizes the farm area efficiently. It was further assumed that water is uniformly available for all the farm plots by its topography. An explanation of this large and complex iteration process is appended below.

The impact of plot-level cropping patterns on farm-level gross margins is evaluated by conducting a forward iteration from plot to the farm. At the second level, the shadow price of water from the farm-level model outcome to the plot is used for optimal crop choice. The plot level optimal cropping decision that maximizes the gross margin subject to water cost is endogenously used to determine farm-level cropping decisions in the third step. A farm-level optimal cropping decision is exogenously utilized in the fourth step to maximize water-saving crop acres, subject to the availability of labour on the farm and the endogenous water supply available at the farm. To test farmers' independent response to water conservation, the model simulated with different prices for water.

4.7.2. Model content in GAMS language

GAMS is a mathematical problem-solving system that optimizes a target function subject to multiple linear equations and/or non-linear equations. Sets are the first component in GAMS that are integral to the modelling process. Below in table 4.5 a list of the sets used in the modelling process in GAMS is described.

The set *topo* incorporates the topography of an individual farm parcel. I classified a farm topography into upland, medium-land, and lowlands. It is a village-scale parameter, which means that an upland farm plot in one village may be at a different elevation from the mean sea level in another village. Another attribute of a plot is its water availability and slope. The decision regarding cropping activity is made at the plot level and the decision concerning water availability, farm family labour, and animal and machine power is made at the farm level.

Cropping patterns are indicated by activity in a farm plot. Respondent farmers typically plant *kharif* rice, followed by green gram or black gram in *rabi*. Farmers also prefer to grow autumn and summer rice, seasonal vegetables, as well as oilseed immediately after *kharif* rice, only under irrigation. In the next section, farm level cropping activities are presented in tabular format for comparison among different farms.

Table 4.5 Declarations and descriptions of model variable indices (GAMS sets)

Declarations	Descriptions	Elements
1. *block*	Block is an administrative unit composed of many villages.	Block 1 - Block 8
2. *farm*	The farm is an agricultural production space owned by a farm household	Farm 1 – farm 53
3. *plot*	Farm plot is the lowest unit land space on which production decision is undertaken	A farm constitutes several parcels, while each parcel is composed of several plots. Parcels are named as A, B, C,…, L and each parcel is named as A1, A2, … A_m for the A parcel.
4. *topo*	Topography of a plot	Upland, medium land, lowland
5. *activity*	Cropping activities and technical activities adopted in a plot	Cropping patterns followed by different representative farms at WUA level is presented section 4.6.3 Technical activities such as purchase of water in different seasons
6. *f_t_p*	GAMS mapping set to relate plots to their farms and their topography	This set is defined to identify a plot that is of specific elevation and belongs to a specific farm. I assigned land area, cropping pattern, and all farms as well level resource demand at plot level through mapping.
7. *b_f*	GAMS mapping set to relate farms to blocks	This set is defined to identify a farm that belongs to a particular block
8. *plot_cons (colitems)*	Constraint at the plot level	Area in ha
9. *farm_cons (colitems)*	Constraint at the farm	This set represents the upper limits of the farm-level resources such as family labour availability in rainy, post rainy and summer season and the annual bullock labour.
10. *well_cons (colitems)*	Constraint at the well	This set is a well level constraint for maximum water availability for each farm.
11. *colitems*	GAMS set to include all column items (for ease of data import in GAMS)	All plot, farm and well level set elements are appended in the columns (plot_cons, farm_cons, well_cons, GM)

Source: Authors own

The labour constraint subset is also defined over the farm_cons set, declaring seasonal labour availability at the farm level, and the set elements are Tot_Labour_Rainy.MD, Tot_Labour_PostRainy.MD, Tot_Labour_Summer.MD. Labour engagement at the farm level is activity-specific and they were paid with an appropriate wage.

To calculate labour provision from own labour, a technical sub-set (non_labour_act_set) of all activities excluding the wage labour activities was created. I added additional activities (added to the set activities) to hire wage paid labourers (WAGE_Rainy.INR.MD, WAGE_PostRainy.INR.MD, and WAGE_Summer.INR.MD). These activities helped to fulfil labour requirements in different seasons and are differentiated by seasonal wage rates and they further limited to respective upper limits.

I collected farm-level data from 53 farms covering 783 farm plots. There were subtle differences in the plot-level activities across the farms. Hence, I grouped 90 percent of the cumulative frequent activities according to similarity and listed them in Table 4.6.

Table 4.6 Plot-wise cropping pattern (activities) followed by farmer respondents

Activities	**Plot frequencies**
1. Rice- pulse crop	196 (25.0)
2. Vegetable-Vegetable	175 (22.4)
3. Vegetables-Fallow	89 (11.4)
4. Rice-vegetables	77 (9.8)
5. Perennial non-food crop (Sugarcane/ Essen. Oil grass/ Fodder)	67 (8.6)
6. Rice-fallow	64 (8.2)
7. Rice-Rice	37 (4.7)

Note: Figure in parentheses are percentage to total frequency

Source: Field survey, 2018-19

One can find from the table that, rainy-season rice was cultivated on 25 percent of the plots followed by pulse crops such as green gram (*Vigna unguiculate*) or black gram (*Vigna mung*). Farmers shared that, in comparison with other seasonal crops such as summer rice, seasonal vegetables, and sugarcane, green gram and black gram require one to two irrigations only during the time of sowing and maturity, that accounts for 80 percentage less water. One term these crops as water saving activities and they are mostly cultivated in the lowlands, which are generally located at the WUA boundary, where water seldom reaches. Normally, a farmer engages in this activity for subsistence, and a portion of the output is also marketed to meet immediate cash requirements.

Vegetables are the second most common activity. It is either grown back-to-back in the *kharif* and *rabi* seasons, covering two seasons, or after rice harvest in 22.4, 11.4 and 9.8 per cent of plots, respectively. In most cases, these activities are conducted in medium and upland plots with controlled irrigation. Sugarcane and other perennial crops account for 8.6 percent of farm plots. I also observed that *kharif* rice is a sole crop in the cropping activity and occupies 8.2 percent of the farm plot. Nonetheless, irrigation provision in the post-rainy season allowed farmers to grow autumn or summer rice on 4.7 percent of the farm plots. In order to accommodate all the plot-specific information about a farm in a single model, *f_t_p* set maps farm, *topo*, and plot sets. It is useful for attributing the land area value to a linear optimization. The *b_f* set maps farms within the respective blocks. I used the mapping set definition because of the multidimensional nature of the dataset.

a. Parameters

The model solving procedure requires parameter definition over sets and they are listed in Table 4.7. The parameter *rhs_plot* is defined at the plot level. In GAMS, this is defined over the sets (farm, plot, topo, plot_cons) and *rhs_farm* is defined at the farm-level over the sets (farm, farm_cons). rhs_well is defined over (block, well_cons) meaning that farmers represent specific block and sourced water from a specific well with possibilities of water sharing. Additionally, I assume that individual wells sourced water independently, implying no inter-well water sharing.

Table 4.7 Model parameters and variables: declaration, types, and descriptions

Parameter declarations	GAMS object types	Over sets	Description
1. *rhs_plot*	Parameter	farm, plot, topo, plot_cons	Resource restrictions at the plot level: plot area
2. *rhs_farm*	Parameter	farm, farm_cons	Resource restrictions at the farm-level: family labour availability, bullock labour availability,
3. *rhs_well*	Parameter	block, well_cons	Resource restrictions at the well level: water availability at the well level
4. *tabledata*	Parameter	farm, plot, topo, activity, colitems	Plot level data on all resources are summarized into a four-dimension matrix
5. *x*	Positive variable	farm, plot, topo, activity	Land use activities at the plot level (ha)

Source: Authors own.

The parameter *rhs_well* is the aggregate value of the water demand at the well level.

In parameter *tabledata*, the set elements are defined over (farm, plot, topo, activity, colitems), where *colitems* contains the elements of a plot_cons_raw, farm_cons_raw, well_cons_raw, and gross margin (GM). In addition, sets are defined based on irrigation water purchases in the *kharif*, *rabi*, and summer seasons. These are the subsets of activities with the set elements of BuyWater_Rainy, BuyWater_PR, BuyWater_Summer. Using this, I choose activities in which the gross margin (GM) changes and measure the marginal value of the level of activities.

b. Variables and equations

The land area (*x*) is endogenously estimated as a positive variable, whose value ranges from zero to infinity. By solving the equations, I can estimate the target value, total gross margin (*tgm*).

c. Objective function

I optimized the *tgm* of a farm by allocating land to crop combinations (cropping pattern). To calculate the tgm, the crop choice decision is made at the plot level and then summed up for each farm. Each plot is distinguished by its elevation and is suited to a particular cropping pattern. So, the farm's objective function is described as follows.

$$tgm = \sum_{\text{farm,plot,topo,activity}} gm_{\text{farm,plot,topo,activity}} * x_{\text{farm,plot,topo,activity}}$$

(……………………….4.1)

Here, the margin is summed up for an activity that is undertaken on a plot of a specific *topo*, and each plot level margin is summed up at the farm level. The GAMS feature “dollar filter” is used technically in the target function to include only the relevant plots into the target function of the individual farms. This is controlled by the mapping index, f_p_t. It is required because not all farms own all plots on all topographies.

d. Resource constraints

The target function is solved using three constraint equations.

A farm's resources include total land, which is the sum of all plot areas, household labour, and animal labour. The sample farms operated at different scale. Therefore, constraint equations at are developed at plot, farm, and well levels.

At the plot level, specific activities are taken up in a specific land area. Therefore, the plot level constraint is defined as

$$\sum_{\text{activity}} tabledata_{\text{farm,plot,topo,plot}_{\text{cons}}} * x_{\text{farm,plot,topo,activity}} \leq rhs_{plot}{}_{\text{farm,plot,topo,plot}_{\text{cons}}} \quad \forall(\text{farm, plot, topo, plot}_{\text{cons}})$$

(………………………4.2)

Constraints on farm resources, such as family labour availability along with animal labour constraints, are modelled at the plot level via cons_eq_farm(farm, farm_cons). Therefore, the farm-level constraint function is written as follows.

$$\sum_{\text{plot,topo,activity}} tabledata_{\text{farm,plot,topo,activity,farm}_{\text{cons}}} * x_{\text{farm,plot,topo,activity}} \leq rhs_{farm}{}_{\text{farm,farm}_{\text{cons}}} \quad \forall(\text{farm, farm}_{\text{cons}})$$

(………4.3)

Water availability constraint is at the well level. I derived the water availability at the block level and used it as the farm's water resource constraint: cons_eq_well(block, well_cons) and it is appended below.

$$\sum_{\text{farm,plot,topo,activity}} tabledata_{\text{farm,plot,topo,activity,well}_{\text{cons}}} * x_{\text{farm,plot,topo,activity}} \leq rhs_{well}{}_{\text{block,well}_{\text{cons}}} \quad \forall\ (block, well_{cons})$$

(……………………4.4)

4.7.3. Model simulations

The base model was simulated under two conditions. In the first case, unlimited water supplies would be provided free of charge, and in the second case, Kaldor-Hicks compensation would be provided. I investigated each simulation using various hypothetical scenarios.

a. Model one: Unlimited water supply with different levels of water cost

As a baseline, I determined that the actual farm water demand is based on the farm's crop water requirements. It is assumed that no inter-farm water exchange takes place. Farms can adopt any cropping pattern in accordance with their suitability and avail water accordingly. A farm's water demand is purely economic, and therefore the price of water influences the cropping activity, that further determines the volume of water demand. Moreover, it was assumed that there are no minimum water requirements in any of the seasons, which implies that a farmer may follow a complete water-saving or intensive cropping pattern on his entire farm.

It was observed that the price of irrigation water and the unit of measurement vary by village. For this reason, the water costs was converted to Indian rupees per hectare-cm. In these eight surveyed blocks, cost of irrigation water varied from 0.01 rupee to 1.5 rupees per cubic meter. During the post-rainy season of 2018-19 I observed the cost of water is further dispersed and ranged from 0.01 rupee to 15 rupees per cubic meter.

During the field survey, I found that a few farm plots are either not irrigated or not suitable for irrigated farming. On the other hand, several farms cultivated *Arbi* (*Colocasia esculenta*) or sugarcane and applied irrigation intensively during *rabi* and summer seasons. During these months, the crop water demand is higher than rainy season and to deliver increased volume of water, a WUA increase pumping hours, that sometime goes beyond the prescribed pumping hours. As a result, the average cost of water increases to INR 3.7 per cubic meter. In the model, I simulated water demand with water price data at a 90 per cent confidence level.

In order to simulate the water demand during the survey, model one can use an array of prices and for that I defined another set, *price_levels* that simulates water demand for 25 levels, and simulations over water prices ranging from zero to 120 percent over the reference water cost. The water price range for a lower limit of INR 0.1 per cubic meter, to an upper limit of INR 16 per cubic meter. In each iteration, the water price is attributed to the parameter *price_level_value* over the *price_levels*, and it is explained below.

$$price_{lev_{value}{}_{price_{levels}}} = price_{lower} + \frac{(\mathrm{price_{upper}} - \mathrm{price_{lower}})}{24} * [ord(price_{levels}) - 1] \;\forall\, price_{levels} \quad (\ldots\ldots\ldots.4.5)$$

Here, ord(priev_levels) is the position of the set elements within the set.

In the previous section it was discussed that, for a farm owner, his decision-making unit, farm, is consisting of many parcels and they are scattered in nature. Further, it was realized that plot level decision is often influenced by the neighbouring plot owner. Hence, farm plot was determined as a basic decision making in the model rather than an entire farm. To solve the model, a linear program was used to maximize the *tgm* for each farm. With every price change, I intended to develop output for water demanded, optimal land use at the plot level, household labour usage, and *tgm* for each farm. A loop function was developed, and it solved the objective function for each change in price level and generated the desired outcome.

Next, I wanted to observe water demand at the farm level when water availability is at 100 percent and without any trade option. In LP, I structured this as a dual approach. During the third stage of simulation, I changed individual water levels without trading. At the well level, the base water level is assumed to be at the current level of water usage. With a linear increment of 0.05 units, I simulated 25 level changes and thus, I derived the demand curve of water. To obtain the cost coefficients, the demand function was transformed into the cost function. According to the farm's water demand, the cost of water is determined, and therefore, the net revenue for each farm is maximized. However, the survey contains cropping patterns for only a single year, which reduces the scope for a diverse choice of crop rotation at the plot level. Thus, the reaction function of water demand for many farms may not show an ideal step-down demand function, and hence, the cost coefficients may not show a significant difference between farms. As an alternative to this method, I develop the block-wise demand function of water. With multiple steps available in the water demand function, the chances of obtaining a robust cost coefficient estimate are high. The coefficients are used exogenously in the principal-agent model in the following chapter.

b. *Model two: Limited water supply with scope for water trade & seasonal water transfer*

The cropping pattern on many farm plots consists of only one crop, while a neighbouring farm plot may consist of two to three crops. A farmer's primary determining factor of cropping pattern is water availability on a farm plot, followed by suitability (I defined suitability constraint in section 4.6.3.a). In this model I assume that during the *Kharif* season, a rational farmer with limited water supply can adopt a water-saving practice at the plot level and opt to conserve water. Additionally, water saved from a particular plot is often spatially redistributed to another plot. In many instances, a cumulative water saving is mane in one season for its use in the next season.

Our survey revealed that, farmers cultivated water-saving vegetable crop during *rabi*. As a result, water saved during the *rabi* season could be used for the same plot in the summer. However, I assumed that water transfer is allowed only within a farm or between farms and not outside the WUA. It was assumed that there is no inter-WUA water transfer. In theory, unutilized water from a farm plot is utilized by another farm (regardless of its WUA membership) creates net financial welfare for the WUA. During 1937, Kaldor-Hicks (KH) proposed that, if a resource is not utilized on a farm plot, but is allocated to another farm plot, may generate a higher gross margin at farm or landscape scale. For that reason, the former plot may be compensated for renouncing resource use. Ultimately, this will generate welfare to the former farm owner (Carmona-Torres, Parra-Lopez, Groot, & Rossing, 2011).

To apply this proposition, I simulated the base model over several farms. Those plots and farms can trade water, but always within the WUA. In addition, it was assumed that a farmer also pays equal attention to the best allocation of water among the farm plots. The disjointed nature of the farm plots and differences in crop choice decision in neighbouring farm plot makes it difficult to relocate the physical transfer of water. Therefore, it was assumed that water can be transferred between farms within a WUA. In the initial modelling stage, I assumed water is available at no cost, but the total water availability is limited to the maximum limit of present water consumption. In this simulation, the shadow price of water is observed, assuming everything else remained at constant level. Additionally, the impact of limited seasonal water transfers at the WUA level is also observed.

In this model, the target function is the sum of gross margins of all the farms similar to the model one. This implies that gross margin losses on a farm can be compensated by gross margin gains in another farm, as proposed by Kaldor-Hicks (S. Sharma, Giri, Haque, & Tetteh, 2018).

c. Model calibration

Once after the re-allocation of water in model two, I proceeded to observe the model reaction at a variable level of water availability. For that purpose, I intended to observe model reaction with modification of water quantities, such as water availability up to 120 percent of the initial entitlement, using the existing assumption of no water cost to the farmer. I expected different levels of water use, over space i.e., water transfer to another farm plot, and over time. Nevertheless, with water use assigned at a lower limit of zero, the model was able to assign no cropping activity to many less profitable farm plots, resulting in an infeasible solution. Furthermore, I stipulated that all farms must use a minimum amount of water, which implies that the model was compelled to use irrigation intensive activities in the cropping patterns in any season, across the entire farm. The same applies to other constraints such as spatial and seasonal water transfer. Soon after the nature of the water trade over space and season is understood, I observed the effects of water prices on water demand. Numerous studies cite similar instances around the globe where farmers were given access to water without any operational cost (Heintzelman, Salant, & Schott, 2009; Steward et al., 2009; Woldewahid et al., 2011). To make the model more realistic, I simulated it with changing water prices within a range of 0.1 to 16 rupees per cubic meters. The water availability was kept at its original reference level, so that model does not allocate more than 100 percent of water supply.

4.7.4. Estimation of shadow price of water and step-down demand function

In model two, I relaxed the assumption of water-sharing restrictions over space and season, which implies that a farmer can share water from his own water allocation with his neighbours. Alternatively, a farm can conserve water in the *kharif* or *rabi* season and use it in the summer. Moreover, I restricted the base model to 100 percent water availability (in order to reflect the status quo) and simulated the quantity of water demanded at varying prices.

In the fieldwork, I observed that farmers demand water in variable quantities according to its unit price. In the classical theory of demand for ordinary goods, if the price of water goes up, one can expect a step-down demand function. In the study area, there are several farms that use water at the lower boundary, indicating that the majority of farm plots are either unirrigated or have already adopted water-saving practices. As a result, an increase in water prices may not affect farm-level water demand. Some farms cultivate sugarcane with a buy back contract. Under both of these extreme scenarios, the possibilities of water reallocation under water price changed is observed. Furthermore, sugarcane cultivation generates relatively higher gross incomes than other comparable activities. The incremental return for a cubic meter of water, however, was significantly higher than that of a unit. Nevertheless, these types of results are usually specific to farms and reflect the overall capacity of a farm.

Initially I was interested to determine the elasticity of water demand for each farm. However, cross sectional data collected for a single year with no crop rotation information left me with an alternative, to gain estimates at the block level. There is, however, a risk of missing out on exact responses for many responsive farms when estimating in aggregate. An average estimate produced by a block level estimate will be much closer to the estimate of the representative farm. The majority of farmer respondents either shared water with the same WUA or were members of neighbouring WUAs. Under these circumstances, it is reasonable to assume that farms representing a single block have a similar cropping pattern.

a. Estimation of marginal cost function of block level water demand

I derived marginal cost function from the inverse demand function.

Let the estimated demand function of water be W_i and I estimated it at the block level as

$$W_i = \gamma * P_w + \delta \qquad \ldots(4.6)$$

where, P_w is average water price in the study area during 2018-19, γ is the slope and δ is the intercept of the demand function. Therefore, the inverse demand function from equation 4.6 can be written as

$$P_w = \left(1/\gamma\right) * W_i - \left(\delta/\gamma\right) \qquad \ldots(4.7)$$

The inverse demand function and block-level mean water availability were used to estimate the marginal cost function of water.

Let the linear marginal cost function of a farm be

$$MC_i = \zeta + \tau * W_i \qquad \ldots(4.8)$$

where, ζ and τ are the intercept and slope coefficient of the marginal cost function.

Now, by utilizing Shepard's Lemma (Kutlu, Liu, & Sickles, 2020) I estimated ζ as below.

$$\zeta = -\left(1/\gamma\right) * (W_i - \delta) \qquad (4.9)$$

and ,

$$\tau = -\left(1/\gamma\right) \qquad (4.10)$$

I further derived the total cost function by integrating the marginal cost function.

$$TC_i = \zeta * W_i + 0.5 * \tau * {W_i}^2 \tag{4.11}$$

I assumed that farmers representing respective block realized similar cost function. I will use these cost coefficients for respective farmers in a principal-agent (P-A) model to understand their cooperation nature in sharing water to reduce total cost of water procurement. In the P-A model ζ is referred as φ and $0.5 * \tau$ is referred as ψ. In the result section I presented the numerical estimations of φ and ψ in table 4.12.

4.7.5. Estimation procedure of gross margin and cost of production

To estimate per hectare gross margin for a farm 'i', I multiplied respective farm plot level outputs of a crop at each harvest (especially for vegetables) with the market prices and finally summed them up.

$$Gross\ Margin_i = \sum_{k,m} Output_{crop_m} * Price_{crop_m} \tag{4.12}$$

Here, m represents different crops cultivated at k plots.

With respect to the cost of production, I first estimated cost of cultivation of a crop under which it is cultivated and then converted to per unit hectare area. Following the manual on cost of cultivation of surveys, developed by Directorate of Economics and Statistics, Government of India, I developed cost A_1, A_2, B_2 and C_2 for each farms (GoI, 2002).

$$(CostA_1)_{crop_m} =$$
$$\sum_m [\text{Value of hired human labour}_m, \text{Value of hired bullock labour}_m,$$
$$\text{Value of owned bullock labour}_m, \text{Value of owned machine labour}_m,$$
$$\text{Value of hired machine labour}_m, \text{Hired machinery charges}_m,$$
$$\text{Value of seed (both farm produced \& purchased)}_m,$$
$$\text{Value of insecticides and pesticides}_m,$$
$$\text{Value of manure (owned and purchased)}_m, \text{Value of fertilizers}_m,$$

$$\text{Irrigation charges}_m, \text{Depreciation of implements and farm buildings}_m, \text{Land revenue cesses and other taxes}_m, \text{Interest on working capital}_m, \text{Misc. expenses (artisans etc.)}_m]$$

(4.13)

$$(CostA_2)_{crop_m} = (CostA_1)_{crop_m} + \text{Rent Paid for leased in land} \quad \ldots(4.14)$$

$$(CostB_2)_{crop_m} = (CostA_2)_{crop_m} + interest\ on\ value\ of\ owned\ fixed\ capital\ assets\ (excluding\ land) + rental\ value\ of\ owned\ land\ (net\ of\ land\ revenue)$$

…(4.15)

$$(CostC_2)_{crop_m} = (CostB_2)_{crop_m} + imputed\ value\ of\ family\ labour$$

…(4.16)

I used Cost C_2 to calculate per hectare net margin of a firm 'i'.

$$Net\ margin_i = Gross\ margin_i - (CostC_2)_i \quad \ldots(4.17)$$

I used farm level gross margins, total costs, and net margins as an input in the LP model along with farm level physical units of input use, wage rates, and product prices that generated simulated gross and net margins in different models. After that, I compared margin and costs recorded during the survey and model outcomes to draw economic inferences.

4.7.6. Estimation of water consumption by a crop in farm 'i'

To estimate farm level volume of water consumption by a crop in an agricultural year, 'W_c', first I multiplied frequency of irrigation $\left(f_{j_i}\right)$ for a crop on jth plot $\left(f_{c_j}\right)$ with duration of irrigation $\left(t_{c_j}\right)$ (estimated in minutes) and derived total duration of irrigation. Then, I multiplied it with the average annual well level water discharge rate (d_{WUA}) (estimated in litre per minutes) to obtain total volume of water used / potential water saving by a crop, c.

$$W_c = \left(f_{c_{j_i}} * t_{c_i}\right) * d_{WUA} \tag{4.18}$$

To measure the scale effect, I estimated the water consumption at different plot size and used land area additionally in the LP model. I further categorized crops into water-saving or water-intensive by their volume of water consumption, with reference to the crop water use recommendations (B. R. Sharma et al., 2018).

4.8. Results of the land-use scenario

At first, I looked at the diversity in cropping patterns and the optimal land-based activities that generate maximum gross margins at the farm level. In the previous chapter I discussed groundwater-based land-use decisions at the village level and highlighted individual decisions at farm level and the potential for collective groundwater management. In this section, I present individual farm plot decisions and attempted to correlate with the aggregate behaviours at the village level. I further estimated farm-level net incomes under the status quo and under different simulations. The shadow price function of water demand at the farm level was derived and was used to compare the results of different sustainability concerns to the status quo.

4.8.1. Status quo: Description of the present cropping pattern and cropping system at the farm-level

Farmers adopted cropping patterns specific to the plot attributes. On many farm plots, they followed cropping pattern similar to a neighbouring farm. In table 4.8, I present cropping patterns adopted at the farm level during the survey period. Here I present descriptive statistics in terms of total area under different cropping pattern followed by the respondent farmers at their different farm parcels in hectares.

It was found that, almost all lowland and medium land plots are traditionally cultivated with rice in the rainy season as a single crop in a year or followed by pulses and seasonal vegetables in the post rainy season. Oilseed crops are cultivated exclusively in the *Ganjam* district farms after *kharif* rice. In *Cuttack* and *Jagatsinghpur* districts I observed that some farmers cultivated rice in the post rainy season (0.3 and 3.8 percentages respectively), whereas many others switched to vegetables to reduce water consumption and costs associated.

Rice cultivation during *Rabi* season was hindered by increasing cost of water. However, technological interventions helped farmers to use farm and family resources more efficiently in vegetable, oilseed, and pulse crop cultivation. During the *rabi* and summer seasons, water-saving seasonal vegetables are cultivated. On all the blocks in Cuttack and Jagatsinghpur, and Hinjilikatu and Patrapur block of Ganjam district water-saving seasonal vegetables are cultivated three times in a row. On some farms, *Arbi* (*Colocasia esculenta*) is cultivated as a second crop with assured irrigation facility, and it fetches comparatively higher return.

In many farms in *Cuttack* and *Jagatsinghpur* districts, sugarcane occupied a minimum of 15 per cent of the land area. Farmers were attracted to this perennial activity by the contractual sale agreement and the custom hire facilities available from the sugar factories. Other plantations included lemon, areca nut, betel vine, and essential oil grasses (lemongrass, citronella grass, *palma rosa* grass, etc.).

Table 4.8 Cropping pattern followed by sample respondents: aggregated at the block level (in ha)

	Cropping pattern	Cuttack	Jagatsinghpur				Ganjam			
		Kantap ada	Baliku-da	Biridi	Jagatsinghpur block	Raghunat hpur	Chikiti	Hin-jilikatu	Pa-trapur	Purushoty-ampur
A. Annuals	1. Rainy Rice (w)-Fallow	5.3 (20.8)	2.65 (32.6)	1.92 (15.5)	0.11 (0.9)	-	0.11 (17.5)	0.8 (8.8)	1.44 (32.3)	-
	2. Rainy Rice (w)-Oilseed (w)	0.4 (1.6)	-	-	-	-	0.4 (64.9)	0.32 (3.5)	1.2 (26.9)	0.96 (38.8)
	3. Rainy Rice (w)-Post rainy Rice (i)	2.09 (8.2)	-	-	1.2 (9.4)	-	-	-	-	-
	4. Post rainy Rice (i)	0.08 (0.3)	-	-	0.48 (3.8)	-	-	-	-	-
	5. Rainy Rice (w)-Pulses (w)	3.36 (13.2)	4.45 (54.7)	3.76 (30.4)	2.94 (23.2)	1.7 (46.7)	-	1.93 (21.2)	0.86 (19.3)	-
	6. Rainy Rice (w)-Pulses (w)-Pulses (w)	-	-	-	-	-	-	0.8 (8.8)	-	-
	7. Rainy Rice (w)- Vegetables (w)	1.46 (5.7)	0.7 (8.6)	0.08 (0.6)	0.64 (5.0)	-	-	0.45 (5.0)	0.09 (2.1)	0.06 (2.4)
	8. Rainy Rice (w)- Vegetables (i)	0.42 (1.6)	-	-	-	-	-	-	0.12 (2.7)	0.12 (5)
	9. Vegetable (w)	2.74 (10.5)	0.06 (0.8)	0.31 (2.3)	0.38 (3.0)	0.19 (5.3)	0.11 (17.5)	1.12 (12.3)	0.5 (11.3)	0.19 (7.6)
	10. Vegetable (i)	0.19 (0.8)	-	0.03 (0.3)	0.27 (2.1)	-	-	-	-	-
	11. Vegetable (w)-Pulse (w)	0.69 (2.7)	-	-	-	-	-	-	-	-
	12. Vegetable (w)-Vegetable (w)	1.57 (6.2)	0.05 (0.6)	0.16 (1.3)	0.62 (4.8)	0.34 (9.2)	-	1.01 (11)	0.16 (3.6)	0.34 (13.7)

	Cropping pattern	Cuttack	Jagatsinghpur				Ganjam			
		Kantapada	Baliku-da	Biridi	Jagatsinghpur block	Raghunathpur	Chikiti	Hin-jilikatu	Pa-trapur	Purushoty-ampur
	13. Vegetable (w)-Vegetable (i)	0.58 (2.3)	-	-	-	-	-	-	-	-
	14. Vegetable (w)-Vegetable (w)-Vegetable (w)	0.11 (0.4)	0.1 (1.2)	0.13 (1.0)	0.14 (1.1)	0.34 (9.4)	-	0.59 (6.4)	0.08 (1.8)	-
	15. Vegetable (w)-Vegetable (w)-Vegetable (i)	-	0.06 (0.8)	-	-	-	-	-	-	-
	16. Pulse(w)	1.93 (7.6)	0.06 (0.8)	3.2 (25.8)	0.06 (0.5)	0.24 (6.6)	-	0.73 (8)	-	-
	17. Pulse(w)-Pulse(w)	-	-	-	0.02 (0.2)	-	-	0.24 (2.6)	-	-
	18. Oilseed (w)	0.06 (0.3)	-	-	-	-	-	0.11 (1.2)	-	-
	19. Others (w)	-	-	-	0.18 (1.4)	0.62 (17.1)	-	-	-	-
B. Perennials	1. Sugarcane (i)	4.54 (17.8)	-	2.8 (22.6)	3.92 (30.8)	-	-	0.62 (6.8)	0 005 (0.1)	-
	2. Lemon(w)	-	-	-	-	-	-	0.32 (3.5)	-	0.8 (32.4)
	3. Essential Oil grass (w)	-	-	-	1.7 (13.3)	-	-	-	-	-
	4. Other perennials (w)	-	-	-	-	0.21 (5.7)	-	-	-	-
	5. Other perennials (i)	-	-	-	0.05 (0.4)	-	-	0.08 (0.9)	-	-
	GCA	**25.51**	**8.13**	**12.38**	**12.72**	**3.65**	**0.62**	**9.12**	**4.46**	**2.47**

Note: Figures in parentheses are percentages to the gross-cropped are.
i and w in parentheses indicate irrigated and water-saving cropping pattern respectively.
Source: Authors' own field survey

CHAPTER 4: OPTIMIZATION OF LAND-BASED WATER-SAVING ACTIVITIES

To understand the similarities and differences in cropping patter followed in different farms, I present the results by grouping the villages based on farm types, that I developed in farm typology chapter. Now, I present the cropping pattern of the respondent farms by the farm types in table 4.9. The farm type classification enabled me to determine the variety of decisions made in crop choice in similar water procurement systems. As a part of the diversification efforts of HDIAM villages, rice is cultivated to fulfil the first objective of food security for a family, while pulses and oilseeds crops complement to it. I observed that, among the sample respondents, marginal and small farms from HDIAM villages allocated their farm resources optimally for year-round cultivation of cereals, pulses, oilseeds, and vegetables in most of their farm plots. In addition to that, 16 percent of the land area was devoted to sugarcane, indicating farmers' preference for perennial crops that have a guaranteed income through a contractual sale agreement. Overall, most of the land is devoted to water-saving activities, although they have tried to exhaust their water quota by growing water-intensive vegetables such as *rabi* or perennial crops, such as sugarcane.

With respect to MDLIAM villages, they mostly followed rainfed rice - pulses (green gram) cropping pattern and never used irrigation on these plots. On 18 percentage of the respondent’s farm plots were under pulse crops (green gram) only, because frequent flash floods destroyed the rainfed rice, resulting in no economic profit. Seasonal vegetables were cultivated on 15 percent of the farmlands. Most single vegetable activities are composed of bitter gourd, pointed gourd, and other annual vegetables. Sugarcane and essential oil grass occupied 21 percent of the land. In section 3.8.b, I discussed that farm household members from these villages were mostly engaged in many non-farm activities that reduced the scope of on-farm labour engagement for adoption of diversified vegetable-based cropping activities that would have contributed to their household income for food and nutritional security.

The third farm type is the least diversified due to the fact that farm plots were primarily planted with rainfed rice-pulse crops (44%), rainfed rice-oilseed (15%), and sugarcane (10%). *Rabi* vegetables were cultivated after the harvest of the *kharif* rice in 7.6 percent of the fields.

Table 4.9 Cropping pattern followed in the study area by farm types (in ha)

Cropping pattern		Farm typology		
		HDIAM	*MDLIAM*	*LDIACM*
A. Seasonal crops	1. Rainy Rice (w)-Fallow	9.93 (21.0)	2 (8.4)	0.4 (5.0)
	2. Rainy Rice (w)-Pulses (w)	9.10 (19.2)	6.4 (26.9)	3.51 (44.0)
	3. Rainy Rice (w)-Post rainy Rice (i)	3.29 (7.0)	-	-
	4. Vegetable (w)	3.07 (6.5)	1.92 (8.1)	0.54 (6.8)
	5. Rainy Rice (w)- Vegetables (w)	2.72 (5.7)	0.15 (0.6)	0.61 (7.6)
	6. Vegetable (w)-Vegetable (w)	2.53 (5.3)	1.69 (7.1)	0.02 (0.3)
	7. Rainy Rice (w)-Oilseed (w)	1.76 (3.7)	0.32 (1.3)	1.2 (15.0)
	8. Vegetable (w)-Vegetable (w)-Vegetable (w)	1.40 (3.0)	0.09 (0.4)	-
	9. Pulse(w)	1.26 (2.7)	4.48 (18.8)	0.49 (6.1)
	10. Rice (w)- Vegetables (i)	0.62 (1.3)	0.04 (0.2)	-
	11. Vegetable (w)-Vegetable (i)	0.58 (1.2)	-	-
	12. Post rainy Rice (i)	0.56 (1.2)	-	-
	13. Rainy Rice (w)-Pulses (w)-Pulses (w)	0.40 (0.8)	0.4 (1.7)	-
	14. Vegetable (i)	0.37 (0.8)	0.13 (0.5)	-
	15. Other perennials (w)	0.21 (0.4)	-	-
	16. Oilseed (w)	0.06 (0.1)	0.11 (0.5)	-
	17. Vegetable (w)-Vegetable (w)-Vegetable (i)	0.06 (0.1)	-	-
	18. Vegetable (w)-Pulse (w)	0.03 (0.1)	0.26 (1.1)	0.4 (5.0)
	19. Pulse(w)-Pulse(w)	-	0.26 (1.1)	-
	20. Vegetables (w)	-	0.06 (0.3)	-
	21. Others (w)	0.61 (1.3)	0.18 (0.7)	0.02 (0.2)
B. Perennial	1. Sugarcane (i)	7.71 (16.3)	3.37 (14.2)	0.8 (10.0)
	2. Lemon(w)	1.04 (2.2)	0.08 (0.3)	-
	3. Essential Oil grass (w)	-	1.7 (7.1)	-
	4. Other perennials (i)	-	0.13 (0.5)	-
Gross cropped area		**47.31**	**23.77**	**7.98**

Note: Farm types are developed in the second chapter. HDIAM - Highly diversified irrigated agriculture for direct market supply, MDLIAM- Moderately diversified limited irrigated agriculture for direct market supply, and LDIACM- Least diversified irrigated agriculture for contacted market supply.
Figures in parentheses are percentages to the gross-cropped are.
i and w in parentheses indicate irrigated and water-saving cropping patterns respectively.
Source: Authors own calculation.

Sugarcane and seasonal water-saving vegetable farm plots mainly used irrigation during the *rabi* and summer seasons. These farms heavily rely on farm mechanization to augment their labour requirements. Alternatively, many farms could obtain water from their own water point or a neighbour. I further examined water demand under several types of water delivery mechanisms and water pricing. I also examine the impact of water pricing and water quotas on the gross margin of farms using a linear program and present in the next section.

4.8.2. Results: Model outcome on optimized land use

Scholars traditionally used total gross margin (*tgm*) as an indicator of farm profitability, and in the case, it is an outcome of land-based activities (Amjath-Babu, 2009; Johnson, Gandhi, & Jain, 2020; Quintana Ashwell et al., 2018). Variations in gross margins are due to the different ways in which exogenous inputs were used in the production process. A variety of agricultural inputs were considered, including farm plot size, family and hired human labour, bullock labour, working capital for factor payments, and water use in cubic meter. To make the model more understandable, exogenous variables were scaled down to per hectare. The seasonal disaggregation of the input application enabled me to calibrate the model at a potentially realistic level. The farm-level gross margin realized in 2018-19 is shown in column two in table 4.10.

Two important model results are presented in Columns 3 and 4. Both models show how a farm can obtain gross margin under unlimited water supply, but without the option of water trade, and under limited water supply with water trade and seasonal water transfer. The intended goal was to observe scale economics, so the results were grouped according to farm size class. It is to be noted that, the estimation procedure of gross margin in two different models vary in some degree with the gross margin estimation in the survey. However, I used similar variables in the models to estimate gross margin estimation against the gross margin estimation in the survey. Thus, I estimated the gross margins in two different models and compared it during the survey period. It enabled me to check the trend and magnitude in gross margin change at different price levels.

In Table 4.10, the total gross margins and average gross margins are presented by land size class. I found that most of the sample respondents operated on 0.6 ha of farmland and generated an average gross margin of INR 31,244 on their land. The average gross margin increased as well with an increase in the scale of operations. In the survey, the average farm area was 1.82 ha, indicating marginal farmers occupied one-third of the average farmland area. Consequently, any increased scale of operation resulted in a greater *tgm* for the landowner. On the other hand, I found that marginal farmers harnessed INR 49,299 in comparison with the overall *tgm* of INR 101,812. This is primarily due to the high proportion of unirrigated land and the limited opportunities for adopting remunerative activities such as irrigation dependent seasonal and off seasonal vegetables, sugarcane, and other plantation crops.

I estimated *tgm* in the model one at the farm level and aggregated them by farm size class to compare survey period *tgm*, and with the model two which is estimated at the WUA level. When I compared *tgm* of model one with survey results, I found that, marginal farmers utilized irrigation water to generate an additional INR 47,676 gross margin, whereas large farmers forfeited INR 90,744 per hectare. With unlimited water supply, marginal farmers were able to combine water-saving and intensive activities on their unirrigated farm plots. The restriction on inter-farm water sharing did not affect their water use behaviour either. Meanwhile, large farmers who chose irrigated agriculture, either water-saving or intensive, had little or no scope for additional benefits. However, the restriction on water trade made it more difficult to share water with neighbouring farms, or to share it over time. When I modified the water supply at the present consumption level and seasonal water transfer is added, I observed that there is also an increase in *tgm* by INR 34,260 for marginal farmers. For large farmers, however, INR 33,544 of gross income over the survey level income must still be forfeited. It may be argued that under model two, large farms should also harness an almost equal level of *tgm* in comparison with the survey level *tgm*. While the model restricted water distribution up to 25 percent, on the other hand, it reduced the scope for cultivating water-intensive activities on a larger scale.

Table 4.10 Gross margin realized (in Indian rupees) by the surveyed farms during 2018-19 by farm size class

1.	2.	3.	4.	5.	6.
Farm size class (% of farm owners) [% area coverage]	Gross margin at survey	Model 1 (Unlimited water supply but no water trade option)	Model 2 (Limited water supply with scope for water trade & seasonal water transfer)	*TGM* gain in model 1	*TGM* gain in model 2
Total *TGM*					
1. Marginal (40.4) [14]	593,637	1,167,730	1,580,271	574,093	412,541
2. Small (29.8) [23.8]	1,317,911	1,737,208	2,490,888	419,298	753,680
3. medium (23.4) [36]	1,923,896	3,735,854	4,322,425	1,811,959	586,571
4. Large (6.4) [26.2]	4,893,690	2,853,049	2,098,714	-2,040,641	-754,335
5. *TGM* total (INR)	8,729,133	9,493,842	10,492,299	764,709	998,457
Average *TGM*					
6. Marginal (40.4)	31,244	64,874	83,172	30,215	21,713
7. Small (29.8)	94,136	124,086	177,921	29,950	53,834
8. medium (23.4)	174,900	339,623	392,948	164,724	53,325
9. Large (6.4)	1,631,230	951,016	699,571	-680,214	-251,445
10. *TGM* average (INR)	185,726	206,388	223,240	16,270	21,244
Average *TGM*/ha					
11. Marginal	49,299	96,975	131,234	47,676	34,260
12. Small	64,718	85,308	122,318	20,590	37,010
13. Medium	62,375	121,121	140,138	58,746	19,017
14. Large	217,613	126,870	93,326	-90,744	-33,544
15. *TGM* average (INR/ha)	101,812	110,731	122,377	8,919	11,645

22. Note: Land size class in India are marginal farms - less than one ha, small farms - within 1 to 2 ha, medium farms - within 2-4 ha, and large farms - larger than four ha.
23. Values in “( )” are percentage to total farmers, and values in “[ ]” are percentages to total land area

Source: Authors own calculation.

I wanted to investigate the model outcome if farms operate under homogeneous neighbourhood situation, and for that I referred to the farm typology (table 4.11). I aggregated farm level estimated *tgm* by farm types to compare survey period *tgm*, and with the model two which is estimated at the WUA level. I found that, there were almost no differences in the size of operations among three of the farm types.

In model one, HDIAM farms' incremental gross margin per hectare was reduced by INR 8,203, whereas under model two it was reduced by INR 2,818 (average *tgm* per ha in survey is INR 124,034). Thus, HDIAM farms received maximum average returns despite the use of irrigation water, ceteris paribus. Consequently, the incremental net benefit of models one and two were reduced due to the additional return from the sale of water to neighbouring farms and the restriction of area on high water-intensive crops, particularly Sugarcane and *Colocasia esculenta*. Meanwhile, MDLIAM farms utilized the irrigation provision to grow a wide range of irrigated activities and generated incremental net benefits of INR 35,543 and INR 60,628 respectively. It is interesting to note that the LDIACM farms diversified their water-saving and water-intensive activities. This proves that irrigation provision under spatial reallocation increases the farms' total gross margin.

Table 4.11 Gross margin realized by the surveyed farms during 2018-19 by farm types (in INR)

Farm types (% of farm owners) [% area coverage]	Gross margin at survey	Model 1 (Unlimited water supply but no water trade option)	Model 2 (Limited water supply with scope for water trade & seasonal water transfer)	*tgm* gain in model 1	*tgm* gain in model 2
Total *tgm*					
1. HDIAM (61.7) [60.2]	6,406,119	5,982,427	6,260,575	-423,691	278,148
2. MDLIAM (27.7) [30.1]	1,866,644	2,784,290	3,431,909	917,647	647,619
3. LDIACM (10.6) [9.6]	456,371	727,124	799,814	270,753	72,690
4. *tgm* total (INR)	8,729,133	9,493,842	10,492,299	764,709	998,457
Average *tgm*					
5. HDIAM (61.7)	220,901	206,291	215,882	-14,610	9,591
6. MDLIAM (27.7)	143,588	214,176	263,993	70,588	49,817
7. LDIACM (10.6)	91,274	181,781	159,963	54,151	14,538
8. *tgm* average (INR)	185,726	206,388	223,240	16,270	21,244
Average *tgm*/ha					
9. HDIAM	124,034	115,831	121,216	-8,203	-2,818
10. MDLIAM	72,301	107,845	132,929	35,543	60,628
11. LDIACM	55,171	87,902	96,689	32,731	41,519
12. *tgm* average (INR/ha)	101,812	110,731	122,377	8,919	20,565

Note: Farm types are developed in the first chapter. HDIAM - Highly diversified irrigated agriculture for direct market supply, MDLIAM- Moderately diversified limited irrigated agriculture for direct market supply, and LDIACM- Least diversified irrigated agriculture for contacted market supply

Values in ( ) are percentage to total farmers, and values in [ ] are percentages to total land area

Source: Authors own calculation.

a. Trend in water demand under variable water prices

The model one water demand was simulated with changes to water prices, and I found that the HDIAM continued to reduce the demand with increases to water prices (Figure 4.7). Model results also indicate that an increase in water price beyond INR 8.24 per cubic meter reduced the water demand from 362400 to 214700 cubic meter. LDIACM farms, on the other hand, were relatively least affected by an increase in water prices. When the water price increased beyond INR 8.24 per cubic meter, the water demand for HDIAM and MDLIAM farms decreased to 141000 cubic meter and remained constant for any further increases in water price.

Results from sections 4.8.1 indicate that sugarcane production and other water-intensive activities were the main activities on farms representing HDIAM and MDLIAM types in lowland farm plots. Due to their pre-contracted agreement for sugarcane cultivation, the farm plots continued to demand a minimum quantity of water, regardless of any increase in water prices. However, LDIACM farms lowered their water use to a greater extent, indicating their flexibility to switch to a total water-saving model or unirrigated farming.

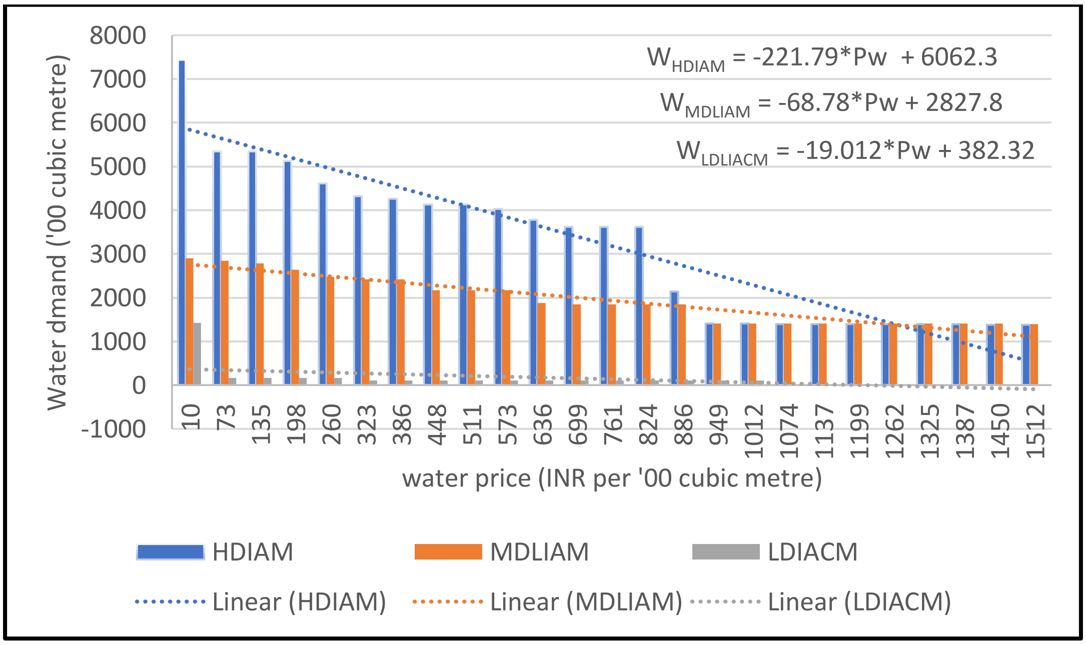


Figure 4.7 Water demand in model one (unlimited water supply but no water trade option) for three different farm types
Source: Authors own estimates.

Figure 4.8 presents the water demand for each farm size class under model one. Marginal farms, compared with other farms, exhibit less reaction to increases in water prices, as illustrated in the figure. Water demand did not decrease after the price topped INR 8.86 per cubic meter. A minimum amount of water, regardless of the size of farming operations, is required to irrigate crops during the rainy season due to the erratic nature of monsoon rainfall. Additionally, they needed to perform a minimum level of water-saving activities after rainy seasons and during the summer.

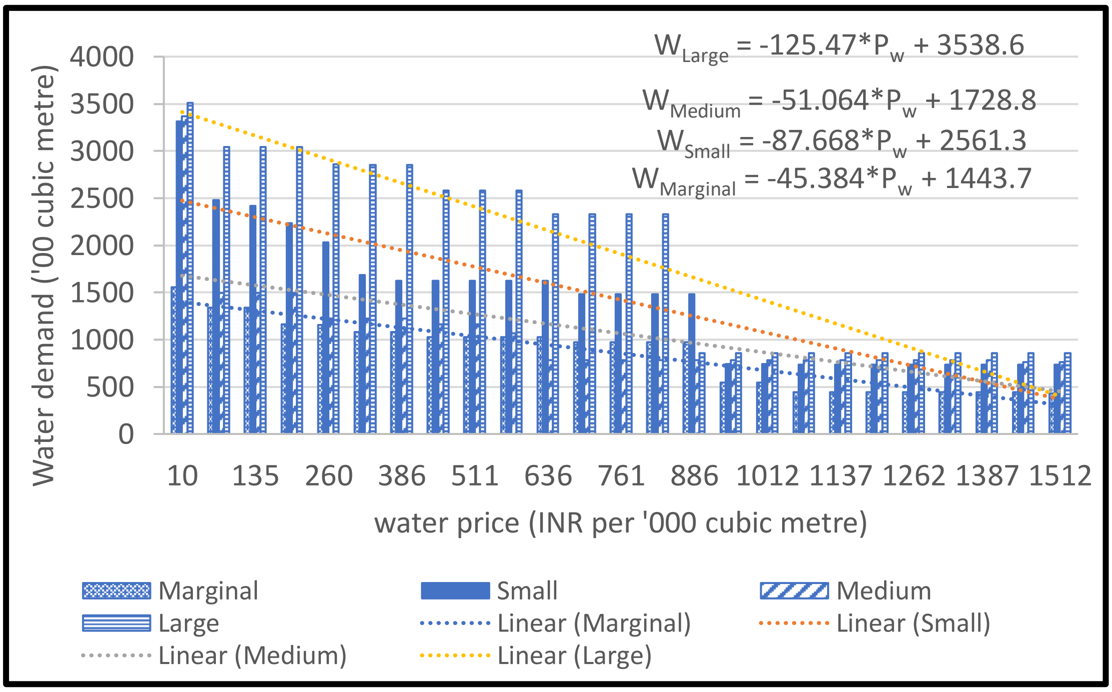


Figure 4.8 Water demand in model one by four different farm size classes.

Source: Authors own estimates.

b. Trend in water demand under restricted and relaxed water sharing option

I compared two different water demand models and results indicated that the reaction functions behaved similarly (Figure 4.9). However, model two offered relatively few crops choice options when the price increased from INR 4.00 per cubic meter to INR 8.00 per cubic meter. Further, model one showed many steps down, which indicates a possibility of income generation with any decrease in water price. Similar to the above explanation, both models showed a steep decline in water demand once the price of water bridged INR 8.86 per cubic meter. Even after successive increases in water price, water demand remained almost constant, indicating a minimum water requirement for agriculture.

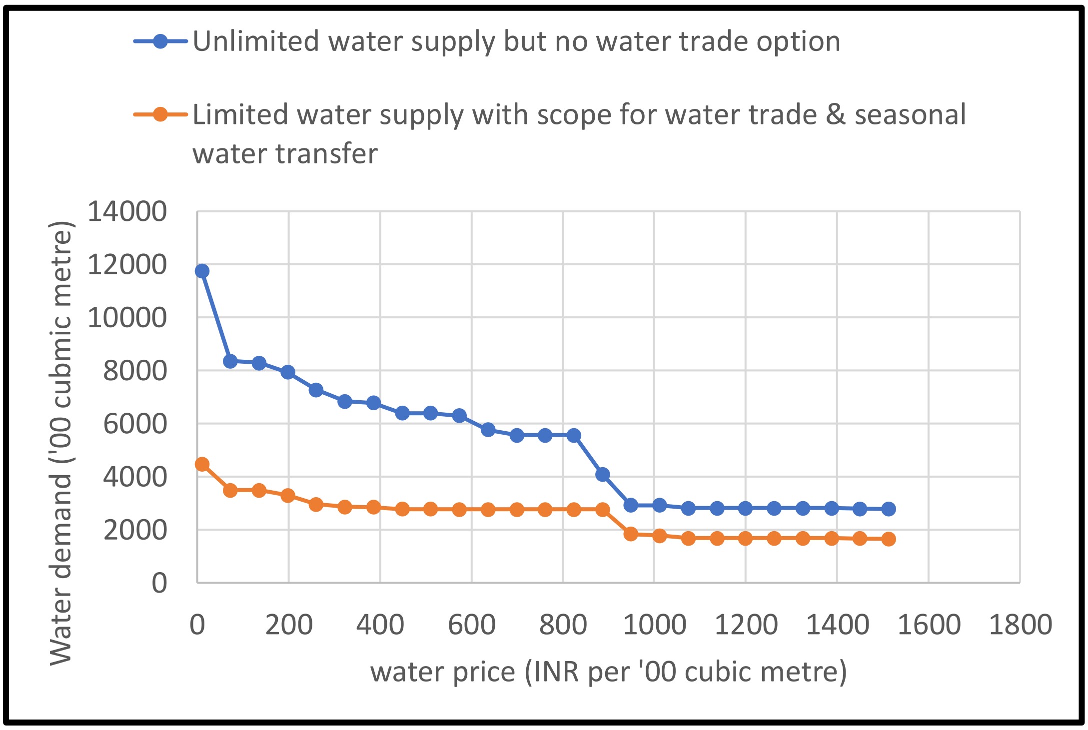


Figure 4.9 Water demand comparison in model one and model two.

Source: Authors own estimates.

Having understood the effects of changing water prices on water demand behaviour, the cost function was estimated using the water demand function.

4.9. Estimation of the demand function of water

The third simulation in model two produced farm-level water demand in response to water price changes. The water demand for eight different blocks was aggregated to determine the average block-level water demand behaviour. At the block level, I calculated the average water demand for the aggregate land area of the representative farms. To estimate the demand function, the quantity of water demanded on the price of water was regressed. A stepwise demand function for water is shown in figure 4.10 for farmers from *Kantapada* block in *Cuttack* district. I determined a linear demand function as it was a prerequisite to study cooperation for sharing incentives in a principal-agent model. By taking a transpose of the coefficients into the resource limits, I transformed the estimated demand function into an inverse demand function.

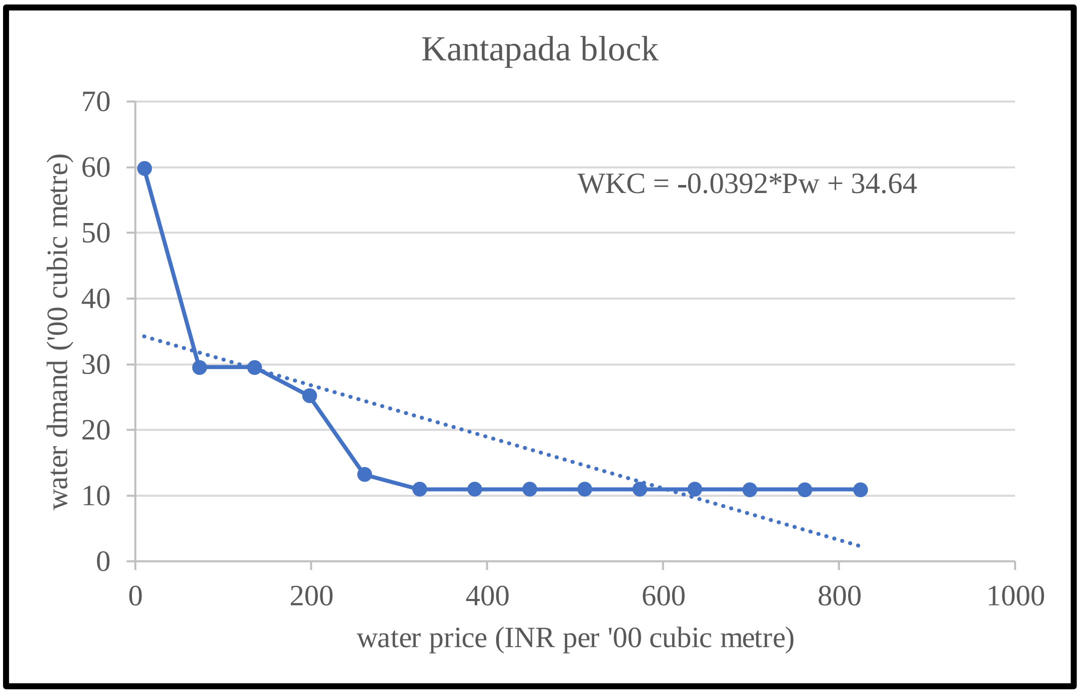


Figure 4.10 Water demand function of *Kantapada* block

I present the estimation procedure in table 4.12. From the estimation process, I found that ζ is positively influenced by the reference level of water volume from where the change in volume water is expected. Therefore, I considered W* as the reference level of water volume that is subtracted from the intercept value calculated in equation 4.6. Meanwhile, τ is the slope coefficient of the inverse demand function. Lastly, column six represents the block level cost function of water and it is quadratic in nature. The cost of water will increase at a disproportional rate with any further increase in volume of water consumption. In this case, the cost function parameters are phi and psi, and the same value is assumed for all the farmers in every block.

Table 4.12 Estimation of marginal cost coefficients of blocks

1.	2.	3.	4.	5.	6.	7.	8.
Blocks	Inverse demand function	W*= Mean water available ('00 cubic meter/Ha)	ζ	τ	Total cost function	φ	ψ
1. Kantapada	$P_{w1} = 883.6 + 25.51 * W_1$	5154	-431.22	25.51	$-431.22*W_1 + 12.76*W_1^2$	-431.22	12.76
2. Biridi	$P_{w2} = 1014.19 + 476.19 * W_2$	243	-141.74	476.19	$-141.74*W_2 + 238.1*W_2^2$	-141.74	238.10
3. Jagatsinghpur	$P_{w3} = 3017.65 + 19.61 * W_3$	7592	1528.99	19.61	$1528.99*W_3 + 9.8*W_3^2$	1528.99	9.80
4. Raghunathpur	$P_{w4} = 13729.17 + 833.33 * W_4$	1556	764.37	833.33	$764.37*W_4 + 416.67*W_4^2$	764.37	416.67
5. Balikuda	$P_{w5} = 1524.62 + 769.23 * W_5$	099	764.29	769.23	$764.29*W_5 + 384.62*W_5^2$	764.29	384.62
6. Hinjilicut	$P_{w6} = 3888.13 + 125 * W_6$	2284	1033.11	125.00	$1033.11*W_6 + 62.5*W_6^2$	1033.11	62.50
7. Purushotyampur	$P_{w7} = 1029.75 + 12.99 * W_7$	9728	-233.61	12.99	$-233.61*W_7 + 6.49*W_7^2$	-233.61	6.49
8. Patrapur	$P_{w8} = 2022.69 + 62.5 * W_8$	2560	422.71	62.50	$422.71*W_8 + 31.25*W_8^2$	422.71	31.25

Source: Authors own calculation.

4.10. Discussion: Optimized land-based activities

A smallholders' limited on-farm resource endowment coupled with poor accessibility to common pool resources such as water narrowed their crop choice avenue. In this chapter, the study seek to know an optimal combination of cropping activities and the role of water-saving methods for reduction of overall production costs that potentially increased the farm level gross margin. It was hypothesised that, in the study area farmers were sub-optimal with respect to the irrigation water use for crop production. The preliminary findings revealed that famers maximized total gross margin by employing a labour-saving but water-intensive activity in annual cropping pattern. A higher number of family labour contribution in diverse farming activates potentially increased number of cropping activities in the cropping pattern and reduced the multifaceted production risk from abiotic and biotic stress.

The state government subsidized wells owned by an individual farm or a community mostly earned a supernormal profit by accommodating a range of irrigated cropping activities. However, subsidized water provision reduced the production cost by on an average ten percent in comparison with a farm that sourced water either from a private water seller or a non-subsidized well. The average tgm/ha earned by a HDIAM farm was 70% higher than a MDLIAM farm and 120% higher than a LDIACM farm, by adopting high level of crop diversification. However, the scale economics favoured large farmers who exploited subsidized water and mono-cropped with rice-rice-fallow or sugarcane cropping pattern.

During the field survey I observed that, in a village, farms are similar to their crop choice, however their resource allocation decision determined tgm/ha. A farm maximized its annual tgm/ha by utilizing available water and family labourers in different cropping activities . In the field survey it was observed that, water price varied from as low as INR 0.1 to INR 16 per cubic meter. Therefore, it can be inferred that farms with similar resource endowment and cropping pattern must have chosen an optimal water-labour combination to actualize least cost of production .

In this connection, when farm level tgm was simulated under unlimited water supply at prevailing water price and no inter-farm water exchange, smallholders accommodated water intensive activities on many previously unirrigated farm plots. An increase in the value of tgm/ha definitely indicates the rational behaviour of a smallholder's family, that substituted labour by cheap water for irrigation intensive activities. However, large farmers who used to conventionally earn from water selling, had to forgo a significant amount of income because of restriction on water exchange. The demographic characteristics of an average large farm owner in the study sample indicated their inability to share family labourers in diverse farm operations. It restricted scope to harness additional return from unlimited water availability that an average smallholder earned by adopting a remunerative crop in the cropping pattern that potentially requested labour engagement.

LDIACM farms owned mostly medium and large farms. But, their least family labour availability reduced any scope to harness additional return from the unlimited water supply at the prevailing water price. The contracted nature of farming system with sugar factories and limited scope to adopt water and labour-intensive cropping activities on rice-green gram farm plots reduced the scope to earn additional income. Overall, reduction in water cost enhanced the net farm income of HDIAM and LDIACM farms. Interestingly, HDIAM farm's average tgm/ha reduced by 6.6 percent from baseline. This might have been due to increase in perennial crop acreage or restriction on water exchange.

The common understanding from field observation indicated that medium and large farmers predominantly benefitted from water sharing. Many LDIACM farms also realized similar outcome. However, HDIAM farms in one hand and smallholders on the other had opposite realization in the first simulation in comparison with the baseline scenario. Therefore, it is not necessary that all HDIAM farms are marginal and small.

To observe any change in tgm/ha due to relaxation of the water sharing restriction, the base model was simulated under limited water supply (at baseline) with scope for water trade & seasonal water transfer. It was further assumed that a farmer may share water with a neighbouring farmer to maximize the tgm/ha. However, it was not necessary to allocate crops on all the farm plots in the optimization process which indicates that some farm plots remained uncultivated. At WUA level the sum total of tgm must increase under this assumption. When the base model was tested under the above simulation, I found that the tgm/ha increased for all the farms irrespective of their scale of operation. Therefore it proved that all the farmers in the study area has potential to gain additional return from water trade across the space and over time.

I further tested whether or not, under increasing price of water does a farmer maintain similar cropping decision for maximization of tgm? Therefore, the model was further simulated under increasing water prices. Consequently, all the farmers continued to decline the water demand with an increase in water price irrespective of their scale of operation. A closer look into the magnitude of decline indicated that farmers adopted different water saving methods to compensate any rise in water cost. However, after the water price increased beyond INR 886 per thousand cubic metres, the water demand remained almost constant for all the farms. Because of perennial nature of cropping activities and scope of substitution of water with labour, many farms continued to demand a minimal amount of water to provide critical irrigation. The similar trend was also observed when farms were grouped by farm types. When the base model was simulated under two different situation of unlimited water supply, and with limited water supply with scope for water trade and seasonal water transfer exclusively among the WUA members above mentioned trend was also observed.

In many MDLIAM villages, I observed that a WUA delineated area is adjacent to a private well irrigated farms. Many of our sample respondents had their farm plots under both types of water sharing systems. Under such circumstances, a sample respondent maximized total gross margin by adopting a water intensive cropping pattern in the WUA irrigated plots and water saving crop in a privately shared irrigation system. When the base model simulated with limited water supply and allowed limited water sharing exclusively among the member farmers, an improvement in tgm indicates that farmers exchange water with a neighbour farm plot and also adopted seasonal water saving practices. From here one can generalize that unlimited water availability may induce self-adjustment behaviour, however any scope for spatial and temporal transfer of water increases marginal productivity of water that ultimately enhance total gross margin of a farm.

4.11. Concluding remarks

The linear program maximized the income of a farm household taking farm and family resources into account. This exercise revealed that in addition to households' rational behaviour of maximizing profits, farmers discount the future value of scarce resources. The model outcome revealed that it is not necessary to utilise the entire land resource to realize the highest total gross income. In this case, coastal Odisha farmers do practice land leasing. It demonstrates the rational behaviour of a farmer to maximize the productivity of their sources. It shows that farmers do communicate with each other in terms of production decisions, and the most critical factor for me is appropriation of water resources. It may be possible to maximize a farm's gross margin using the above exercise. However, any collective action for maximizing overall gross margins was beyond the scope of the program.

The Klador-Hicks compensation is purposefully introduced to demonstrate the likelihood and scope of cooperation, that I introduced in the following chapter in a principal-agent model. When many farmers share water from a common WUA well, they follow water distribution as well as cost and profit-sharing regulations. The WUA aim to maximize the gross margin by sharing water to the member farmers. WUA also want to simultaneously minimize the cost of water procurement and other adjacent transaction costs (monitoring of water distribution, water fee collection, organizing regular meetings to share WUA functioning, dispute settlement, etc.). However, a WUA is not completely informed about a farmer’s annual water demand and his interaction with a neighbour for sharing water and any other crop production decision. Furubotn and Richter (2005) explained this types of situation as an information asymmetry and WUA experiences moral hazard. Under these circumstances, WUA offers different types of incentives to a farmer to fulfil his objective, collective action in reduction in volume of water use, and thereby to reduce overall reduction in cost of production. I discussed it in the next chapter.

CHAPTER 5: COOPERATION MODEL IN A PRINCIPAL-AGENT MODE

5. Designing a cooperation model for sustainable groundwater governance

In the linear program, I maximized the farm-level gross margin by modelling the complex agricultural production decisions in different farm types and farm size class. The base model was simulated with a scope of spatial water-sharing and seasonal water transfers added. The model indicated that farms responded proportionately with an increase in water price, and they shared additional water from their entitlement and gained economic benefit. I explained this phenomenon using the Kaldor-Hicks hypothesis in section 4.7.3. However, in the LP, I could not determine the scope of associability of farms within a given geo-hydrological boundary. Hence, in this section I examine the scope of collective action in sharing water from a common groundwater well.

The study area has many formal and informal water distribution systems, under which an individual or a group provides water, and another farm receives it in payment for its use (water cost in per hour, or per hectare, or per crop season), according to agreed measurements. To minimize gross water use at a community level, many such water distribution arrangements have been explored in a principal-agent model (P-A) (Libecap, 1990).

The marginal return from groundwater can be maximized by adopting a maximum area for water-saving activities. The optimal cropping pattern that generates maximum gross margin for a farm was further utilized endogenously in the agent-based model. In order to overcome the limitations of farm-level estimates, cost functions at the block level were estimated in the LP. The P-A model indicates that water sharing decisions vary between farms according to their water requirements and efforts to adopt water-saving practices. The maximum amount of water saved by a WUA was then determined.

5.1. Measures to tame the anarchic groundwater extraction

So far, economic literature has indicated that an efficient allocation of water is always subject to specific laws and regulations, organizations, and the infrastructure of water resources (Dinar, Rosegrant, & Meinzen-Dick, 1997). Although, the guiding principles for water allocation seek to achieve either economic efficiency or equity, and sometimes both at the same time. Dinar et al. (1997) have further discussed the application of major economic instruments and asserted that the primary mechanisms in water allocation are marginal cost pricing, public sector allocation, water markets, and its user-based allocations. The implementation of property rights on water allocation was advocated by policymakers in order to regulate the unrestrained extraction of groundwater (Amjath-Babu, 2009; Graveline, 2016; Libecap, 1990; Rosegrant & Binswanger, 1994).

In terms of groundwater extraction, the first assumption is that most of the publicly subsidised or privately owned wells serve land based agricultural and allied activities. They often enhanced irrigation accessibility. In India, the vast majority of water sources are unorganized and, therefore, water rights assignment is a near-impossible task due to a high transaction cost associated with it (Figureau, Montginoul, & Rinaudo, 2015; T. Shah, 2009). On the other hand, government provided subsidies in drilling a well, and electricity for pump operation to the millions of farmers (Figureau et al., 2015). Recent estimates on well ownership indicate that over 96 percent of wells are operated privately, and there is no regulation of their extraction behaviour (GoI, 2014). Thus, any physical control on water extraction is also nearly impossible for a centralized public or private agency in the Indian context (Chaitra & Chandrakanth, 2005; M. Shah et al., 2021).

5.2. Scope of cooperation in water-sharing

Because of the enormous uncontrolled extraction by millions of public and private wells, the future of groundwater ecology can potentially be preserved by collective action (Lopez-Gunn, 2003; Meinzen-Dick, Raju, & Gulati, 2002; Tilman, Levin, & Watson, 2018). A centralized water allocation system could reduce establishment and transaction costs, and it is possible for groundwater irrigation management as well

(Amjath-Babu, 2009). Cooperatives so far have shown mixed results, but government intervention through subsidy schemes has inflated success rates. In Odisha, the government subsidy program for medium-deep tube well installation addressed the economic issue of groundwater procurement. In the state, water user associations (WUA) on groundwater were formed in the 1970s to facilitate collective action for providing cheap irrigation water. However, issues related to water distribution and unplanned expansions of irrigation command area (ICA) have led to a decline in the groundwater table below the reach of the submersible pump set and an increase in transaction costs due to over extraction from a deepest level (Chaitra & Chandrakanth, 2005; Chandrakanth & Arun, 1997). Studies have demonstrated that expansion of a WUA area can be accomplished even without increasing pumping hours (Tilman et al., 2018). In many cases, due to the inappropriate management of the groundwater resource system and its physical structure, cooperation collapsed (Ghosh et al., 2019; Meinzen-Dick et al., 2018). Furthermore, reduced pumping costs for a WUA exaggerated water extraction, which further threatened the sustainability of the water table. Regulation of groundwater extraction on the one hand and distribution on the other is, therefore, one of the key challenges for a WUA. Heintzelman et al. (2009) described this aspect as teamwork, which includes the participation of the member farmers to align with the irrigation distribution institutions. I assigned an initial water volume to each team member using a tradable property right scheme. Additionally, I introduced an incentive scheme for trading water rights among team members who are involved in land-based agricultural activities (Amjath-Babu, 2009). In addition to the theoretical conceptualization, the empirical exercise is conducted in coastal districts of Odisha, India.

With this background, I aim to answer how to design a water distribution strategy at the well level by integrating farm-level decisions. I developed the following research objective and supportive hypothesis.

5.3. Research objective and claim

To develop a cooperation model in water distribution at the well level by linking farm-level decisions.

I claim that farmers as an agent, who do cooperate with the principal, in this case, WUA, in saving water, can realize incentives to maximize the total gross margin at the community level by adopting water-saving activities.

5.4. Data and methodology

In the previous chapter I observed that, a farmer maximizes his gross margin from irrigated agriculture by following a cropping pattern that meets its water needs. Most of the sample farmers obtained their water from a community well. Now, I will discuss the potential for cooperation in sharing water and the immense potential to harness the discounted benefit.

5.4.1. The Principal– Agent model

Amjath-Babu (2009) in his study contemplated that water-saving and its trading activities among the member farmers in a WUA may leverage the market mechanism through cooperation. In addition, he explained that a contractual arrangement between the water supplier and the member beneficiaries may incentivize the habit of water conservation. As a part of the incentive scheme, I aimed to maximize water conservation by adopting water saving cropping activities and that contribution is made by every farmer in a WUA. In this connection, Amjath-Babu (2009) described a contractual arrangement that a WUA designs for its members in a Principal-Agent (P-A) model. In this model, a WUA has sufficient water rights for crop cultivation under contemporary irrigation technology.

During field study I observed that, the gravity-fed surface system distributed water via underground pipe networks or through open channels up to the perimeter of a WUA. In the LP model, I described the scope of water-saving activities at the farm level. I introduced water-saving activities under contemporary irrigation distribution system in a present cropping pattern. An increase in water saving was expected at the WUA level. That surplus water saving typically translate into a reduction in hours of pumping operation and hence pumping costs, thereby reducing the cost of production of the water-saving activities. In this exercise, a WUA is cooperative in nature and extends a variety of incentives for saving water to the member farmers. This study aimed to maximize water saving in a WUA to reduce pumping costs by conserving groundwater in contrast to Amjath-Babu (2009).

In the research setting, most of the farmers irrigated their farm plots in complete or partial and sourced water from any of the formal or informal water distribution systems, of which WUA is served as a community water distribution system. Scholars found that high value crop growers are more responsive to water sharing institutions and participate in most of the government subsidized irrigation distribution system to gain from subsidized water (Fang & Nuppenau, 2009). In the typology section, I discussed adoption of water distribution norms in different WUA inhibited villages. Because of scarcity nature of water, I emphasised on its conservation rather than trading and earning profit.

To optimize the volume of water conservation in a WUA, I adopted Amjath-Babu (2009) water sharing model and modified the objective function by replacing the land area under water saving scheme with volume of water saving or in other words, reduction in water user. Instead of expanding the water saving model by including the cropping pattern component in the constraint and objective function, I used the optimized volume of water saving in the next step into model a LP as an exogenous variable to know the farm level optimized cropping pattern.

As a principal of a cooperative nature, the WUA offers member farmers, henceforth I term as ‘agents’, a revenue-sharing contracts in order to maximize water savings. By adopting the optimal cropping pattern, agents can maximize their gross margins. In the LP model, I used wide range of activities that reduced water consumption keeping gross margin at the constant level. In this process, labour was substituted for water in varying proportions in different farms. Thus, the transition to a water-saving activity may or may not be expensive to a farmer since its effectiveness is further determined by the availability of household family labour and other resource endowments. In this way, one could save an additional amount of water by allocating a higher area for water-saving activities.

a. The cost of adopting a water-saving activity

A transition from a water-intensive cropping pattern to a water-saving one would likely to increase costs for farmers if labour or capital are substituted for water. I assumed a linear marginal cost that increases disproportionately, corresponding to a quadratic cost function, $C(W_s)$.

$$C(W_s) = \varphi_s W_s + 0.5\Psi_s W_s^2 \qquad \ldots(5.1)$$

Here, φ_s and Ψ_s are the parameters of the cost function. W_s denotes the volume of water saved/ reduced measured in cubic meter by a member farmer ("s") who chose to cultivate crops from an array of water saving to water intensive crops in a cropping pattern. In contrast to Amjath-Babu (2009), the study considers a range of cropping activities that potentially saved water due to the adoption of a water-saving activity over a water-intensive one by the s^{th} father (in cubic meter). In addition to that, a higher value of W_s indicates higher reduction in volume of water usage. Therefore, W_s is the outcome of a reduction effort of a farmer by adopting water saving cropping activities in a cropping pattern. This is a opposite understating with respect to Amjath-Babu's proposition of increase in land area under water saving activities. Therefore, to keep the modelling logic in parallel with Amjath-Babu (2009), I multiplied a conversion factor, ${}^{1}/_{m_s}$, that is measured in hectare per cubic meter. Thus, I write the equation 5.1 as below.

$$C(W_s) = \varphi_s W_s * \left({}^{1}/_{m_s}\right) + 0.5\Psi_s\left\{W_s * \left({}^{1}/_{m_s}\right)\right\}^2 \ldots \qquad (5.2)$$

b. The contract scheme offered by WUA

To fulfil his interest of maximizing water saving, the principal (WUA) offered a revenue-sharing scheme. Furubotn and Richter (2005) originally devised this incentive scheme into two parts i.e. a fixed component (r_s), that is intended to encourage a risk-averse farmer to adopt a water-saving activity. Secondly, a variable component, that encourages greater efforts to conserve water. Therefore, incentive scheme, $E(W_s)$ is

$$E(W_s) = r_s + \alpha_s P_w W_s \left(1/m_s\right) \qquad \ldots(5.3)$$

In the above linear incentive scheme, r_s is the fixed part of the incentive that is paid in advance. $P_w W_s \left(1/m_s\right)$ constitute the revenue earned or cost saved by the WUA, where P_w is the price of water (measured in rupees per cubic meter) in a WUA inhibited village.

α_s is the variable part of the incentive scheme that WUA offer to the farmers for saving water over and above the reference water usage. In other words it is the revenue share of s^{th} farmer from the total revenue realized or cost saving by the WUA due to his effort in water saving. For a WUA, the total volume of water saving is $\sum_s W_s$. It is to be noted that, member farmer are obliged to pay for electricity costs (it is subsidised by 50 percentage) even though government subsidized the drilling of well, and underground pipe distribution and outlet construction for water distribution by 80 percentage . Hence, a WUA aim to reduce the water extraction cost by reducing the hours of pumping operation. This recurring cost saving is further redistributed to the member farmers by a WUA according to their effort in water saving.

c. Incentive constraint

It is intriguing to note that a farmer can realize gains due to a lower cost of transition to the water-saving activity and an incentive program provided by the WUA. The gain of a farmer is the surplus over the cost. I derived it by subtracting the agent’s cost function from the principal’s incentives function (equation 5.3 – equation 5.2).

$$E(W_s) - C(W_s) = r_s + \alpha_s P_w W_s \left(1/m_s\right) - \varphi_s W_s \left(1/m_s\right) - 0.5\Psi_s \left\{W_s * \left(1/m_s\right)\right\}^2 \qquad \ldots(5.4)$$

In this case, a farmer may shift to any water-saving crop from existing one that may require either less frequent irrigation or less duration of irrigation, and sometime a combination of both. I assumed that the well discharge rate remained at the same level during a short period of time. To maximize the gain of a farmer, I equated the first-order derivative of equation 5.4 for the W_s to zero.

$$\alpha_s P_w\left({}^{1}/_{m_s}\right) - \varphi_s\left({}^{1}/_{m_s}\right) - \Psi_s W_s * \left({}^{1}/_{m_s}\right)^2 = 0 \qquad \ldots (5.5)$$

After rearranging equation 5.5, I obtained the linear response function of an agent.

$$W_s = \Psi_s^{-1}\alpha_s P_w\left({}^{1}/_{m_s}\right)^{-1} - \varphi_s\Psi_s^{-1}\left({}^{1}/_{m_s}\right)^{-1} \qquad \ldots (5.6)$$

Equation 5.6 is an agent's response function to a principal's incentive scheme, where the principal can induce optimal water usage by sharing a variable amount of α. This function is named as an incentive constraint.

d. Participation constraint

In setting up the P-A model, Furubotn and Richter (2005) assumed that farmers would ensure their participation in the contract scheme when they realize an extra income over their reservation utility ($\bar{R}$). Reservation utility is determined by an agent's next best employment opportunity. In this case, when a farmer participates in the contract scheme, he saved a minimum amount of water cost by reducing a minimum amount of water $kW_s\left({}^{1}/_{m_s}\right)$.

$$E(W_s) - C(W_s) = r_s + \alpha_s P_w W_s\left({}^{1}/_{m_s}\right) - \varphi_s W_s\left({}^{1}/_{m_s}\right) - 0.5\Psi_s\left\{W_s * \left({}^{1}/_{m_s}\right)\right\}^2 \geq \bar{R} \qquad \ldots (5.7)$$

Now, if one assume a minimum gain per unit cubic meter of water saving (k) is required to ensure farmers' participation in the contract scheme, then I equate 5.7 with $\bar{R}$ or $W_s\left({}^{1}/{}_{m_s}\right)$. However, under no alternatives to a present cropping activity, $\bar{R}$ is just set to zero. Thus, by rearranging the equation 5.7, one can derive the participation constraint as followings.

$$r_s = 0.5\Psi_s\left\{W_s * \left({}^{1}/{}_{m_s}\right)\right\}^2 + \varphi_s W_s\left({}^{1}/{}_{m_s}\right) - \alpha_s P_w W_s\left({}^{1}/{}_{m_s}\right) \qquad \ldots(5.8)$$

e. The objective function of the principal

The Principal or a WUA aims to maximise its income by maximizing volume of wate saving that one can directly translate to area under the water-saving scheme. The water price is determined by its steering committee, which is just to cover the operational cost and overheads. Hence, the revenue of a cooperative WUA ($P_w \sum W_s * \left({}^{1}/{}_{m_s}\right)$) depends on the annual total volume of water saving or the total virtual land area under different water-saving activities ($\sum W_s * \left({}^{1}/{}_{m_s}\right)$). As mentioned above, it accommodated a range of water-saving activities in the cropping pattern at the plot level in the model. It is important to note that, farmers paid water cost as per their crop choice at different season. To simplify the cost of water, a WUA collected water cost at flat rate for similar genus (type of crops) of crops per unit hectare of land. Therefore, the principal's revenue function is formulated as below.

$$PI = \sum\left[(1-\alpha_s)\left(P_w W_s * \left({}^{1}/{}_{m_s}\right) - r_s\right)\right] \qquad or$$

$$PI = (1-\alpha_s) P_w \sum W_s * \left({}^{1}/{}_{m_s}\right) - (1-\alpha_s)\sum r_s \qquad \ldots(5.9)$$

The principal realizes his net revenue after the paying a fixed incentive r_s and the variable part α_s from each agent as $(1-\alpha_s)$. Now, the objective of a principal is to maximize the net revenue from maximum water saving subject to the incentive constraint and participation constraint. However, in this case, a WUA is a cooperative organization, and its goal is to maximize water extraction cost saving by rather than to maximize its profits.

f. Bonus scheme

A WUA, as a cooperative, shares its profits after maintaining an emergency fund for repairs and replacement of the physical structure of the irrigation lifting and distribution system. Traditionally, a decent remuneration is set aside for the WUA steering members, and the remaining profits are distributed to the farmers. Zumman (1991) suggested that a bonus (B) could be a share of profits earned by the WUA.

$$B = (\beta)\left[(1-\alpha_s)P_w \sum W_s \left({}^{1}\!/_{m_s}\right) - (1-\alpha_s)\sum r_s\right] \qquad \ldots(5.10)$$

However, the proportion of profit that may be redistributed among the member farmers, is determined by β. In other words, value of β indicates the power of a principal in the contract scheme. If the value of β is zero, then all the profit rests with the principal, and when it is one, the entire profit is redistributed among the agents. Since WUA is cooperative in nature, a higher β value is desirable. In the result section, I consider scenarios with variable β values.

In bonus sharing, either equal or equitable types are decided upon. Equal bonuses are distributed to the member beneficiaries irrespective of their effort level in saving water, whereas equitable bonuses vary by their efforts in water saving. In this case, the predominance of smallholders makes the problem more scale neutral, and on the other hand, it is interesting to observe their capacity for conserving water. As a result, the farmer gets a bonus of B_s under the equitable bonus scheme, and the total bonus offered by the principal is $\sum B_s$.

$$B_s = \left(\frac{\beta W_s\left({}^{1}\!/_{m_s}\right)}{\sum W_s\left({}^{1}\!/_{m_s}\right)}\right)\left[(1-\alpha_s)P_w \sum W_s \left({}^{1}\!/_{m_s}\right) - (1-\alpha_s)\sum r_s\right] \qquad \ldots(5.11)$$

Romstad (2003) referred to this bonus scheme as a team incentive. Collins and Maille (2008) further articulated this team incentive into the social behaviour of the member farmers. So, farmers bring other parcels of land under the contract scheme and motivate non-members to join the team, which is entirely at no cost to the principal. In order to include the team incentive in the bonus scheme, a correction factor (c.f.) is added to B_s.

$$\text{c.f.} = \left(\sum W_s\left(1/m_s\right)\right)^2 \Big/ (A)^2 \qquad \ldots(5.12)$$

If the entire WUA area is covered by the water-saving contract ($\sum W_s\left(1/m_s\right) = A$), the correction factor becomes a unit, implying that the member farmers will be able to realize the full bonus, when everyone implements the scheme of water-saving. In order to achieve the gain, the squared term of A should be considered due to increased water savings in favour of the agents. After the inclusion of the correction factor, the new bonus function is stated below.

$$B_s = \left(\frac{\beta W_s\left(1/m_s\right) \sum W_s\left(1/m_s\right)}{(A)^2}\right)\left[(1-\alpha_s)P_w \sum W_s\left(1/m_s\right) - (1-\alpha_s)\sum r_s\right] \qquad \ldots(5.13)$$

g. Updated incentive constraint

Now, the bonus scheme was added to the return function (equation 5.3) of a farmer.

$$
\begin{aligned}
&E(W_s) - C(W_s) \\
&\qquad = r_s + \alpha_s P_w W_s\left({}^{1}/{m_s}\right) \\
&\qquad + \left(\frac{\beta W_s\left({}^{1}/{m_s}\right)\sum W_s\left({}^{1}/{m_s}\right)}{(A)^2}\right)\Big[(1-\alpha_s)P_w \sum W_s\left({}^{1}/{m_s}\right) \\
&\qquad - (1-\alpha_s)\sum r_s\Big] - \varphi_s W_s\left({}^{1}/{m_s}\right) - 0.5\Psi_s W_s^2\left({}^{1}/{m_s}\right)^2
\end{aligned}
$$

… (5.14)

To maximize the gain from a unit volume of water-saving, the first-order derivative for $W_s\left({}^{1}/{m_s}\right)$ is taken and equated t to zero.

$$
\alpha_s P_w + \left(\frac{\beta \sum W_s\left({}^{1}/{m_s}\right)}{(A)^2}\right)\left[(1-\alpha_s)P_w \sum W_s\left({}^{1}/{m_s}\right) - (1-\alpha_s)\sum r_s\right] - \varphi_s - \Psi_s W_s\left({}^{1}/{m_s}\right) = 0
$$

…(5.15)

In contrast to Amjath-Babu (2009), I am concerned with maximising water savings by its distribution among the members, and most of them are marginal and small farmers. In this connection, the correction factor enabled me to reduce any bias from large farm owner's cropping cum water use decision. The extension of the team by lobbying with other non-members also increases the amount of the bonus and the return as well. A new incentive constraint can now be achieved by rearranging equation 5.15.

$$
W_s = \alpha_s \Psi_s^{-1} P_w - \Psi_s^{-1}\varphi_s + \frac{\beta \sum W_s\left({}^{1}/{m_s}\right)\Psi_s^{-1}}{(A)^2}\left[(1-\alpha_s)P_w \sum W_s\left({}^{1}/{m_s}\right) - (1-\alpha_s)\sum r_s\right]
$$

…(5.16)

h. Updated participation constraint

In equation 5.8, I assumed that reservation utility for a farmer is kW_s, and Amjath-Babu claimed it as a 'minimum wage gain', a prerequisite to enter the contract.

$$r_s + \alpha_s P_w W_s \left(1/m_s\right) - \varphi_s W_s \left(1/m_s\right) - 0.5\Psi_s W_s^2 \left(1/m_s\right)^2 + \left(\frac{\beta \sum W_s \left(1/m_s\right)}{(A)^2}\right)\left[(1 - \alpha_s) P_w \sum W_s \left(1/m_s\right) - (1 - \alpha_s) \sum r_s\right] = k W_s \left(1/m_s\right) \qquad \ldots(5.17)$$

The updated participation constrain is as follow,

$$r_s = \varphi_s W_s \left(1/m_s\right) + 0.5\Psi_s W_s^2 \left(1/m_s\right)^2 - \alpha_s P_w W_s \left(1/m_s\right) - \left(\frac{\beta \sum W_s \left(1/m_s\right)}{(A)^2}\right)\left[(1 - \alpha_s) P_w \sum W_s \left(1/m_s\right) - (1 - \alpha_s) \sum r_s\right] = k W_s \left(1/m_s\right) \qquad \ldots(5.18)$$

I assumed that a WUA is a benevolent cooperative organization formed by member farmers. Furthermore, I assumed that the steering committee members would receive an honorarium after the bonus was distributed to ensure the smooth operation of the WUA. Therefore, the upper limit of β is fixed, implying a minimum remuneration to be paid to the WUA. In addition, I also introduce a lower limit of β so that farmers will also receive a minimum bonus. Therefore, the β value ranges between $\beta_L \leq \beta \leq \beta_U$. Amjath-Babu (2009) suggests that lower and upper limits of β are determined by negotiation between WUA and farmers. The standard principal-agent theory suggests that negotiations between WUA and farmers result in a larger share for the agents than for the principal. To maximize water saving, the principal is encouraged to retain a maximum bonus by setting a higher level of β_L.

I introduce η (eta) in order to maintain the cooperative nature of the principal. β is used to define the lower and upper limits of the profit share, which indicates how much profit is to be held for the principal and distributed to the farmers. Further, it is important to reaffirm that, most of the member farmers are marginal and small and operated in less than two hectares of land. Therefore, each farm is small relative to the overall size of the WUA. At the same time, η ensures that the WUA's delineation does not exceed its maximum size.

i. Summary of the contract scheme

I now summarize the P-A scheme as follows:

The objective function of the principal is

Maximize PI = maximize $(1-\alpha_s)P_w \sum W_s \left({}^{1}/_{m_s}\right) - (1-\alpha_s)\sum r_s$

Subject to

the incentive constraint (IC)

$$W_s = \alpha_s \Psi_s^{-1} P_w - \Psi_s^{-1}\varphi_s + \eta \frac{\beta \sum W_s\left({}^{1}/_{m_s}\right)\Psi_s^{-1}}{(A)^2}\left[(1-\alpha_s)P_w \sum W_s\left({}^{1}/_{m_s}\right) - (1-\alpha_s)\sum r_s\right]$$

the participation constraint (PC)

$$r_s = \varphi_s W_s\left({}^{1}/_{m_s}\right) + 0.5\Psi_s W_s^2 - \alpha_s P_w W_s\left({}^{1}/_{m_s}\right) - \eta\left(\frac{\beta \sum W_s\left({}^{1}/_{m_s}\right)}{(A)^2}\right)\left[(1-\alpha_s)P_w \sum W_s\left({}^{1}/_{m_s}\right) - (1-\alpha_s)\sum r_s\right] + kW_s\left({}^{1}/_{m_s}\right)$$

the bonus constraint

$$B_s = \left(\frac{\beta W_s\left({}^{1}/_{m_s}\right)\sum W_s\left({}^{1}/_{m_s}\right)}{(A)^2}\right)\left[(1-\alpha_s)P_w \sum W_s\left({}^{1}/_{m_s}\right) - (1-\alpha_s)\sum r_s\right]$$

the honorarium constraint

$$\beta_L \le \beta \le \beta_U$$

From the viewpoint of the principal, a WUA offers a fixed advance payment(r_s), a variable revenue share (α_s) according to farmer's effort level, and a profit share (B_s) to maximize the water saving. This is attained by adopting water-saving activities and lobbying other farmers to join the contract scheme.

5.4.2. Estimation of optimized cropping pattern

Now, once the P-A model generated optimized volume of water reduction, I use them exogenously in the second model of LP, that allowed me to limit water supply with scope for water trade & seasonal water transfer among the WUA members. The LP model generated optimized cropping pattern by using reduced water volume. I extracted the optimized cropping pattern of representative farms from every district, and they also simultaneously represent different farm types. To visualize the change in cropping pattern due to adoption of incentive scheme, I prepared a map of a representative WUA level cropping pattern of a representative farm. It should be noted that, due to the lack of information of all other farm plots other than a respondent farm in a WUA, I could only develop cropping pattern under different simulations for a representative farm.

5.4.3. Data for empirical simulation

I used plot-level input-out data from 53 farms for the empirical simulation similar to the LP from the previous chapter. Several community irrigation distribution systems (CIDA) are organized by the government (such as WUA, CTW), and others are privately organized. While explaining different forms of organizing irrigation distribution system in the typology section, I found that farmers acquire irrigation water from multiple sources and that they often combine public and private CIDAs when using irrigation water.

In the empirical exercise, in the pooled model, I assumed that all farms source water from one WUA. I further tested model validity separately for different districts, that implies model was tested only with respective district farmers. To know any improvement in the model result in terms of reduction in water saving, I tested the model with the farmers representing different farm types. Secondary data was used to estimate parameters and variables. They are discussed in the following sub-section.

5.5. Exogenous parameter calibration

5.5.1. Rate of water-saving per ha (m_s)

Our research found that farmers used a variety of cropping patterns that saved water in variable amounts. Agricultural trials in the same region showed that a mixed vegetable cropping system could save eight percent of water versus the rice-based cropping pattern (Palanisami et al., 2015). However, a change in irrigation method led to an increase in water savings of 48 percentage, though the extent of adoption of water-saving techniques varies by type of farm operation, scale of farm production, and geographical location of a farm. (Palanisami, 2006; Toorop et al., 2020). Further, I assumed that the farmers in respective blocks are similar in this regard. To maintain symmetry in structure of mathematical equation with Amjath-Babu, I used m_s to convert the volume of water-saving into virtual land. I estimated m_s by taking a ratio of the block-level total area to the block-level maximum water-saving. Therefore, in the structure of equation, instead of land area under water saving scheme, l_s, I used a product value of reduction in water use and $\left(1/m_s\right)$.Thereby, I maintained the mathematical structure of P-A model with Amjath-Babu (2009). In table 5.1 I present the values of the exogenous parameters.

5.5.2. Water price (Pw)

The price of water played an important role to calibrate the model simulations. Farmers from three different districts realized different water prices, and that also varied in three different seasons. Therefore, weighted water prices from three different seasons were estimated and an average water price per cubic meter was attained. In the model simulations, I used the price parameter exogenously in three different levels to observe the contract outcomes.

5.5.3. Reservation utility (k)

The reservation utility of an agent is his next best employment possibility. The minimum gain for a farmer per unit of water-saving is $kW_s({}^{1}/_{m_s})$, and this positively influences the farmers' participation in the contract scheme. I assume in the model that a farmer switches to a completely new cropping pattern that requires less water. Therefore, there is a possibility of reducing the production costs. In the pooled model, I used a pessimistic value of INR 5.00 per cubic meter for *k*. I developed a district-wise model and tested with an increasing k value of INR 5.0, 23.0, and 30.0 per cubic meter, since farmers from different regions are endowed with different levels of resources and realize the value differently.

Table 5.1 Description of parameters and variables of the contract scheme

<table>
<tr><th>Parameter</th><th>Description</th><th colspan="2">Value</th><th>Unit</th><th>Remarks</th></tr>
<tr><td colspan="6">Parameters</td></tr>
<tr><td rowspan="9">m_s</td><td rowspan="9">Conversion coefficient for the volume of water saved into the virtual land area under water-saving technologies</td><td>Block</td><td>value</td><td rowspan="9">Ha per 100 cubic meters</td><td rowspan="9"></td></tr>
<tr><td>Kantapada</td><td>0.019402</td></tr>
<tr><td>Biridi</td><td>0.411955</td></tr>
<tr><td>Jagatsinghpur block</td><td>0.013172</td></tr>
<tr><td>Raghunathpur</td><td>0.064277</td></tr>
<tr><td>Balikuda</td><td>1.011707</td></tr>
<tr><td>Hinjilicut</td><td>0.043783</td></tr>
<tr><td>Purushotyampur</td><td>0.01028</td></tr>
<tr><td>Patrapur</td><td>0.039063</td></tr>
<tr><td>P_W</td><td>Price of water</td><td colspan="2">1.50, 2.0, 5.0</td><td>Indian Rupees/ cubic meter</td><td>Weighted average estimates</td></tr>
<tr><td>k</td><td>Reservation utility of the farmer per ha</td><td colspan="2">500, 2300, 3000</td><td>Indian Rupees/ha</td><td>Difference of minimum gross margins of irrigated and rain-fed plots for a particular farm.</td></tr>
<tr><td rowspan="9">Ψ_s</td><td rowspan="9">Slope of cost function</td><td>Block</td><td>value</td><td rowspan="9">Indian Rupees per 100 cubic meters</td><td rowspan="9"></td></tr>
<tr><td>Kantapada</td><td>12.76</td></tr>
<tr><td>Biridi</td><td>238.10</td></tr>
<tr><td>Jagatsinghpur block</td><td>9.80</td></tr>
<tr><td>Raghunathpur</td><td>416.67</td></tr>
<tr><td>Balikuda</td><td>384.62</td></tr>
<tr><td>Hinjilicut</td><td>62.50</td></tr>
<tr><td>Purushotyampur</td><td>6.49</td></tr>
<tr><td>Patrapur</td><td>31.25</td></tr>
<tr><td colspan="6">Variables and restrictions</td></tr>
<tr><td>r_S</td><td>Amount paid in advance for joining the contract</td><td colspan="2">Endogenous</td><td>Indian Rupees</td><td></td></tr>
<tr><td>α_s</td><td>the revenue share offered to a farmer ‘s’</td><td colspan="2">Endogenous</td><td>Percentage</td><td></td></tr>
</table>

Parameter	Description	Value	Unit	Remarks
β	the profit share offered to all WUA members	Endogenous	Percentage	
β_L	The minimum profit share offered to member farmers	0.00015	Indian Rupees	Limits the maximum profit share of the principal
β_U	The maximum profit share offered to members	0.9	Indian Rupees	protects the minimum profit share (10%) of the principal
B_s	Bonus to the individual farmer	Endogenous	Indian Rupees	Bonus to individual farmer
W_s	Volume of water saved under the contract scheme by the farmer 's'	Endogenous	Cubic meter	W_S is less than or equal to total water used by the farmer 's' in 2018-19

Source: Authors own

5.5.4. Cost function parameters: $\boldsymbol{\varphi_s}$ and $\boldsymbol{\Psi_s}$

In section 4.7.4.a, the methodological background of the cost function development was described and in subsection 4.9, φ_s and Ψ_s were empirically estimated by using LP. I estimated block-level cost coefficients in order to examine each farm's response to the contract scheme.

5.5.5. Endogenous variables

WUA, as a principal, offers three economic instruments, a fixed amount paid in advance for joining the contract (r_s), revenue share offered to a farmer, ‘s’ (α_s), and profit share offered to all WUA members, (B_s) in order to motivate farmers to join the contract scheme, for achieving maximum water savings. Similarly, farmers respond to the incentive scheme by reducing water use by adopting water-saving agronomic practices.

An overview of the exogenous and endogenous parameters can be found in the table 5.1. The principal-agent model was developed using GAMS, and the code is listed in Appendix 1.

5.6. Empirical evidence from the numerical simulations

The contract scheme presented in section 5.5 was estimated and the optimised values of the principal’s instrument and respective farmers’ responses to it were obtained. The baseline scenario and the simulation with comparative explanations are presented below.

5.6.1. Baseline scenario with the optimized endogenous variables

In the baseline model, the objective is to observe agent’s response to the principal’s incentive scheme with a minimum amount of reservation price offering (k), at INR 500 per ha, a modest price of water at INR 1.50 per cubic meter, and no restriction on principal to share a minimum amount of profit to the agents (β_L). Here I assumed that the total cost of production changes because of a change in cropping activity. Hence, I considered no intercept cost functions in the empirical exercise. Keeping all other parameters constant as indicated in table 5.1, I observe that, the aggregate volume of water use reduction is 316651 cubic meters, which is 98.09 percentage of the annual water availability, due to the adoption of water-saving practices. WUA offered an average initial payment of INR 0.13/cubic meter. Participants in the water saving scheme received an average revenue share of 0.024 (α_s) from the principal, which returned an average payment of INR 2.28 per hundred cubic meters of water saved. The model indicates that the WUA does not share any bonus with farmers but generates a net revenue of INR 438,827 through its water saving program. In the contract scheme, the WUA shares a total revenue of INR 8933.93 with the farmers.

To observe any change in the reduction of water volume use and the incentive parameters, I simulated the baseline model with water prices of INR 1.50, 2.0, and 5.0 per cubic meter. In figure 5.1 illustrates individual farm responses to the water-saving scheme. As a consequence, the contract scheme is in favour of the WUA, which determines a farm's profit-sharing by water-saving behaviour.

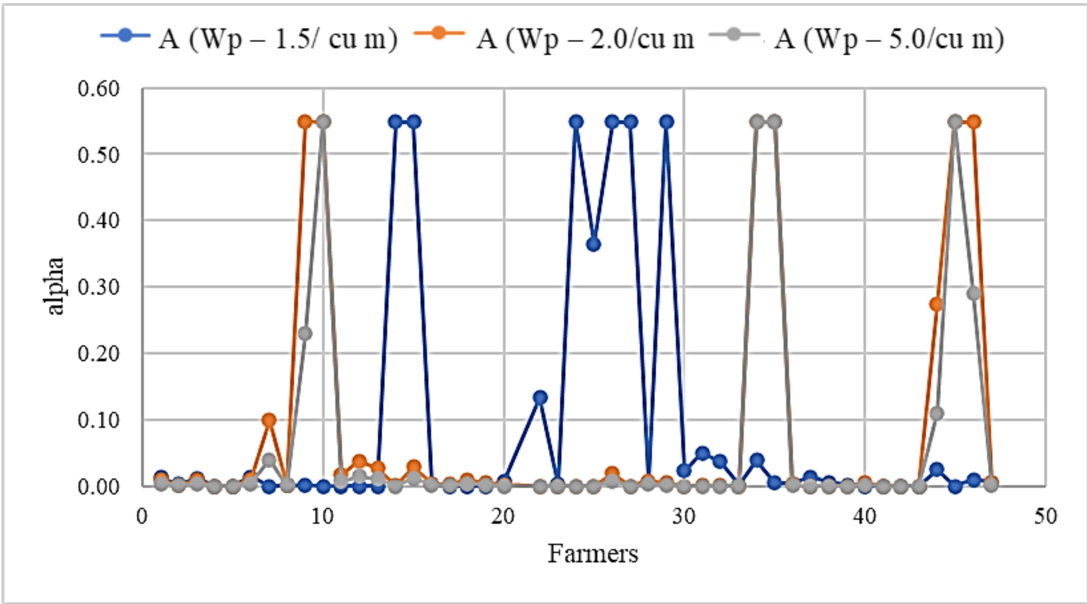


Figure 5.1: Response of the principal's instrument $\boldsymbol{\alpha_s}$ (A) at the water price of INR 1.50, 2.0, and 5.0 per cubic meter (cu m)

In this case, when a farmer adopted a complete water-saving activity from a previous water intensive activity or converted a complete or partial fallow plot, he experience no reservation utility, because that is the least or no economic activity. Now, if a positive value of **r** is assumed, WUA is obliged to pay the fixed part of the incentive. With the initial value of the reservation price, all the farmers contributed to the contract scheme and interestingly, most of them contributed back in variable amount to the WUA for availing subsidized water. However, farmers received incentives for saving water (an average payment of INR 6.53 per ha). Further, I found that all the farmers accepted the contract scheme offered by WUA and obtained an average revenue share of 0.089. The WUA generated net revenue of INR 469,980 from which he distributed INR 10,554 to farmers.

To uncover principal's behaviour to offer increased incentives, if any, when price of water is increased, I simulated the baseline model with a price increase of 2.0 and 5.0 rupees per cubic meter. As a result of adopting water-saving activities, 98 percent of water was saved, therefore a water price of INR 5.0 per cubic meter increased the water-saving percentage to 99.09 percent, r_s to 66.99 percent, and α_s to 0.037 percent. The average return per hundred cubic meter of water-saving was 8.95 INR. Furthermore, the results showed that the adjustment factor (η) had gained the value of unity, indicating the maximum possible water saving is achieved.

The assumption of a positive reservation utility in the incentive scheme suggests that the principal has relatively higher bargaining power. Hence, it is now evident that farmers are collectively taking action to save water to avoid unforeseen consequences due to water shortages in the future. When water prices increase, it is often evident that the contract favours the principal. I also observed that many framers who did not engage in any water-saving activity, with a cheaper water price, accepted the contract scheme at the later stage with the higher *k* value. Second, WUA began offering a bonus to their member farmers, though it was a meagre sum, and increased the total payment up to INR 43410.17.

Similar to Amjath-Babu (2009), this study also explain the nature of bonuses (B_s), initial payments per farm (r_s) and r_s per cubic meter by the scale of operation of farmers. In the farm typology chapter, I found that, farms representing different districts use different farming methods. I further observed differences in labour to water substation and that motivated me to disaggregate the model by the district. Therefore, I developed three different district level model and disaggregated the principal into three and observed their water savings behaviour.

5.6.1.1. Spatial disaggregation and impact of the incentive scheme

The agent's independent behaviour to the contract scheme was also observed when water within similar regional farms was shared. Different outcomes were expected in comparison to the former base model. Therefore, the incentive scheme for three different districts with similar exogenous parameters and similar simulations was modelled.

Concerning to the technical specification of the model, other parameters were maintained at the same level as in the previous model. Results showed that a negligible lower limit to β_L.is inevitably required in obtaining a feasible solution with reduced gradient. In Cuttack district model, when the principal offered an initial incentive almost all the farmers contributed to water-saving activities and saved 77.1 percentage of water. However, with an increase in water price, their response to water saving decreased, indicating decreasing scope for water saving.

With the same level of parameter specifications, farmers in Jagatsinghpur district saved 94.7 percentage of water, but only 56 percent of farmers engaged in the contract scheme. With an increase in water price, its saving increased marginally up to 97.5 per cent. In the case of Ganjam district, with the initial offerings, all the farmers responded to their maximum attainable water-saving activity and saved 96.8 percentage of water. However, an increase in water price to INR 2.0 and 5.0 per cubic meter declined their scope to purchase water to 85.44 and 69.85 percentage respectively.

In Figure 5.2, I plot the relationship between B_s, r_s per farm, and r_s per hectare for Cuttack district representative farms. With an increase in per farm water savings, the initial incentive per farm increased, but the incentive per hectare decreased. These results are consistent with Amjath-Babu (2009) findings. With respect to Ganjam district, the results showed that the economics of scale operated similarly as with Cuttack district farms. However, Ganjam farmers prefer to plant perennial plantation crops such as lemon, sugarcane, and others on their farms. It suggests that many farms were restricted to responding to the incentive scheme for saving water (Figure 5.2-b).

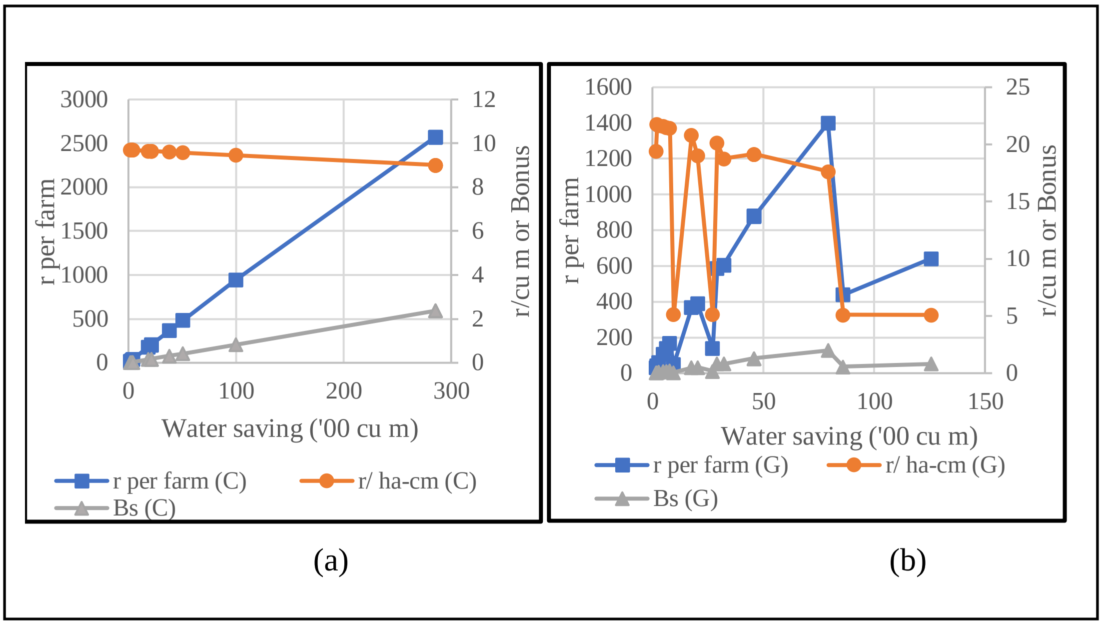


Figure 5.2 Relation of r_s /ha, r_s /farm, and B_s/ farm to the volume of water-saving at water price INR 1.50/cubic meter (cu m) in Cuttack (a) and Ganjam (b) districts.

I draw similar inferences with Amjath-Babu (2009) that, small farms, who are generally risk-averse, should receive higher incentives per hectare to encourage their water saving cropping activities. Although the bonus is small, it indicates that it is still possible to include other farmers into the contract scheme. There is further scope for water conservation on all farms, irrespective of their geographical location. The marginal and small farms, in particular, can benefit from higher initial incentives. However, this requires a further specification in the incentive scheme, for which I model by farm types in the following sub section.

5.6.1.2. Impact of incentive scheme by farm types

To understand the model behaviour by farm type, the incentive schemes for HDIAM, MDLIAM, and LDIACM farms were constructed independently. I found that highly diversified irrigated agriculture for direct market supply (HDIAM) farms were most frequent (60 %), and that they are willing to adopt maximum water-saving activities with greater crop diversification. In this study, I assumed that the WUA offers a cooperative contract that is equally competitive in their locality. I tested the impact of the incentive scheme for these farms with a similar level of parameter specification to the pooled model.

The results of the model revealed that at INR 1.50 per cubic meter water prices, the scope for water savings increased and farmers were paid with a decent initial fixed incentive per farm (r_s). The initial incentive for each additional unit of water savings (r/cubic meter) was the same regardless of the total volume of water savings. This indicates that most HDIAM farms respond to the incentive scheme in the same way. At a water price of INR 1.50 per cubic meter, their water saving was 86.35 percent, while their initial endowment was 308380 cubic meters. After increasing the water price to INR 2.0 per ha and INR 5.0 per cubic meter, the results showed that the water savings decreased from 75.28 percent to 50.10 percent. It is worth mentioning here that, in section 4.8.1, I observed that many farm plots are already under water-saving practices and others are under sugarcane. Any further increase in water prices would result in a decrease in irrigated area coverage for the annual plots and, as a consequence, a decrease in water usage. In the same range of price changes, this also reduced the total incentive share from INR 19953.4 to 17170.1 and 10153.1.

Unlike HDIAM farms, the least diversified irrigated agriculture for contracted market supply (LDIACM) farms continued to harness an increasing incentive because of their larger scale of operation. In contrast, r/cubic meter showed a decreasing trend (Figure 5.3.b). It is interesting to note that with the increase in water price to INR 2.50 and 5.0 per cubic meter, water saving increased from 80.40 to 84.84 percent. Regardless of any further increase in water prices, water conservation does not change, indicating their minimum water requirement for perennial crops. As shown in section 4.6.3.c, any increase in water price is likely to encourage the adoption of water saving activities such as increased acreage under water-saving vegetables, water-saving methods such as System of Rice Intensification (SRI), reduced irrigation frequency for perennial crops such as Sugarcane, and strict regulation on water waste. In these farms, household labour is limited, which limits the potential for adopting any water-saving vegetable crops within the current farming plan. As for the MDLIAM farms, I observed a similar response to the incentive scheme in comparison with the LDIACM farms.

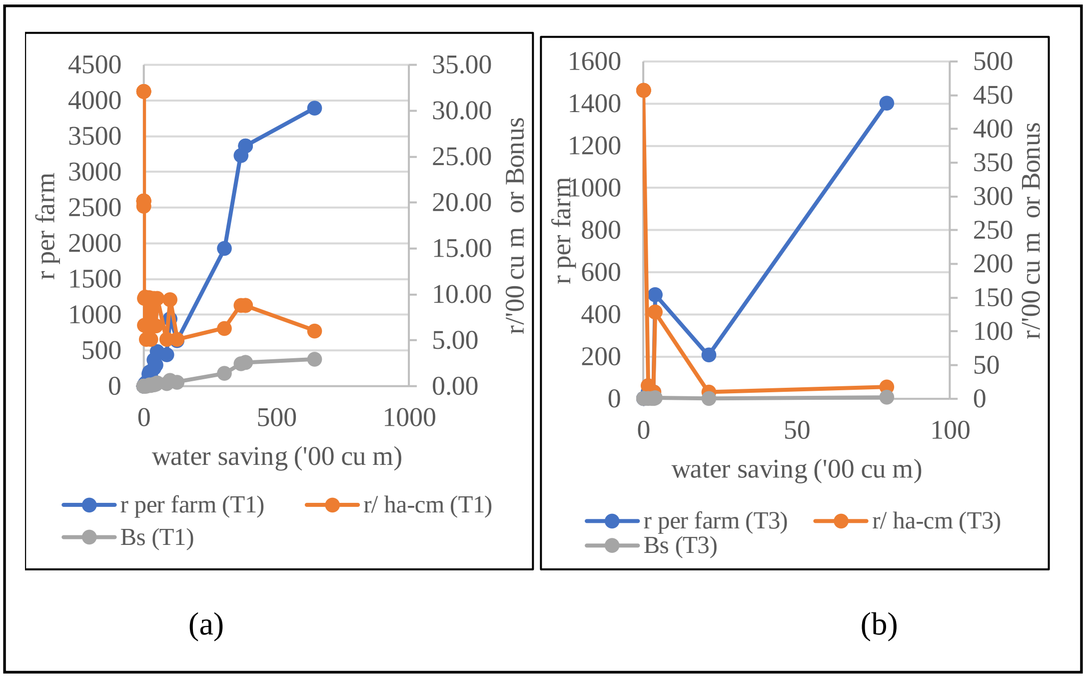


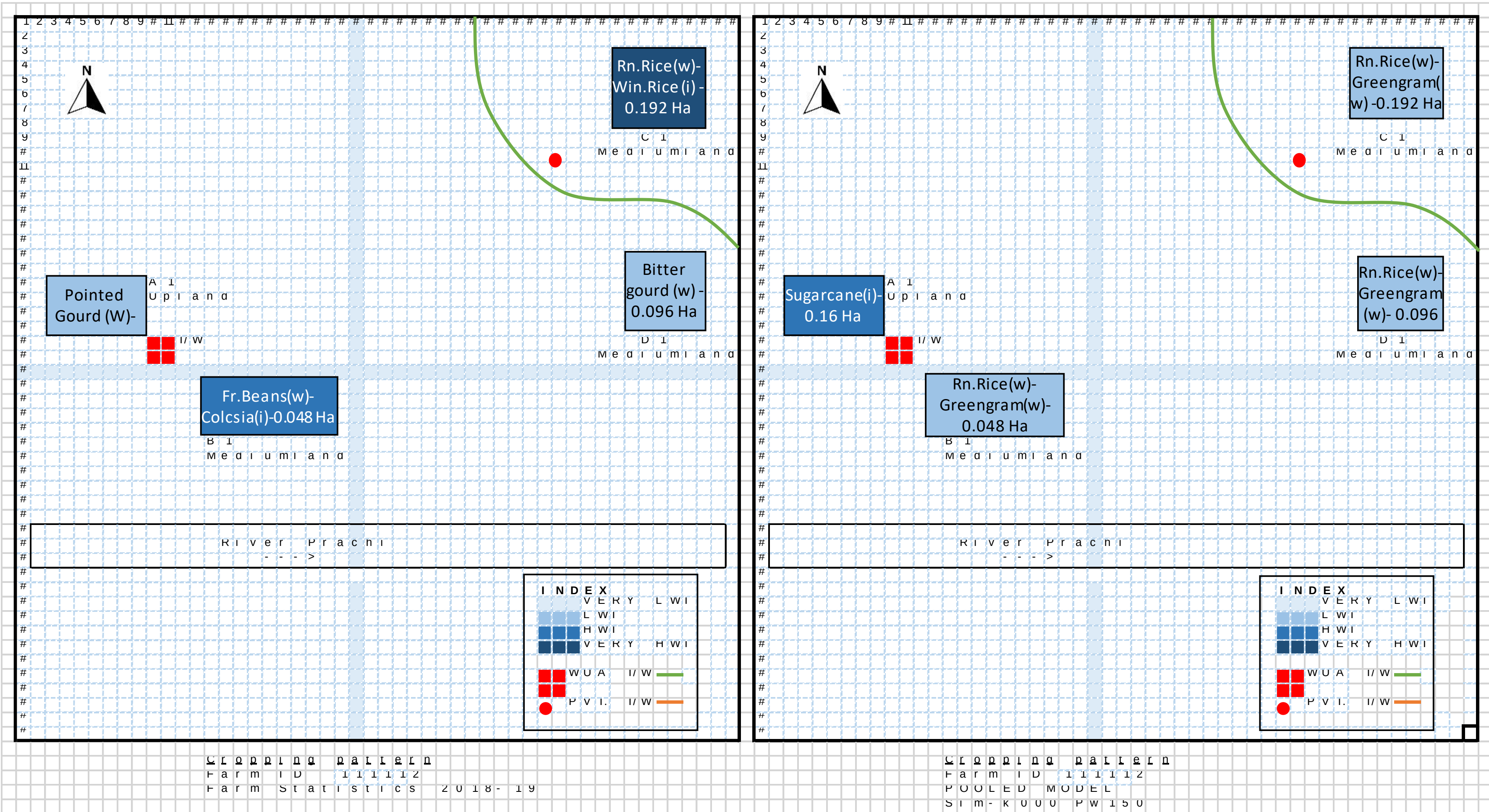
Figure 5.3 Relation of r_s /ha, r_s /farm, and B_s/farm to the volume of water-saving at water price INR 1.50/cubic meter (cu m) for HDIAM (c) and LDIACM (d) farms.

5.6.1.3. Optimal cropping pattern that maximized water savings

In the P-A model I observed farmers' response to the incentive scheme offered by the WUA and found variable quantity of water saving at the farm level. In section 4.6.3, I illustrated the nature of the farming system at WUA level through GIS maps. Now, to visualize the results of each P-A simulations, I used the farm level optimal volume of water saving exogenously at the first model of LP. The outcome of the LP generated optimal cropping patter at the plot level. I present here the representative farms that also simultaneously represent different farm types. In section 4.6.3, I presented the GIS maps of different representative WUA and indicated representative farm's plot level cropping during the survey period (2018-19). Here I represent the cropping patterns of farms 111112, 311115, and 211114 that represent the Cuttack, Ganjam, and Jagatsinghpur districts, respectively. However, the study is limited with land use data from the representative farm plots only. Hence, in the following visual illustration, I could only present cropping pattern of a representative farm plots. I further assume that there is no change in water use behaviour at the plot level and cropping decision at the neighbour farm plots.

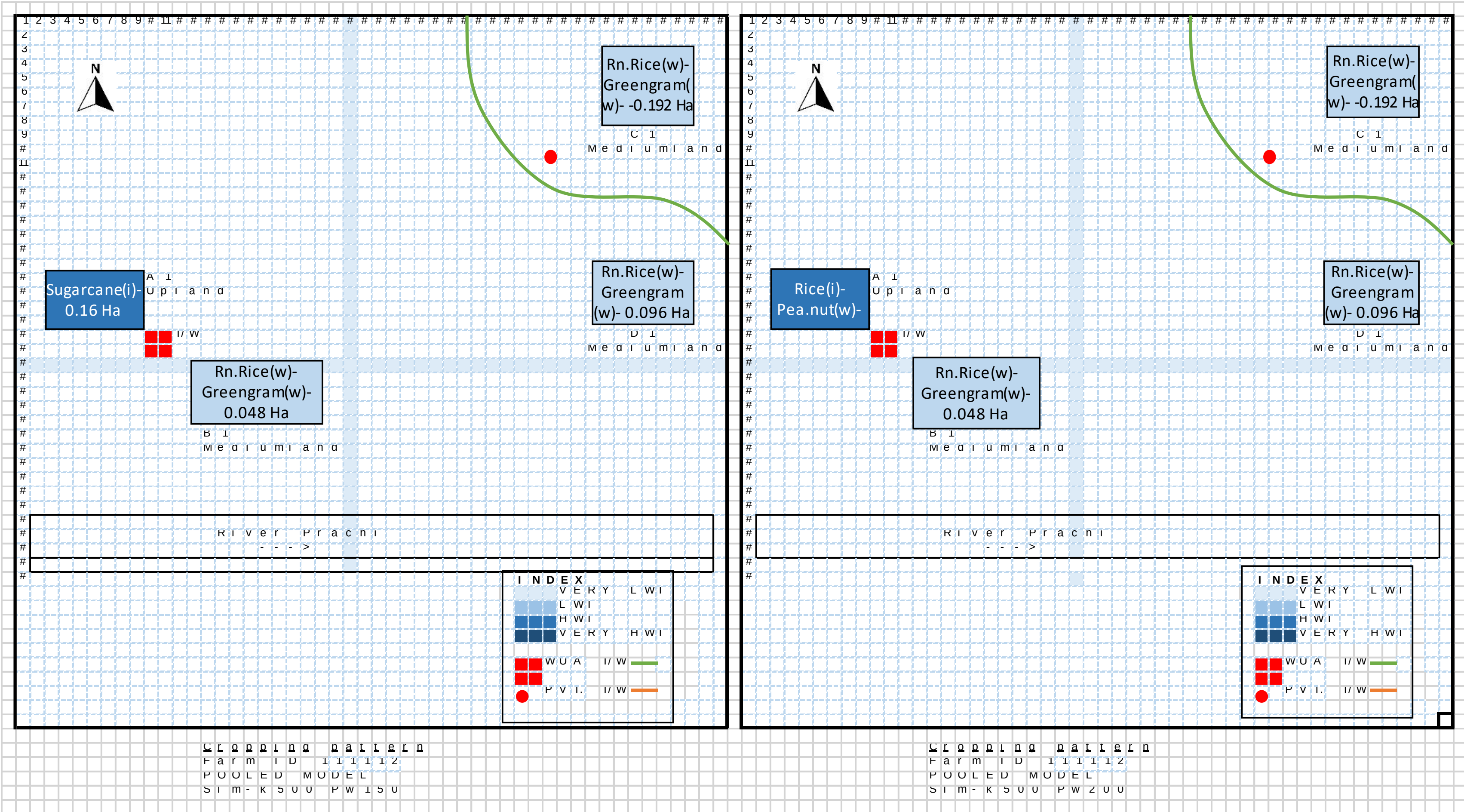
The cropping pattern of farm 111112 can be seen in figure 5.4 (a), where the red square and red circle indicate the location of a WUA tube well and a privately installed tube well (PTW) respectively. The farm owner cultivated pointed gourds on the A_1 plot, which is an annual vegetable harvested in the summer and rainy seasons. In farm plot B_1, he cultivated French beans in *rabi* and *Arbi* in summer. While French beans is a low-water-intensive (LWI) crop, *Arbi* is a high-water-intensive crop that requires a submerged environment for proper growth. The proximity of a farm plot to a water point allowed farmers to select water-saving or water-intensive activities. The C_1 farm plot is the furthest from the water source and for this reason, he grew bitter gourd during the late *rabi* season. D_1 is located outside the WUA delineated area (delineated by a green line), and irrigation is sourced from an individually owned government-subsidized tube well (STW). He cultivated rice throughout the *kharif* and *rabi* seasons. *Rabi* rice is a highly water-intensive crop, and he had to pay the well owner a relatively higher water fee. Thus farmer generated a net income of INR 85652 in 2018-19.

In the above subsection, I observed the cooperative nature of a farmer. In figure 5.4 (b) I present the cropping pattern developed by the first P-A simulation where there is no reservation price (k=0), and water is priced at 1.50 INR per cubic metre. Most HWI activities are replaced by LWI activities, and the farm generated a net margin of INR 66663. Similarly, I developed cropping pattern at k= INR 500 and Wp= INR1.50/ cubic meter(figure 5.5(a)), at k= INR 500 and Wp= INR2.0/ cubic meter (figure 5.5(b)), and k= INR 500 and Wp= INR 5.0/ cubic meter (figure 5.6) and I observe that model developed LWI cropping pattern. However, the total gross margin remained unchanged.



(a) (b)

Figure 5.4 Spatial explicit of cropping pattern of farm 111112 in different farm plots during 2018-19 (left) and in first simulation of model one (right)



(a) (b)

Figure 5.5 Spatial explicit of cropping pattern of farm 111112 in different farm plots in second (left) and third simulation (right) of model one.

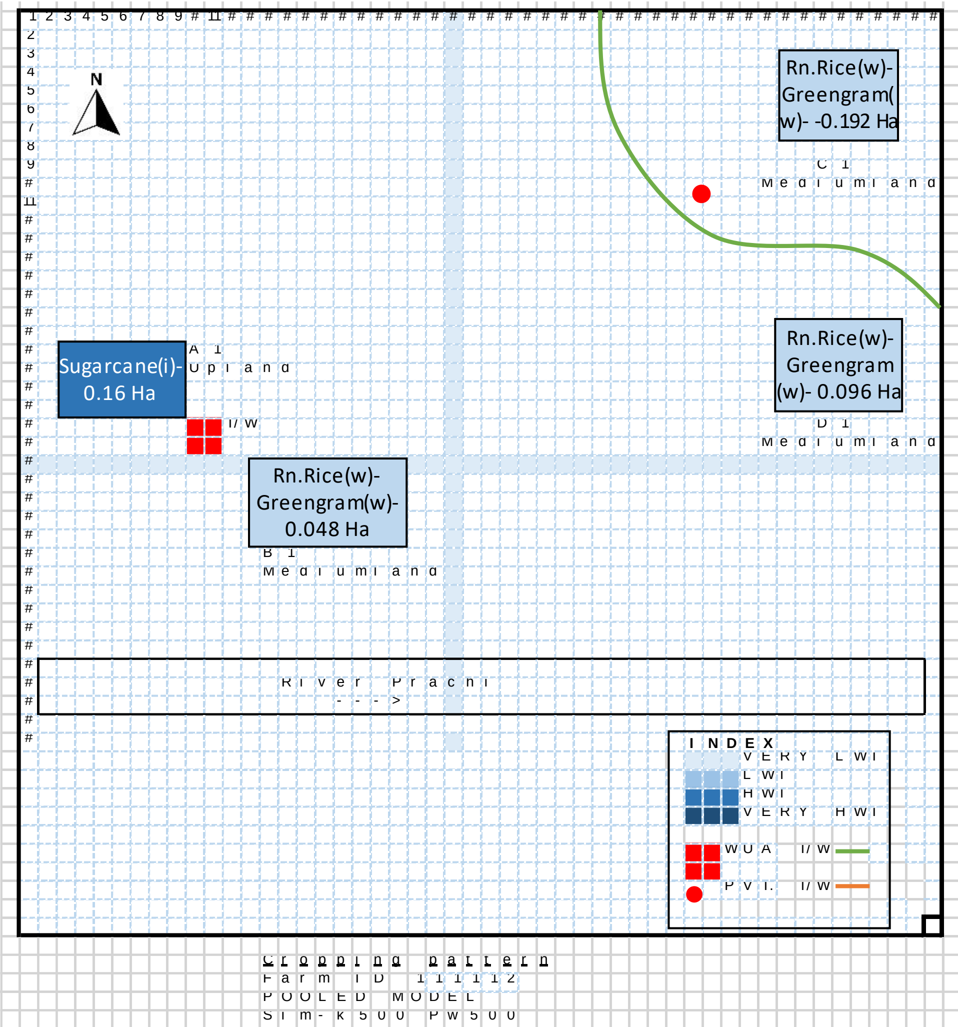
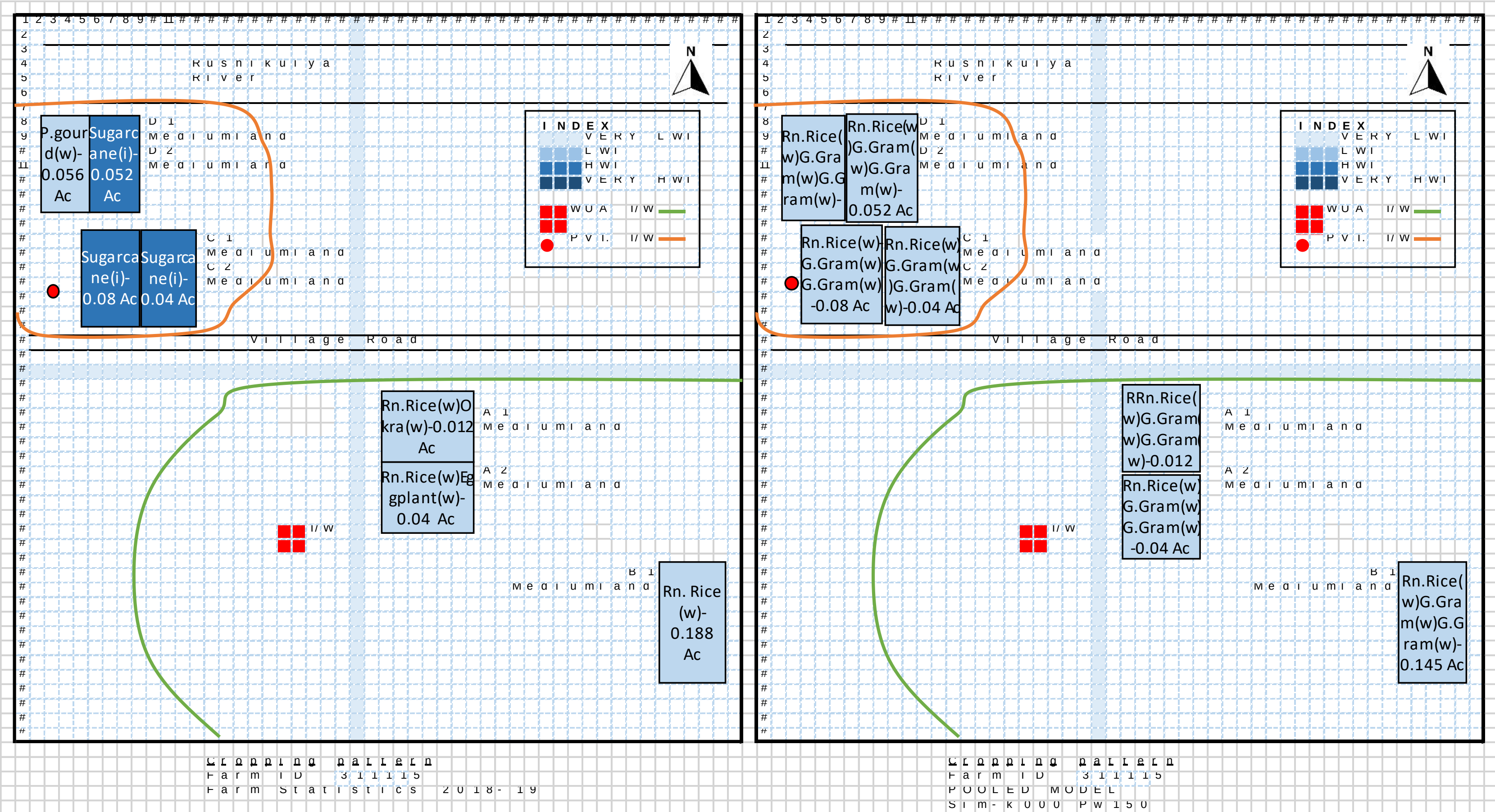


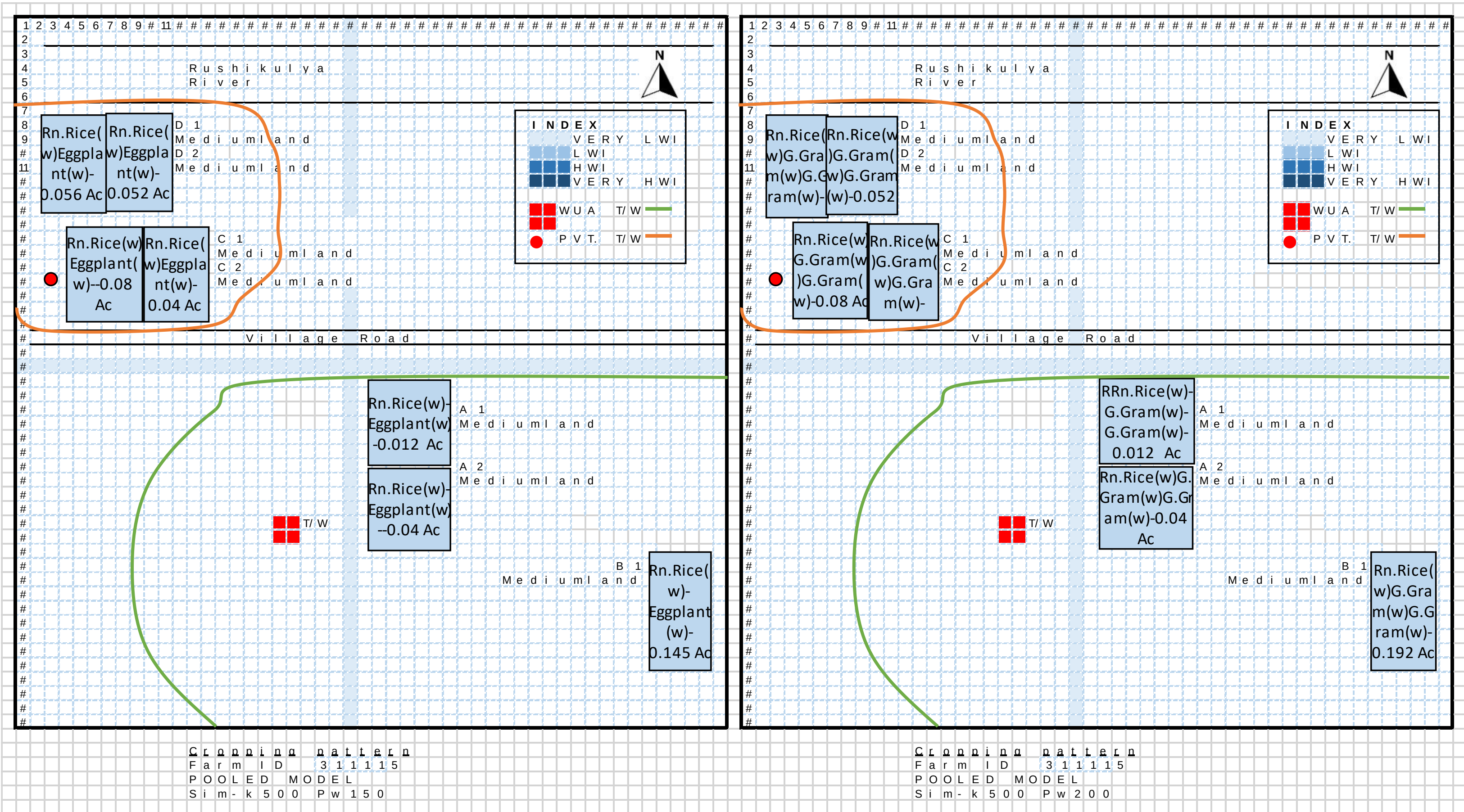
Figure 5.6 Spatial explicit of cropping pattern of farm 111112 in different farm plots in fourth simulation of model one.

For farm 311115, which represents Ganjam district as well as second farm type, I developed a similar copping pattern. The farm owner cultivated sugarcane in three parcels C_1, C_2, and D_2, and obtained irrigation water from a PTW. The Khari rice was planted followed by the Okra and Eggplant on A_1 and A_2, and water was obtained from the WUA. He planted LWI kharif rice on his B_1 plot but was unable to cultivate any crop because of a drought in that cropping season. The model suggested adopting a LWI *kharif* rice-green gram- green gram cropping pattern for all farm plots (figure 5.7(b)). With k=INR 500 per ha and Wp=INR 1.50/cubic meter, the model suggested *kharif* rice-eggplant cropping for all farm plots (figure 5.8(a)). With the increase in water price to INR 5.0 per cubic metre, the model recommended all farm plots adopt the LWI *kharif* rice- green gram- green gram cropping pattern. In the first simulation, gross margin increased from INR 76476 during 2018-19 to INR 152138, and INR 18052 in the second simulation. Under successive simulations, the gross margin dropped to INR 152138.



(a) (b)

Figure 5.7 Spatial explicit of cropping pattern of farm 311115 in different farm plots during 2018-19 (left) and in first simulation of model one (right)



(a) (b)

Figure 5.8 Spatial explicit of cropping pattern of farm 311115 in different farm plots in second (left) and third simulation (right) of model one

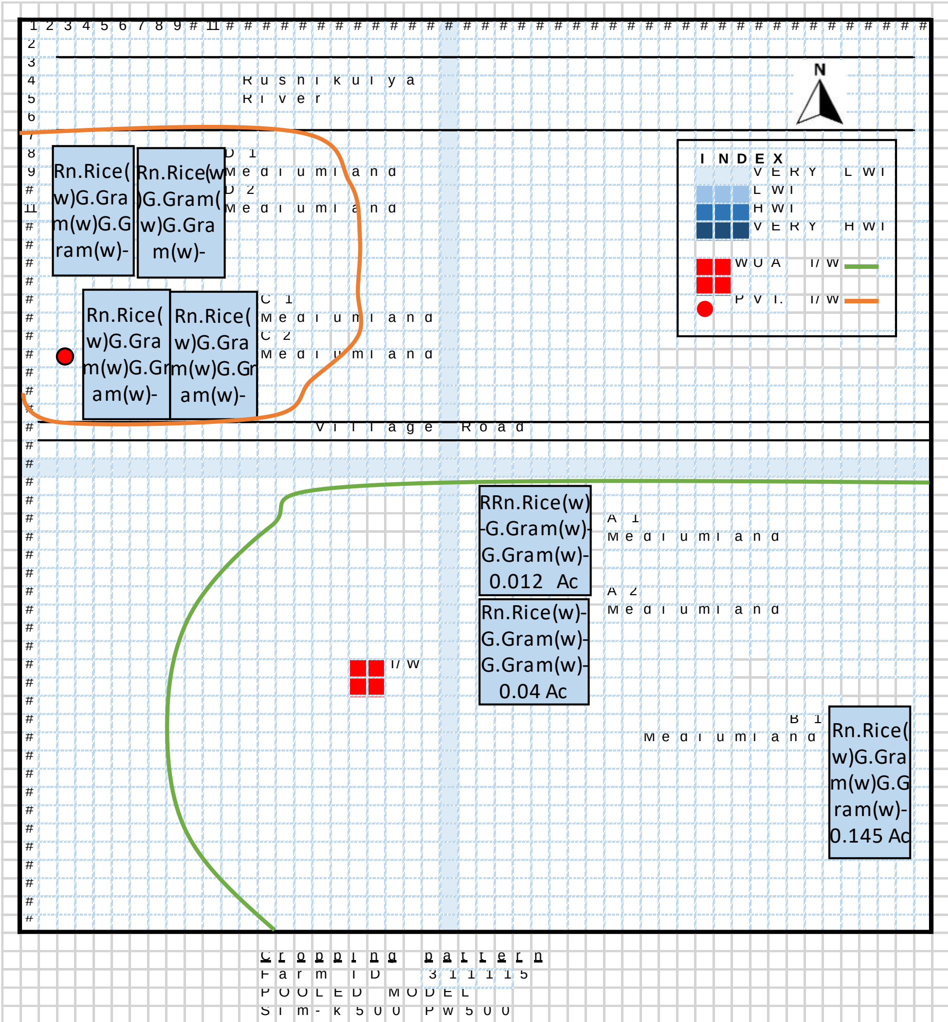
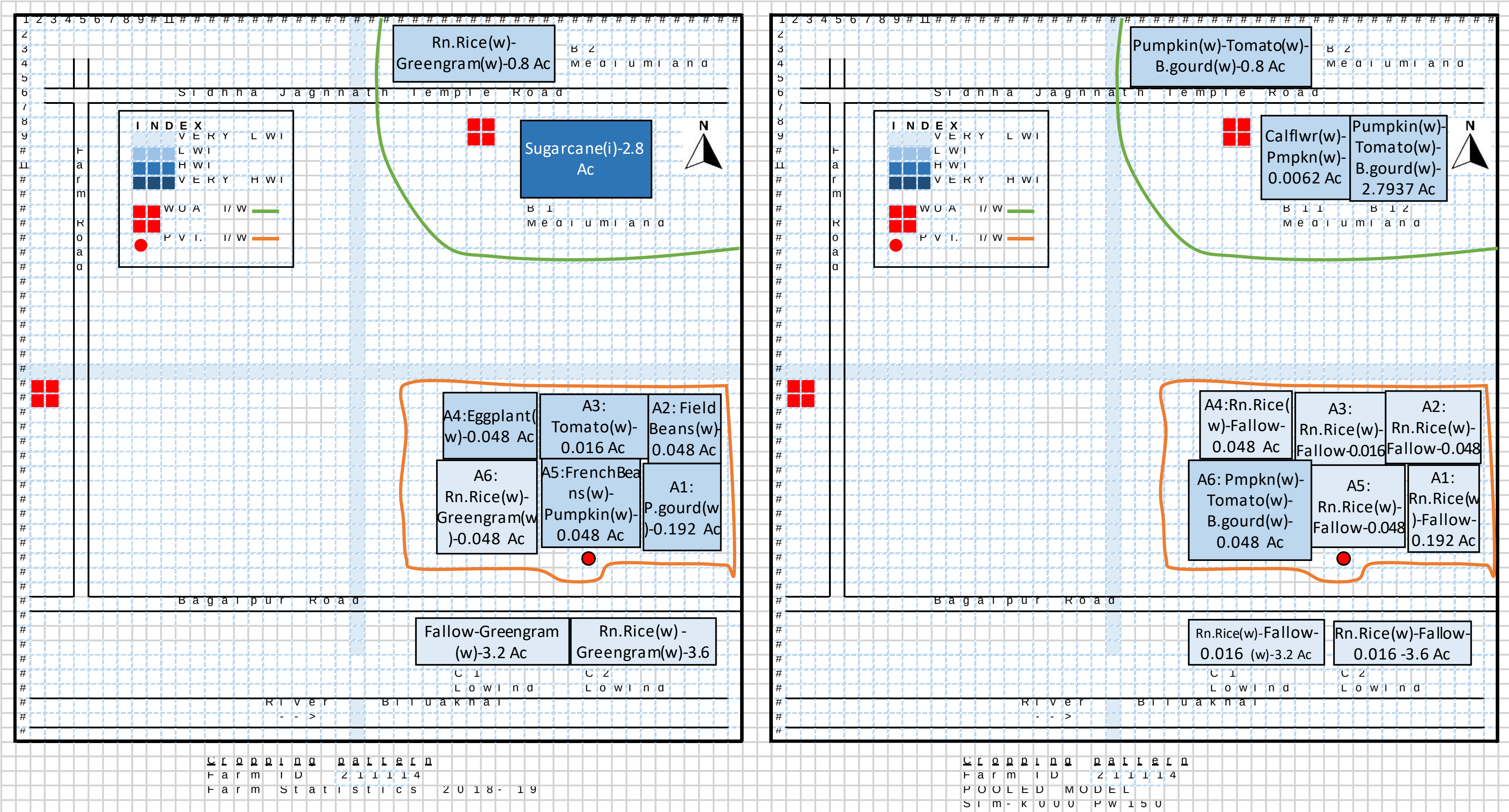


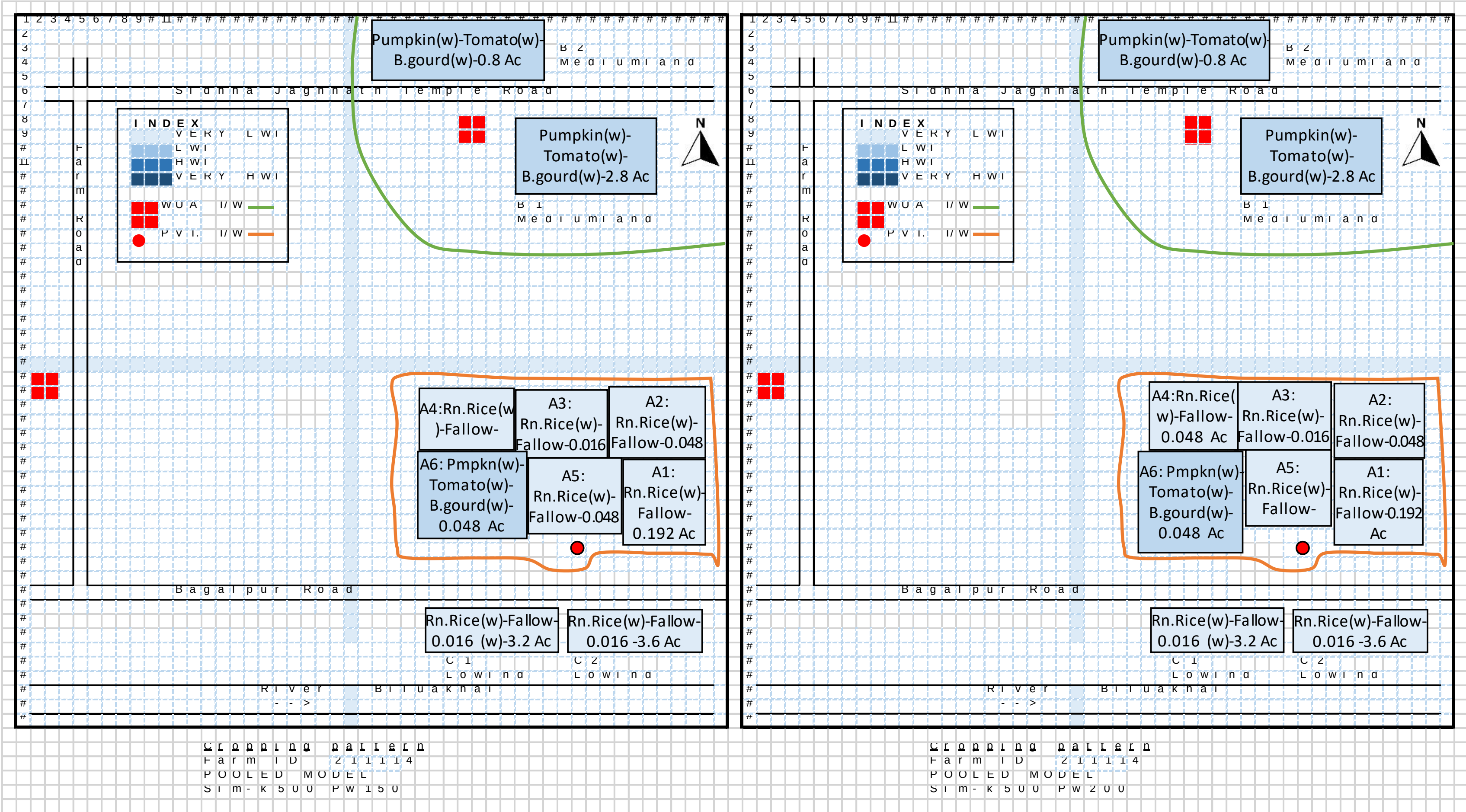
Figure 5.9 Spatial explicit of cropping pattern of farm 311115 in different farm plots in fourth simulation of model one.

The farm 211114 represents the Jagatsinghpur district and the third farm type, least diversified irrigated agriculture for contacted market supply (LDIACM). In the farm typology chapter, I found that these LDIACM farms are constraint with family labourers for performing seasonal low water intensive (LWI) cropping activities such as vegetables. In addition to that, these types of farm household sourced household income from other non-farm salaried occupations, that strengthened their decisions on farm mechanization in terms of owning a tractor, different tractor mounted implements for sugarcane cultivation, installation of tube well, and contract farming. I found that high water intensive (HWI) cropping patterns are dominant in these WUA irrigated farms where either mono cropped sugarcane or *kharif* rice - green gram cropping pattern is adopted. Typically, farmers own a vegetable-based low water intensive (LWI) small-scale kitchen garden and sourced water from an own private tube well (PTW). During the survey period (2018-19), the farm owner generated a gross margin of INR 330,570. One can see from figure 5.10 (b) that the model recommended a LWI cropping patterns for all of the farm plots, while HWI sugarcane was replaced with an LWI crop on B_1 farm plot. Model suggested subdivision of plot B_1 into two so that optimal cropping patterns could be accommodated in order to maximize gross margin. The model simulation indicated that cropping patterns remained relatively unchanged despite any increase in water price, and gross margins remain at the same level (figure 5.11(a) and 5.11(b)). Model outcome indicates possibilities to substitute sugarcane with LWI vegetables (figure 5.12). It indicates that a farmer can hire-in wage paid labourers or suitable farm mechanization, with complete or partial public subsidies, for performing different farming operations when they adopt any LWI cropping activity.



(a) (b)

Figure 5.10 Spatial explicit of cropping pattern of farm 211114 in different farm plots during 2018-19 (left) and in first simulation of model one (right)



(a) (b)

Figure 5.11 Spatial explicit of cropping pattern of farm 211114 in different farm plots in second (left) and third simulation (right) of model one

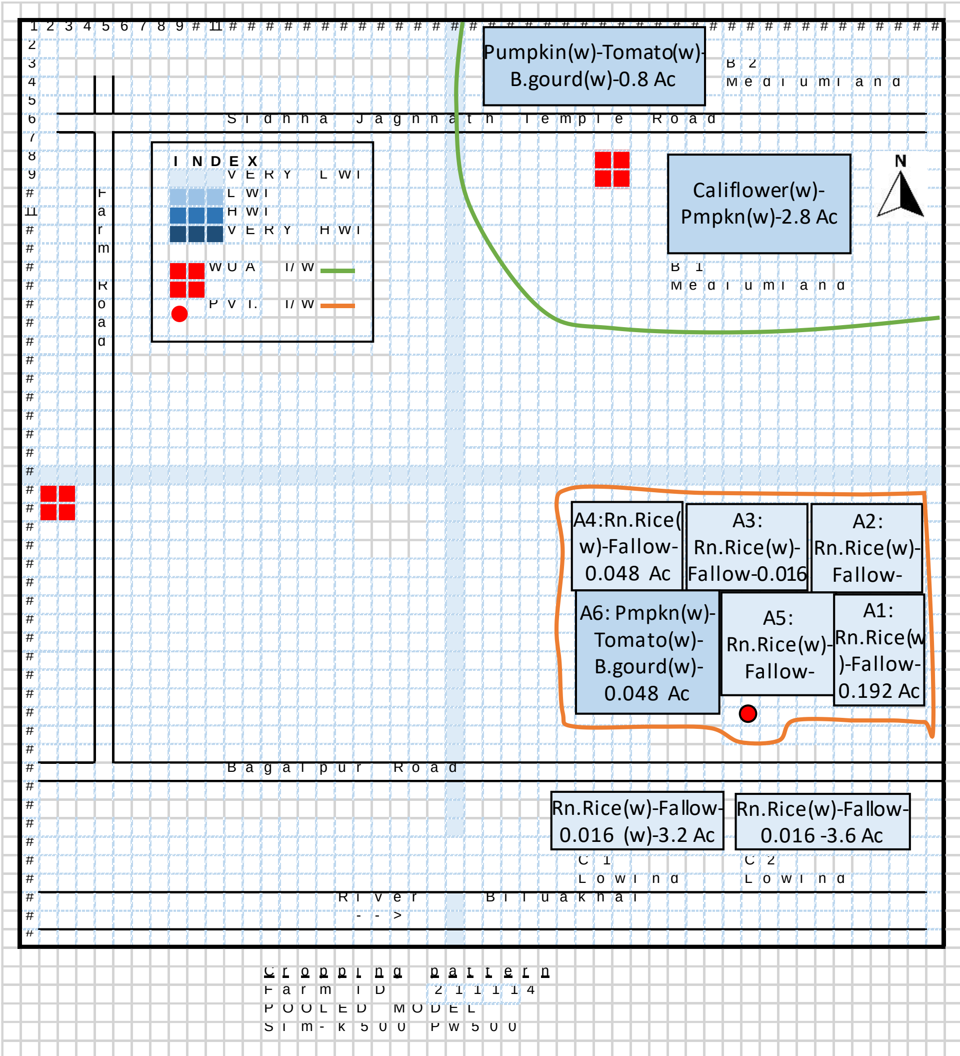


Figure 5.12 Spatial explicit of cropping pattern of farm 311115 in different farm plots in fourth simulation of model one.

5.6.1.4. Water-saving nature of the WUA

With the intention to observe the scope of water conservation in an WUA through water saving incentive scheme, I performed all simulations with β_L, minimum profit that a WUA should offer to the member farmers at the level of 0.00015. I observed that, any further increase in β_L value reduced the viability of the contract, and this was evident when the model produced a negligible total initial incentive and total revenue share. From here, I reaffirm the previous inference that WUA retained maximum authority to extend the contract agreement to the farmers. Therefore, to ensure a maximum redistribution of profit to the farmers, a lower limit of beta was assumed. However, any value higher than 0.01 did not yield a viable solution. Thus, I can be understood that WUA as principal is not in favour of redistribution of profits after extending variable and initial incentives. From here I can infer that the WUA favours water conservation. Although the scope of water conservation varies according to farm type.

When I disaggregated the P-A model by farm types, I observed that WUA among the HDIAM farms saved highest quantity of water, that I can translate into a direct reduction in cost of water procurement. On the other hand, WUA at MDLIAM and LDIACM farms were constrained by their perennial crop choice. These farm households lack family labourers to perform round the year on-farm activities. On the other hand, these households are relatively better off to own or hire in farm machineries, that substituted human and animal labour engagement.

5.7. Discussion: Sustainable water extraction in a cooperation model

Owing to a huge amount of transaction cost (monitoring of water distribution, water fee collection, organizing regular meetings to share WUA functioning, dispute settlement, etc.) for organizing of millions of well owners and their water extraction behaviour, policymakers suggested collectivising water extraction and its distribution at village community scale. In the study areas, a community irrigation distribution system (CIDA) distributed irrigation water to the member farmers at a comparatively lesser price than other water sellers. However, variability in adaptation of statutory regulations of *Pani Panchayat* Act 2001 by the CIDA members determined their level of performance and sustainability. This study chose groundwater user association (WUA) as one of the successful form CIDA and reviewed literature on their group dynamics performances (Abdullaev, Kazbekov, Manthritilake, & Jumaboev, 2010; Ghosh, Kumar, Nanda, & Anand, 2010; Nagrah, Chaudhry, & Giordano, 2016; Rouillard & Rinaudo, 2020; Wegerich, 2008).

In the third chapter, three identified farm types revealed performances of WUAs at the village level and their group performance is elaborated with appropriate theoretical viewpoints. In this chapter, an institutional solution is suggested to improve the performance of a WUA in a cooperation model. The cooperation model aimed to maximize water conservation by adopting water saving cropping activities in a cropping pattern. In the previous chapter, water saving nature of a sample farmer was derived at farm level and total gross margin (tgm) was maximized. Further, scope of water saving was simulated under increasing water price scenarios. In this chapter, the cooperation model revealed those individual farmer's collective willingness to save water and to maximize overall water saving at WUA scale. This study aimed to maximize water saving in a WUA to reduce pumping costs by conserving groundwater. I adopted the water sharing model designed in a principal agent (P-A) mode from Amjath-Babu (2009) and modified the objective function as volume of water saving and accommodated cropping pattern as a determinants.

In this P-A model, the WUA as a principal offered three types of incentives in order to motivate farmers to join the contract scheme, for achieving maximum water savings. By accepting the membership of water saving scheme, a member farmer received a fixed initial incentive (r_s), a revenue share by saving variable amount of water due to adoption of water saving cropping activities (α_s), and a profit share (B_s).

As an individual, to respond to an increase in water price, a farmer adopted either water saving method(s) in an existing cropping activity or changed to a water saving activity, and thereby maximize the farm level tgm. However, when many farmers sourced irrigation water from a WUA, and received incentives for water saving, that promoted wilful but variable effort to save water by any combination of above-mentioned methods. In the P-A model, a WUA awarded α_s to every member farmer, which was a variable incentive which is directly proportional to the effort for reduction in water use by the member farmers.

In addition to the fixed and variable incentives, a WUA distributed the profit among the member farmers and that worked as a team incentive, B_s. The value of B_s was found to be higher for a farmer who not only reduced water consumption on his own farm plots but also encouraged neighbour farmers to become a member in the incentive scheme of the WUA. Overall, by becoming a member farmer to the contract scheme, a farmer insured the production system with the assured irrigation system and ensured sustainability of the groundwater irrigated agriculture. This study further assumed that total land area of a single member farmer is always lesser than total area of ICA. This implies that a community tube well distributed water among at least two member farmers, who adopted water saving activities for maximum reduction in water extraction.

The incentive scheme was tested with different combination of water price and a lower limit of profit share β_L, and it was observed that many member farmers chose to adopt water saving activities and received incentives. Spatial disaggregated models revelated that around half of the member farmers from Jagatsinghpur district contributed most to save water by adopting rice – *Vinga mungo* cropping pattern. During the primary survey it was observed that water price differs by WUA and was influenced by a neighbouring CIDA that offered either a competitive water price or other set of incentives. Under such circumstances, a farmer maximized his water saving and sourced water from a WUA. Further, it can be argued that, when model was simulated under a higher water price but also with higher incentives, a farmer had a choice to source water from a neighbouring CIDA as a short-term adjustment to continue with the chosen cropping activities and irrigated that. However, the interaction effect among CIDA is beyond the scope of the present incentive scheme.

In the LP model, under increasing water price, an individual farmer showed a reduction in water demand and that may seem to solve the overall problem . Thus, a WUA would have increased water price for achieving the goal of water saving. However, mare increase in water price would only increase cost of production, and that would reduce farm level tgm, and thereby total gross margin of WUA would reduce. Though water pricing mechanism sufficiently reduce water extraction and conserve groundwater ecology, but do not compensate member farmers for forgoing the income earned from irrigated agriculture. In addition to that, such mechanism discourage member farmers to comply with the WUA and member farmers may seek alternate source of irrigation to meet immediate water requirement. Therefore, the incentive mechanism rightly motivated member farmers to continue to reduce water demand and get paid for that.

To know the effect of P-A model after its suggested decline in water demand on crop choice, the LP model was utilized to know the optimal cropping pattern under endogenous volume of water. The LP model suggested mostly Rice- *Vigna radiata* (green gram) or Rice-peanut crops on most of the farm plots. If a WUA continue to remain myopic and extract groundwater without any planning, the lifetime of an irrigation well will decline rapidly. In my research fieldwork, such instances were found to be common in many neighbouring villages to the study villages.

5.8. Concluding remarks

From the point of view of groundwater ecology in the study area, extraction of water for cash income in the present has already created externalities, such as raising pumping costs. Groundwater aquifers were to be conserved by reducing pumping hours in the original proposal. Within the study area, WUAs are owned and managed by the member farmers who owned farm parcels inside the WUA irrigated command area. As a result, it is relatively easy to devise any favourable incentive scheme to conserve water in *kharif* and *rabi* seasons and to use the saved water in summer. In the linear program, I attempted to capture these possibilities and derived farmers' responses based on the cost function and used it in the incentive scheme.

To encourage farmers to conserve water and investigate water distribution through community action, an incentive scheme was introduced in a principal-agent model. It appears the community has higher bargaining power in benefit sharing after the fixed and variable parts of the incentives are distributed among members who generally adopt new LWI cropping patterns. Moreover, simulations that increased water prices by two and threefold (from the initial level: INR 150 /Cubic meter) did not result in significant water savings on many farms, indicating a dominant type of cropping pattern in the farming system.

The simulations of highly diversified irrigated agriculture for direct market supply (HDIAM) farms demonstrate that they are sensitive to water price increases, though they are able to adopt maximum water-saving practices. The cropping pattern changed when a reasonable reservation price was introduced, and this further increased farmer’s gross margin. The least diversified irrigated agriculture for contracted sale farms showed indifferent water use behaviour with increasing water prices because they had a greater area covered by perennial water-intensive crops such as sugarcane. As I worked on the acceleration of water-saving incentives, I found that there should be a lower redistribution of water in the second round given incentives since the marginal value of water is higher in the second round.

Hence, with the introduction of the incentive scheme I found that, farmers showed their willingness to save water by adopting water-saving cropping pattern, that reduces volume of water extraction. With the decrease in volume of water extraction, it unfolds ecological and economic benefits. First, it encourages conservation of groundwater ecology as well as sustainability of the groundwater extraction structures. On the other hand, it reduces cost of water that reduces cost of cultivation, that has potential to enhance net return of the farm household.

CHAPTER 6: SUMMARY, CONCLUSION, AND POLICY RECOMMENDATIONS

6. Summary

6.1. Research background and framework

Mounting water demand to irrigate water-scarce farm plots has challenged pre-existing water management strategies in recent decades. The technological advancements in irrigation water provision anchored the success of the green revolution and secured India from food shortages. Agricultural and rural development policies also promoted localized, small-scale irrigation solutions, and groundwater was explored as an alternate source of irrigation water. However, indiscriminate water extraction for water-intensive crop activities such as winter and summer rice plots eventually depleted the groundwater table and increased the cost of water extraction. To address these challenges, the central government formed the central water commission (CWC) and the central groundwater board (CGB), and at the state level, the state groundwater board (SGB). These organizations monitor groundwater flow, recharge, and quality parameters, and report the maximum amount of water that can be replenished. Nevertheless, conflict resolution over access to water and its optimal use remained largely grey area. The availability of low-cost farm machines to extract and distribute groundwater permitted smallholders to irrigate their crops successfully, although it adversely affected groundwater ecology. Further declines in the groundwater table and gradual increases in water costs added to the overall cost of production. Smallholders who depend on irrigated farming are increasingly threatened by the competitive market condition and volatile product prices.

The problem can be explained from Hardin's (1968) perspective, in which he claims that most farmers began to suffer from the 'tragedy of commons'. Thus, any institutional solution, whether enforced externally or locally, could sustain groundwater usage and arrest groundwater table depletion. A range of multiscale and multidisciplinary solutions have been presented, ranging from the use of market solutions and water pricing mechanisms to physical control through water quotas. Although these solutions were intended to improve water security for smallholders in India, in practice they did not succeed due to the high monitoring costs of unorganized smallholders who drilled their own well or received investments from government. As a result, Ostrom (1999) stressed the importance of collective action by its users for owning and managing the resources. There have also been advances in methodological formulations and empirical evidence with respect to her proposition (Kotchen & Segerson, 2019, 2020; Lopez-Gunn, 2012; Ostrom, 1990; Rouillard & Rinaudo, 2020).

In Odisha state of India, Odisha Lift Irrigation Corporation Ltd. (OLIC) has organized smallholders to participate in subsidized irrigation water from a community well by forming a water user association (WUA) since the early 1970s. The underperformance of many WUAs during the later period compelled the state government to strengthen, restructure and redesign the institutions for water sharing and enacted *Pani Panchayat* (PP) Act 2001, a Hindi name for WUA. In the new PP act, member farmers owned the irrigation system and managed the water distribution system. The new organizational structure allowed farmers to make crop production decisions free of government restrictions and plan irrigation extraction accordingly. Many PP on groundwater, however, collapsed within a decade or two due to damage of the physical structure or a dispute over water distribution. The central cause of the decline in the groundwater table due to uncontrolled water extraction has largely remained unexplored. The following questions were developed to address this issue.

(a) How can a farmer optimize land-based water-saving activities?

(b) How does an individual farmer's farm-level decision exaggerate a well scale water extraction?

To address the research questions, the following research objectives were constructed.

(a) To classify the diverse farming systems into homogeneous types,

(b) To optimize farm-level land-based activities, and

(c) To develop a cooperation model in water distribution by linking farm-level decisions at a well level.

6.2. Summary of the main findings

6.2.1. Diversities in an agricultural production system

In the coastal aquifers of Odisha state, thousands of well owners extract groundwater to irrigate their farm plots for a variety of land-based production activities. In addition, canal irrigation sources were used by many farmers to supplement irrigation water supplies. In the post-rainy and summer seasons, farms drew water from groundwater sources for irrigation due to low water delivery from the canal system. The survey found that groundwater wells were owned and managed either by individuals, a small informal group of individuals or by a community. irrigation distribution systems also varied according to production activities. Therefore, I inquired about heterogeneity in water sharing, its institutions, and cropping patterns at the village level.

I conducted surveys in Cuttack, Jagatsinghpur, and Ganjam districts of Odisha. I surveyed 33 WUAs from seventeen villages of three districts to elucidate the irrigation requirements of a wide range of land-based production. By utilizing multiple correspondence analysis (MCA), I was able to construct a simple representation of diverse agricultural production systems at the village level. A total of 35 parameters were analysed, which were categorized under land resources, crop characteristics, farm structure, farming practices, irrigation provision, irrigation distribution regulations, market access and farm economic performance.

Three major types of farms have been identified: highly diversified irrigated agriculture for direct market supply (HDIAM), moderately diversified limited irrigated agriculture for direct market supply (MDLIAM), and least diversified irrigated agriculture for contacted market supply (LDIACM). The HDIAM farms were primarily marginal and small (operated on < 2 ha of land). These farms adopted maximum crop diversification, and their family members contributed to all aspects of production. WUA member farmers planned their annual cropping activities in advance. The majority of the crop output is consumed in variable proportions by households and the surplus quantities are sold on the market. MDLIAM farms are semi-subsistent. The rainy season rice is mostly followed by green gram or black gram for market purposes in this farm type. The WUA delineated area is mostly encompassed by privately well ICA. In many of these villages, family labour was shared with neighbouring farms for various cropping activities. A majority of LDIACM farms are small and medium sized, and they specialize in rice or sugarcane production. A contract sale agreement with sugar factories increased sugarcane production in these villages. WUA members also own private tube wells, and they were located in and around the WUA demarcated area. Moreover, farms collectively perform many farming operations using farm machines due to the scarcity of family labour. To meet household food and nutritional needs, vegetables are grown on their homestead kitchen garden. Interestingly, two villages did not belong to any of these groups. Nevertheless, they were collectively managing and owning private wells to irrigate their farm plots for diverse seasonal vegetables on a limited scale. Theoretically, co-evolution and cooperation were observed in HDIAM farms, whereas institutional mono cropping and path dependency largely explain MDLIAM and LDIACM farms.

6.2.2. Maximization of net return through optimal farm-level activities

An examination of the farming system at the village level revealed that different water distribution systems developed under various circumstances. I explored that different water distribution systems supported specific production systems. Subsidized groundwater irrigation has enabled farmers to adopt diverse cropping practices, and many decisions related to cropping are collective in nature. On the village level, I observed that different farms adopt different cropping patterns, which are typically plot specific. Furthermore, farms have been constrained by the suitability of a cropping activity. Accordingly, I inquired about how a farmer could optimize land-based water-saving activities. I claimed that an increase in the adoption of water-saving activities will reduce per unit area cost of production and may increase scope of labour to water substitution. I further claimed that to balance the total water budget at the farm level a water-intensive activity must be succeeded by a water-saving one.

A survey was conducted on 53 farms from the study villages that used the various groundwater sharing systems including groundwater user associations (GWUAs), cluster tube wells (CTWs), private well owner wo sell water, and private wells. Research findings revealed that most of the respondents were in their 50s and had completed a middle school education. However, their 23 years of farming experience made them successful farm entrepreneurs who have learned the art of farming from their families. Most of the farms sourced water from multiple water sources, and most of them are subscribed to a WUA. On average, a farm planted *kharif* rice + mung bean as a cropping pattern on 54.19 percent of the total arable land. With the advent of irrigation technology, vegetables, pulse, or oilseed crops composed the cropping activity on 30.52 percentage of the land area. Sugarcane occupied 15 percent of the land area in medium and lowland plots, and irrigation was primarily required in the *rabi* and summer season. There are also a few farms that replaced rice on their medium elevation plots with lemon grass and other essential oil grass. The study found that many farms experienced limited contribution from family members in diversified farm activities. On the other hand, high costs for casual labour hiring for farming operations compelled them to replace annual cropping activities with perennial crops. The analysis of cropping patterns by farm types revealed that farms in HDIAM villages diversified their farm plots with various water-saving practices. In contrast, LDIAMS farms cultivated labour-saving, but water-intensive crops. In regard to perennial crops, HDIAM farms cultivated sugarcane on sixteen percentages of the gross cropped area (GCA) while MDLIAM and LDIACM farms cultivated the same crop on fourteen and ten percent, respectively. Therefore, the results confirm the initial finding, that despite fewer acres under perennial crops, LDIACM farms cultivated rice, followed by mung beans or vegetables, and sugarcane with contractual agreements for sales.

The farm plot level diversified land use decision allowed me to measure their profitability and optimize it under increasing water cost conditions. A linear program was used to model the problem, and the results of the model were compared to the status quo. With the assumption that there were no costs associated with water, most of the farms adopted a water-intensive cropping pattern on their plots. It was found that the gains are different depending on the size of the farm. In comparison to the initial total gross margins, marginal farms had a higher marginal benefit from a unit ha cm of additional water, while large farms had to forego fifty percent of their income. In model one, restrictions on water trade limited the opportunity to earn a few more rupees from trading water with neighbouring farms. As part of model two, the water supply is limited at the initial level and introduced spatial water trading with seasonal water transfers of up to 25 percent. Large landowners, however, experienced a reduction in their gross margin from baseline, while smallholders continued to harness a higher *total gross margin (tgm)*. The tgm/ha of different farm types was compared, and the results showed that HDIAM farms earned the highest, followed by MDLIAM farms and LDIACM farms. HDIAM farms employed the maximum amount of family labour and, therefore, were able to lower their production costs and increase their *tgm*/ha. It was difficult for the other two types of farms to adopt any water-saving practices due to the limited labour contribution from their family members. As a result, they substituted water for labour.

Further, the degree of responsiveness in water demand in response to changes in water prices and compared it to farm types and size classes is assessed. Marginal and small farmers were most affected by the increase in water prices. By using a stepwise reaction function in water demand, one can deduce that farms organized their plot-specific activities towards water conservation. However, after the water price increased beyond INR 886 per cubic meter, water demand remained low. It indicates that many uplands and medium land farm plots require lifesaving irrigation in order to maintain diversified cropping activities in HDIAM and MDLIAM farms. In a linear program exercise, I was only able to observe the water-saving behaviour of a farm, but the scope of collective action in water conservation was outside the scope of the programme. The Kaldor-Hicks compensation was introduced to test the feasibility of cooperation in water sharing and saving. However, information asymmetry on farmer's annual water demand and their interaction for sharing water and crop production decision left WUA with moral hazards. Therefore, to know the cooperation behaviour of a farmer, and to save water in a WUA, I proposed a principal agent model in the next chapter.

6.2.3. Cooperation in water-sharing to harness optimal net farm income

I realized that water pricing as an economic instrument has the potential to shift cropping patterns towards water-saving practices without causing economic losses to the community. Although farmers did not gain any economic benefit by adopting any water-saving measures, regardless of the scale of operations. However, farmers who continued to engage in water-intensive practices externalized their water use onto neighbouring farms. In order to combat this, I devised an incentive scheme that features a cooperative model to maximize water conservation across a community. The incentive scheme is based on Amjath-Babu (2009) 's Principal-Agent (P-A) model. This model was originally proposed by Furubotn and Richter (2005). Each farmer's cost function was derived from their respective block-level estimates in LP. It was assumed in the initial run that all farmers would be equally interested in saving water by switching to water-saving activities, which is a complete shift in the cropping pattern. The model was simulated with an increase in water prices from INR 150 to 200 and 500 per cubic meter, and these prices were within the range of the actual water price. The results from the model were quite interesting, both in terms of the initial and variable payments. With the initial parameters specified, the model predicted an annual water savings of 98.09 percent by adopting the water-saving scheme. Nevertheless, this does not translate to the proportion of farm plots under water-saving, since many farm plots already have water-saving practices in place, so no change in cropping patterns is observed. Furthermore, any increase in the price of water does not translate into a significant increase in the amount of water saved, as many farm plots remain uncultivated. During the numerical simulation, it was revealed that WUA as a principal has a higher bargaining power to decide the revenue share (alpha) in order to convince farmers to participate in the contracting scheme. This study, in contrast to Amjath-Babu (2009), infer that WUA retains most of its profits and does not distribute any additional bonuses with an increase in the lower bound of beta. Model results also illustrate the depleting groundwater table in the sampled villages, although farmers showed variable willingness to save water through their plot-level cropping activities.

I explored spatial diversities and tested the incentive scheme by districts with similar parameter specifications. Farmers from the three districts achieved different levels of water saving with the same initial parameter specifications. Cuttack farmers saved a maximum of 77.1 percent of their water, but Jagatsinghpur and Ganjam farmers saved up to 94.7 and 96.8 percent. I observed that, with an increase in per farm initial fixed incentive, the initial per hectare fixed incentive continued to decline. However, the relationships varied by district. Farms in the Ganjam district preferred perennial activities and that reduced the scope of water saving on those farm plots. Therefore, marginal and small farmers who prefer to remain risk-averse should be offered higher initial incentives.

The model was also tested for different farm types. Under a modest water price and with limits on water transfers, highly diversified irrigated agriculture for direct market supply (HDIAM) farms saved 86.35 percent of water. However, as water prices increased, water demand decreased. The limited resources, high water prices, and marginal scale of operations made it difficult to save additional water. On the other hand, the least diversified irrigated agriculture for contacted market supply (LDIACM) farms did not have the same opportunity to save water since a large portion of their farms were devoted to perennial crops. Therefore, due care should be taken in prescribing any institutional solutions for water distribution.

To illustrate the model outcome in terms of crop choice, I used the volume of water saving endogenously in the first model of LP. I observed that, farmers adopted water saving cropping pattern on the lowland plots, whereas vegetables are mostly adopted on the medium and uplands. HDIAM farms showed greater response to the incentive scheme and adopted rice-green gram cropping pattern on most of the lowland plots and seasonal vegetables on the medium and upland plots. Interestingly, the water saving cropping pattern did not decrease the aggregate income for HDIAM farms. LP suggested to shift sugarcane plots to rice-seasonal vegetables on the medium and lowland for the MDLIAM farms. However, for LDIACM farms a few farm plots showed shift in cropping pattern to rice-vegetables or rice-mung bean, and remaining farm plots are left with sugarcane. In these types of farms, present incentive structed was not sufficient to attract farmers to conserve water to extent of an average HDIAM farm. Hence, the study unveiled the scope of water saving by altering cropping pattern at a community level. It further unfolds dual benefits at the WUA level, in ecological and economic front. Reduction in groundwater extraction conserve groundwater ecology and sustain agriculture. This further sustain the groundwater extraction structures. On the other hand, it reduces cost of water and in total, reduces cost of cultivation. This has potential to enhance net return of the farm household.

6.3. Conclusion

In the coastal districts of Odisha, small-scale farming has flourished under the umbrella of the water user association (WUA). Government financial assistance to establish irrigation extraction and distribution networks, the formation of the farmer's organizations (FOs) and registration under the *Pani Panchayat* (PP) Act 2002 benefited farmers by relieving them from the distressing situation of water monopolies. On the other hand, it increased farmers' real farm income by reducing the cost of water. However, opaque institutions involved in water extraction and distribution would jeopardize the sustainability of a WUA. In this regard, a cooperative model has been introduced to incentivize the conservation of water by a member farmer in a Principal-Agent (P-A) model. By implementing various types of incentives and promoting the adoption of water-saving practices, a WUA was able to maximize water savings. However, I observed subtle variations in socio-economic-geo-climatic parameters that impacted water savings. Accordingly, sub-models were developed by farm type, farm size class, and region. The study found that highly diversified irrigated agriculture for direct market supply (HDIAM) farms demonstrated a higher willingness to fulfil the primary objective (WUA), i.e., saving water in return for incentives. The results of the sub-model by farm type indicated that smallholders who adopted water-saving practices, relied heavily upon family labour, and benefited from labour exchange facilities in their villages and thus received the greatest benefit from this incentive program. In contrast, medium and large farms benefited from varying levels of incentives due to the preference they place upon perennial crops. A meagre variable incentive share showed that the contract model is in favour of principal’s planning to retain the benefit and conserve water.

I draw the following policy suggestions from the above salient findings.

6.4. Policy recommendation

A WUA member farmer is relatively better off with respect to the water availability and its per unit cost than a neighbour who is not a member. However, the member farmer experiences higher water price when he sourced water from a private water seller for his non-WUA farm plot. Farmer takes utmost care in water management to reduce the cost of water on those non-WUA plots. In the linear program, I observed that with an increase in water price from the survey period, farmers adopted water saving cropping activities or shifted to a water saving crop in a cropping pattern. Therefore, existing *Pani Panchayat* regulations should be amended to encourage crop diversification towards low water intensive activities, that will conserve groundwater aquifer. However, capital endowed farmers' water demand remained same irrespective of any increase in water price. Therefore, water pricing instrument stand alone may not be effective to induce water conservation behaviour among the farmers. Hence, water pricing mechanism should be combined with volumetric restrictions and other economic incentives.

In the principal-agent model I introduced three types of economic incentives to conserve water with the survey period water price and with increasing water price. Model results indicated water saving over and above the surveyed period water use by adopting water saving crops in the cropping pattern. Farm type wise model further indicated that HDIAM farms are more responsive to the economic instruments, in which the initial fixed incentive attracted them most to adopt water saving activities. However, LDIACM farms continued with existing crops to a greater extent and adopted water saving activities in a few farm plots. Therefore, a WUA should amend existing institutions for water sharing to promote water-saving cropping pattern by advancing multiple fixed and variable incentives to the members in a contract scheme.

Economic incentives for water saving showed different response among different farm types. Hence, the scope of water sharing exclusively among the member farmers creates a water market in an WUA that encourage water saving in the present, and receive an incentive from the WUA, thereby helping to sustain the future of groundwater aquifer.

6.5. Limitation of the research and possible improvisation in the cooperation model

I have observed cooperative behaviour among members in sharing water for incentives. The bonus scheme was included in order to see if a farmer has the ability to show water-saving methods to convince a neighbouring farmer to join the scheme. However, the possibility of interaction with adjoining WUAs is completely overlooked. The moderately diversified limited irrigated agriculture for direct market supply (MDLIAM) farms are typically enclaved by WUAs or privately organized water-sharing systems. Thus, the model can be extended by considering inter-WUA water sharing. By doing so, the model can be scaled up to the village level where many WUA extract water from the same aquifers, and it is the responsibility of each well owner to interact with the other to conserve water in the present.

Moreover, teams may be formed among the farmers based on their land-based activities. In addition, it will further segregate them into net reducers (higher areas under LWI) or net extractors (higher areas under HWI).

I further incorporated this into the incentive scheme to further motivate them to continue water-saving land-based activities and to continue expanding their acreage of water-saving activities. The farms with limited labour availability continue to cultivate a certain area under water-intensive activities (and are deemed as net extractors). As a result, by enforcing the optimal water extraction and distribution plan, the WUA incentivizes the net reducers and extractors. This will allow WUAs to report their water entitlements as net buyers or sellers. An incentive scheme can then be devised to incentivize farmers who conserve water, and the incentive comes from the net buyer. This will ultimately lead to the creation of a village-wide water market that recognizes the choice of cropping for each individual farm. The present research could not take on this noble project, and therefore it is left for future studies.

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APPENDICES

8. Appendices

8.1. Appendix 1: GAMS Code for LP

```
$eolcom #
#3-level LP model for three plot types with Excel-import
#10/2020 for many farms with two stages on farm and on well level
# Set definitions and input
Set block; # from table rhs_well
SET farm;  # from table rhs
SET activity; # from table CropPat
Set plot; # from Table plots
Set topo /lowland, medium, upland/;
Set f_p_t(farm, plot, topo);
Set b_f(block, farm);

Set colitems ;
Set plot_cons_raw /'area.ha'/;
Set farm_cons_raw; # from table rhs
Set well_cons_raw; # from table rhs_well

$setglobal inputfile LPData20210310.xlsx

$call gdxxrw.exe %inputfile% o=blocks_set_re.gdx DSet=block Rng=re_rhs_well!B2  Cdim=0 Rdim=1
$call gdxxrw.exe %inputfile% o=farms_set_re.gdx DSet=farm Rng=re_rhs!C2  Cdim=0 Rdim=1
$call gdxxrw.exe %inputfile% o=plots_set_re.gdx DSet=plot Rng=plots!D2 Cdim=0 Rdim=1
$call gdxxrw.exe %inputfile% o=activities_set_re.gdx DSet=activity Rng=CropPat!G2 Cdim=0 Rdim=1
$call gdxxrw.exe %inputfile% o=farm_cons_set_re.gdx DSet=farm_cons Rng=re_rhs!D2 Cdim=0 Rdim=1
$call gdxxrw.exe %inputfile% o=well_cons_set_re.gdx DSet=well_cons Rng=re_rhs_well!D2 Cdim=0 Rdim=1
$call gdxxrw.exe %inputfile% o=f_p_t_re.gdx Set=f_p_t Rng=plots!C2 Cdim=0 Rdim=3 values=noData
$call gdxxrw.exe %inputfile% o=b_f_re.gdx maxDupeErrors=1000 Set=b_f Rng=re_rhs_well!B2 Cdim=0 Rdim=2 values=noData
$gdxin blocks_set_re.gdx
```

```
$load block
$gdxin farms_set_re.gdx
$load farm
$gdxin plots_set_re.gdx
$load plot
$gdxin activities_set_re.gdx
$load activity
$gdxin farm_cons_set_re.gdx
$load farm_cons_raw=farm_cons
$gdxin well_cons_set_re.gdx
$load well_cons_raw=well_cons
$gdxin f_p_t_re.gdx
$load f_p_t
$gdxin b_f_re.gdx
$load b_f
Set colitems /set.plot_cons_raw, set.farm_cons_raw, set.well_cons_raw, GM/;
Set plot_cons(colitems) /'area.ha'/;
Set farm_cons(colitems); # from table rhs
Set well_cons(colitems); # from table rhs_well
$gdxin farm_cons_set_re.gdx
$load farm_cons
$gdxin well_cons_set_re.gdx
$load well_cons
Display block, farm, plot, activity, plot_cons, farm_cons, well_cons, colitems, f_p_t, b_f;
# Data input
Parameter rhs_plot(farm, plot, topo, plot_cons);
Parameter rhs_farm(farm, farm_cons);
Parameter rhs_farm_backup(farm, farm_cons);         #backup of data
Parameter rhs_well_disag(block, farm, well_cons);   #to load data from rhs_well
Parameter rhs_well(block, well_cons);               #but use the data in aggregated form on well
level
Parameter rhs_well_backup(block, well_cons);        #backup of data
$call gdxxrw.exe %inputfile% o=rhs_plot_re.gdx    Par=rhs_plot  Rng=plots!C1 cdim=1
rdim=3
$call gdxxrw.exe %inputfile% o=rhs_farm_re.gdx    Par=rhs_farm  Rng=re_rhs!C2 cdim=0
rdim=2
$call gdxxrw.exe %inputfile% o=rhs_well_re.gdx    Par=rhs_well_disag  Rng=re_rhs_well!B2
cdim=0 rdim=3
$gdxin rhs_plot_re.gdx
$load rhs_plot
```

$gdxin rhs_farm_re.gdx

$load rhs_farm

$gdxin rhs_well_re.gdx

$load rhs_well_disag

rhs_farm_backup(farm, farm_cons) = rhs_farm(farm, farm_cons);   # backup of constraints because of stage 1

rhs_well(block, well_cons) = SUM(farm$b_f(block, farm), rhs_well_disag(block, farm, well_cons));   # aggregate the rhs on well level

rhs_well_backup(block, well_cons) = rhs_well(block, well_cons); # backup of constraints because of stage 1

Display rhs_plot, rhs_farm, rhs_well_disag, rhs_well;

Parameter tabledata(farm, plot, topo, activity, colitems);

$call gdxxrw.exe %inputfile% o=activitydata.gdx   par=tabledata Rng=CropPat!D1 cdim=1 rdim=4

$gdxin activitydata.gdx

$load tabledata

$gdxin

Display tabledata;

Set water_farm_set(activity) /BuyWater_Rainy, BuyWater_PR, BuyWater_Summer/;   #selection of activities of which gm shall be changed and x.l be observed

Set labour_con_set(farm_cons) /'Tot_Labour_Rainy.MD', 'Tot_Labour_PostRainy.MD', 'Tot_Labour_Summer.MD' /;

Set labour_act_set(activity) /'WAGE_Rainy.INR.MD', 'WAGE_PostRainy.INR.MD', 'WAGE_Summer.INR.MD'/;

Set non_labour_act_set(activity);   #to calculate overall labour use

non_labour_act_set(activity) = yes;

non_labour_act_set(labour_act_set) = no;

Set relev_waterbuy_act(farm, plot, topo, activity);

relev_waterbuy_act(farm, plot, topo, water_farm_set)$(f_p_t(farm, plot, topo) and (sum(farm_cons, abs(tabledata(farm, plot, topo, water_farm_set, farm_cons)))>0)) = yes;

*Display relev_waterbuy_act;

*execute_unload "relev_waterbuy.gdx" relev_waterbuy_act;

Variables and equations

positive variable x(farm, plot, topo, activity);

x.fx(farm, plot, topo, activity) = 0;

x.up(farm, plot, topo, activity)$f_p_t(farm, plot, topo) = INF;

variable *tgm*;

Equations

cons_eq_plot(farm, plot, topo, plot_cons), cons_eq_farm(farm, farm_cons), cons_eq_well(block, well_cons), target_eq;

cons_eq_plot(farm, plot, topo, plot_cons)$f_p_t(farm, plot, topo) .. sum(activity, tabledata(farm, plot, topo, activity, plot_cons) * x(farm, plot, topo, activity)) =l= rhs_plot(farm, plot, topo, plot_cons);

cons_eq_farm(farm, farm_cons) .. sum((plot, topo, activity)$f_p_t(farm, plot, topo), tabledata(farm, plot, topo, activity, farm_cons) * x(farm, plot, topo, activity)) =l= rhs_farm(farm, farm_cons);

cons_eq_well(block, well_cons) .. sum((farm, plot, topo, activity)$(f_p_t(farm, plot, topo) and b_f(block, farm)), tabledata(farm, plot, topo, activity, well_cons) * x(farm, plot, topo, activity)) =l= rhs_well(block, well_cons);

target_eq .. sum((farm, plot, topo, activity)$f_p_t(farm, plot, topo), tabledata(farm, plot, topo, activity, "GM") * x(farm, plot, topo, activity)) =e= *tgm*;

model indialand /all/;

#Stage 1 - without water transfer between farms

#Stage 1.1 vary individual water prices and allow any amount of water to buy (primal approach)

rhs_well(block, "WATER_Rainy_W.HaCm") = INF; # enough water in total

rhs_well(block, "WATER_PostRainy_W.HaCm") = INF;

rhs_well(block, "WATER_Summer_W.HaCm") = INF;

rhs_farm(farm, "Minimum_Water_Rainy")= 0; # no minimum constraint to allow for all levels in loop

rhs_farm(farm, "Minimum_Water_PR")= 0;

rhs_farm(farm, "Minimum_Water_Summer")= 0;

Set price_levels /p1*p25 /; #0% to 120% of reference price

Parameter price_lower /10/;

Parameter price_upper /1600/;

Parameter price_lev(price_levels);

price_lev(price_levels) = price_lower + ((price_upper-price_lower)/card(price_levels)-1) * (ord(price_levels)-1);

Parameter water_demand(farm, water_farm_set, price_levels); # for results

Parameter Xout_pl(farm, plot, topo, activity, price_levels); # for results

Parameter hh_total_labour_pl(farm, price_levels);

Parameter farm_*tgm*_pl(farm, price_levels);

loop (price_levels,

tabledata(farm, plot, topo, water_farm_set , "GM")$relev_waterbuy_act(farm, plot, topo, water_farm_set) = -price_lev(price_levels);

solve indialand using lp maximizing *tgm*;

water_demand(farm, water_farm_set, price_levels) = sum((plot, topo), x.l(farm, plot, topo, water_farm_set));

Xout_pl(farm, plot, topo, activity, price_levels) = x.l(farm, plot, topo, activity);

hh_total_labour_pl(farm, price_levels) = sum((plot, topo, non_labour_act_set, labour_con_set)$f_p_t(farm, plot, topo), tabledata(farm, plot, topo, non_labour_act_set, labour_con_set) * x.l(farm, plot, topo, non_labour_act_set)) ;

farm_*tgm*_pl(farm, price_levels) = sum((plot, topo, activity)$f_p_t(farm, plot, topo) , tabledata(farm, plot, topo, activity, "GM") * x.l(farm, plot, topo, activity));

);

Parameter agr_water_demand(price_levels);

agr_water_demand(price_levels) = SUM((farm, water_farm_set), water_demand(farm, water_farm_set, price_levels));

Parameter hh_water_demand(farm, price_levels);

hh_water_demand(farm, price_levels) = SUM(water_farm_set, water_demand(farm, water_farm_set, price_levels));

Display water_demand, agr_water_demand;

execute_unload "S1.1_water_demand.gdx" water_demand price_lev;

execute 'gdxxrw.exe S1.1_water_demand.gdx o=S1.1_water_demand.xlsx par=water_demand rng=water_demand! par=price_lev rng=price_levels!';

execute_unload "S1.1_aggr_water_demand.gdx" agr_water_demand price_lev;

execute 'gdxxrw.exe S1.1_aggr_water_demand.gdx o=S1.1_aggr_water_demand.xlsx par=agr_water_demand rng=water_demand! par=price_lev rng=price_levels!';

execute_unload "S1.1_hh_water_demand.gdx" hh_water_demand price_lev;

execute 'gdxxrw.exe S1.1_hh_water_demand.gdx o=S1.1_hh_water_demand.xlsx par=hh_water_demand rng=water_demand! par=price_lev rng=price_levels!';

execute_unload "S1.1_hh_total_labour.gdx" hh_total_labour_pl;

execute 'gdxxrw.exe S1.1_hh_total_labour.gdx o=S1.1_hh_total_labour.xlsx par=hh_total_labour_pl';

execute_unload "S1.1_xresults.gdx" Xout_pl farm_*tgm*_pl;

execute 'gdxxrw.exe S1.1_xresults.gdx o=S1.1_xresults.xlsx par=Xout_pl par=farm_*tgm*_pl rng=farm_*tgm*_pl!';

*execute_unload "activitydata_1.1.gdx" tabledata;

#Stage 1.2

#usage of 100% of farm-level water without trade (dual approach) -> reference solution with water price = 0 and limit of water

tabledata(farm, plot, topo, water_farm_set , "GM")$relev_waterbuy_act(farm, plot, topo, water_farm_set) = 0;

Parameter water_buy_farm_ref(farm, activity);

loop (block,

water_buy_farm_ref(farm, "BuyWater_Rainy")$b_f(block,farm) = rhs_well_disag(block, farm, "WATER_Rainy_W.HaCm");

water_buy_farm_ref(farm, "BuyWater_PR")$b_f(block,farm) = rhs_well_disag(block, farm, "WATER_PostRainy_W.HaCm");

water_buy_farm_ref(farm, "BuyWater_Summer")$b_f(block,farm) = rhs_well_disag(block, farm, "WATER_Summer_W.HaCm");

);

Display water_buy_farm_ref;

x.fx(farm, plot, topo, water_farm_set)$relev_waterbuy_act(farm, plot, topo, water_farm_set) = water_buy_farm_ref(farm, water_farm_set);

solve indialand using lp maximizing *tgm*;

```
Display cons_eq_farm.m;

Parameter Xout12(farm, plot, topo, activity);

Xout12(farm, plot, topo, activity) = x.l(farm, plot, topo, activity);

Parameter farm_tgm(farm);

farm_tgm(farm) = sum((plot, topo, activity)$f_p_t(farm, plot, topo)    , tabledata(farm, plot,
topo, activity, "GM") * x.l(farm, plot, topo, activity));

execute_unload "S1.2_xresults.gdx" Xout12 farm_tgm;

execute 'gdxxrw.exe S1.2_xresults.gdx o=S1.2_xresults.xlsx par=Xout12 rng=xresults!
par=farm_tgm rng=farm_tgm!';

#Stage 1.3

# Modify individual water levels without trade  # REC 36:00, THEN I compare 1.3 and 2.2 #

tabledata(farm, plot, topo, water_farm_set , "GM")$relev_waterbuy_act(farm, plot, topo, wa-
ter_farm_set) = 0;

Set water_levels1 /w1*w25/;

Parameter water_increment1 /0.05/;

Parameter Xout13(farm, plot, topo, activity, water_levels1);

Parameter farm_tgm1(farm, water_levels1);

loop(water_levels1 ,

loop (block,

 water_buy_farm_ref(farm, "BuyWater_Rainy")$b_f(block,farm) = rhs_well_disag(block, farm,
"WATER_Rainy_W.HaCm") * ord(water_levels1) * water_increment1;

 water_buy_farm_ref(farm, "BuyWater_PR")$b_f(block,farm) = rhs_well_disag(block, farm,
"WATER_PostRainy_W.HaCm")  * ord(water_levels1) * water_increment1;

 water_buy_farm_ref(farm, "BuyWater_Summer")$b_f(block,farm) = rhs_well_disag(block,
farm, "WATER_Summer_W.HaCm")  * ord(water_levels1) * water_increment1;

 );

Display water_buy_farm_ref;


x.fx(farm, plot, topo, water_farm_set)$relev_waterbuy_act(farm, plot, topo, water_farm_set) =
water_buy_farm_ref(farm, water_farm_set);

solve indialand using lp maximizing tgm;

Xout13(farm, plot, topo, activity, water_levels1) = x.l(farm, plot, topo, activity);

farm_tgm1(farm, water_levels1) = sum((plot, topo, activity)$f_p_t(farm, plot, topo)  , ta-
bledata(farm, plot, topo, activity, "GM") * x.l(farm, plot, topo, activity));

);


execute_unload "S1.3_xresults.gdx" Xout13 farm_tgm1;

execute 'gdxxrw.exe S1.3_xresults.gdx o=S1.3_xresults.xlsx par=Xout13 rng=xresults! par=tgm
rng=tgm!';


#Stage 2 - allow for water trade within well blocks
```

#Stage 2.1: Limited Kaldor-Hicks compensation with water price = 0 and limited overall water quantity including limited seasonal water transfer on well level

rhs_well(block, well_cons) = rhs_well_backup(block, well_cons); # restore the aggregate water capacities on well level

rhs_farm(farm, farm_cons) = rhs_farm_backup(farm, farm_cons); # restore minimum constraints on farm-level

x.lo(farm, plot, topo, water_farm_set)$relev_waterbuy_act(farm, plot, topo, water_farm_set) = 0; # unfix water purchase again

x.up(farm, plot, topo, water_farm_set)$relev_waterbuy_act(farm, plot, topo, water_farm_set) = INF;

execute_unload "activitydata_2.1.gdx" tabledata;

solve indialand using lp maximizing *tgm*;

farm_*tgm*(farm) = sum((plot, topo, activity)$f_p_t(farm, plot, topo) , tabledata(farm, plot, topo, activity, "GM") * x.l(farm, plot, topo, activity));

Parameter Xout21(farm, plot, topo, activity);

Xout21(farm, plot, topo, activity) = x.l(farm, plot, topo, activity);

execute_unload "S2.1_xresults.gdx" Xout21 farm_*tgm*;

execute 'gdxxrw.exe S2.1_xresults.gdx o=S2.1_xresults.xlsx par=Xout21 rng=xresults! par=farm_*tgm* rng=farm_*tgm*!';

#Stage 2.2: Sensitivity on quantities on well level 0 to 120 % of well-specific reference level #including limited seasonal water transfer on well level water price = 0

* # Here min water level is set above 0 because with previous statement, many farms showed infeasible solution until 9th water level.

rhs_farm(farm, "Minimum_Water_Rainy")= rhs_farm_backup(farm,"Minimum_Water_Rainy")*0.5; # minimum constraint at 0.5

rhs_farm(farm, "Minimum_Water_PR")= rhs_farm_backup(farm,"Minimum_Water_PR")*0.5;

rhs_farm(farm, "Minimum_Water_Summer")= rhs_farm_backup(farm,"Minimum_Water_Summer")*0.5;

Set water_levels /w1*w25/;

Parameter water_increment /0.05/;

Parameter Xout22(farm, plot, topo, activity, water_levels);

Parameter farm_*tgm*_wl(farm, water_levels);

Parameter hh_total_labour_wl(farm, water_levels);

Parameter water_demand_wl(farm, water_farm_set, water_levels);

Parameter agr_water_demand_wl(water_levels);

```
Parameter hh_water_demand_wl(farm, water_levels);


*to test the model status (as text) optimal, unbounded, infeasible, etc.
* I used put function to output the Status of model by using "TModstat" function.


File statfile /Modelstat2.2.txt/;
put statfile;
put statfile "Modelstat2.2.txt";


loop(water_levels,
  rhs_well(block, "WATER_Rainy_W.HaCm") =  rhs_well_backup(block, "WATER_Rainy_W.HaCm") * (ord(water_levels)-1) * water_increment;
  rhs_well(block, "WATER_PostRainy_W.HaCm") =  rhs_well_backup(block, "WATER_PostRainy_W.HaCm") * (ord(water_levels)-1) * water_increment;
  rhs_well(block, "WATER_Summer_W.HaCm") =  rhs_well_backup(block, "WATER_Summer_W.HaCm") * (ord(water_levels)-1) * water_increment;
  solve indialand using lp maximizing tgm;
  put water_levels.tl indialand.TModstat / ;
  Xout22(farm, plot, topo, activity, water_levels) = x.l(farm, plot, topo, activity);
  hh_total_labour_pl(farm, price_levels) =  sum((plot, topo, non_labour_act_set, labour_con_set)$f_p_t(farm, plot, topo), tabledata(farm, plot, topo, non_labour_act_set, labour_con_set) * x.l(farm, plot, topo, non_labour_act_set))  ;
  water_demand_wl(farm, water_farm_set, water_levels) = sum((plot, topo), x.l(farm, plot, topo, water_farm_set));
  hh_total_labour_wl(farm, water_levels) =  sum((plot, topo, non_labour_act_set, labour_con_set)$f_p_t(farm, plot, topo), tabledata(farm, plot, topo, non_labour_act_set, labour_con_set) * x.l(farm, plot, topo, non_labour_act_set))  ;
  farm_tgm_wl(farm, water_levels) = sum((plot, topo, activity)$f_p_t(farm, plot, topo)  , tabledata(farm, plot, topo, activity, "GM") * x.l(farm, plot, topo, activity));
);
putclose statfile;


hh_water_demand_wl(farm, water_levels) = SUM(water_farm_set, water_demand_wl(farm, water_farm_set, water_levels));
agr_water_demand_wl(water_levels) = SUM((farm, water_farm_set), water_demand_wl(farm, water_farm_set, water_levels));


execute_unload "S2.2_xresults.gdx" Xout22 farm_tgm_wl;
execute 'gdxxrw.exe S2.2_xresults.gdx o=S2.2_xresults.xlsx par=Xout22 rng=xresults! par=farm_tgm_wl rng=S2.2.farm_tgm!';
execute_unload "S2.2_hh_total_labour.gdx" hh_total_labour_wl;
```

execute 'gdxxrw.exe S2.2_hh_total_labour.gdx o=S2.2_hh_total_labour.xlsx par=hh_total_labour_wl';

execute_unload "S2.2_water_demand.gdx" water_demand_wl;

execute 'gdxxrw.exe S2.2_water_demand.gdx o=S2.2_water_demand.xlsx par=water_demand_wl rng=water_demand!';

execute_unload "S2.2_hh_water_demand.gdx" hh_water_demand_wl;

execute 'gdxxrw.exe S2.2_hh_water_demand.gdx o=S2.2_hh_water_demand.xlsx par=hh_water_demand_wl rng=water_demand!';

execute_unload "S2.2_aggr_water_demand.gdx" agr_water_demand_wl;

execute 'gdxxrw.exe S2.2_aggr_water_demand.gdx o=S2.2_aggr_water_demand.xlsx par=agr_water_demand_wl rng=water_demand!';

execute_unload 'S2.2_shadow.gdx' cons_eq_farm;

execute 'gdxxrw.exe S2.2_shadow.gdx o=S2.2_shadow.xlsx par=cons_eq_farm rng=water_demand!';

*#Stage 2.3: Sensitivity of Model 2 with different prices

#well level water availability = 100% of reference

rhs_farm(farm, farm_cons) = rhs_farm_backup(farm, farm_cons);   # restore minimum constraints on farm-level

rhs_well(block, "WATER_Rainy_W.HaCm") = rhs_well_backup(block, "WATER_Rainy_W.HaCm")*2.0;

rhs_well(block, "WATER_PostRainy_W.HaCm") = rhs_well_backup(block, "WATER_PostRainy_W.HaCm")*2.0;

rhs_well(block, "WATER_Summer_W.HaCm") = rhs_well_backup(block, "WATER_Summer_W.HaCm")*2.0;

loop (price_levels,

tabledata(farm, plot, topo, water_farm_set , "GM")$relev_waterbuy_act(farm, plot, topo, water_farm_set) = -price_lev(price_levels);

solve indialand using lp maximizing *tgm*;

Xout_pl(farm, plot, topo, activity, price_levels) = x.l(farm, plot, topo, activity);

water_demand(farm, water_farm_set, price_levels) = sum((plot, topo), x.l(farm, plot, topo, water_farm_set));

hh_total_labour_pl(farm, price_levels) = sum((plot, topo, non_labour_act_set, labour_con_set)$f_p_t(farm, plot, topo), tabledata(farm, plot, topo, non_labour_act_set, labour_con_set) * x.l(farm, plot, topo, non_labour_act_set)) ;

farm_*tgm*_pl(farm, price_levels) = sum((plot, topo, activity)$f_p_t(farm, plot, topo) , tabledata(farm, plot, topo, activity, "GM") * x.l(farm, plot, topo, activity));

);

agr_water_demand(price_levels) = SUM((farm, water_farm_set), water_demand(farm, water_farm_set, price_levels));

hh_water_demand(farm, price_levels) = SUM(water_farm_set, water_demand(farm, water_farm_set, price_levels));

execute_unload "S2.3_aggr_water_demand.gdx" agr_water_demand price_lev;

execute 'gdxxrw.exe S2.3_aggr_water_demand.gdx o=S2.3_aggr_water_demand.xlsx par=agr_water_demand rng=water_demand! par=price_lev rng=price_levels!';

execute_unload "S2.3_hh_water_demand.gdx" hh_water_demand price_lev;

execute 'gdxxrw.exe S2.3_hh_water_demand.gdx o=S2.3_hh_water_demand.xlsx par=hh_water_demand rng=water_demand! par=price_lev rng=price_levels!';

execute_unload "S2.3_hh_total_labour.gdx" hh_total_labour_pl;

execute 'gdxxrw.exe S2.3_hh_total_labour.gdx o=S2.3_hh_total_labour.xlsx par=hh_total_labour_pl';

execute_unload "S2.3_xresults.gdx" Xout_pl farm_*tgm*_pl;

execute 'gdxxrw.exe S2.3_xresults.gdx o=S2.3_xresults.xlsx par=Xout_pl rng=xresults! par=farm_*tgm*_pl rng=farm_*tgm*!';

*execute_unload "activitydata_2.3.gdx" tabledata;

8.2. Appendix 2: GAMS code for Principal-agent Model

```
$TITLE A Principal-agent Model of water-saving contract: An empirical validation
```

The modelling framework

```
set J farmers /1*52/
    T year /2019/
;
Table fwa(J,T) input data for per farm water availability in cubic metre
        2019
#water data#
;
Table psia(J,T) input data for farm-level psi i.e slope of the cost functions
# data: farm-level cost coefficients #
;
Table phi(J,T) input data for farm-level phi i.e intercept of the cost functions
         2019
# data: farm-level cost coefficients #
;
Table ms(J,T) input data for farm-level phi i.e intercept of the cost functions
         2019
#data: farm-level cost coefficients #
;
Table kappa(J,T) reservation price i.e next best employment possibility by Furubtn & Richter
2011
*This is estimated by taking the difference of minimum gross margins of irrg
*and rainfed plots for a farm from LP croppat data from excel.
         hs (J,T)        conversion coefficient for land to water cubic meter per ha
         psi(J,T)        slope of cost function INR per ha
         phi(J,T)        intercept of the cost function INR per ha
         kappa           reservation utility of farmer (next best employment possibility by Furubtn &
                             Richter 2011. This is estimated by taking the difference of minimum gross
                             margins of irrigated and rainfed plots for a farm) INR per ha /500/
         Land_data(J,T)  data of land area
         member          number of the farmers /18/
         pricewat        water price in INR per cubic meter /1.50/
         A               total land area of WUA  ha
;
         Land_data(J,T) =fwa(J,T)*ms(J,T);
         A= sum(T,sum(J,land_data(J,T)));
         hs(J,T) = (1/ms(J,T));
         psi(J,T)= psia (J,T)*1;
positive variables
         alpha(J,T)      share of farmer
         beta            share of farmer as bonus
         ls(J,T)         land area under contract
         eta             adjustment factor
;
Display hs, psi, phi, kappa, land_data, A;
variables
```

```
        PI(J,T)                principals obj
        totarea                total area under contract scheme
        nprincipinc(J,T)       principals income
        bonus(J,T)             bonus offered by principal
        agbonus                aggreagte bonus
        revenue
        r(J,T)                 initial payment in water-saving contract
        netprincipinc          Net principal income
        tPI                    total income of principal
        totrs                  total initial incentive
        totshare               total revenue share
*control test variable
;
Equations
        qrevenue               revenue of WUA
        qprincipinc(J,T)       principals income
        qtotprincipinc         gross income of principal
        qincconstr(J,T)        incentive constraint
        qnetprincipinc(J,T)    principals net income
        qtnetprincipinc        toatl net income of principal
        qpartconstr            participation constraint
        qlandconstr(J,T)       constraint on land under contract scheme
        qbonus(J,T)            bonus calculation
        qagbonus               aggregate bonus
        qtotarea               total area under the contract scheme
        qbeta                  bargaining share - on upper side
        qbeta2                 restriction on beta on lower side
        qtotrs                 total rs  -
        qtotshare              total revenue share   -
        qeta                   restrictions adjustment factor upper limit    -
        qeta2                  restrictions on eta as lower limit  -
*       qr (J,T)               restriction on r i.e minimum initial payments
*       qnetincconstr          principal decent net income
*       qsecincostr second incentive constraint
*       qcontrol
;
****************** PRINCIPAL INCOME EQUATION       *********************
qprincipinc(J,T)..             PI(J,T)=E=
                               (1-alpha(J,T))*(pricewat*hs(J,T)*ls(J,T)-r(J,T))
;
*******************GROSS INCOME OF THE PRINCIPAL******************
qtotprincipinc..               tPI=E=
                               sum(T,sum(J,(PI(J,T))))
;
*****************PRINCIPAL'S NET INCOME**********************
qnetprincipinc(J,T)..          nprincipinc(J,T)=E=
                                   (1-beta)*PI(J,T)
;
*********TOTAL NET INCOME OF PRINCIPAL******************
```

```
qtnetprincipinc..              netprincipinc=E=
                                   sum(T,sum(J,nprincipinc(J,T)))
;
*********INCENTIVE CONSTRAINT   ****************************
* In order to make the water-saving contract viable, linear incentive provided to farmers must
cover the cost of transition to new mode of irrigation or cultivation. Hence
**************************************************************
qincconstr(J,T)..              ls(J,T)=E=
                              (alpha(J,T)*(1/psi(J,T))*pricewat*hs(J,T))
                              -((1/psi(J,T))*phi(J,T))+(beta
                              *(1/psi(J,T))*((totarea)/(A*A))*tPI)
;
*********TOTAL AREA UNDER CONTRACT SCHEME**************
qtotarea..                   totarea=E=
                              sum(T,sum(J,ls(J,T)))
;
*********REVENUE OF WATER USER ASSOSICATION *********************
*qrevenue..                    revenue=E=
*                               totarea*hs(J,T)*pricewat
qrevenue..                   revenue=E=
                              sum(T,sum(J,ls(J,T)*hs(J,T)))*pricewat
;
*********PARTICIPATION CONSTRAINT   *************************
* Participation of farmers is ensured when the additional benefit realized by engaging in con-
tract is at least equals to farmer's reservation utility. I simplify this condition by constraining the
additional income from the contractual arrangement to be greater than or equal to zero.
*************************************************
qpartconstr(J,T)..             r(J,T)=E=
                              (phi(J,T)*ls(J,T))
                                   +(0.5*psi(J,T)*ls(J,T)*ls(J,T))
                                        -(alpha(J,T)*pricewat*hs(J,T)*ls(J,T))
                                             -eta*(beta*ls(J,T)*((totarea)/(A*A))*tPI)
                                                  +(kappa*ls(J,T))
;
*********CONSTRAINT ON LAND UNDER CONTRACT SCHEME**************
qlandconstr(J,T)..             ls(J,T)=L=
                              Land_data(J,T)
;
*********BARGAINING SHARE   ******************************
qbeta..                 beta=L=0.9
;
qbeta2..                 beta=G=0.00015
;
*********ADJUSTMENT FACTOR  ******************************
qeta..                 eta=L=1
;
qeta2..                 eta=G=0.00
;
*********BONUS CALCULATION   *****************************
```

```
qbonus(J,T)..                bonus(J,T)=E=
                             beta*((ls(J,T)*totarea)/(A*A))*tPI
;
*********AGGREGATE BONUS   *******************************
qagbonus..                  agbonus=E=
                             sum(J,sum(T,bonus(J,T)))
;
*qcontrol..control=E=sum(T,sum(J,r(J,T)))/(pricewat*hs(J,T));
*qsecincostr..totarea=L=control;
*********TOTAL NET PRINCIPAL INCOME     **************************
****************A minimum income to be earned by Princi-
pal**************************
*qnetincconstr..              netprincipinc=G=20000;

****************************************************
qtotrs..                   totrs =E=sum(T,sum(J,r(J,T)))
;
***********************************************
qtotshare..                       totshare =E=sum(T,sum(J,alpha(J,T)*(pricewat*hs(J,T)*ls(J,T)-
r(J,T))))
;
*qr(J,T)..                        r(J,T) =G=0;
*********MODEL NAME DECLARATION   ***************************
Model princagent /all/
;
*********SOLVE STATEMENT   *******************************
Solve princagent using DNLP maximizing tPI
;
*********DISPLAY STATEMENT    *******************************

Display r.l,alpha.l,beta.l,tPI.l,ls.l,totarea.l,bonus.l,nprincipinc.l, agbonus.l, revenue.l,eta.l, totrs.l,
totshare.l, netprincipinc.l
;
$ontext
```

8.3. Appendix 3: Survey tools

The data collection is now sub divided into 3 parts.

A. FGD at village level

Goal: What types of group arrangements in groundwater irrigation distribution are sustainable in Odisha?

Aim1: I want to know how crops does are irrigated since 1960s. When was the groundwater irrigation system first introduced at this village and by whom? *Please provide information on all sorts of irrigation system in a timeline till present.*

i. When was it first constructed by a villager at his own cost or by availing a financial subsidy scheme from govt./NGO source? How many bores were installed and what is the present number of bores? What was the irrigated area and present irrigated area? Did he share water to another farmer? How much was the water cost and present water cost?
ii. When was it constructed by a govt. initiative? How many bores were installed and what is the present number of bores? What was the irrigated area and present irrigated area? How many farmers shared water and present no. of benefitted farmer? How much was the water cost and present cost? How is the cost decided?
iii. When was it constructed by a group of villagers at their own cost or through a scheme from govt./ NGO source (ex. Cluster tube well)? How many bores were installed and what is the present number of bores? What was the irrigated area and present irrigated area? Did he share water to another farmer? How much was the water cost and present water cost?

Aim2: I want to know what the crops are being cultivated since 1960s with or without irrigation at different type of farm plots (upland, medium land, low land) with respective varieties. *Please provide information on all sorts of crops cultivated in a timeline till present.*

i. What are the crop area with and without irrigation in *kharif*, *rabi* and summer in different type of farm plots?
ii. What agronomic operations (such as plot making, ridge and furrow making, land levelling, etc.) and other technological knowledge were applied for saving water on unirrigated plots and water management on irrigated plots?
iii. What crop requires minimal, medium, and high irrigation, and during which crop growth period?
iv. On which crop and in what farm operation, labour involvement are minimal, medium, and high, and why?
v. Since when and how different farm technologies (such as chemicals for weed/insect-pest/disease management, IPM, INM, IDM) are being used in this village? Whether these technologies saved labour engagements on different farm operations? If yes, how the save labour are re-employed in other farm or no farm operations?

Aim3: I want to know, how did farmers of this village self-organized as a group to perform different farm activities?

i. How do farmers decide the optimal/ functional group size for sharing groundwater?
ii. What are the determining factors for optimal/ functional group size? *Please probe on determinants such as Hydrology: depth of water table, water discharge, etc.; Nature: Land topography and gradient, soil type, depth of soil, crop suitability, and other farm requirements; Farmers' own experience in group water-sharing; Administrative intelligence of OLIC such as official guidelines, irrigation structure suitability as per socio-cultural-economic behaviour of farmer*
iii. How does farmers collectively perform respective farm activities in this village (such as land preparation, sowing, irrigation, harvesting, marketing, etc.)?
iv. In this village, how do the group action in groundwater resource management, labour sharing, and other crop production and post-harvest management practices takes place?
v. What is the present level of awareness and action taken, if any for the sustainability of the groundwater resources in this village?
vi. How do any rules and regulations can be implemented for sustainable management of groundwater resource?
    a. By adopting precision farming method (performing right crop at right plot at right season)
    b. By developing a common reference level of groundwater irrigation for a unit area or for a farmer
    c. Charging fee for additional water demanded and by offering benefit for saving water with reference to the common reference level of groundwater

B. Secondary and Primary data (observation and measurements)

Aim4: I want to know total labour force available at the village, their emigration and immigration pattern; and seasonal variation in soil water moisture from variables rainfall and river base flow.

i. What is the present number of Households in this village? How many village labourers are frictionally available at village?
ii. How many agricultural and non-agricultural labourers emigrate seasonally and for the long time period?
iii. How many labourers immigrates to this village to meet seasonal agricultural production?
iv. What is the monsoon rainfall onset time in this village? Has there been any change on it? How?
v. Whether cropping pattern and crop rotation, irrigation frequency types of decision are influenced by that? How?
vi. What is the present water table in house bore? *Please answer by number of pipes are fitted or by measurement in feet/ metre.*
vii. How does the nearby river water flow in different season determines crop production decision? Does it also influence irrigation frequency? Does it also influence crop yield?

C. GES level (WUA or GSP, JWE, CTW)

Please provide me the delineated area map of the WUA. Please show me the present status of underground water distribution system and surface channel system functioning in the WUA on the map. Please also show any additional piped water distribution system developed by the WUA themselves or constructed by the OLIC in the subsequent development phase.

Aim5: I want to know, how the group size was decided, in terms of its membership and ayacut area.

i. How do you decide the ayacut area of the *Pani Panchayat* (PP), specifically the delineation of the ayacut area?
ii. How does a farmer become beneficiary farmer? Is the membership transferable and under what conditions?
iii. What are the objectives of a farmer to avail PP membership? What benefit and cost he foresee by joining the PP
iv. When PP bore is provided by a govt. organization, whether the cropping pattern and crop rotation decisions are taken collectively, to cover all operational costs?
v. How do the PP decide the water fee for the member farmer?
    a. Is it per unit area for a year or per unit area per crop growing period or per hours?
vi. Does the PP shares/lend water to neighbouring PP farmland? How are the payments decided?
vii. Does the PP shares/lend water to non-PP member? How are the payments decided?
    Please probe that, whether the payment is direct per unit area per year/ per unit area per crop growing period/ per hour/ others. Also ask if the water price is higher than PP member cost or not, by how much and why?
viii. In case of JWE/CTW, how does a well owner influences the water buyer’s crop choice decision? How does the well owner decide the water cost?
ix. What are the objectives of a farmer to avail water from a JWE? What benefit and cost he foresee by availing water from JEW?
x. What are the objectives of a farmer to avail water from a CTW? What benefit and cost he foresee by availing water from CTW?

Aim6. I want to know what functional rules and regulation PP has developed/implemented from PP Act.

i. What are the functional regulations applicable when a member farmer do not pay the commonly greed water fee?
    a. Is there any regulation to discontinue water provision or fine on the outstanding amount?
ii. What are the functional regulations applicable when a farmer cultivates a crop by disobeying the commonly agreed cropping pattern or crop rotation?
iii. What do the PP do when the well discharge decreases and is not sufficient to meet regular water demand?
    a. Do they reduce irrigated ayacut area in a particular season?
    b. Do they charge higher water fee for meeting the required water demand when pump is operated for increased number of hours?
    c. Are there any alternate arrangements made for meeting required water demand by the PP?

Aim7. I want to develop the water equivalent unit to measure the physical output of the water and the group dynamics. I want to know the marginal returns to water.

Aim8. I want to know, how the PP has experienced its optimal area of operation to which irrigation can be provided. How does the PP realize optimal/functional number of beneficiary farmer for this WUA?

i. What are the technical problems WUA realized in terms of bore and pump functioning across the seasons? How do they attempt to solve the problems?
ii. What are the organizational problems WUA realized in terms of dispute of water distribution, water fee collection, emergency fund requirement when pump break down or damage of pipeline, etc.? How do they attempt to solve the problems?
iii. Are there any social or cultural disparities in terms of decision-making process for bore installation, water distribution, water fee determination?
iv. Are there any subgroup formation in this PP that shares farm inputs as well as costs for optimizing group benefit? How does they affect the PP objective?

2) Farm plot level
   A. Demographic info of the farm household
   B. The detailed farm information on the parcel map
   C. I-O data of major crops at each plot level

D. Questionnaire for farm surveys

Survey Questionnaire on the PhD Research Topic:
CONFIDENTIAL
For research purpose only
HOUSEHOLD QUESTIONNAIRE
INTRODUCTION

"My name is Surajit Haldar I am pursuing my P.hD. at the Justus Liebig University Giessen, Germany. This research carried out with the aim of examining the institutional innovation in groundwater governance community lift irrigation system in Odisha. Your answers will help us to understand the experiences and concerns of the people living in the area.
Please ask me to explain if you don't understand any of the questions I am asking. Everything you will tell me will be kept confidential and your name, farm identification will not be used in any research. May we begin now?
Thank you very much for your participation!"

A. BACKGROUND

1. Date:_______________________________________
2. Household number/ID: ________________________
3. Name of enumerator: ____
4. Language of the Interview: (1) Odia (2) Hindi(3) English (5) Other:_________________
5. GPS North: ____
6. GPS East: ___________________________________

7. Outcome of Interview: Did the household participate?

Yes O
No O

B. GENERAL INFORMATION

1. Name of respondent:		2. Caste/tribe:	3. Religion:
4. Contact No.:	5. Village:	6. Block:	7. Police station:
8. District:	9. How long you have been in farming (years)? _	10. In what crop you are a specialized?	

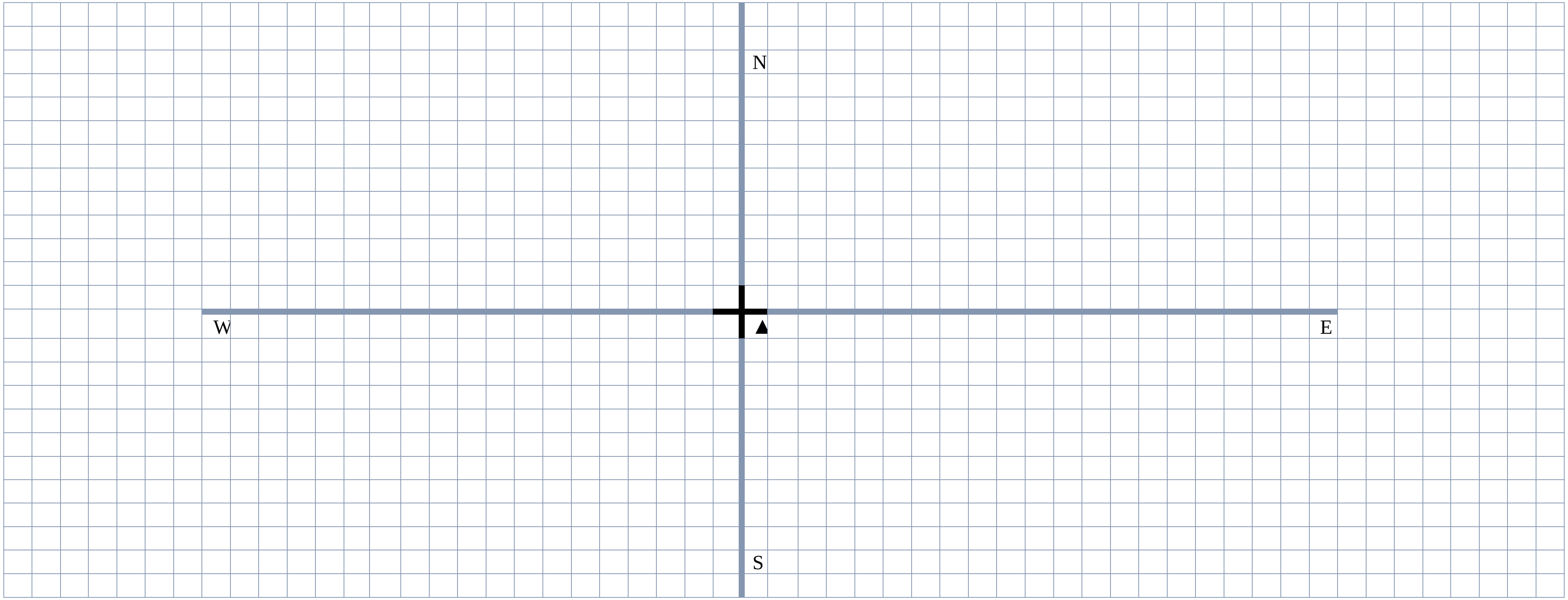
C. DEMOGRAPHY INFORMATION(Include family and non-family members living permanently in the household & taking food from the same kitchen)

1. HH member	2. Relation to head[a]	3. Sex 1=male, 2=female	4. Age	5. Civil status[c]	6. Education (Years of schooling)	7. Occupation and Income					
						7.1 Primary			7.2 Secondary		
						7.1.1 Vocation[e]	7.1.2 Mandays	7.1.3 Income (INR)	7.2.1 Vocation[e]	7.2.2. Mandays	7.2.3 Secondary income (INR)

Relation to head[a] 0= Household head 1=Wife/Husband 2= Son 3=Daughter 4=Parents 5=Grandparents 6=Son/Daughter-in-law 7=Grandson/daughters	8=Parents-in-law 9 = Brother/Sister-in-law 10 = Brother/Sister 11 = Nephew/Niece 12 = Uncle/Aunt 13 = Domestic helper 14. Others Sex[b]:1=Male, 2=Female	Civil status[c] 1=Married, 2=single, 3= widow Vocation[e] 1=Agriculture(farming) 2=Salaried job(Govt. as well as private employee) 3=Service (carpenter/ blacksmith/ barber etc.) 4= business 5=Non-farm labourer	6=Agricultural labourer 7=Household job 9=Handicraft/processing/cottage industry 10=Livestock/poultry farming 11=Fisherman 12=Mechanic(electrical repairing/ electronic repairing/ plumber/fitter/motor cycle garage/etc.) 13=Student 14=Others

D. PARCEL MAP(DURING THE SELECTED REFERENCE PERIOD)

Resource mapping including farm/sources of irrigation/cattle shed/storage godown/farm machinery shed/etc. Write approximate distance from the house (assuming in the centre)



E. DETAILS OF TOTAL LANDHOLDING

1) Particulars	Total area (local unit __________________)	No. of parcels
2) Owned		
3) Homestead		
4) Cultivated land		
5) Aquaculture area		
6) Long-term pasture		
7) Leased-in		
8) Leased-out		

APPENDICES

E.1 DETAILS OF AGRICULTURAL LANDHOLDING

1. Parcel Name	2. Plot No.	3. Area (unit ____)	4. Topography[a]	5. Soil type[b]	6. Tenurialstatus[c]	7. Rent paid/ Received (INR/ kind)	8. Sources of irrigation[d]	9. Parcel location[e]	10. Irrigation method[f]	11. Sources of energy[g]	12. Land Management[h]	
											12.1 Type of conservation (key)	12.2Initial cost (INR)

(Local land measurement reference- 1 Guntha=4 Cent, 1 Bharana = 33 or 28 Cent,1Bharana=32 Niyati, 1 Mano= 100 Cent, 100 cent= 1acre, 2.5 acre= 1 ha)

[a]. Topography	[b]. Soil type	[c]. Tenurial status	[d]. Sources of irrigation	[e]. Parcel location	[f]. Irrigation method	[g]. Sources of energy	[h]Land Management :
1=Upland (bunded) 2=Upland(unbunded) 3=Medium 4=Lowland 5=Very lowland	1=Clay 2=Clay loam 3=Sandy clay loam 4=Sandy loam 5=Loamy sand 6=Loam 7=Sandy(balia)	1=Owned 2=Leased-in(share cropping) 3=Leased–in(fixed rent) 4=Leased-out 5=Mortgage- in	1=Community T/W (GSP) 2= Cluster T/W (CTW) 3=Joint invested pvt. T/W (JWE) 4= Own private T/W 5=Dugwell 6=Canal 7=River lift 8=Pond, 9= Unirrigated	1=Head 2=Middle 3=Tail	1=Gravity flow 2=Sprinkler 3=Drip	1=Electric motor 2=Diesel motor 3= Kerosene motor	1=Drainage, 2= Green manuring, 3=Nutrient management, 4=Tillage 5= Crop rotation, 6= Vermiculture, 7= others

F. LANDUSE DURING KHARIF (Rainy season), RABI (Post rainy) AND SUMMER

1. Parcel	2. Plot	3. Crop Name	4. 1=Sole, 2= Inter 3= mixed cropping	5. Variety Name	6. Seed source[¥]	7. 1=Modern, 2=Traditional Var.	8. Cropped Area (local unit _____)	9. Crop. Estd. Method. (1: Dry Seeded 2: Wet seeded 3: Transplanted)	10. Planting Time (MM-WW)	11. Harvesting Time (MM-WW)	12. Freq. of irrigation	13. Duration ofwater Supply		14. How much do you pay/invest for availing irrigation?	15. Unit [€]	16. Main Product		17. By-product	
												13.1 Normal year	13.2 Dry year			16.1 Production (local unit _________)	16.2 Price (Rs)	17.1 Production (local unit ______)	17.2 Price (Rs)
F.a. Kharif (Rainy season crops: June-																			
F.b. Rabi (Post-rainy season crops: Winter season crops)																			

F.c. Summer crops																			
F.d. Annual Crops																			

¥ Seed source: 1: own, 2: neighbour farmer, 3: seed dealer, 4: govt. seed farm, 5: seed company, 6: others:___________________________

€Unit=per: 1-Hour, 2= Guntha, 3= Bharana of 28 decimal, 4= Bharana of 32 decimal, 5= acre, 6= crop, 7=year, 8= others _______

F.2 PLANTATION CROP

Parcel	Plot	Crop Name	Sole crop, Inter /mixed crop	Variety Name	1=Modern, 2=Traditional Var.	Cropped Area(local unit ______)	Planting method. (square/ hexagonal/ others ______)	Plant density/ac	Spacing	Date of planting (year)	No. of harvest /annum	Production (local unit _______)	Price (INR/ unit)

G. To be asked at second level FGD for WUA/JWE

G.1 Irrigation facilities used for crop production: Well information

1 Type *(key)*	2 Yr.of installation	3 If Govt. project? (1-Y, 2-N)	4 Name of the project	5 PP formed? (1-Y, 2-N)	6 If WUA project, no. of beneficiary	7 Investment made (INR)	8 Well depth (bgl in m)	9 Initial Ayacat area (ha)			10 Present Ayacat area (ha)			11 Who owns? *(key)*
								9.1 Kharif	9.2 Rabi	9.3. Summer	10.1 Kharif	10.2 Rabi	10.3 Summer	

Note- BGL: Below ground level

G.2 Pump information

1 Pump ownership	2 Type (key)	3. Pump horse power (hp)	4. Per hour diesel/kerosene/ electric consumes (kw)	5 Year purchased (if you own it)	6 Purpose (key)	7 Lifespan (No. of years)	8 Initial purchase value (INR)	9 Current Purchase price (INR)	10 Repair cost during 2018-19 (INR)	Discharge (l/min)		13 Pumping head (static) (bgl in m)	14 Diameter of the lifting pipe (inch)	15 Diameter of the distribution pipe (inch)
										11 Initial	12 Present			

Well type:	Who owns/ ownership:	Pump type:	Purpose
1: DW-Dug well, 2: STW- shallow tube well 3: DTW- Deep tube well, 4: CTW-Cluster tube well, 5: CSW-Cluster submersible bore well 6: WW- WUA well, 7: Groundwater + canal irrigation, 8: Groundwater + river 9. GW+ Pond, 10. GW+ ditch/creak (*khala*) 11. GW+ Other (______________)	1: household has ownership; 2: jointly owned with other households/farm entities 3.Farmer association 4.Water user association, 5. private water seller 6. other_______	1: Diesel centrifugal, 2: Diesel submersible 3: electric centrifugal, 4: electric submersible 3: manual (specify method___________________), 5: others [specify___________________]	1: irrigation of crops, 2: irrigation of garden, 3: drainage, 4: domestic uses; 5: selling water to neighbour farmer 6: other (specify)_________

G.2.2 Pump information on costs

1. Pump ownership	2. How much does it cost for operating pump motor?				3. How many hours does it take for you to irrigate a plot of unit area (mention unit:______________) when the soil is:			4. How many hours does it take for you to irrigate a plot of unit area (mention unit:______________) when it varies by the topography?		
	2.1 Per Litter of fuel	2.2 Per hour of operation	2.3 Per unit area (local Unit[€]_____)	2.4 Per day	3.1 Clay /clay loam soil	3.2 sandy-loam soil	3.3 Loamy-sand/ sandy	4.1 Upland	4.2 Medium land	4.3 Low land

[€]Unit=per: 1-Hour, 2= Guntha, 3= Bharana of 28 decimal, 4= Bharana of 32 decimal, 5= acre, 6= crop, 7=year, 8= others _______

H. FARM INVENTORY

ITEMS	1. No.	2. Year of purchase/ construction	3. Cost of purchase/ construction	4. AMC
A. Residence (Type: 1= Kutcha, 2: Pucca)				
B. Farm machinery & equipment				
a. Tractor				
b. Tractor drawn equipment				
c. Power tiller				
d. Rice transplanter				
e. Mechanical Weeder				
f. Thresher				
g. Chaff cutter				
h. Seed drill				
i. M. B. plough				
j. Sprayer/ duster				
k. Bullock cart				
l. Small implements				
m. Others1: ________				
n. Others2: ________				

C. Livestock	1. Type of ownershipµ	2. No. of heads	3. Total value	4. Annual maintenance cost (AMC)		
				4.1 Own input	4.2 Purchased input	4.3 Others (community pasture)
a. Milch animal						
b. Draft animal						
c. Calf/ heifer						
d. Goat						
e. Sheep						
f. Pig						
g. Chicken						
h. Ducks						
i. Others1						

D. Credit use	1.Soures€	2. Amount of loan (Rs)		3. Period of loan	4. Rate of interest	5. Purpose of loan£
		2.1 Cash	2.2 Kind			

[Note:µ**Type of ownership**: 1=owned, 2= contract growing, 3= combination of 1 and 2, 4= Others
€Source of credit: 1=Banks, 2=Money lender, 3=Trader, 4=Cooperative, 5=Other farmers/friends/relatives, 6=Self Help Groups, 7= Micro finance, 8=Others _______________.
£Purpose of loan: 1= Short term crop production (KCC), 2= Medium and long term investment, 2= Non-farm investment, 3=Medical expenses, 4=Education expenses, 5=House improvement, 6=Consumption7=Social/Cultural/Religious/Death ceremony, 8=Others ____________]

I. I.1COST OF PRODUCTION AND INPUT USE OF MAJOR CROPS GROWN: Seasonal crop (Ex. Rice)(*take separately for irrigated and non-irrigated plots*)

Crop name: ________________________________	Parcel name: _____	Plot name: _______	Plot size: ___ ____ (local unit_______
Cropped area (local unit____________):	Season ___ (1=Kharif, 2=Rabi, 3=Summer)	Crop technology: _____	Variety type: ________ (1=modern, 2= TV)
Crop establishment method:___ 1=dry seeded/ 2=wet seeded / 3=transplanted in line/ 4=transplanted randomly	Irrigated/Un-irrigated:	If irrigated, source (refer from landholding table):	
	Main product (Name):		By-product (Name):

Operations		Material Inputs					Human labour								
		Freq	Unit	Qty	®Source	Cost	Quantity						Cost		
							FL-M	FL -F	FL-C	HL-M	HL-F	HL-C	HL-M	HL-F	HL-C
Land preparation	Bullock pair														
	Machine: ___ €														
FYM/Compost															
FYM carrying cost															
Seed_____ kgs/Seedbed preparation(Bullock, Machine, Human)															
Fertilizer as basal dose	Name1 _______________														
	Name2 _______________														
Micro-nutrient (Name)															
Uprooting of seedling/Transporting seedling to main plot															
Sowing/transplanting (Date: ____ __________)	Human Labour														
	Animal labour														
	Machine: ___ €														
Fertilizer as top dressing	Name1 _______________														
	Name2 _______________														
Micro-nutrient (name___________________)															
Inter-culture/ Beushening/ Khedua	Human Labour														
	Animal labour														
	Machinery: ___ €														
Weeding															
Plant protection chemicals	Type: ____£ Name1 __________														
	Type: ____£ Name2 __________														
Irrigation															
Watching expenses(labour)															
Harvesting (Date:_________)	Human labour														
	Machinery:														
Threshing costs including drying	Human labour														
	Machinery € _______														
Marketing costs (incl. bagging, storing, transporting)															
Rental value per season															
Others costs 1 (if any)															
Others costs 2 (if any)															
Grain yield			Unit:		Qty		Grain price				Unit		Rate		
By product1 : ______________			Unit:		Qty		By product1 price				Unit		Rate		

Note: Human labour:FL-M= Family labour-Male, FL-F= Family labour-Female, FL-C= Family labour children, HL-M= Hired labour-Male, HL-F= Hired labour-Female, HL-C= Hired labour children,**Source**: 1= Owned/ 2= Purchased, €**Machine**: (1= Trac./2= Pow.tiller), £PPC type- 1=herbicide, 2-inceticide, **Crop technology**:1=Variety, 2= Hybrid

I.2COST OF PRODUCTION AND INPUT USE OF MAJOR CROPS GROWN: Vegetables

Crop name: ________________________________	Parcel name: _________	Plot name: ________	Plot size: ___ ____ (local unit________)
Cropped area (local unit____________):	Season ___ ____(1=Kharif, 2=Rabi, 3=Summer)		
Sole/inter-crop:	Crop technology: __	Name: _____ _______	Variety type: ____ (1=modern, 2= traditional)
Crop establishment method:___ 1=dry seeded/ 2=transplanted in line/ 3=transplanted randomly	Irrigated/dry:	If irrigated, source (refer from landholding table):	
	Main product (Name):		By-product (Name):

Operations		Material Inputs					Human labour								
		Freq.	Unit	Qty	®Source	Cost	Quantity						Cost		
							FL-M	FL -F	FL-C	HL-M	HL-F	HL-C	HL-M	HL-F	HL-C
Land preparation	Bullock pair														
	Machine: ___ €														
FYM/Compost															
FYM carrying cost															
Fertilizer as basal dose	Name1 _______________														
	Name2 _______________														
Micro-nutrient (Ex. Zinc, Boron, etc.)															
Seed															
Seed bed preparation															
Sowing/Transplanting (Date: ____ __________)	Human Labour														
	Animal labour														
	Machine: ___€														
Fertilizer top dressing	Name1 _______________														
	Name2 _______________														
Plant growth regulator 1 (Vitamin/Hormone (name____________)															
Plant growth regulator 2 (Vitamin/Hormone (name____________)															
Inter-culture operations	Human Labour														
Staking	Material and Human Labour														
Weeding															
Plant protection chemi-cals	Type: ____£ Name1 _________														
	Type: ____£ Name2 __________														
Irrigation															
Watching expenses(labour)															
Harvesting(Date:_________)	Human labour														
	Bullock/ Machine														
Marketing costs (incl. Sorting, grading, bagging, transporting)															
Rental value per season															
Others costs 1 (Ex. Netting/_________________)															
Grain yield			Unit:		Qty		Grain price				Unit		Rate		
By product1yield: ____________			Unit:		Qty		By product1 price				Unit		Rate		

Note: Human labour:FL-M= Family labour-Male, FL-F= Family labour-Female, FL-C= Family labour children, HL-M= Hired labour-Male, HL-F= Hired labour-Female, HL-C= Hired labour children,Source: 1= Owned/ 2= Purchased, €Machine: (1= Trac./2= Pow.tiller), £PPC type- 1=herbicide, 2-inceticide, **Crop technology**:1=Variety, 2= Hybrid

I.4 COST OF PRODUCTION AND INPUT USE OF MAJOR CROPS GROWN: Annual crop (Ex. Sugarcane/ Colocasia/ Banana/Lemon/ ______________)

Crop name: ___ ___ ____ ____ ____ ___	Parcel name: _________	Plot name: ________	Plot size: ___ __ (local unit________):
Cropped area (local unit____________):	Season ___ (1=Kharif, 2=Rabi, 3=Summer)		Crop technology: __
Sole/inter-crop:	Variety type: (1=modern, 2= tradition)		Irrigated/unirrigated:
Crop establishment: Trench method/Flat bed/Ridge and furrow	If irrigated, source (refer from landholding table):		

Operations		Material Inputs					Human labour								
		Freq	Unit	Qty	®Source	Cost	Quantity						Cost		
							FL-M	FL -F	FL-C	HL-M	HL-F	HL-C	HL-M	HL-F	HL-C
Land preparation	Bullock pair														
	Machine: ___€														
FYM/Compost															
FYM carrying cost															
Fertilizer as basal dose	Name1 _______________														
	Name2 _______________														
Micro-nutrient (Name)															
Seed material, Transport cost of sets, two or three budded sets															
Planting (Date: ____ _)	Human Labour														
	Animal labour														
	Machine: ___€														
A. Fertilizer top dressing1	Name1 _______________														
	Name2 _______________														
B. Fertilizer top dressing2	Name1 _______________														
	Name2 _______________														
Inter-culture operations	Human Labour														
	Animal labour														
	Machinery: _______ €														
Weeding															
Plant protection chemicals	Type: ____£ Name1 __________														
	Type: ____£ Name2 __________														
Irrigation															
Plant growth regulator / Vitamin/Hormone (name_______ __)															
Propping expenses (labour)															
Harvesting (Date:_________)	Human labour														
	Machinery:														
Marketing costs (incl. Transporting)															
Rental value per season															
Others costs 1 (if any___________________________)															
Cane/ Colocasia/ Banana/ Lemon yield:			Unit		Qty		Product price				Unit		Rate		

Note: Human labour:FL-M= Family labour-Male, FL-F= Family labour-Feale, FL-C= Family labour children, HL-M= Hired labour-Male, HL-F= Hired labour-Female, HL-C= Hired labour children, Source: 1= Owned/ 2= Purchased, €Machine: (1= Trac./2= Pow.tiller), £PPC type- 1=herbicide, 2-inceticide,

J. COST OF AQUACULTURE PRODUCTION& MANAGEMENT PRACTICES

Pond size:____(local unit _________), Water area: _________(local unit_________) No. of harvest________ Total catch _________ (local unit_________)

A. Material Input	1. Quantity (No./qt)	2. Cost (Rs)	B. Labour activity	1. Freq.	2. No. of Hours spent	3. No of persons				4. Male Wage (Rs)	5. Female Wage (Rs)
						3.1Family		3.2 Hired			
						3.1.1 Male	3.1.2 Female	3.2.1 Male	3.2.2 Female		
Lime			Cleaning								
Fry/fingerling			Liming								
Transportation cost of fingerling											
Cow dung			Application of cow dung								
Fertilizer: SSP			Application of fertilizer								
Urea			Water quality check by experts								
MOP											
Feed: G.N. oilcake			Feeding								
Rice bran			Watching								
Others			Netting (check)								
Fishing net			Harvesting								
Medicines			Marketing if made by self								
Lease value/ annum											

K. INSURANCE

1. Season	2. Crop/Livestock	3. Sources ofInsurance	4. Area covered(in ac)/ (unit sizefor live stocks)	5. Sum insured(inRs.)	6. Premium paid(inRs.)	7. Claim (inRs.)	8. Benefit received(in Rs)

(Note: Season= 1: Kharif, 2: Rabi, 3: Summer)

L. **Market Management**: Major value chain actors for the farm/off produces: (**For SS**: To be asked at second level FGD)

1. Crops Ω	2. Intermediaries	3. Time of sale£	4. Frequency of sale$^{\alpha}$	5. Place of sale$^{\beta}$	6. Distance from farm(in KM)	7. Mode of communication ¥

[Note: CropsΩ= 1: Rice, 2: Pulses, 3: Oilseeds, 4: Vegetables, 5: Fruits 6: Sugarcane 7: Others___________________,
Time of sale£= 1: Immediately after harvest, 2: < 15 days 3: >15 days – 2 months 4: > 2months- < 6months 5: > 6 months;
Frequency of sale α= 1: weekly once 2: once in 2 weeks 3: monthly 4: all at once;
Place of sale β= 1: village market 2: Mandi3: regulated market 4: city market 5: Others
Mode of communication ¥= 1: Self, 2: hired, 3: traders' vehicle, 4: Others _____________________

M. TOTALCROP OUTPUT USAGE AND HOUSEHOLD INCOME (ANNUAL)

1. Sources	2. Total output (Qtls)	3. Consumption of farm products (Qtls)			4. Sale of own farm products		
		3.1 Used as Food	3.2 Kept as Seed	3.3 Share payment	4.1 Quantity(Qtls)	4.2 Unit price(Rs/unit)	4.3 Value (Rs)
A. On-farm							
a. Rice							
b. Pulses							
c. Oilseeds							
d. Vegetables							
e. Spices							
f. Sugarcane							
g. Fruits							
A.1Livestock/poultry							
h. Live animal							
i. Milk							
j. Chicken/ Ducks products							
k. Farm Yard Manure (FYM)							
l. Fish							
m. Others(Specify_______)							
B. Off-farm labour						5. Days worked	6. Gross income (INR)
a. Crop farming							
b. Livestock rearing							
B.1 Crop output value from leased out plots							
C.Non-farm income(Wage-MGNREGA, Road works, earth work, construction work, thatching, mason etc.)							
a. Small scale village industry							
b. repairing activity							
D.Other sector employment: a. Salaried job/service sector (name ___________________)							
E.Business: (Mention the activity name ________________________)							
F.Pension & remittances: (Mention the activity name ________________________)							

APPENDICES