A MARKET-BASED ARID-REGION WATER RESOURCES PLANNING MODEL: APPLICATION TO THE GUHAI WATER DISTRIBUTION SYSTEM, CHINA

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ABSTRACT

The arid regions in China, which own a pivotal position in national agriculture production, have confronted water supplying crisis triggered by the rapid growth of local economy. The Arid Zone of Ningxia Hui Autonomous Region (AZN) is one of the arid regions that severely suffer from water shortage. Since 1970s, local people has been relying on the water delivered from the Yellow River by water distribution systems, among which Guhai Water Distribution System (GWDS) is the largest and earliest one. Due to the limited capacity of GWDS and the decreasing precipitation caused by changing climate, the water availability in AZN is becoming scarcer. In recent years, emerging industrial sectors and growing food demands have become the major driving forces for water conservation in AZN, especially for those areas covered by GWDS. Development of an Integrated Water Resources Management (IWRM) approach has been placed as a priority in the government agenda with a combination of technology innovation, institutional development and system consideration. However, inherent complexities and uncertainties in natural, social and economic contexts are posing great challenges for decision makers to bring out a comprehensive water management strategy. Therefore, this research aims to develop a Market-Based Arid-Region Water Resources Planning (MAWRP) model for GWDS, with a focus on water trading under uncertainty.

The MAWRP model encompassed a board perspective of technological, political and social factors to reflect the tradeoffs between food production and gains from water trading in the GWDS. This model is useful for exploring the full potential of water conservation through a combination of three approaches, including cropping pattern optimization, irrigation infrastructure improvement and water trading. The results show that the proposed

method can help generate optimal cropping patterns, water trading rules, and improved irrigation infrastructure areas under various uncertainties. Moreover, decision makers can obtain useful information to formulate reasonable water allocation strategies and to design the most beneficial subsidization policies through the comparison of various policy scenarios with different water prices and opportunity cost of water.

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CHAPTER 1

INTRODUCTION

1.1. Background

Water resources management has become a serious subject in the development of arid regions (Ragab and Prudhomme, 2002). As is highlighted by Bantilan et al. (2006), the development in arid regions usually reflects the pervasiveness of poverty, continuing concerns about growing constraints of water scarcity, and the lack of infrastructure and dissemination of improved technologies (Bantilan et al., 2006). The arid region is defined by UNEP as those lands with an annual precipitation over the annual potential evapotranspiration ratio between 0.03 and 0.2 (Bantilan et al., 2006). Arid regions are home to most of the poorest population and have the most fragile ecosystem. At the beginning of 21th century, water resources planners have started to use an Integrated Water Resources Management (IWRM) approach to support water allocation in arid regions. The aim of IWRM is to coordinate land and natural resources to maximize economic benefits without compromising the sustainability of ecosystems (Agarwal et al., 2004). IWRM shows a good promise in arid regions, as it recognizes the holistic nature of the water cycle and the importance of managing trade-offs within it. It emphasizes the importance of effective institutions and it is inherently adaptive (Sadoff and Muller, 2009). Such essentials of IWRM are reflected in many arid-region water resources management strategies through a combination of technological innovations, political interventions and systematic optimizations (Agarwal et al., 2004; Thomas and Durham, 2003). For the last decade, China has made remarkable progresses with the IWRM in terms of the water-saving technology investment and the institutional reformation. The adaptation of innovative irrigation technologies such as dripping and sprinkling irrigation as well as deficit irrigation have substantially reduced the irrigation water use in five northwestern provinces (Zhu and Yang, 2006). In addition, the revised water law in 2002 has become the starting point of the institutional reformation for China switching from a centralized, highly regulated water allocation system toward a market-oriented system underpinned by water rights (Shen and Speed, 2009).

1.2. Necessities of Water Market for Arid Regions in China

In China, most of the agricultural activities are still governed by centralized water allocation systems (Varis and Vakkilainen, 2001), by which the water conflicts among different water users are usually settled through ad hoc measures rather than using a water rights transfer mechanism (Speed, 2009). Since the last two decades, tremendous institutional development efforts have been done by Chinese government, which has realized that administration orders in the future will no longer be capable of mediating growing water conflicts for the country's dry north land (Wu, 2003). As water shortage issues become intensified, the adaptation of water rights systems has been in the forefront to reduce conflict and provide incentives for saving water (Ruth, 2014). The desire to apply a market-based approach for sustainable social development in China, particularly in the Arid Regions of Yellow River Basin (ARYRB), cannot be more desperate than in any other arid regions (Macgrach et al., 2006; Shen and Speed, 2009; Speed, 2009). There are several factors pushing the development of a water market in the ARYRB.

The foremost and essential need is the necessity of solving the water conflict between competing users (Cai, 2008). In ARYRB, over 90% of the water consumption goes to agricultural activities (Duan et al., 2002), so it has the unshakable responsibility of releasing water for all water related stakeholders, who have created innumerable demands on water (Wu, 2003). However, to release water for other users is not an easy task for the agricultural sector, since it has to preserve its own water rights to: (a) guard against the water shortage triggered by the climate change (Gleick, 2000) and to (b) meet the demand for high crop yields to ensure the national food security (Cai, 2008; Cai et al., 2003). Simply shifting water away from agricultural producers may not be a wise approach to solve the multi-player conflict since the reduced agricultural production is unacceptable for the government (Cai, 2008; Shen and Speed, 2009; Speed, 2009). There are two internal problems within the agricultural sector in ARYRB that need to be solved with institutional arrangements. The first is extensive water management, which has long been plagued for poor irrigation technology and high irrigation quotas (Duan et al., 2002; Zhen and Lv, 2002). As for ARYRB, rainfall alone is insufficient to produce vast amount of food (Gleick, 2000), so supplementary irrigation is critical to maintain high crop yields. Due to the large volumes of water required for irrigation, famers in the ARYRB typically pay only for pumping and conveyance costs for water and do not yet pay for the value associated with water scarcity (Rosegrant et al., 2014). The extremely low cost of water encourages the production of crops that are low-valued and highly water intensive, and for more importantly, provides no incentive for irrigators to use water efficiently since they will not be volunteered to adopt advanced irrigation infrastructures (Feder and Umali, 1993; Gleick, 2000). Against the above facts, the water management problem in ARYRB cannot be solved with technological innovation alone, but requires a well-developed institutional mechanism to address the current, improperly managed water resources (Cai, 2008). The second is policy heritage. The already over-allocated water to famers are difficult to retrieve, leaving inadequate water for successive users (Dridi and Khanna, 2005). In ARYRB, famers are of the most vulnerable water users, for whom at the meantime, are also the main forces of food producers, thus entitled with adequate amount of water resource to sustain their own livelihood as well as maintain the national food security. Therefore, the reallocation of water resources in ARYRB is a sensitive subject that closely related with social stability and the well beings of senior water users (i.e. famers). To cope with the two problems mentioned above, water market is desired to provide a secondary phase of water allocation strategy to maintain high crop yields by incentivizing irrigation efficiency thus the interests of vulnerable water users will be protected (Easter and Huang, 2014; Feder and Umali, 1993; Zuo et al., 2014). In addition, any conserved water can be shifted from the senior water rights owned and used by famers to junior water users with more important social gains (Easter and Huang, 2014).

Another reason for the occurrence of a water market in ARYRB is the scarce and uneven natural distribution of available water and the decreasing trends in precipitation (Cai, 2008), which pose serious challenges to water resources planning (Rosegrant et al., 2014). As Sadoff and Muller (2009) described, one of the essential tasks for IWRM is to build institutions, information and capacity to predict, plan for and cope with seasonal and inter-annual climate variability as a strategy to adapt to long-term climate change. Changing climates are a value-added factor for the successful implementation of water markets, as market adjustment will ‘smooth’ the risks associated with water surplus or deficit introduced by climate uncertainty (Rosegrant et al., 2014). When the natural ‘allocation’ of water resources fails to meet the demand from all users, the water market will become an ideal strategy of sharing available water among all competing users (Shen and Speed, 2009). In Australia, the uncertainty in water availability has increased considerably in recent years, which encourages the water authorities to shift most of the uncertainty associated water supply to irrigators (Bjornlund, 2003).

One last reason for the development of a water market in ARYRB is the need from all water users, especially high risk water users like cash crops growers who want to buy more water to secure current production (Bjornlund and McKay, 2002). On the contrary, a moderate reduction for irrigation water only has a small impact on crop production for irrigators growing low-valued crops (i.e. food crops). Therefore, they will have the option of benefiting from water trading by selling their low efficient ‘portion’ of water rather than pour it into the fields (Easter and Huang, 2014).

1.3. Challenges for Water Trading

There are many successful cases of water transfer programs in China showing the effectiveness of water trading (WET, 2006; WET, 2007). In 2000, a trading agreement was reached between Dongyang and Yiwu counties in Zhejiang Province, becoming the first case of water trading in China (Speed, 2009). In ARYRB, the Ningxia Hui Autonomous Region realized more than 70 million cubic meters of water transfer until 2011 (Macgrach et al., 2006). Also, the Inner Mongolia Region has made tremendous efforts in terms of encouraging downstream industries to invest in upstream channel lining, so the industries will receive water conserved from reduced leakage (Calow et al., 2009). However, comparing to other countries with well-developed water markets like Chile, Mexico and Australia, the current water market in China is still in its embryonic stage, under which the water trading can only be conducted at the administration level, rather than rooted into individual water users (Cai, 2008; Speed, 2009). In other word, governments still dominate the water rights entitled to entire communities (e.g. dwellers within water distribution systems) (Easter and Huang, 2014). As a consequence, individual irrigators are more likely to see their water rights expropriated with some sort of ‘compensation’ rather than getting involved directly into water trading (Budds, 2004). Such trading limitation is caused by a lack of clearly defied water rights and its associated issues. A review by Bjornlund and McKay (2002) addressed that it was essential to clearly specify and define the water rights, so that buyers had all the information about the product they were buying, and ownership was secured. However, the allocation and management of water rights at the individual level is not an easy task in arid regions of China due to the presence of two fundamental challenges. The first is how to establish a functional water trading systems for a huge number of individual irrigators with affordable trading prices of water. The second is how to design a structured approach to regulate and supervise the water transaction process, so as to protect vulnerable water users (Speed, 2009).

There are two crucial important factors that decide the trading prices of water: The full opportunity cost of water and the transaction costs. The full opportunity cost of water includes the compensation of losing water and associated benefits. This cost varies depending on availability of water resources and whether the water is actively used for agriculture production. The transaction cost is another important component of the trading price of water, ranging from 3 – 70 % of the total trading price of water depending on the complexity of natural and social conditions (Easter and Huang, 2014). The transaction cost includes the cost for evaluating the potential value of transferrable water, negotiating trading agreements and other externalities (Easter and Huang, 2014; Garrick et al., 2013; Marshall, 2013; McCann, 2013). The key to the design of a feasible and profitable trading system is to reduce the sum of the two costs (Easter and Huang, 2014; Marshall, 2013; McCann, 2013). For this purpose, appropriate subsidization policies, support programs and water allocation plans (and caps) must be provided (Ruth, 2014; Speed, 2009; Wu, 2003). The effectiveness of subsidization policies is reviewed by Feder and Umali (1993): As the incentives enlarge the benefit distribution, the increased scale will generate more information that stimulates potential trading. However, inappropriate subsidization policies may also lead to resources misallocation problems and increase the risk of market failure (Feder and Umali, 1993). As is illustrated by Speed (2009), if water permit holders are over-subsidized from water trading, they may have a windfall gain by cashing their water rights. This action will consequently transfer the water out of agriculture and lead to production losses, which are not politically acceptable in China (Cai, 2008; Rosegrant et al., 2014; Speed, 2009). To avoid this from happening, specific trading rules have to be implemented to reduce the risk of losing agricultural production (Speed, 2009). For example, some transfers that deplete farmers' water below their basic needs should be prohibited (Cai, 2008).

1.4. Needs of Mathematical Programming Model

The needs of Chinese water markets have been calling for a comprehensive water allocation strategy with the recognition of IWRM. Mathematical programming models are capable of providing long-term water allocation plans. The merits and importance of water management optimization models have been recognized by numerous scholars worldwide (Arnold et al., 2014; Li et al., 2013; Li et al., 2010; Lu et al., 2010; Lv et al., 2010; Merot, 2010; Wang and Huang, 2011; Zeng et al., 2015). As addressed by Maqsood et al. (2005) and Wang and Huang (2011), mathematical programming approaches can effectively deal with uncertainties existing in natural, social and economic contexts. Moreover, mathematical programming approaches can be used as important tools to test different water policy scenarios, infrastructure operational options and water allocation rules (Berger, 2001).

Previously, two types of mathematical models were developed for water resources planning problems. The first is simulation-based optimization models, which employ water-demand simulations to support the irrigation water management. In arid regions, 85 to 90 percent of water withdrawal goes to agricultural activities which therefore deserve more attention and efforts from water resources planners (Gleick, 2000; Schaible and Aillery, 2012). The presence of simulation-based optimization models enables the irrigation water to be allocated with more efficiency, directing to a sound water quota system. However, most simulation-based optimization models have neither considered system uncertainties nor water trading into the modelling process, the model performance can thus be severely limited.

The second is stochastic optimization models, which can effectively deal with uncertainties expressed as intervals, probability distributions and fuzzy sets. A few stochastic optimization models developed previously have incorporated water trading into the modelling process (Li et al., 2014; Luo et al., 2003; Zeng et al., 2015). These models disclosed that water trading effectiveness was explicitly influenced by various uncertainties existing in water resources systems (Li et al., 2014). For instance, the design of the initial water rights and crop irrigation quotas must rely on the relationships between crop production laws and the uncertainties in natural water cycles (Geerts and Raes, 2009). Moreover, the presence of uncertainties in water availability can be a value-added factor for the water trading in dry seasons (Li et al., 2014; Rosegrant et al., 2014). Furthermore, uncertainties exist in social and economic contexts such as social recognition for institutional reformation and government budgets, also have a great influence in water trading. If the aforementioned uncertainties are not properly addressed in the market design, they will ultimately lead to inaccurate estimates during the trading process. System uncertainties are not the only factor to be thoroughly considered in market-based optimization models. The water market design may vary dramatically according to physical conditions, legal contexts and social developments (Easter and Huang, 2014; Grafton et al., 2011). For example, irrigation technology reformation may provide the physical feasibility for water trading, since water conserved from improved irrigation techniques can be traded directly for an additional revenue (Feder and Umali, 1993). In addition, the superior irrigation technology may also be a growing asset for water market, as it addresses the value of water and facilitates the trading process. Moreover, the crop yield simulation technology may help deliver comprehensive and convincing water allocation plans for agricultural activities and gain more effectiveness in water trading under arid climates. Furthermore, designing water markets in China involves a series of challenges to avoid production loss and to make water trading feasible and profitable without adding further burden to the government. Failure to consider any of the aforementioned factors may compromise the modelling performance of the water market.

1.5. Objectives

In this study, an analytical systems approach coupled with a crop yield simulation module and stochastic processing programming will be developed to provide supportive information for the arid-region water market formulation under uncertainty. The proposed Market-Based Arid-Region Water Resources Planning (MAWRP) model is able to improve upon conventional market-based optimization methods with the following advantages: Firstly, the proposed model will be the first attempt to build a link between technological innovation and institutional arrangements and jointly serve the long-term regional water resources planning. Secondly, the model integrates deficit irrigation schemes and water trading into the mathematical modelling process, so as to provide a flexible trading environment for a variety of water users. At the meantime, deficit irrigation will function as an auxiliary tool to increase water efficiency during the transmission period from extensive farming under flood irrigation to precision farming under dripping and sprinkling irrigation. Thirdly, the model equips a build-in module for crop yield simulations with the knowledge of plant physiology and nature water cycles, which allows the model to deliver a more precise agricultural water allocation plan under arid climates. Finally, the model can reflect system uncertainties through various uncertain expressions such as intervals and probability distributions to provide scientific and reliable information for the optimal function of water trading. The proposed model will be applied to the Guhai water distribution system (GWDS), located in the Arid Zone of the Ningxia Hui Autonomous Region (AZN), China. This study will entail the following objectives:

(1) Examine the water resources planning strategies in arid regions. IWRM will be reviewed in terms of its three components, including technological innovations, institutional arrangements and mathematical programming approaches. In specific, deficit irrigation schemes, water markets and stochastic programming models as the three essential instruments within the IWRM framework will be intensively studied.

(2) Investigate study background in terms of social, economic and natural conditions as well as water related activities and institutional arrangements. System components will be further analyzed for their interrelationships and associated system complexities and uncertainties. A comprehensive evaluation will be conducted for current institutional arrangements to identify the key constraints impeding the water market development in the study region. Data support will be provided for the modelling process.

(3) Develop a MAWRP model for the GWDS. The proposed model will provide tradeoffs between penalties for food production and economic targets under the inexact two-stage stochastic (ITSP) framework. A series of supportive and incentive water policies will be designed to help irrigators manage water and yields without compromising food production. Comparative analysis will be performed to reveal interactions between institutional arrangements and interests of multiple stakeholders.

(4) Determine water rights and water quota systems under the proposed MAWRP framework. Valuable information will be generated to assist local governments to establish the initial water rights and revise the current irrigation quotas. Taking the credits of climatic uncertainties, the MAWRP model will explore the full potential of the water market in the study region and allow irrigators to fairly exchange their tradable water in long-term contracts (achieved through irrigation infrastructure improvement) and temporary (seasonal) contracts (achieved through deficit irrigation). With the provision of water rights and water quota systems, the MAWRP model will provide crucial and indispensable bases for supporting the IWRM in the GWDS.

CHAPTER 2

LITERATURE REVIEW

2.1. Water Resources Management Strategies for Arid Regions

Over the past decades, scholars from all over the world have been looking for comprehensive and effective water management approaches to alleviate water stress in arid regions (Cai, 2008; Shen and Speed, 2009; Varis and Vakkilainen, 2001; Xie, 2009; Wu, 2003). Viessman Jr. (1990) asserted effectively managed water resources for dry land need to be achieved through technical innovations and institutional reform with consideration of social attitudes, political viewpoints and technical constraints. New circumstances for the 21st century have endowed water management in arid regions with more challenges and opportunities for innovative and fresh thinking. As Sadoff and Muller (2009) suggested, better water resources management for arid regions must possess the capability of resiliency for today and adaptability for the future. This concept was structured by the Global Water Partnership (GWP), which firstly proposed an Integrated Water Resources Management (IWRM) in 2004.

The essentials of IWRM are reflected in many arid-region water resources planning strategies through three mainstream water resources management approaches known as technological innovations, political interventions and system optimizations (Thomas and Durham, 2003). In Uganda, IWRM is advocated with the provision of comprehensive institutional arrangements and management tools (i.e. system modelling techniques) to ensure the water service are provided and managed with increased efficiency (Rubarenzya, 2008). In Sri Lanka, the adaptation of IWRM helps the country increase water productivity and improve water quality at the river basin scale (GWP, 2011). In Namibia, IWRM is tailored to specific circumstances for an optimal water allocation among various sectors with the consideration of innovative water supplying technologies and under a stable legal and institutional structure (IWRM, 2010). All the above achievements suggest a promise future of IWRM in arid regions.

2.2. Technological Innovation and Deficit Irrigation

Technological innovation has been widely applied around the world as a crucial component in IWRM to improve the water efficiency and enhance the water resources management capacity (Dridi and Khanna, 2005). In Israel, through a combination of technology diffusion such as upgraded water transport, rainwater harvesting, and wastewater reuse and desalination along with a variety of water conservation measures, the country has been keeping the industrial and domestic per capita water consumption steady despite the rise in living standards during the past 40 years (Tal, 2006). In United State, technological innovation has been applied to most water intensive agricultural activities in 17 Western states and counted for 50% of their total irrigation water (Schaible and Aillery, 2012). From 1984 to 2008, the total irrigated area in Western US has increased for 2.1 million acres, while the total water use for irrigation was declined by 123 million cubic meters (Schaible and Aillery, 2012). In northwestern China, the improved irrigation techniques such as sprinkler and dripping irrigation have been applied to most newly reclaimed land, for which irrigation efficiency has been increased by 40% in comparison with flood irrigation (Peng and Ding, 2004).

The term “innovation” is not necessarily referring to the creation of innovative technologies or related to expensive capital investment. In many mid- and low-income countries, the innovative design in water demand management also counts for a promising and cost effective approach for the arid region water management (Feder and Umali, 1993). Deficit Irrigation (DI) is an innovative approach for water demand management, which has been widely applied as a valuable and sustainable irrigation strategy in arid regions (Geerts and Raes, 2009). The concept of deficit irrigation was firstly introduced by English (1990), as a deliberate under-irrigation for crops to increase overall net benefits. The practice of DI must rely upon crop water-production functions relating water use to crop yields (English, 1990), based on which a marginal amount of water will be obtained and applied during each of the crop’s drought-sensitive growing stage (Geerts and Raes, 2009; Azimi, 2013). Under a limited water withdrawal, DI will be able to maximize the overall agricultural production by reducing crop production per unit area (Shan and Xu, 1991). Even though the inherent uncertainty of water-production functions makes DI virtually impossible to predict exact yields and delivers a precise level of water use for the maximum profits (English, 1990), the effectiveness of DI has been proven by numerous researchers as a superior water demand management strategy under water scarcity and high-price conditions (Geerts and Raes, 2009; Liu et al., 2012; Liu et al., 2010; Liu et al., 2013; Mannocchi and Mecarelli, 1994; Reca et al., 2001; Azimi, 2013). Geerts and Raes (2009) evaluated the effectiveness of DI toward different crops and the research suggested crop water-production functions were non-linear, crop-specific, and often differ by phonological stage, genotype and location. Liu et al. (2010) examined several drought-resistant crop water-production functions for the DI application to a case study in northwestern China, with the consideration of precipitation distributions and crop water demands. Azimi, et. al (2013) developed a non-linear programming model for DI in northwestern Iran according to regional limitations and water resources constraints. With increasing demand for food production and limited water resources and land, deficit irrigation will gain more importance over time (Geerts and Raes, 2009).

2.3. Water Rights Systems and Institutional Arrangements

With either innovative irrigation infrastructure or a deficit irrigation scheme, irrigators are provided with physical feasibilities to manage their limited water with maximum benefits (Cai, 2008). However, more rapid change in adaptation of innovative water conservation technology has not occurred worldwide because economic and institutional structures in many arid regions still encourage inefficient water use (Gleick, 2000). As addressed by Rosegrant and Binswanger (1994), the adaptation of irrigation technology improvement could be enhanced substantially by institutional arrangements.

Water rights systems as the essential component of institutional arrangements have been vigorously pursued by policy makers in many arid regions (Bjornlund and McKay, 2002; Easter and Huang, 2014; Garrick et al., 2013). In Chile, the institutional reformation for water resources planning began in 1973, with its government shifting from a centralized socialist economy to a market-oriented economy, which allowed the water rights to be freely traded with a few restrictions (Budds, 2004; Rosegrant and Gazmuri, 1995). Mexico also began its process of institutional reformation in 1990, by shifting from a state centralized, highly regulated system toward a market-oriented one, under which the water rights were secured to famers (Rosegrant and Gazmuri, 1995). In Australia, institutional development has been undertaken for two decades, with a series of key reformations conducted by the Council of Australian Governments (COAG), and contributing to the current water transfer protocols (Turral et al., 2005). In China, the revised water law published in 2002 has been helping the country shift from the centralized water allocation system to IWRM with an emphasis on water conservation strategies (Calow et al., 2009). Under the new legal framework, a transparent and rights-based system is initialized, which provides a starting point for water trading and the potentials for water conservation (Calow et al., 2009).

Beyond the water rights systems previously mentioned, other institutional arrangements such as water pricing mechanisms (Dige et al., 2013), supportive water policies (Feder and Umali, 1993; Gleick, 2000) and water quota systems (Bjornlund and McKay, 2002; Dridi and Khanna, 2005) also contribute to the long-term sustainable water resources management of arid regions. The European Environmental Agency (EEA) has proposed various water pricing instruments including taxes, charges and tariffs to help realize environmental and economic policy objectives in a cost-effective way (Dige et al., 2013). Supportive water policies are widely advocated around the world as an economic incentive for low-income households who cannot afford the full recovery cost of water and low efficiency water users who need to adopt new technologies (Bjornlund and McKay, 2002; Dridi and Khanna, 2005). The water quota system is designed to reduce the inefficient water use, especially for famers owning more water than they need (Dridi and Khanna, 2005). In many states in the western US, specific water quotas are designed for all kinds of products, and they are regularly revised according to improved technology in order to stimulate water conservation (Bjornlund and McKay, 2002).

2.4. Mathematical Programming Approaches

A mathematical programming approach is able to join technological innovations and institutional arrangements to facilitate water management, thus playing a crucial role in the IWRM framework (Anil et al., 2004). Over the past several years, numerous mathematical programming models have been developed for arid regions around the world (Arnold et al., 2014; Li et al., 2013; Li et al., 2010; Lu et al., 2010; Lv et al., 2010; Merot, 2010; Wang and Huang, 2011; Zeng et al., 2015). These can be generalized into two categories, including simulation-based optimization models and stochastic programming models (Huang, 1998; Kuo and Liu, 2003; Maidment and Hutchinson, 1983). The former classification addresses the agricultural crop yield simulation, which relates plant physiology to the water consumption, thus the water under scarce situations can be allocated with more efficiency. There are many simulation-based optimization models developed for the water resources management in arid regions (Arnold et al., 2014; Berger, 2001; Kuo and Liu, 2003; Merot, 2010; Reca et al., 2001). Arnold et al. (2014) developed a hydro-economic agent-based model that consists of a hydrological balance and a system optimization modules, for quantifying agricultural benefits in a Chilean watershed while considering the irrigation water reuse. Kuo and Liu (2003) proposed a simulation-based optimization model based on climate–soil–plant relationships, which in turn facilitated the crop pattern change and water allocation for a sustainable agriculture for central Utah, USA. Rosegrant et al. (2000) presented an economic-hydrologic model for the evaluation of essential hydrologic, agronomic and economic relationships for water, food production, economic welfare and environmental impacts, and applied the model to a case study of

Maipo river basin in Chile. Reca et al. (2001) developed an economic optimization model for water resources planning under deficit irrigation schemes, and applied the method to a case study in the southern Iberian Peninsula.

Another classification for mathematical programming approaches is stochastic programming models (Li et al., 2013; Li et al., 2010; Lu et al., 2010; Lv et al., 2010; Wang and Huang, 2011; Zeng et al., 2015). These models share a common advantage of possessing extraordinary strength when dealing with uncertainties. To differentiate simulation-based optimization models, stochastic programming models use supply-derived allocation mechanisms, in which the water demands for each users are pre-defined, the maximum system benefit can thus be achieved through determining the economically optimal water allocations under various stochastic events. There are many stochastic programming models developed previously. Wang and Huang (2011) proposed an interactive two-stage stochastic fuzzy programming (ITSFP) approach to tackle dual uncertainties presented as fuzzy boundary intervals for solving a water resources management problem. Li et al. (2008) developed an inexact multistage stochastic integer programming (IMSIP) method for dealing with the uncertainties expressed as probabilities and discrete intervals. Lu et al. (2010) presented an interval-valued fuzzy linear-programming (IVFL) method to address individual and dual uncertainties for obtaining more reliable results for water allocation decisions. Lv et al. (2010) applied the interval fuzzy bi-level programming (IFBP) approach to tackle the uncertainties within water resources planning issues, expressed as interval values in constraints and the upper- and lower-level objective functions. Even though stochastic programming approaches have been vigorously developed and widely applied (Huang, 1998; Huang and Loucks, 2000;

Huang et al., 2005; Li et al., 2006; Li et al., 2010; Li et al., 2008; Li et al., 2006; Lu et al., 2010; Luo et al., 2003), few models integrate water trading into modelling processes. Luo et al. (2003) developed an inexact two-stage stochastic nonlinear programming (ITSNP) model for water resources management through water trading under uncertainty. Li et al. (2014) proposed a hybrid fuzzy-stochastic programming method for water trading under uncertainties of randomness and fuzziness. Zeng et al. (2015) presented a two-stage interval-stochastic water trading model and applied to a case study in northwestern China. The models developed by Luo et al. (2003), Li et al. (2014) and Zeng et al. (2015) suggested that water trading can effectively deal with system uncertainties in a variety of formats (i.e. interval, probability distribution or fuzzy sets). While, due to the tremendous agricultural water use in arid regions, stochastic programming models alone sometimes are insufficient to provide a detailed water allocation for agricultural activities (Arnold et al., 2014; Berger, 2001; Kuo and Liu, 2003; Merot, 2010; Reca et al., 2001). Therefore, the capacity of stochastic programming models aforementioned can be further expanded with the aid of crop yield simulations.

2.5. Summary

The development of sustainable approaches for water resources planning in arid regions has been an urgent task for improving the living conditions of poor populations in developing countries. At the beginning of the 21st century, the presence of IWRM gave the water resources planning a fresh look at the challenges in the present and future. The essence of IWRM is to use a combination of technological innovations, institutional reformation and mathematical programming approaches to establish a sustainable society with resiliency and adoptability.

Technological innovation and institutional arrangements are two fundamental components in IWRM; their interrelationships were disclosed as a comprehensive legal and institutional structure may stimulate the technological innovation, which at the meanwhile may provide physical conditions for institutional development. DI, a cost-effective agricultural water management approach, is advocated and widely applied in many arid regions worldwide. To promote water-saving technologies, a water rights system along with other institutional arrangements are required to incentivize low-efficient water users for increasing the water use efficiency since the conserved water can be traded for an additional revenue.

Mathematical programming approaches include simulation-based optimization and stochastic programming models, and they will communicate with technological applications and institutional arrangements. The simulation-based optimization models aim to deliver practical and convincing water allocation plans for agricultural activities under arid climates. However, the limitations for most simulation-based optimization models are a lack of consideration to system uncertainties. In real-world practice, the water resources planning system is always fraught with numerous uncertainties (Li, 2012). To address the uncertainties that exist in system components and their interrelationships, stochastic programming models have been developed. Numerous scholars have demonstrated that stochastic programming models are capable of tackling the uncertainties expressed as intervals, probability distributions and fuzzy sets. A few stochastic optimization models have been applied to water trading programs in recent years (Li et al., 2014; Zeng et al., 2015). These studies suggested that the effectiveness of a water market can be significantly affected with the presence of uncertainties in the natural climates, social, legal and economic contexts.

CHAPTER 3

OVERVIEW OF THE STUDY AREA

3.1. Social Economic Conditions in the Guhai Water Distribution System

Ningxia Hui Autonomous Region (Ningxia) is a renowned rice-planting province in northwestern China. The Yellow River is a gift endowed to Ningxia from Mother Nature, nourishing its northern land for 3000 years (Feng et al., 2013; Wu, 2003). However, the Guhai Water Distribution System (GWDS), located in the Arid Zone of Ningxia (AZN), has the opposite situation, severely affected by arid climate and poverty. Water availability per capita of the region is 51 m^3 (2.2% of the national average). According to the Ningxia bureau of statistic (Zhang, 2014), the AZN has an area of 28.5 thousand square kilometers, constituting 43% of the entire province. The total population of this region is 1.43 million, sharing 23.8% of the total population of this province. However, the gross domestic product (GDP) in AZN had only contributed 6% of the total amount to the province (Jia, 2006). Moreover, the average income of this region was less than 2/3 of the national average (Pan and Shang, 2014). Over 1/3 of the total population in this region was in extremely poor conditions with an annual income per capita of 4075 yuan, equivalent to 3/5 of the national average ((Pan and Shang, 2014). Helping local famers overcome poverty has become an unshakable responsibility for local governments.

3.2. System component

Since the 1970s, pumping systems have been introduced in AZN, marking the most revolutionary change in the local social and economic developments. Until now, there are 5 large-scale and 8 mid-scale pumping systems built in AZN. The GWDS, constructed in 1970s, is the pioneer of the 5 large-scale pumping systems. It lies within the Qingshui river valley, and ranges from 104°47’14’’-105°28’00’’E and 36°00’56’’-37°20’26’’N. The GWDS has two subsystems named as Guhai and Tongxin pumping systems with a total designed service area of 1.1 million Mu (1 Mu equals to 0.16 acre), in which 672,000 Mu is currently serviced by GWDS. Construction began on the Guhai pumping system in 1978 and was put into use in 1982, with a pumping capacity of 20 m^3/s. Construction began on the Tongxin pumping system in 1975 and was completed in 1978, with a pumping capacity of 8.5 m^3/s. Table 3.1 shows the detailed operation data for the Guhai and Tongxin pumping systems. The water is drawn from the Yellow River and is delivered to Zhongning (ZN), Tongxin (TX) and Haiyuan (HY) three counties and Changshantou (CST) farm through 22 pumping stations and 18 channels (subareas). Figure 3.1 shows the detailed composition of the GWDS.

3.3. Hydrological and Climatic Conditions

According to Bantilan et al. (2006), the study area is classified as arid climate with annual precipitation ranging from 190 to 370mm from north to south. Correspondingly, the annual evaporation ranges from 1600 to 1210 mm (E601). Roughly 80% of rainfall happens during May to September, in which the average monthly rainfall follows the

Table 3.1 Operation data for Guhai and Tongxin pumping systems

Pumping station	Lift height (m)	Pumped water (10^4 m^3)	Energy used (10^4 kwh)	Subareas serviced
QYS	29.5	22666.99	2348.47	GH1
GC	30.7	22498.13	2876.03	GH2
STG	27.64	1018.05	142.89	GC2
CST	58.2	21600.75	4928.44	GH3
DLM	34.08	19585.5	2469.96	GH4, GHL4
WH	40.36	3389.5	636.15	GD1, GD2
BFD	44.45	2490.05	539.26	GD3
HSG	37.45	12183.89	1647.34	GH5
LW	25.8	7173.08	769.93	GH6
MT	70.1	1326.99	342.14	MT
LP	50.2	6146.72	1208.26	GH7
SXK	50.6	1967.58	391.13	GH8
DZC*	48.72	9823.16	1847.19	GT1
TY*	40.5	7690.21	1078.13	GT2
TJ*	43	5105.71	799.99	GT3
HBW*	43.96	590.03	121.12	GHB

Note: “*” denotes the station belongs to Tongxin pumping system.

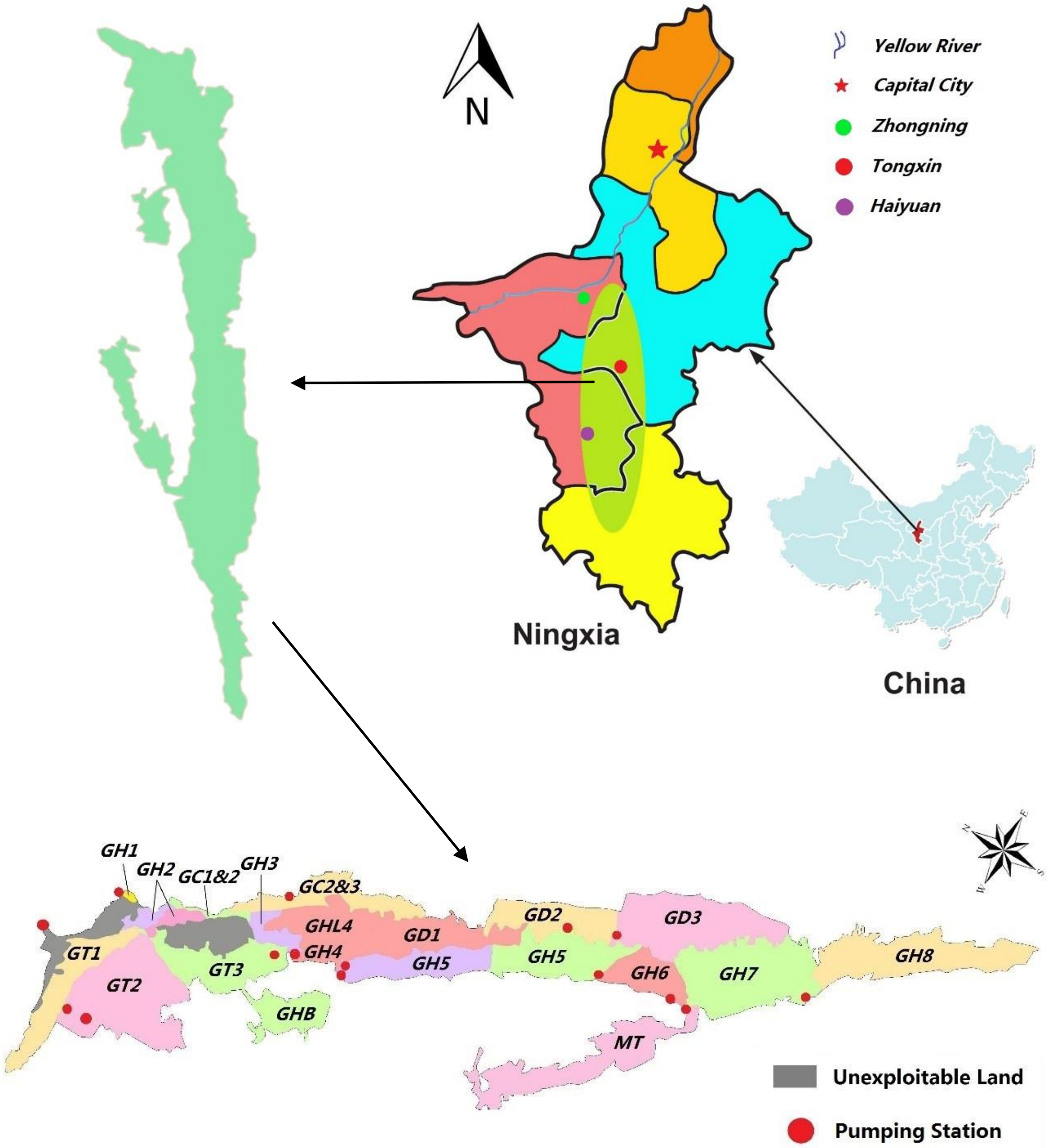

Figure 3.1 The Guhai water distribution system

Table 3.2 Precipitation probability distributions

PDF	ZN (mm)	TX (mm)	HY (mm)
5%	280.7	353.9	474.3
25%	227.4	252.9	354.7
50%	162.3	206.5	292.7
75%	121.9	166.5	243.4
95%	84.8	109.1	175.1

Note: ZN, TX and HY denotes Zhongning, Tongxin and Haiyuan counties, respectively.

distribution as 12% in May, 14% in June, 20% in July, 20% in August and 14% in September. Table 3.2 shows the probability distribution functions (PDFs) of precipitation in each county. The study region is fraught with scarce surface water. Pressurized pipes supply almost all of the water consumed in this region. Notably, due to the long time (40 years) flood irrigation, the groundwater in some subareas (i.e. CH3 and GHL4) have been elevated substantially. The elevated ground water has formed several water ponds, which provide local people extra water resource. Table 3.3 shows the detailed water availability for each subarea. The annual average days without frost are about 180. The annual average temperature is ranging between 8-10 ℃. The annual quantity of solar radiation is between 5714-6029 MJ/m^2. The annual sunshine hours are between 2881-2963.

The changing climate has worsened the water shortage situations since the last century, presenting as increasing drought frequency and decreasing precipitation. From 1955 to 2013, for a total of 59 years, the drought frequency increased from 40% to 70% per decade in which 2 years were extreme drought years (30% or more precipitation less than average) and 5 years were light drought years (10% or more precipitation less than average). It also indicates that the average temperature in the study region raised 0.4 ℃ per decade and the precipitation dropped 10 mm per decade (as shown in Figure 3.2).

Table 3.3 Water availability for each subarea

Subarea	Water delivered (m^3)	Available surface water (m^3)
GH1	137000	0
GH2	5010800	0
GC2	2399000	0
GH3	7013114	3790000
GH4	1594450	0
GHL4	10318350	2240000
GD1	22277500	0
GD2	4611000	0
GD3	20761850	0
GH5	36514135	0
GH6	10268400	0
MT	9684900	0
GH7	18097850	0
GH8	13527700	0
GT1	11664649	0
GT2	15675820	0
GT3	34069800	0
GHB	5474400	0

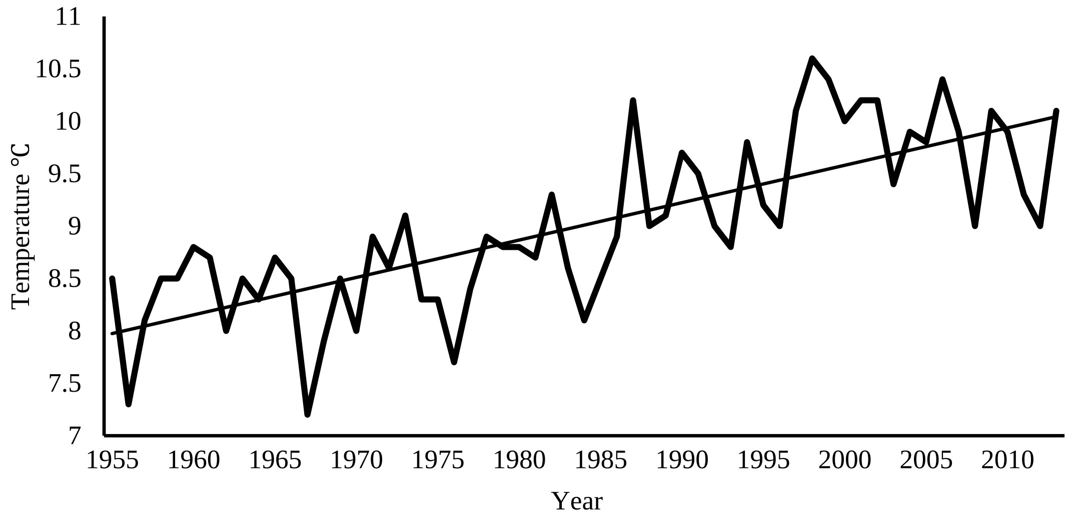

Figure 3.2 (a) Annual temperature for TX county

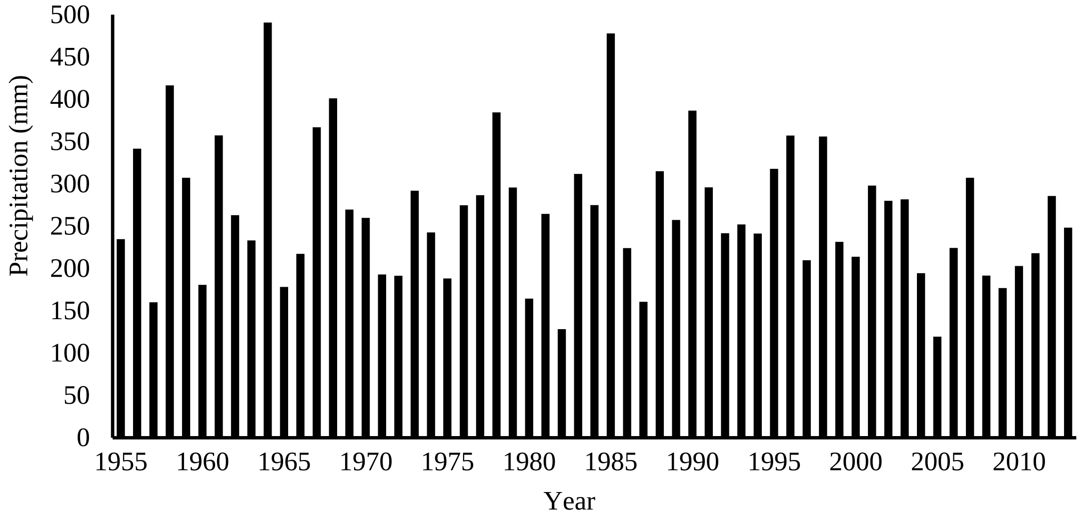

Figure 3.2 (b) Annual precipitation for TX county

3.4. Geological and Vegetation Conditions

The GWDS encompasses valleys, loess hills and depressions three hydrogeological units. The Aeolian sandy soil, loess soil and calcareous clay are three dominant soil types in the study region with the water retention capacity ranging between 21% and 27% (Zhang and Feng, 2013). It is also indicated that the water retention capacity is high in the southern loess hills and relatively low in the northern river valley. In particular, the subareas of GT1, GT2 and GT3, which are located in the river valley, are dominated by shallow Aeolian sandy soil, with the water retention capacity of only 15.3%. The primary topography of the study region is wavy ramps with numerous gullies. The elevation of the study area ranges from 1200-1235 meters. The vegetation distribution of the study region is characterized by scattered xeric shrubs and semi-shrubs, which cover 10 – 40 % of the study region. The presence of GWDS has significantly improved the local ecosystem by protecting the vegetation from deforestation and grazing. Moreover, the developed irrigation land has gradually changed the soil property from Aeolian sandy soil into the sandy loam. Such change has considerably increased the water retention capacity thus in turn avoided soil erosion. For more importantly, the improved soil quality has provided possibility for the transition from the previously desert-dominated landscape to oasis and allowed plant diversity and a healthier ecosystem.

3.5. Agriculture

Agriculture is the supporting industry in GWDS, consuming almost all water carried by the system. After the GWDS was put into use, the irrigators serviced by irrigation systems had been started to enjoy high crop yields regardless of the unevenly distributed rainfall. At the same time, the local irrigation communities had been seeking more beneficial cropping patterns in order to generate more revenue with the limited water carried by the system. After 40 years of trial and error, they formulated the current crop pattern, for which corn occupied 78% of the irrigation area, with rest of the area shared by cash crops and other crops to sustain famers' own livelihoods. Table 3.4 shows the detailed crop growing areas of the GWDS. The low irrigation efficiency and limited water resources are two main reasons for irrigators to choose corn instead of other crops: (a) corn is able to benefit more from precipitation during the rainy season (August and September) unlike other food crops like wheat harvested in July and (b) corn needs less care and water than cash crops. This allows irrigators to earn extra money beyond the farm. With the aforementioned merits, famers are more willing to accept a fair revenue by growing corn rather than taking the chance to grow cash crops with their limited water permits. Table 3.5 shows the unit area production for each crop.

The poor irrigation infrastructure in this area refrains famers from gaining further benefit. To date, nearly all of the irrigated lands in the study region are using flood irrigation, which inevitably leads to high irrigation quotas, as they are usually two or three times higher than the actual crop water demands (Zhu and Yang, 2006). Table 3.6 shows the crop water demands under different irrigation techniques and with respect of the soil properties and climatic conditions. Irrational agricultural water use and low irrigation efficiency in Ningxia has received dozens of criticisms by downstream water users (Duan et al., 2002; Wang et al., 2004; Zhen and Lv, 2002). To address the inefficient water use in AZN, the agricultural sector has been placed at the forefront of water conservation reforms (Wang et al., 2011). Since 2006, innovative irrigation technologies such as dripping and

Table 3.4 Crop growing areas

County & Subarea	Corn (Mu)	Wolfberry (Mu)	Apple (Mu)	Wheat & Vegetable (Mu)
ZN				
GT1	10610	4290	580	6400
GT2	20100	3200	2000	3900
GT3	49500	7650	5570	6080
GHB	12200	1010	1100	1000
GH1	400	0	0	0
GH2	5060	4300	2000	640
GC2	2900	2750	0	50
GH3	7560	4500	0	1330
GH4	520	0	0	450
MT	41050	0	0	5360
CST				
GH3	400	1180	490	256
GH4	2650	0	300	750
GHL	23800	0	400	3800
GD1	10500	0	300	2650
GH5	11000	320	950	2050
TX				
GD1	40000	0	300	5050
GD2	11000	200	100	2400
GD3	46700	2350	825	5125
GH5	66810	5590	985	10595
GH6	25900	0	0	2600
MT	6920	50	300	175
GH7	24970	0	0	1820
HY				
GH7	24640	300	0	8270
GH8	51360	1710	0	11930

Table 3.5 Crop profile data

	Corn	Wolfberry	Herb	Apple	Millet
Production (Kg/Mu)	[900, 950]	[240, 260]	[100, 110]	[2300, 2700]	[450, 500]
Cost under traditional irrigation (yuan/Mu)	[522, 559]	[5475, 5858]	[1760, 1883]	[2500, 2675]	[484, 518]
Cost under advanced irrigation (yuan/Mu)	[767, 821]	[5560, 5949]	[1895, 2028]	[2700, 2889]	[568, 608]
Price (yuan/Kg)	[2.1, 2.6]	[70, 90]	[40, 50]	[3, 4]	[3.4, 5.9]

Table 3.6 (a) Crop water demands under flood irrigation

County/Subarea	Corn (m^3/Mu)	Wolfberry (m^3/Mu)	Herb (m^3/Mu)	Apple (m^3/Mu)	Millet (m^3/Mu)
ZN	[400,500]	[490, 520]	[400, 440]	[290, 300]	[300, 320]
CST	[375,475]	[465, 495]	[380, 420]	[275, 285]	[285, 305]
TX	[350,450]	[440, 470]	[360, 400]	[260, 270]	[270, 290]
HY	[325,375]	[415, 440]	[340, 375]	[245, 255]	[255, 270]
GT1	[650,750]	[760, 800]	[620, 680]	[450, 465]	[465, 495]
GT2	[525,625]	[640, 675]	[520, 570]	[380, 390]	[390, 415]
GT3	[450,550]	[560, 600]	[460, 505]	[330, 345]	[345, 370]

Note: GT1, GT2 and GT3 subareas belong to the Zhongning county

Table 3.6 (b) Crop water demands under dripping and sprinkling irrigation

County/Subarea	Corn (m^3/Mu)	Wolfberry (m^3/Mu)	Herb (m^3/Mu)	Apple (m^3/Mu)	Millet (m^3/Mu)
ZN	[180,200]	[320, 350]	[200, 220]	[180, 200]	[230, 240]
CST	[175,195]	[310, 340]	[195, 215]	[175, 195]	[220, 230]
TX	[170,190]	[300, 330]	[190, 210]	[170, 190]	[210, 220]
HY	[165,185]	[290, 320]	[185, 205]	[165, 185]	[200, 210]
GT1	[210,230]	[350, 400]	[230, 250]	[190, 210]	[230, 255]
GT2	[200,220]	[340, 385]	[220, 240]	[200,220]	[240, 265]
GT3	[190,210]	[330, 370]	[210, 230]	[210,230]	[250, 275]

Note: The water demand for millet is estimated under sprinkling irrigation; the water demands for other crops are estimated under dripping irrigation.

sprinkling irrigation systems have been adopted to most newly reclaimed land in AZN (Zhang and Su, 2009). In addition, DI has been applied to the MT subarea for corn production (Liu et al., 2012; Liu et al., 2010).The implementation of high efficiency irrigation practice has increased the gross water efficiency from 0.38 to 0.43 in 2010 (WRDN, 2011).

The unique culture and social characteristics of this area also raised attention from local and central governments. Over half of the populations in AZN are the minority (i.e. Hui) nationality. The pumping systems have facilitated the fusion of different nationalities. To maintain this ethnic unity, local farmers enjoy considerable amount of subsidy (more than 75% of the shadow water price) from the government. The widespread subsidies on one side alleviated the water bills for irrigators. However, on the other side, they hindered water efficiency efforts and caused a tremendous waste of water resource (Gleick, 2000), because irrigators were more likely to pour water onto the field rather than losing it (Bjornlund and McKay, 2002). In 2014, the local government initiated another water price called the preferential water price, which is between the shadow and current water prices. The shadow water price (yuan/m^3) reflects the value of all the resources used for delivering one cubic meter of water. The preferential water price (yuan/m^3) reflects the value of all the resources except electricity which is partially paid by the government. The current water price (yuan/m^3) only reflects the fixed cost of the irrigation system. In this study, shadow water price is regarded as the actual water cost, which also equals to the full recovery cost of water. Figure 3.3 indicates the current water price (yuan/m^3) is running far below the water cost.

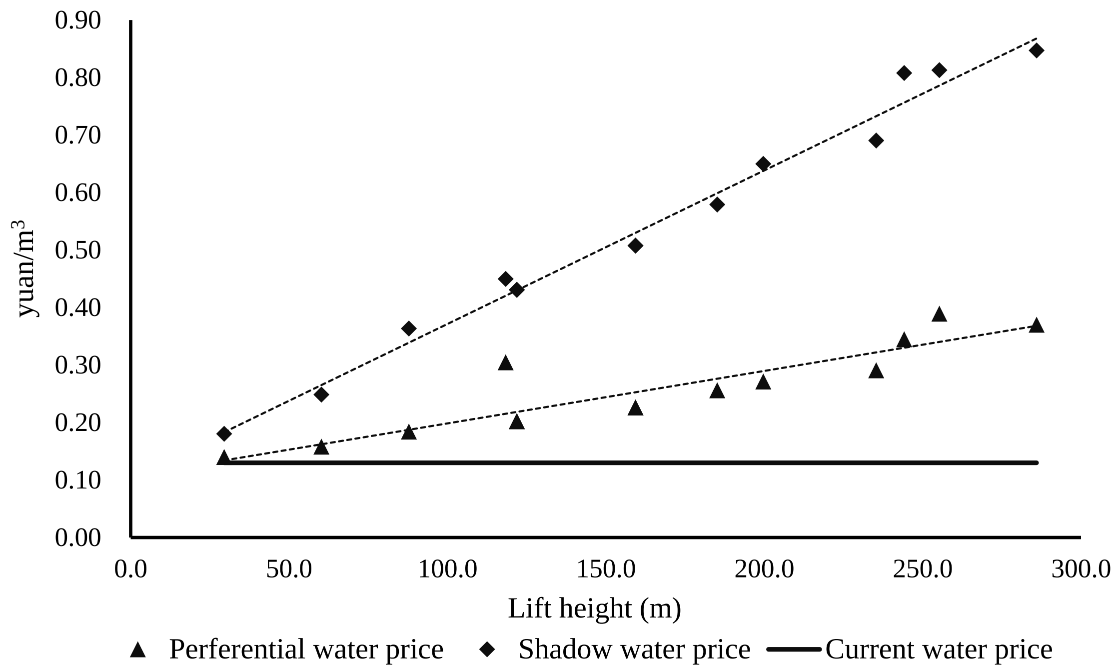

Figure 3.3 Relations of water prices and pumping stations

3.6. Water Demands

To date, only 22.5% of the arable land is covered by the water distribution systems in AZN, leaving the rest of the dry land in poor-yield conditions. In AZN, the yields from a unit of fully irrigated field are four times higher than a unit of rain-fed field. In addition, irrigation also eliminates the risk of drought-caused production failure. The huge potential for land reclamation has been motivating the government to seek for more agricultural production to secure the increasing food demand, and for more importantly, to create more wealth for local famers. The most serious obstacle for the agricultural expansion in AZN is limited water. Once more water can be secured to this region, the more agricultural production will be generated.

In addition, the local industries are also expecting a rapid growth in the next few years. Many counties are promoting their featured industries to support their economy. For example, the supreme quality of gypsum produced in ZN county has been favored by many fields, such as medicine, civil engineering and even by artists. Also, the cashmere industry in TX county and the sheep fur industry in HY county are promising due to increasing demands for luxury clothing from mid-high class families. The strong market demands have become main driving forces for the industry to expand its production capacity. Table 3.7 shows the industrial data including unit product water consumption, unit water profit and producing expansion capacity.

Furthermore, the improving living standards from the local population has asked more water from the existing system. In August 2014, the local government initiated an increase in the municipal water use standard from 15 L^3/day to 50 L^3/day per capita in rural areas and from 90 L^3/day to 110 L^3/day per capita in urban areas (WRDN, 2014). This new

Table 3.7 Industrial profile data

	Gypsum	Dry wall	Cashmere	Blanket	Sheep fur
Unit product water consumption (m^3)	[3, 3.9]	[1, 1.3]	[200, 260]	[100,130]	[1, 1.3]
Unit water profit (yuan/m^3)	[10, 11]	[288,317]	[268, 295]	[407, 448]	[30, 33]
Producing capacity (10^3 unit)	[200, 210]	[200, 210]	[2, 2.1]	[2, 2.1]	[400, 420]

standard will be taken effect in 2015. Moreover, due to the urban expansion and population growth, the water use in the future will further intensify the water shortage situations. By 2015, the GWDS is required to meet 35%-45% of the municipal water demand from TX and HY counties. The municipal water supply for ZN county will be fulfilled by other water distribution systems. Assuming the urbanization rates for the two counties are at 1% and the population growth rates are at 1.25%, the water demand projections for TX and HY counties at 2017 and 2020 are listed in Table 3.8.

3.7. Water Trading Policies

The importance of initiating water conservation and institutional reformation in AZN has received wide attention from local governments and the Central Committee of the Communist of China (CPC). In 2005, Ningxia was proposed for the first pilot water conservation province at the Third Session of the Tenth National People's Congress. The proposal earned widespread support from the NPC Committee, and was approved by the Ministry of Water Resources (MWR) and the State Development and Reform General Office (SDRGO). In 2006, the first Water Conservative Society (WCS) was established in Ningxia, featuring a revolutionary change for the institutional reformation in China. The essence of WCS is to use the water market to create incentives for water conservation and realize the sustainable water use (YRCC, 2004).

In accordance with the suggestions from MWR and the Yellow River Conservancy Commission (YRCC), Ningxia water administration initiated a series of water trading rules based on unique social and economic characteristics (YRCC, 2004). First, the water trading program respects the legacy of past policies and protects current water users' (especially

Table 3.8 Municipal water demands for TX and HY counties

Year	TX (10^3 m^3)	HY (10^3 m^3)
2017	[725.0, 1190.8]	[1087.6, 1531.0]
2020	[1450.1, 2381.6]	[2175.1, 3062.1]

famers') interests. Secondly, water trading places ecological water demand as a priority. Thirdly, water trading follows the law of economy and shifts water from low efficient users to high efficient users. Fourthly, water trading ensures food security and meets basic agricultural water demands. Finally, water trading must be conducted under an accurate water liquidation system.

Current water trading emphasizes the function of local government, which plays dual roles as an investor and a negotiator. To ensure a steady growth in agricultural production, the local government prohibits direct water trading between irrigators and industries. Alternatively, the local government joins industries to finance irrigators with irrigation infrastructure investments. In return, the conserved water will be an asset allowing local government to irrigate more dry land and enable industries to expand their capacity. The entire process requires the system optimization to provide information for each subarea's water conservation potential, based on which the government can generate detailed reformation plans and sign contracts with industries to complete the water trading. In 2011, the total volume of water transaction from the agricultural to industrial sector reached 70 million cubic meters, creating a net revenue of 10.7 billion yuan. To date, over 13 industries have expressed interest in water trading with a total water conservation potential of 130 million cubic meters of water. The aforementioned facts show the water trading is a win-win policy for the local economy and agricultural sustainability. In one hand, water trading reduces the exploitation of groundwater and maintains the environment. In the other hand, it substantially improves irrigation efficiency and paves the way to sustainable agriculture.

3.8. Challenges and Opportunities for Water Resources Management

The GWDS is facing a series of challenges deriving from rapid social and economic developments and changing climates. In specific, there is a great potential for developing more irrigated land in AZN as long as water can be delivered. In the GWDS, the poor irrigation infrastructure and extensive water management have become two vital problems for the retarded agricultural development. Therefore, how to overcome these two issues has become the foremost challenge for agricultural sustainability. Another challenge is the rapid development of the local industry and the improving living standards of local people, which desire a more rapid technological and institutional reform toward water conservation. Furthermore, changing climate has exacerbated the tension on water stress and intensified the water conflicts among water users. These challenges are closely related with the local economy, food security and households' incomes, which need to be addressed with the provision of a more comprehensive water market mechanism.

Even though the water market in GWDS has been successful in transferring water to where it is needed most, trading still happened to a very limited degree. This is because only permanently 'saved' water can be traded. In fact, under most of the well-developed institutional mechanisms around the world, permanent or long-term water transfer has not always been favored by water permit holders who would permanently lose their water rights (Bjornlund and McKay, 2002). On the contrary, the trading of annual or seasonal water allocation always generates greater social and economic benefits as some farmers who grow low-valued crops may prefer to abandon production and sell water permits to generate cash income instead of pouring water into the fields (Zuo et al., 2014). Moreover, some urgent water demands caused by climate and social uncertainties can be quickly mitigated through the temporary water trading. Therefore, seasonal water trading (i.e. temporarily trade water to other water users) should be introduced in the GWDS to fill the gap between no trading and permanent or long-term trading, providing more flexibility and trading opportunities for water users.

CHAPTER 4

DEVELOPMENT OF THE MARKET-BASED ARID-REGION WATER RESOURCES PLANNING MODEL

4.1. System Complexities and Uncertainties

The Guhai Water Distribution System (GWDS) is complicated with a variety of water-related activities in social-economical, technical and environmental contexts. The study region is characterized by multi-culture and low-income population, holding a significant role of ethnic unity. Therefore, the design of water market in the GWDS should respect the principle of equality and social recognition. For example, irrigators who save more water should receive more benefits to compensate their water loss and associated loss in revenue. In addition, due to the unevenly distributed household economic, irrigators may not spontaneously response to the reformation policies. Thus, decision makers should respect the willingness of irrigators and progressively perform the water conservation policies. Industrial participation is the core component in the water trading program. To ensure a constant agricultural production, local industries should be introduced to the system with a minimum disturbance to agricultural activities.

Apart from the aforementioned social and economic complexities, the study system is further complicated by multiple irrigation techniques and environmental uncertainties. There are three types of irrigation techniques applied in this study region: traditional (flood) irrigation, advanced (dripping and sprinkling) irrigation and deficit irrigation (hereinafter DI). The crop productions and benefits under the first two types of irrigation method are pre-defined, while the crop productions under DI practice are subject to the crop's water-production functions. Due to the local climatic and geophysical conditions, crop productions and irrigation quotas may vary significantly in both water availability and soil conditions. For example, less water will be applied to the soil with greater water retention capacity under the same climatic zone. In addition, the simulation of water-production functions for DI practice faces a number of uncertainties due to fitting errors and simulation performance. The interactions among different irrigation methods (i.e. the conversion from traditional to advanced irrigation techniques) will also complicate the water distribution system.

4.2. Methodology

4.2.1. Deficit Irrigation and Corn Crop Yield Simulations

Among three types of irrigation techniques, DI is the prerequisite for seasonal water trading of this study because all the delivered water is actively used and consumed by various water related activities. Assuming the value of water is responsive to drought frequencies, once water becomes scarier and pricy, irrigators are encouraged to switch to DI and curtail a certain amount of crop production so that the conserved water can be traded for more benefits. The success of DI practice is depending on the evaluation of the crop's marginal water cost, which is defined as the crop profit for applying one more unit of water. The evaluated marginal water cost will form the basis for irrigators to judge the profitability of water trading. In practice, the application of deficit irrigation scheme is limited to plants or crops such like corn and wheat, which are usually characterized with intensive water use and higher drought tolerance. In this study, corn was chosen rather than wolfberry, herb, apple and millet as the target crop for the DI practice with the following reasons: (a) it has intensive water use and higher drought tolerance; (b) it shares the largest growing area and owns the lowest irrigation efficiency and (c) it has already been practiced under DI scheme in the MT subarea and its adaptability has been proved in the GWDS.

Crop yield simulation is essential to provide a relatively accurate evaluation for crop's marginal water cost. In order to deliver a reliable DI practice in the GWDS, intensive investigations for the corn water-production relationships have been conducted at three experimental sites located in ZN, TX and HY counties. The water-production relationships describe the relation of the crop water consumption and crop productivity. Due to the limitation of on-farm water liquidation, local irrigation communities divide the water into uniformed 'shares' (1 share equals to 25 m^3). Thereafter, based on the real-time monitoring data of soil moisture, irrigators can decide how many 'shares' should be applied to their lands. Integer numbers are used to represent the 'shares' of water. Table 4.1 shows the experimental data for corn water-production relationships. Three drought levels denoted as wet year (precipitation PDF is less than 25%), normal year (precipitation PDF is between 25% and 75%) and dry year (precipitation PDF is greater than 75%) are simulated for three sites by using parabolic curves, which demonstrate good fittings results (the values of R^2 are greater than 0.98) for the corn water-production functions. Figure 4.1 shows the simulated water-production relations for the three counties. It should be noted that some exceptional areas within the GWDS require additional fitting adjustments. For example, the GT1, GT2 and GT3 subareas have lower water retention capacity and require more intensive water use than other subareas within the same county. Therefore, based on the corn growing practices in the GT1, GT2 and GT3 subareas, their water-production

Table 4.1 (a) Corn water-production relations for ZN County

Production (Kg/Mu)	Applied water (m^3/Mu) or (share/Mu) Wet year	Normal year	Dry year
200 - 300	150 (6)	200 (8)	250 (10)
400 - 500	200 (8)	250 (10)	300 (12)
730 - 830	250 (10)	300 (12)	350 (14)
850 - 950	300 (12)	350 (14)	400 (16)
900 - 1000	350 (14)	400 (16)	450 (18)
920 - 1020	400 (16)	450 (18)	500 (20)

Note: 150 (6) denotes 150 cubic meters of water or 6 shares of water for per unit area

Table 4.1 (b) Corn water-production relations for TX County

Production	Applied water (m^3/Mu) or (share/Mu)		
(Kg/Mu)	Wet year	Normal year	Dry year
300 - 400	100 (4)	150 (6)	200 (8)
500 - 600	150 (6)	200 (8)	250 (10)
750 - 850	200 (8)	250 (10)	300 (12)
850 - 950	250 (10)	300 (12)	350 (14)
930 - 1030	300 (12)	350 (14)	400 (16)
950 - 1050	350 (14)	400 (16)	450 (18)

Table 4.1 (c) Corn water-production relations for HY County

Production	Applied water (m^3/Mu) or (share/Mu)		
(Kg/Mu)	Wet year	Normal year	Dry year
300 - 400	50 (2)	75 (3)	100 (4)
500 - 600	100 (4)	125 (5)	150 (6)
650 - 750	175 (7)	200 (8)	225 (9)
800 - 900	225 (9)	250 (10)	275 (11)
840 - 940	275 (11)	300 (12)	325 (13)
850 - 950	325 (13)	350 (14)	375 (15)

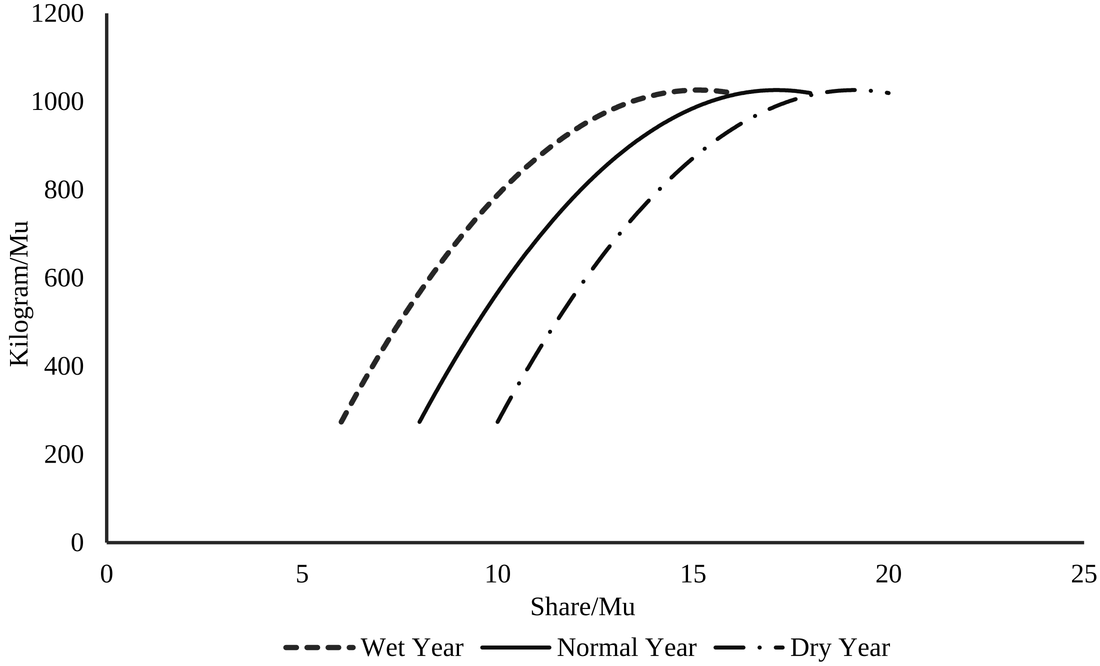

Figure 4.1 (a) Simulated corn water-production relations for ZN county (upper bound)

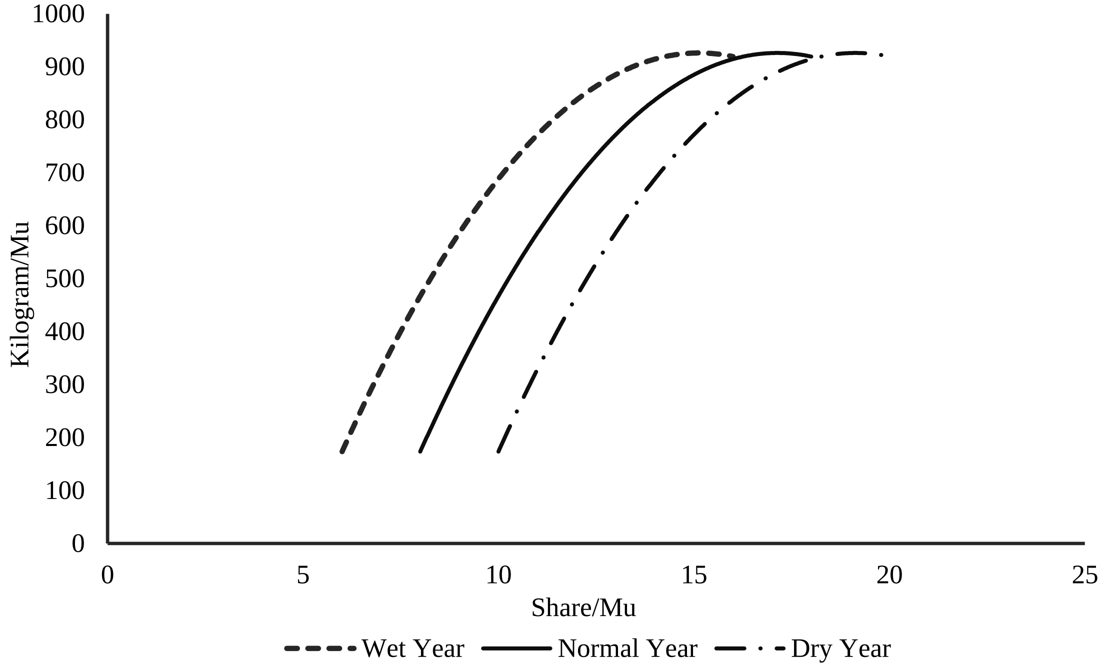

Figure 4.1 (b) Simulated corn water-production relations for ZN county (lower bound)

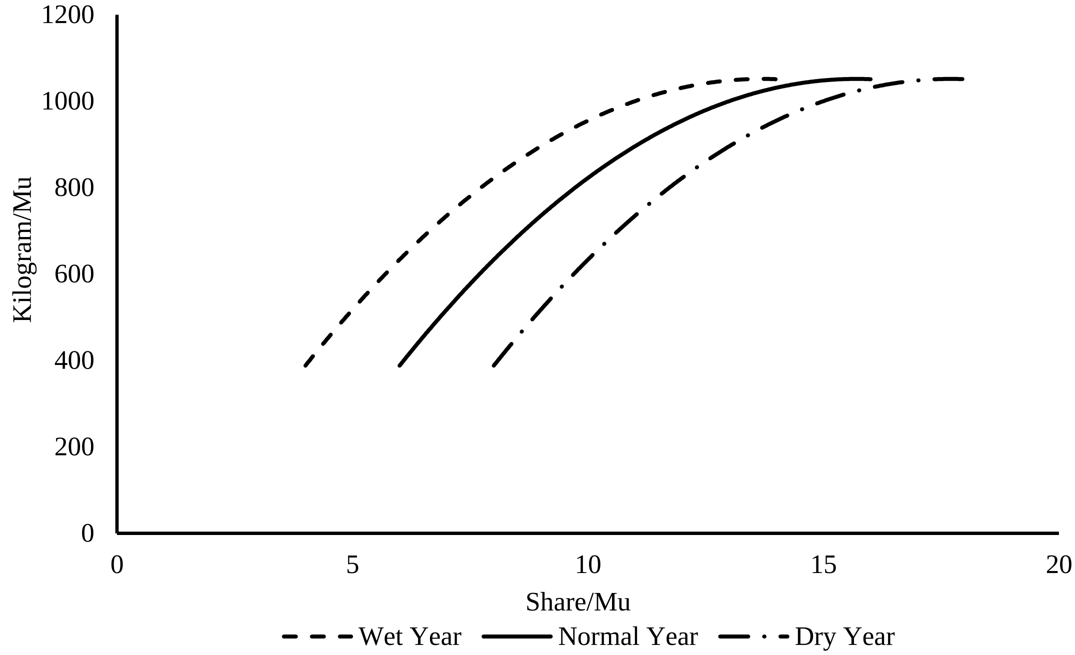

Figure 4.1 (c) Simulated corn water-production relations for TX county (upper bound)

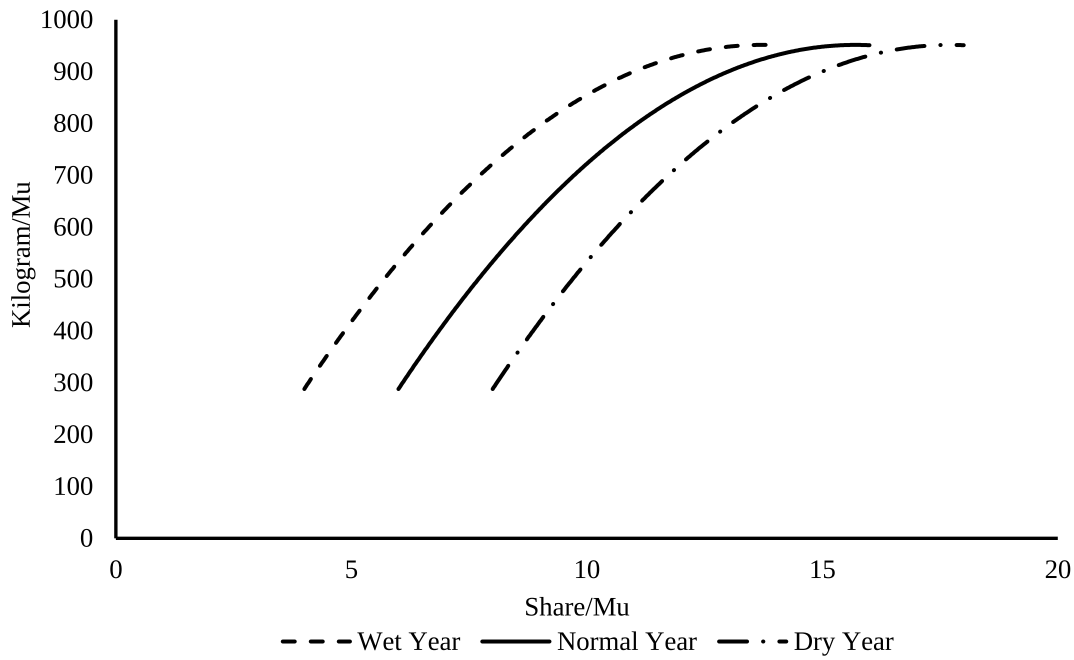

Figure 4.1 (d) Simulated corn water-production relations for TX county (lower bound)

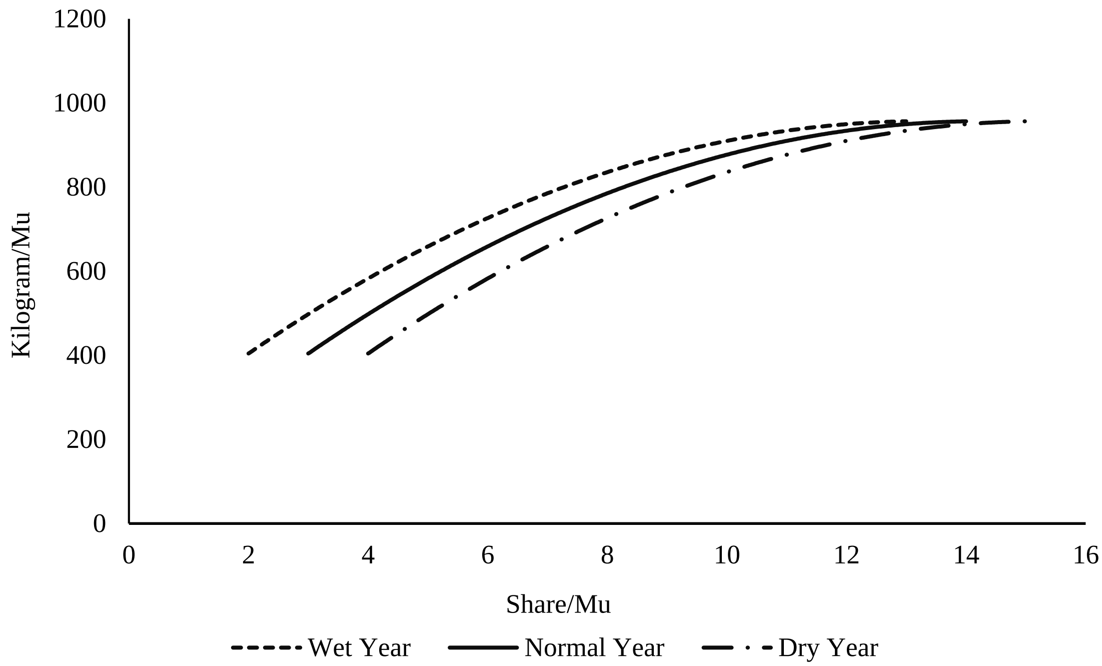

Figure 4.1 (e) Simulated corn water-production relations for HY county (upper bound)

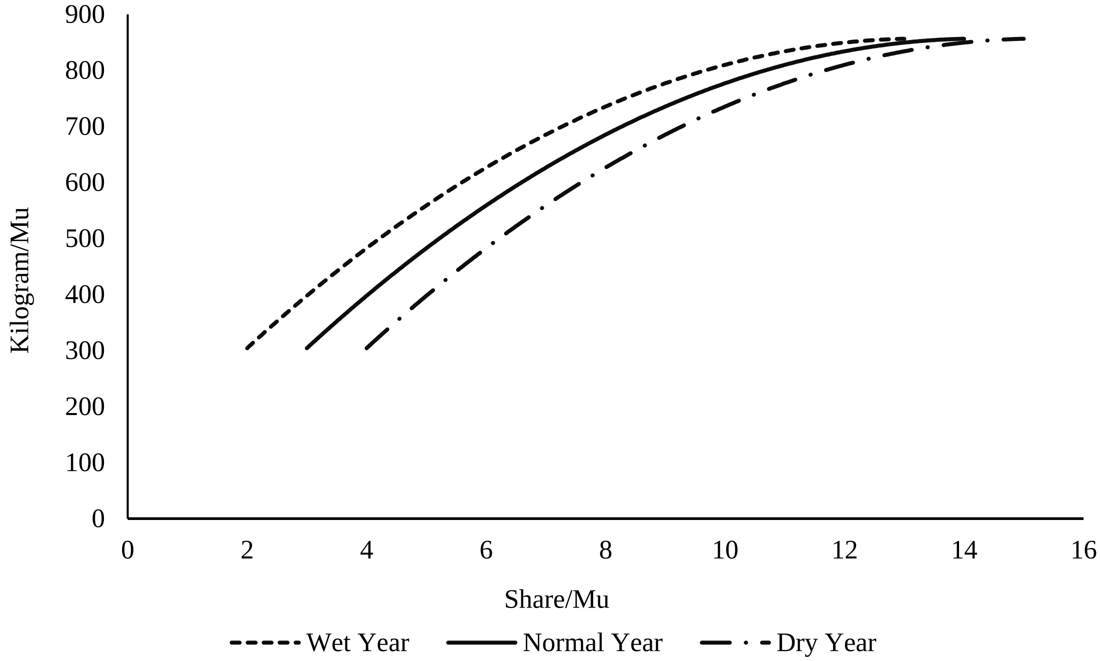

Figure 4.1 (f) Simulated corn water-production relations for HY county (lower bound)

functions are simulated against the water-production relation in the ZN county by using three amplification coefficients. Moreover, due to the increasing trend of local precipitation from north to south, the corn water demands for CST farm should range between those of ZN and TX counties. To deal with this complexity, the linear interpolation method is used to simulate the water-production functions for CST farm. Table 4.2 shows the corn water-production functions for all three counties and CST farm.

4.2.2. Two-Stage Stochastic Programming Method

Two-Stage Stochastic Programming (TSP) method has been provide to be effective for supporting long-term planning problems where decisions need to be made dynamically to achieve an optimal objective function value (Li et al., 2013). The classic TSP model was given by Birge and Louveaux (2011), as follows:

$$Max\ f = \sum_j NB_j TW_j - E\left[\sum_j C_j D_{jM}\right] \tag{4.1a}$$

subject to:

$$TW_j - D_{jM} \le Q_M \quad \forall j, M \tag{4.1b}$$

$$0 \le D_{jM} \le TW_j \quad \forall j, M \tag{4.1c}$$

where f is the net system benefit over the planning period; NB_j and TW_j represent the net benefit (i.e. revenue minus expense) and water demand (m^3) of the j_{th} water user

Table 4.2 (a) Corn water-production functions (upper bound)

County/ Subarea	Wet year	Normal year	Dry year	R^2
ZN	$y=-9.02x^2+272.96x-1039.6$	$y=-9.02x^2+309.04x-1621.6$	$y=-9.02x^2+345.11x-2275.7$	0.984
CST	$y=-9.02x^2+254.93x-775.63$	$y=-9.02x^2+291x-1321.6$	$y=-9.02x^2+327.07x-1939.6$	0.984
TX	$y=-7.05x^2+249.68x-1158.1$	$y=-7.05x^2+221.46x-687$	$y=-7.05x^2+193.25x-272.29$	0.994
HY	$y=-4.33x^2+115.21x+191.21$	$y=-4.33x^2+123.88x+71.66$	$y=-4.33x^2+132.55x-56.522$	0.991
GT1	$y=-9.02x^2+453.32x-4671$	$y=-9.02x^2+489.39x-5613.7$	$y=-9.02x^2+525.46x-6628.6$	0.984
GT2	$y=-9.02x^2+363.14x-2629.8$	$y=-9.02x^2+399.21x-3292.2$	$y=-9.02x^2+435.29x-4226.7$	0.984
GT3	$y=-9.02x^2+309.04x-1621.6$	$y=-9.02x^2+345.11x-2275.7$	$y=-9.02x^2+381.18x-3002$	0.984

4.2 (b) Corn water-production functions (lower bound)

County/ Subarea	Wet year	Normal year	Dry year	R^2
ZN	$y=-9.02x^2+272.96x-1139.6$	$y=-9.02x^2+309.04x-1821.6$	$y=-9.02x^2+345.11x-2375.7$	0.984
CST	$y=-9.02x^2+254.93x-875.63$	$y=-9.02x^2+291x-1421.6$	$y=-9.02x^2+327.07x-2039.6$	0.984
TX	$y=-7.05x^2+249.68x-1258.1$	$y=-7.05x^2+221.46x-787$	$y=-7.05x^2+193.25x-372.29$	0.994
HY	$y=-4.33x^2+115.21x+91.21$	$y=-4.33x^2+123.88x-28.34$	$y=-4.33x^2+132.55x-156.522$	0.991
GT1	$y=-9.02x^2+453.32x-4771$	$y=-9.02x^2+489.39x-5713.7$	$y=-9.02x^2+525.46x-6728.6$	0.984
GT2	$y=-9.02x^2+363.14x-2729.8$	$y=-9.02x^2+399.21x-3392.2$	$y=-9.02x^2+435.29x-4326.7$	0.984
GT3	$y=-9.02x^2+309.04x-1721.6$	$y=-9.02x^2+345.11x-2375.7$	$y=-9.02x^2+381.18x-3102$	0.984

respectively; C_j is the penalty of net benefit (Yuan/m^3) caused by insufficient water supply ($C_j \le NB_j$); D_{jM} is the water deficit when the available water flow is Q_M; $E[\cdots]$ is the expected value of a random variable; Q_M is the total water availability of the M_{th} water level during the planning period.

For the traditional TSP model, the initial decision in the first stage is based on the prediction about random variables, and the recourse decisions provided at the preceding planning stage (i.e. second stage) are to assign a penalty to recourse activities taken to amend the first-stage decision errors (Birge and Louveaux, 2011; Huang and Loucks, 2000). Stream flow is regarded as the only water resource for most of the conventional TSP model developed for water resources planning purposes. However, for rain-fed agriculture, deficit irrigation is widely applied with the emphasis on water harvesting systems, allowing for more efficient water use in arid regions. In order to provide more resiliency and adoptive water allocation systems for arid regions, an improved TSP model is proposed by regarding rainfall as the starting point of available water resources. Therefore, the initial decision in the first stage will be based on crop actual evapotranspiration. In the second stage of the TSP model, the recourse decision will be focused on precipitation rather than stream flow. When the uncertainties in precipitation cause insufficient water supply, irrigators face system penalties which can be split into two practices: (a) paying for the water cost with additional water use from the water distribution system and/or (b) stop irrigation by accepting the loss of production caused by the water deficit. Thus, a more flexible and efficient water management method can be formulated as follows:

$$Max\ f = \sum_j NB_j TW_j - \sum_j \sum_{m=1}^{n} \alpha\left(A_j X_{jm} + B_{jm} Y_{jm}\right) k_m \quad (4.2a)$$

subject to:

$$\alpha\left(X_{jm} + Y_{jm}\right) \le D_{jm} \quad \forall j, m \quad (4.2b)$$

$$TW_j - \alpha\left(X_{jm} + Y_{jm}\right) \le prec_m \quad \forall j, m \quad (4.2c)$$

$$0 \le \alpha\left(X_{jm} + Y_{jm}\right) \le TW_j \quad \forall j, m \quad (4.2d)$$

$$X_{jm} + Y_{jm} \ge 0 \quad \forall j, m \quad (4.2e)$$

$$X_{jm} \le Cap \quad \forall j, m \quad (4.2f)$$

Where X_{jm} and Y_{jm} are integer decision variables representing the unit water applied to crops and the unit water deficit for the curtailed crop production, respectively; D_{jm} is the total crop water deficit when precipitation is under m_{th} drought level; $prec_m$ is the amount of precipitation under m_{th} drought level; α is the volume of per 'share' of water; A_j denote the costs for water resources carried by the system ($Yuan/m^3$) and B_{jm} are the nonlinear interval functions representing unit area production loss responding to water deficit in the m_{th} drought level (kg/m^3); and Cap is the maximum water resource carried by the irrigation system (m^3).

4.2.3. Inexact Two-Stage Stochastic Programming

Even though the TSP method has been proven as an effective approach to deal with the uncertainties, in most real world situations, some uncertain factors cannot be expressed as possibility distributions due to a lack of information. But they can be quantified as interval values. In order to tackle this form of uncertainty in the modelling process, an inexact two-stage stochastic (ITSP) model will be developed (Huang, 1998).

Let x be a closed and bounded set of real numbers. $x^{\pm}$ is defined as a set of intervals with crisp lower and upper bounds but unknown distribution information for x (Huang, 1996).

$$x^{\pm} = \left[x^{-}, x^{+} \right] = \left\{ t \in x \middle| x^{-} \leq t \leq x^{+} \right\} \tag{4.3}$$

where x^{-} and x^{+} represent the lower and upper bound of $x^{\pm}$, respectively. Thus, the model (4.2) could be reformulated into an inexact water management model as follows:

$$Max\ f^{\pm} = \sum_{j} NB_j^{\pm} TW_j^{\pm} - \sum_{j} \sum_{m=1}^{n} \alpha \left(A_j^{\pm} X_{jm}^{\pm} + B_{jm}^{\pm} Y_{jm}^{\pm} \right) k_m \tag{4.4a}$$

subject to:

$$\alpha \left(X_{jm}^{\pm} + Y_{jm}^{\pm} \right) \leq D_{jm}^{\pm} \quad \forall j, m \tag{4.4b}$$

$$TW_j^{\pm} - \alpha \left(X_{jm}^{\pm} + Y_{jm}^{\pm} \right) \leq prec_m^{\pm} \ \forall j, m \tag{4.4c}$$

$$0 \leq \alpha \left(X_{jm}^{\pm} + Y_{jm}^{\pm} \right) \leq TW_j^{\pm} \ \forall j, m \tag{4.4d}$$

$$X_{jm}^{\pm} + Y_{jm}^{\pm} \geq 0 \ \forall j, m \tag{4.4e}$$

$$X_{jm}^{\pm} \leq Cap^{\pm} \ \forall j, m \tag{4.4f}$$

Model 4.4 can be transformed into two deterministic sub-models corresponding to the lower and upper bound of the model solutions. Based on the interactive algorithm, this model can be solved by integrating the two sub-models (Huang, 1998). The solutions for this model provide interval values for the objective function and decision variables and can be interpreted to generate decision alternatives (Huang and Loucks, 2000). Numerous literatures have provided evidence for the efficiency of using interval values to reflect system uncertainties (Li et al., 2006; Li et al., 2010; Lu et al., 2010; Lv et al., 2010; Maqsood et al., 2005). In this study, all the uncertainties involved in the modelling process are grouped into two categories: decision and functional intervals. The decision intervals tackle uncertainties introduced by social-economic development and political interventions. Examples include the area limitation for each crop, proportions of industrial participation in irrigation infrastructure investment, and the overall crop yields rate. Functional intervals handle uncertainties existing in a natural context like the coefficients in water-production functions. A flow chart in Figure 4.2 illustrates the detailed components of the entire modelling process.

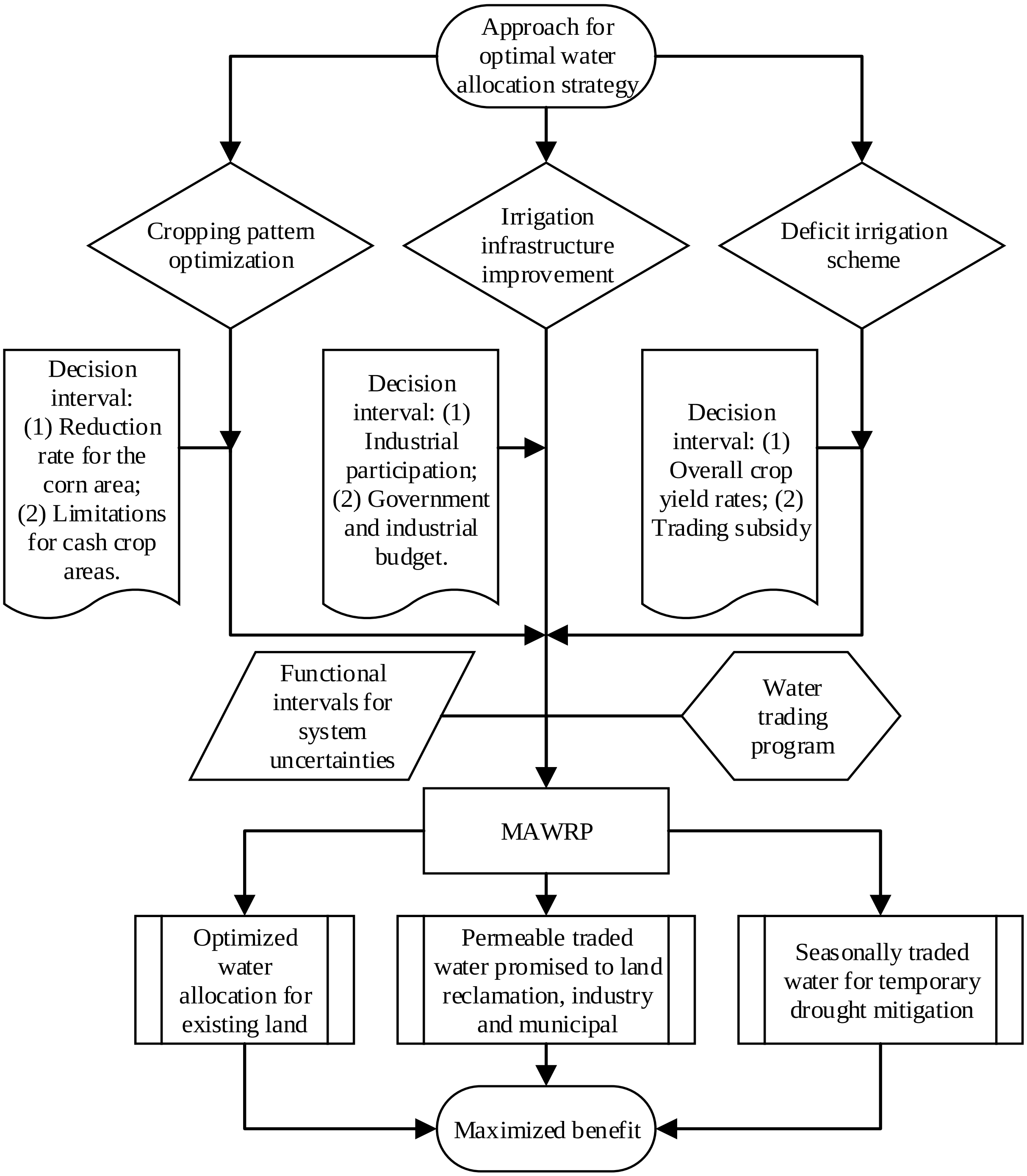

Figure 4.2 Generalized framework for optimal water distribution strategy

4.3. Development of the MAWRP Model

4.3.1. Model Configuration

Water resources allocations are directed by lots of man-made decisions. Usually, these decisions are made by decision makers with their own experiences in order to achieve social stability and a harmonious human-nature relationship. In the MAWRP model, these decisions will be indicated as decision variables and interpreted by using interval values. For example, the tolerance range of a crop production failure and the desired degree of policy enforcement can be denoted as intervals. Thoughtfully designed decisions will be helpful to reduce the risk of market failure and improve the water allocation efficiency. To deliver a reliable water allocation plan, it is necessary to identify all the decision variables and evaluate their effects on water resources planning decisions. In this study, the identification and selection of decision variables are conducted with consideration of the economic and political targets and the experience of water policy enforcement for the past decades.

According to the 5th Year Investigation Report of Ningxia Water Conservation Society (WRDN, 2011), the provincial government has initiated a plan to equip the AZN region with 1 million Mu of advanced irrigation infrastructure by 2020. The conserved water will be allotted for industrial expansions and cropping pattern modification. The plan was divided into two phases as 2015-2017 and 2017-2020. Table 4.3 shows the concrete plans for infrastructure investment in each county within the GWDS. To help improve local famers' income, the government encourages local famers to adopt more beneficial cropping patterns by reducing the corn growing area and increasing cash crop area. Regarding social acceptance to new crops and advanced irrigation technology, the

Table 4.3 Infrastructure investment targets

	ZN	CST	TX	HY
Infrastructure investment areas (10^3 Mu/phase)	[90, 135]	[30,45]	[90, 135]	[30,45]

modification to cropping patterns and the reformation to irrigation infrastructure should be progressively performed. For example, it is suggested that the reduction rate of the corn growing area should be controlled at [7, 10]% per year. In addition, the infrastructure investment for each phase will be evenly allocated to the three years within the planning phase. Moreover, to maintain the minimum food production and prevent the water from transferring out of agricultural sector, the overall crop yield rates should be kept at a desired level of [85, 90]%, which is defined as the ratio of actual and potential crop yield. The industrial participation to agricultural investment should be performed with the respect of famers' willingness toward water trading and the recognition of trading rules to avoid a water monopoly. Based on the aforementioned criteria, the water allotted to industrial sector shares [15, 30]% of the total conserved water. It is assumed that all the industrial expansions are performed at the beginning of each planning phase. In accordance with the progressively adopted agricultural reformation, the newly expanded industries will be operated under 1/3 and 2/3 of their producing capacities for the first and second years in each phase, respectively.

Considering apple and wolfberry are perennial plants and need two-year's growing time to bear fruit, there is no benefit until the fruiting years of apple and wolfberry. Therefore, the first two-year's revenue for apple and wolfberry will be subtracted from the total revenue. Moreover, about 13% of the irrigation area is growing wheat and vegetables. Because they are mainly planted at the famers' back yards and used for sustaining their own livelihoods, thus are excluded from the economic objectives. In the MAWRP model, fixed irrigation quotas is assigned to these irrigation areas. Thus, their water consumption can be regarded as constant values in the modelling process.

4.3.2. Objective Function

The model objective is to maximize the system benefit for the two 3-year periods (2015-2017 and 2018-2020). The total economic benefit is determined by the sum of the two periods' original irrigation area's revenue, reclaimed land's revenue, industrial revenue, and the revenue from the seasonal water trading minus the corn production penalty. The revenue from the original and reclaimed lands comprises the revenue from traditional and advanced irrigation areas. Therefore, the objective function can be expressed as:

$$
\begin{aligned}
Max\ f =& \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{c=1}^{C}\left(2X_{kjic}^{\pm}+X_{(k-1)jic}^{\pm}\right)\cdot FNB_{jic}^{\pm}\cdot FTW_{jic}^{\pm}\\
&-\left(2X_{kjic}^{\pm}+X_{(k-1)jic}^{\pm}\right)\cdot C_j\cdot FA_{kjimc}^{\pm}\\
&-\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{c=1}^{C}P_m\cdot PR_f\left(2X_{kjfc}^{\pm}+X_{(k-1)jfc}^{\pm}\right)\cdot\left(FPRO_{jfc}^{\pm}-UCP_{kjmfc}^{\pm}\right)\\
&+\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{c=1}^{C}\left(2Y_{kjic}^{\pm}+Y_{(k-1)jic}^{\pm}\right)\cdot\left(DNB_{jic}^{\pm}-C_j\right)\cdot DA_{jic}\\
&+\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{c=1}^{C}\left(2R_{kic}^{\pm}+R_{(k-1)ic}^{\pm}\right)\cdot\left(RNB_{jic}^{\pm}-C_c\right)\cdot RA_{jic}\\
&-\tfrac{5}{3}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{e=1}^{E}\sum_{c=1}^{C}\left(X_{kjec}^{\pm}+Y_{kjec}^{\pm}-X_{(k-1)jec}^{\pm}-Y_{(k-1)jec}^{\pm}\right)\cdot PR_e\cdot PRO_{jec}^{\pm}\\
&-\tfrac{5}{3}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{e=1}^{E}\sum_{c=1}^{C}\left(R_{kec}^{\pm}-R_{(k-1)ec}^{\pm}\right)\cdot RNB_{ec}^{\pm}\cdot RA_{ec}\\
&+2\sum_{k=1}^{K}\sum_{t=1}^{T}\sum_{c=1}^{C}\left(INB_{tc}^{\pm}-C_c\right)\cdot IP_{ktc}\cdot IA_{ktc}^{\pm}\cdot DB_{ktc}^{\pm}\\
&+3\sum_{k=1}^{K}\sum_{m=1}^{M}P_m\cdot WTS_{km}^{\pm}\cdot TW_{km}^{\pm}
\end{aligned}
\tag{4.6a}
$$

where

$$
UCP_{kjmfc}^{\pm}=FA_{kjfmc}^{\pm}\cdot FA_{kjfmc}^{\pm}\cdot CA_{jmc}^{\pm}+FA_{kjfmc}^{\pm}\cdot CB_{jmc}^{\pm}+CO_{jmc}^{\pm}\ \forall;k,j,f,m,c \tag{4.6b}
$$

$$TW_{km}^{\pm} = TWD - \sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{c=1}^{C}\left(X_{kjic}^{\pm} \cdot FA_{kjimc}^{\pm} + Y_{kjic}^{\pm} \cdot DA_{kjic}^{\pm} \right) - \sum_{j=1}^{J}\sum_{c=1}^{C} OIW_{jc}$$
$$- \sum_{i=1}^{I}\sum_{c=1}^{C} R_{kjic}^{\pm} \cdot RA_{kjic}^{\pm} - \sum_{t=1}^{T}\sum_{c=1}^{C} IP_{ktc}^{\pm} \cdot IA_{ktc}^{\pm} \cdot DB_{ktc}^{\pm} - \sum_{c=1}^{C} MUN_{c}^{\pm} \quad \forall; k, j, f, m, c \qquad (4.6c)$$

4.3.3. Constraints

(1) *Irrigation area constraints*. Irrigation area should not beyond the current (original) land serviced by the GWDS.

$$\sum_{i=1}^{I}\left(X_{kjic}^{\pm} + Y_{kjic}^{\pm} \right) = \sum_{i=1}^{I}\left(X_{(k-1)jic}^{\pm} + Y_{(k-1)jic}^{\pm} \right) \quad \text{k = 2, ...,7;} \quad \forall; j, c \qquad (4.6d)$$

(2) *Deficit irrigation water balance constraints.* The sum of the corn applied water, corn water deficit and precipitation should be greater than the corn total evapotranspiration.

$$FA_{kjfmc}^{\pm} + B_{kjmfc}^{\pm} \le D_{jfmc}^{\pm} \;\; f \in i \;\; \forall; k, j, f, m, c \qquad (4.6e)$$

$$FTW_{jfc}^{\pm} - FA_{kjfmc}^{\pm} - B_{kjmfc}^{\pm} \le prec_{m}^{\pm} \;\; f \in i \;\; \forall; k, j, f, m, c \qquad (4.6f)$$

$$0 \le FA_{kjfmc}^{\pm} + B_{kjmfc}^{\pm} \le FTW_{jfc}^{\pm} \;\; f \in i \;\; \forall; k, j, f, m, c \qquad (4.6g)$$

$$FA_{kjfmc}^{\pm} + B_{kjmfc}^{\pm} \ge 0 \;\; f \in i \;\; \forall; k, j, f, m, c \qquad (4.6h)$$

$$FMIN_{jfc} \le FA_{kjfmc}^{\pm} \le FTW_{jfc}^{\pm} \;\; f \in i \;\; \forall; k, j, f, m, c \qquad (4.6i)$$

(3) *Cropping pattern constraints.* Based on market demands, crop adaptability and crop rotations, limitations of cultivation to food and cash crops are identified as interval values and summarized in Table 4.4 and 4.5, respectively.

Table 4.4 Cropping pattern constraints

	Original land	Reclaimed land
Corn	[40, 60]%	[40, 55]%
Wolfberry	[12, 15]%	[15, 20]%
Herb	[15, 18]%	[20, 25]%
Apple	[10, 12]%	[10, 15]%
Millet	[20, 25]%	[20, 25]%
Wheat	7.9%	0
Vegetable	5.2%	0

Note: the corn growing area cannot be lower than the limitation, and the other crops cannot exceed the limitation. Wheat and vegetable are excluded from the economic targets.

Table 4.5 Limitation for the cash crops of each county

	ZN	CST	TX	HY
Wolfberry	[35, 40]%	[10, 12]%	[10, 12]%	[10, 12]%
Herb	[10, 15]%	[10, 15]%	[20, 25]%	[25, 30]%
Apple	[20, 35]%	[20, 35]%	[20, 35]%	0

Note: Apple is not suitable for growing in the HY county due to its cold climate.

(5) *Food security constraints.* Since corn is associated with local food security, its annual reduction area and yield rates need to be kept at a desired level.

$$\sum_{j=1}^{J}\sum_{c=1}^{C} X_{kjfc}^{\pm} \geq \sum_{j=1}^{J}\sum_{c=1}^{C} SEC^{\pm} \cdot X_{(k-1)jfc}^{\pm} \quad \forall; k, f \tag{4.6j}$$

$$\sum_{c=1}^{C}\sum_{j=1}^{J} X_{kjfc}^{\pm} \cdot UCP_{kjmfc}^{\pm} \geq ENS_{mf}^{\pm} \cdot \sum_{c=1}^{C}\sum_{j=1}^{J} X_{kjfc}^{\pm} \cdot FPRO_{kjmfc}^{\pm} \quad \forall; k, m, f \tag{4.6k}$$

(5) *Irrigation infrastructure improvement.* The improved-infrastructure areas should not exceed the target areas of each county.

$$\sum_{j=1}^{J}\sum_{i=1}^{I} Y_{kjic}^{\pm} - \sum_{j=1}^{J}\sum_{i=1}^{I} Y_{(k-1)jic}^{\pm} \leq BUD_{c}^{\pm} \quad \forall; k, c \tag{4.6l}$$

(6) *Water rights constraints.* The reallocation of water resources among counties must respect their water rights. Table 4.6 shows the water rights in each county.

$$\left[\begin{array}{l} \sum_{j=1}^{J}\sum_{i=1}^{I}\left(X_{kjic}^{\pm} \cdot FA_{kjimc}^{\pm} + Y_{kjic}^{\pm} \cdot DA_{kjic}^{\pm}\right) + \sum_{j=1}^{J} OIW_{jc} \\ + \sum_{i=1}^{I} R_{kjic}^{\pm} \cdot RA_{kjic}^{\pm} + \sum_{t=1}^{T} IP_{ktc}^{\pm} \cdot IA_{ktc}^{\pm} \cdot DB_{ktc}^{\pm} + MUN_{c}^{\pm} \end{array}\right] \leq \left(1+\eta^{\pm}\right) \cdot WR_{c} \quad \forall; k, m, c \tag{4.6m}$$

(7) *Industrial expansion constraints*. The industrial water use is determined by total conserved water and the transferable portion allotted to industries. The expansion capacity for each type of industry is governed by water availability, production chains and budget. The expansion decisions in dry wall and blanket industries must be based on gypsum powder and cashmere industries, respectively. The maximum expansion times for each industry and in each period are presented as intervals values and listed in the Table 4.7.

Table 4.6 Water rights in each county

	ZN	CST	TX	HY
Water Rights ($10^4\ m^3$)	1041672	264792	106143	298122

Table 4.7 Maximum industrial expansions

	ZN	CST	TX	HY
Gypsum powder	[2, 3]	0	0	0
Dry wall	[2, 3]	0	0	0
Cashmere	0	0	[2, 3]	0
Blanket	0	0	[2, 3]	0
Sheep fur	0	0	[2, 3]	[2, 3]

Note: The interval values denotes the times of expansion

$$\sum_{t=1}^{T} IP_{ktc}^{\pm} \cdot IA_{ktc}^{\pm} \leq \sum_{j=1}^{J}\sum_{i=1}^{I} Y_{kjic}^{\pm} \cdot SAVE_i \cdot IPW^{\pm} \quad \forall; k, c \tag{4.6n}$$

$$DB_{k1c}^{\pm} \geq DB_{k2c}^{\pm} \quad \forall; k, c \tag{4.6o}$$

$$DB_{k3c}^{\pm} \geq DB_{k4c}^{\pm} \quad \forall; k, c \tag{4.6p}$$

(8) *Water balance constraints.* The maximum volume of water extracted by each pump and the total water use of the system should not exceed its maximum water-carrying capacity.

$$\begin{bmatrix} \sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{c=1}^{C}\left(X_{kjic}^{\pm} \cdot FA_{kjimc}^{\pm} + Y_{kjic}^{\pm} \cdot DA_{kjic}^{\pm} \right) + \sum_{j=1}^{J}\sum_{c=1}^{C} OIW_{jc} \\ + \sum_{i=1}^{I}\sum_{c=1}^{C} R_{kjic}^{\pm} \cdot RA_{kjic}^{\pm} + \sum_{t=1}^{T}\sum_{c=1}^{C} IP_{ktc}^{\pm} \cdot IA_{ktc}^{\pm} \cdot DB_{ktc}^{\pm} + \sum_{c=1}^{C} MUN_c^{\pm} \end{bmatrix} \leq TWD \quad \forall; k, m \tag{4.6q}$$

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{c=1}^{C}\left(X_{kjic}^{\pm} \cdot FA_{kjimc}^{\pm} + Y_{kjic}^{\pm} \cdot DA_{kjic}^{\pm} \right) + \sum_{j=1}^{J}\sum_{c=1}^{C} OIW_{jc} \leq PUMC_j \quad \forall; k, m \tag{4.6r}$$

(9) *Technique constraints.* The areas with improved irrigation technology and growing perennial plants (wolfberry and apple) should not be retreated.

$$\sum_{i=1}^{I} Y_{kjic}^{\pm} \geq \sum_{i=1}^{I} Y_{(k-1)jic}^{\pm} \quad \text{k = 2,...,7;} \ \forall; j, c \tag{4.6s}$$

$$\sum_{e=1}^{E}\left(X_{kjec}^{\pm} + Y_{kjec}^{\pm} \right) \geq \sum_{e=1}^{E}\left(X_{(k-1)jec}^{\pm} + Y_{(k-1)jec}^{\pm} \right) \ e \in i \quad \text{k = 2,...,7;} \ \forall; j, c \tag{4.6t}$$

The detailed definitions for the above variables and parameters are listed as below:

k denotes the index for planning period, where k = 1 corresponds to the baseline year (2014); k = 2 corresponds to the mid-period (2015-2017); and k = 3 corresponds to the terminal period (2018-2020);

j denotes the index for irrigation subareas (channels), for which j =1, 2…18;

i denotes the index for all agriculture activities, where $i = 1$ is for corn; $i = 2$ is for wolfberry; $i = 3$ is for herb; $i = 4$ is for apple and $i = 5$ is for millet;

e denotes the index for perennial plants, namely: e =1 is for wolfberry and $e = 2$ is for apple;

f denotes the index for corn with deficit irrigation method;

c denotes the index for counties, where $c = 1$ is for Zhongning (ZN); $c = 2$ is for Changshantou (CST); $c = 3$ is for Tongxin (TX) and $c = 4$ is for Haiyuan (HY);

m denotes the index for drought frequencies, where $m = 1$ denotes wet year (precipitation PDF less than 25%); $m = 2$ denotes normal year (precipitation PDF between 25% and 75%) and $m = 3$ denotes dry year (precipitation PDF greater than 75%);

t denotes the index for industries, where $t = 1$ corresponds to gypsum powder; $t = 2$ corresponds to dry wall; $t = 3$ corresponds to cashmere; $t = 4$ corresponds to blanket and $t = 5$ corresponds to sheep fur;

$BUD_c^{\pm}$ denotes the government budget (i.e. investment targets) of adopting advanced irrigation methods in county c;

C_c denotes the water price for county c;

C_j denotes the water price for channel j;

$CA_{jmc}^{\pm}$ denotes the coefficient (A) of corn water-production function in county c of channel j under $m's$ drought level;

$CB_{jmc}^{\pm}$ denotes the coefficient (B) of corn water-production function in county c of channel j under $m's$ drought level;

$CO^{\pm}_{jmc}$ denotes the coefficient (O) of corn water-production function in county c of channel j under $m's$ drought level;

$DA^{\pm}_{kjic}$ denotes the water applied per unit area for crop i in county c of channel j with advanced irrigation methods;

$DB^{\pm}_{ktc}$ denotes the times of expansion for industry t in county c in period k;

$DNB^{\pm}_{jic}$ denotes the unit water profit for crop i in county c of channel j under advanced irrigation methods;

$ENS^{\pm}_{mf}$ denotes the overall corn yield rates per unit area (kg/mu) under $m's$ drought level;

$FA^{\pm}_{kjimc}$ denotes the water applied per unit area for crop i in county c of channel j under $m's$ drought level with traditional irrigation methods;

$FMIN_{jfc}$ denotes the corn minimum water demands;

$FNB^{\pm}_{jic}$ denotes the unit water profit for crop i in county c of channel j under traditional irrigation methods;

$FPRO^{\pm}_{jfc}$ denotes the fully irrigated corn production per unit area under flood irrigation in county c of channel j;

FTW_{jic} denotes the total water requirement (based on crop evapotranspiration) for crop i in county c of channel j under traditional irrigation methods;

$IA^{\pm}_{ktc}$ denotes the water consumed per unit product for industry t of county c;

$IP^{\pm}_{ktc}$ denotes the production capacity of industry t;

$IPW^{\pm}$ denotes the portion of conserved water allotted to industrial sector;

$INB_{tc}^{\pm}$ denotes the unit water profit for industry t in county c;

$MUN_{c}^{\pm}$ denotes the water demand for municipal sector in county c;

OIW_{jc} denotes the water demands for crops (i.e. wheat and vegetables) growing in irrigators' back yards in county c of channel j;

P_m denotes the probability of drought events (precipitation frequencies);

PR_e denotes the unit price for cash crop e;

PR_f denotes the unit price for corn;

$PRO_{jec}^{\pm}$ denotes the unit area production for cash crop e in county c of channel j;

$prec_{m}^{\pm}$ denotes the precipitation under $m's$ drought level;

$PUMC_j$ denotes the maximum volume of water can be delivered to channel j;

$R_{kic}^{\pm}$ denotes the reclaimed areas with advanced irrigation methods;

$RA_{kic}^{\pm}$ denotes the water applied per unit of reclaimed area for crop i of county c;

$RNB_{ic}^{\pm}$ denotes the unit water profit for crop i in county c for reclaimed land under advanced irrigation methods;

$SAVE_i$ denotes the amount of water can be conserved for crop i through irrigation technology improvement;

$SEC^{\pm}$ denotes the reduction ratio for corn growing area with traditional irrigation method;

TW_{km} denotes total traded water under $m's$ drought level;

TWD denotes total amount of water carried by the GWDS;

$UCP^{\pm}_{kjmfc}$ denotes the actual corn production based on the non-linear corn water-production functions;

WR_c denotes the water rights of county c;

$WTS^{\pm}_{km}$ denotes trading prices of water under $m's$ drought level;

$X^{\pm}_{kjic}$ denotes the arable land areas with traditional (flood) and deficit irrigation methods;

$Y^{\pm}_{kjic}$ denotes the arable land areas with advanced irrigation methods (dripping and sprinkling irrigation);

$\eta^{\pm}$ denotes the percentage of water rights can be traded among counties;

4.4. Seasonal Water Trading

4.4.1. Development of Water Rights and Trading Prices of Water

The theoretical basis for seasonal water trading assumes irrigators are price responsive to their water use. Once they lease an amount of water for one season, the trading benefit can at least compensate the loss from agricultural production, otherwise, the water will not be transferred. The proposed MAWRP model will help with designing a feasible and profitable seasonal (temporary) water trading policy to benefit both water permit holders and buyers. Two fundamental problems will be solved in the MAWRP modelling framework. The first is how to establish initial water rights to minimize the impacts to agricultural production while maximize the system gross revenue. The second is how to formulate the subsidization policies to maximize irrigators’ interests while minimizing the government’s financial burden.

A common issue for market-based optimization models is the interest of vulnerable water users have usually been compromised. For example, in the method developed by Luo et al. (2003) and Li et al. (2014), water users with greater water efficiency (i.e. industry and cash crop producers) have priority accessing water. As a result, food producers with lower water efficiency will sell their water permits to other users with higher water efficiency, and produce undesired crop yields. To address this problem, the proposed MAWRP model has combined necessary political interventions allowing decision makers to control to what extent seasonal water trading should be conducted. In detail, by employing deficit irrigation scheme coupled with TSP method, the MAWRP model is able to generate the optimal corn irrigation quota at each drought level, and the irrigation quota for the driest years can be defined as the initial water rights. Therefore, in wet and normal seasons the uncertainties in precipitation will benefit irrigators by selling their 'unnecessary' water permits. Similarly, the irrigation quota for the least drought level (wet year) can be defined as the minimum water quota for crop production. To prevent irrigators from cashing their water rights, the tradable water rights can be established in the MAWRP model as the difference between the initial water rights and the minimum water quota for maintaining the overall corn yield rates.

By providing the aforementioned mechanisms for water rights establishment, the local irrigators will at least have the confidence to trade their water rights. However, the dilemma for the current temporary water market is that most potential water buyers cannot afford the high trading price of water unless they generate enough profit. Therefore, the success of seasonal water trading relies on policy incentives to lower the trading price of water and make it affordable to water buyers. The trading price of water comprises opportunity cost and transaction cost. In typical water trading practice, the prerequisite for water permit holders to sell their water occurs is that they can receive their full opportunity cost of water, including the compensation of losing water and associated benefits. In this study, the full opportunity cost of water is a major component of the trading price of water since the water carried by this system is used sparingly for agricultural production, which inevitably leads to high opportunity cost. In the MAWRP model, the transaction cost is assumed to completely rely on buyers' expenses. Due to the profit generated by seasonally transferred water varies dramatically with different usage, this portion of the revenue is excluded from the gross revenue in this study. Therefore, the water transaction cost is not involved into the modelling process. Based on this assumption, the full opportunity cost of water is the only factor affects the effectiveness of water trading in the MAWRP model. If the full opportunity cost of water can be minimized and reduced to an affordable level for potential water buyers, seasonal water trading can become feasible.

4.4.2. Scenarios for Government Subsidization Policies

The government subsidization policy is a straightforward approach to realize seasonal water trading by providing water buyers subsidized opportunity cost of water. For water permit holders, they will receive their full opportunity cost and change their irrigation behaviors from 'irrigate as much as possible' to 'think before irrigate'. Besides the subsidized water trading, necessary supportive policies are also required to ensure the fairness of all water users especially the vulnerable who cannot afford the full cost recovery price. Moreover, a subsidized water price will encourage irrigators to maintain their corn production, since growing corn is a low-profit agricultural activity. However, the design of subsidization policies will face the problem of to what extend the policy will perform its desired results. Excessive subsidies to water price may lead to low irrigation efficiency and inadequate subsides may frustrate irrigators and impede the agricultural activities. To strike the balance between irrigators' interests and water use efficiency, three sets of subsidization policy scenarios are established under the MAWRP framework. They are the market-driven scenario (labeled as the IDEP scenario), government subsidization scenarios, representing 50% of government subsided water price plus subsided opportunity cost of water (labeled the PRAP scenario) and No-Trading (NT) scenarios including a baseline scenario (with 75% subsided water price and no water trading) and a neutral scenario (no subsided water price and no water trading). To identify the most beneficial water subsidization policies for the local economy, the IDEP and PRAP scenarios will be compared with NT scenarios.

Under the IDEP scenario, the water price is based on the actual water cost (shadow water price) of the pumping system. Meanwhile, water buyers pay a high opportunity cost of water. The detailed subsidized opportunity cost of water is listed in Table 4.8. This is an ideally designed scenario that is unlikely to be realized under the current practice. Therefore, this scenario could be used as a contrast to other scenarios to measure the water conservation potential and economic growth.

Under the PRAP scenario, irrigators enjoy two forms of subsidy which comprise about 50% of water cost subsidy (preferential water price) from local government and [25, 50]% of the full opportunity cost of water under the PRAP-A scenario and [50, 60]% of the full opportunity cost of water under the PRAP-B scenario. The water buyer and government paid opportunity cost of water is listed in Table 4.9 and Table 4.10, respectively. The subsidized opportunity cost of water could have a significant influence on seasonal water conservation. However, it can also add a burden for local government. The information obtained from the comparison between different subsidization policy scenarios will provide the in-depth analysis on this trade-off situation and support the design of the most beneficial subsidization policy.

To obtain more information to support the design of the subsidization policy, social net value will be introduced as an indicator to evaluate the effectiveness of a government subsidy. The social net value is defined as the difference between gross revenue and government subsidy. The gross revenue and social net value will reflect the direct and indirect contributions of government subsidies, respectively. Hence, the interrelationships for government subsidies and social net value will be revealed and become valuable information for developing optimal subsidization policies.

Table 4.8 Full opportunity cost of water under each scenario at three drought levels

Scenario	Wet Year (yuan/m^3)	Normal Year (yuan/m^3)	Dry Year (yuan/m^3)
IDEP	[2, 4]	[3, 5]	[4, 6]
PRAP-A	[1, 3]	[2, 4]	[3, 5]
PRAP-B	[2, 4]	[3, 5]	[4, 6]

Table 4.9 Full opportunity cost of water paid by water buyers

Scenario	Wet Year (yuan/m^3)	Normal Year (yuan/m^3)	Dry Year (yuan/m^3)
IDEP	[2, 4]	[3, 5]	[4, 6]
PRAP	[0.5, 1]	[1.5, 2]	[2.5, 3]

Table 4.10 Full opportunity cost of water paid by government

Scenario	Wet Year (yuan/m^3)	Normal Year (yuan/m^3)	Dry Year (yuan/m^3)
IDEP	0	0	0
PRAP-A	[0.5, 2]	[0.5, 2]	[0.5, 2]
PRAP-B	[1.5, 3]	[1.5, 3]	[1.5, 3]

CHAPTER 5

RESULTS ANALYSIS

In this chapter, the results obtained from the MAWRP model will be summarized into three parts: (1) the changes in cropping patterns, infrastructure enhancement and water allocation, (2) the effectiveness of seasonal water trading and its associated tradeoffs, and (3) the profitability of seasonal water trading under different subsidization policy scenarios. Among the three sets of policy scenarios, IDEP and PRAP-A scenarios are thoroughly examined to disclose interrelationship of the local economic development and water conservation reforms. The PRAP-B and NT scenarios will be further analyzed for evaluating the profitability of seasonal water trading and supporting subsidization policy design. All the results are unfolded from the perspective of social-economic and environmental conditions in the study area. Furthermore, the revelations will provide valuable references for decision making.

5.1. Results and Discussions

5.1.1. Cropping Patterns

The generated cropping patterns for two planning periods and two policy scenarios (IDEP and PRAP-A scenario) are shown in Figure 5.1. The interval-valued solutions from each policy scenario (presented as lower and upper bounds), reflect the uncertainties existing in the system. The results demonstrate there are no significant differences between

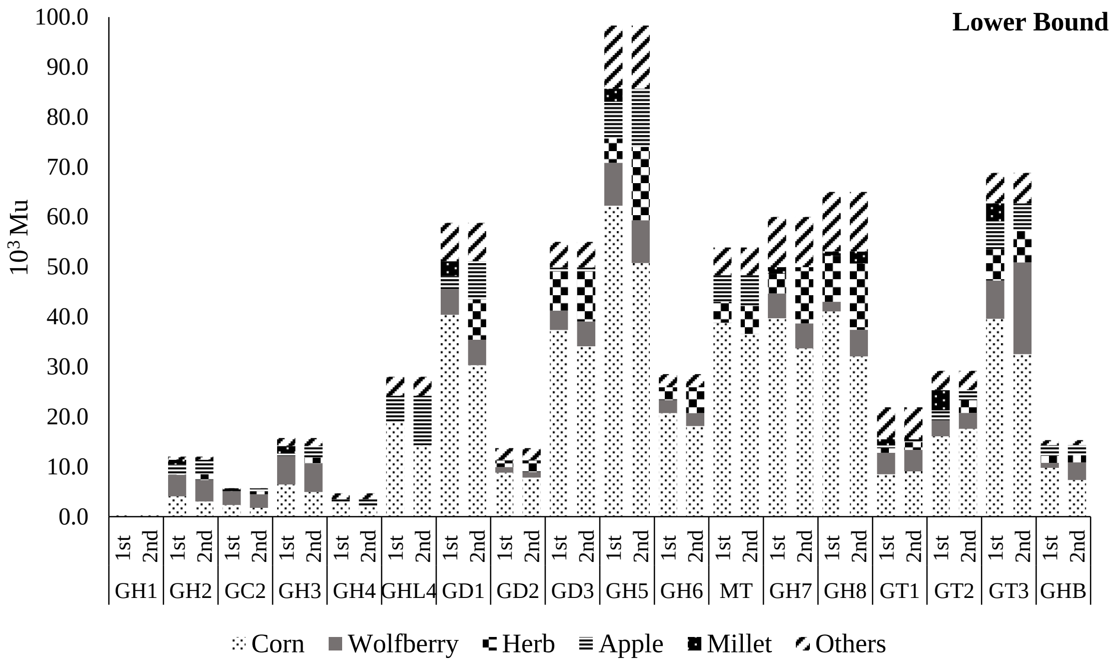

Figure 5.1 (a) Cropping pattern for IDEP scenario (lower bound)

Note: 1st and 2nd denote the first and second planning horizons

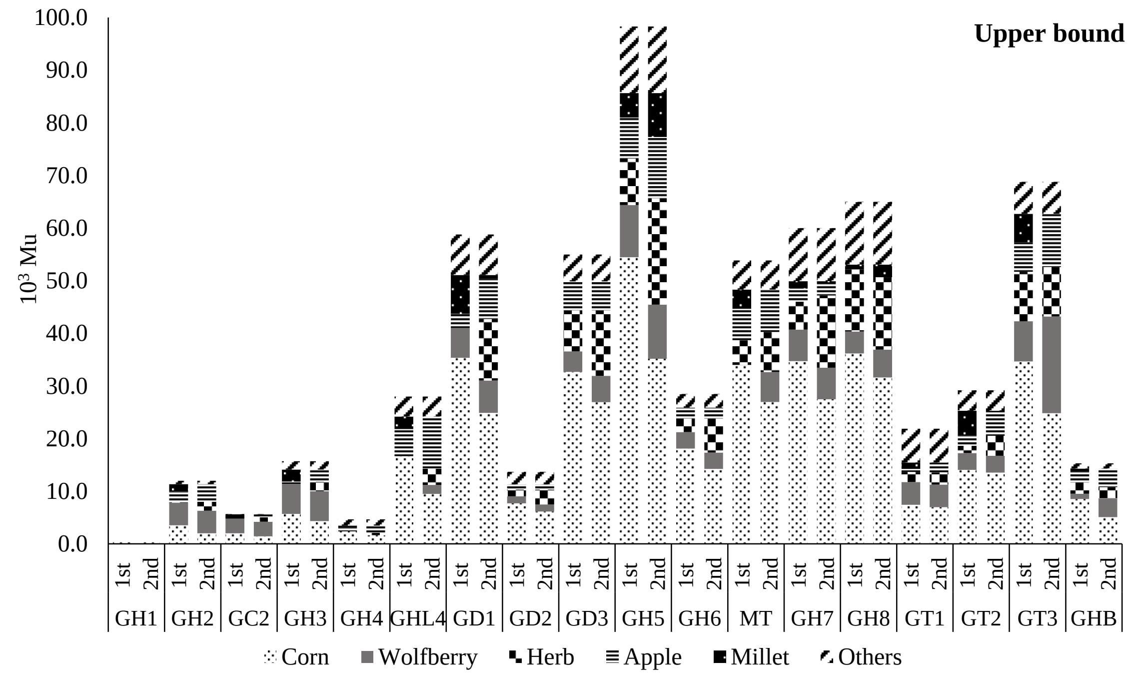

Figure 5.1 (b) Cropping pattern for IDEP scenario (upper bound)

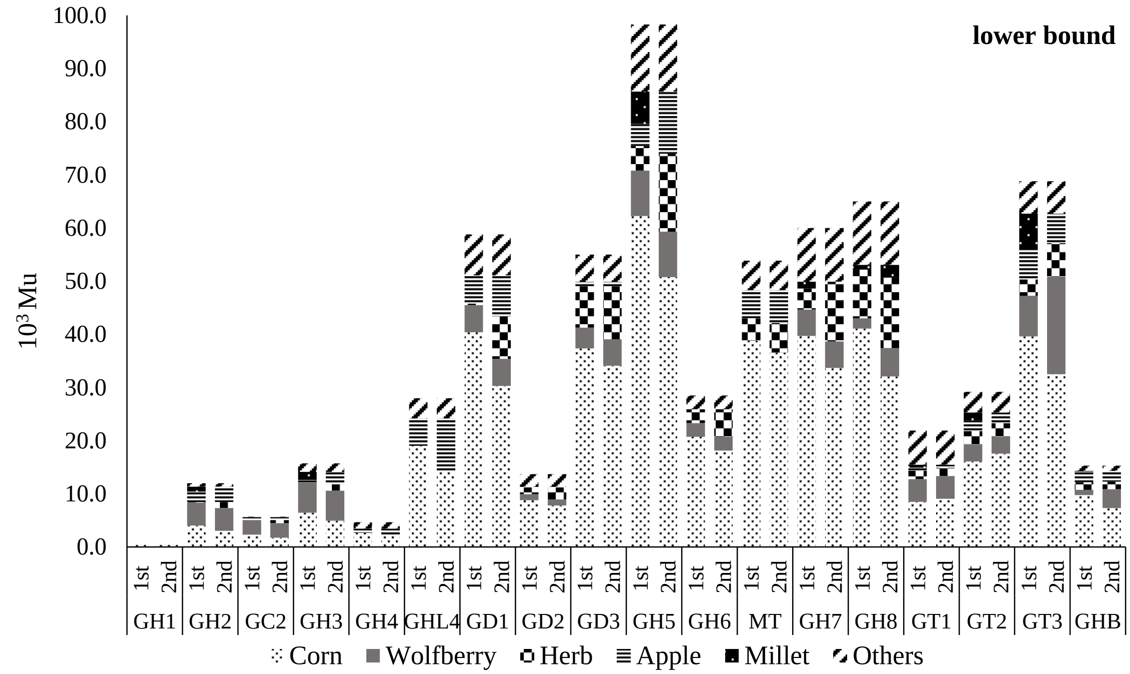

Figure 5.1 (c) Cropping pattern for PRAP-A scenario (lower bound)

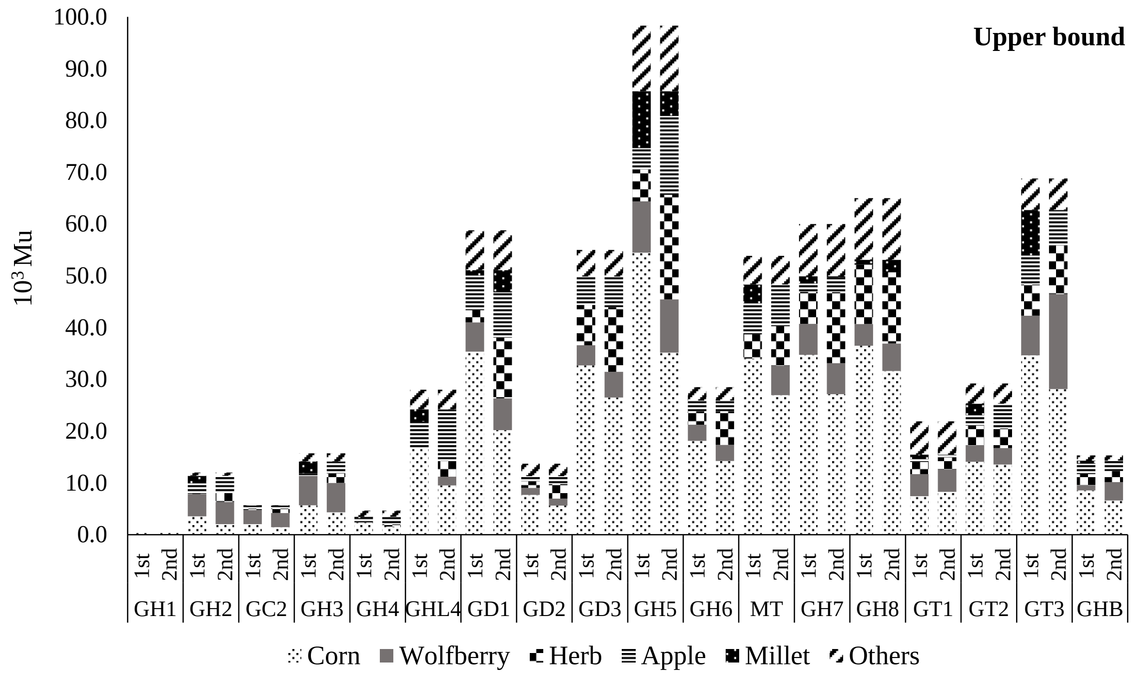

Figure 5.1 (d) Cropping pattern for PRAP-A scenario (upper bound)

cropping patterns of different policy scenarios. This implies the cropping pattern does not have an acute response to the water prices or the trading prices of water. Moreover, the optimal cropping patterns are identified based on its resiliency to water availability. The pie chart in Figure 5.2 indicates the area of millet (as a drought-resistance crop) has increased from zero to [3, 6]% in the 1st period and then reduced to [0, 2]% in 2nd period for both scenarios (i.e. IDEP and PRAP-A scenarios). This is because irrigation infrastructure improvement and cropping pattern modification in the 1st period cannot meet the water demand resulted from increasing cash crops and other water users (i.e. industry and municipal sectors). Therefore the presence of the drought resistant crop (i.e. millet) is helpful to eliminate the water deficit. In the 2nd period, with continuing improvements in irrigation infrastructure, more water will be released for 2nd stage cropping pattern modification in which the millet area will experience a substantial reduction and yield to more cash crops. Figure 5.2 also indicates the ratio of food crops against cash crops will be reduced from 17:3 in 2014 to [3:1, 7:3] in 2017 and to [3:2, 1:1] in 2020 for both scenarios.

5.1.2. Irrigation Infrastructure Improvement

Figure 5.3 shows the solutions for crop growing areas with improved irrigation infrastructure in 2020. The total improved irrigation infrastructure area for both scenarios (i.e. IDEP and PRAP-A scenarios) will surge from zero to [21, 30]% in 2017 and to [42, 62]% in 2020. The results also indicate various water prices reflected by two policy scenarios will not have a noticeable impact to improved-infrastructure areas. There are two factors that would contribute to the infrastructure improvement, unit water profit and crop area restrictions. In this case, the various water prices reflected by the two scenarios only

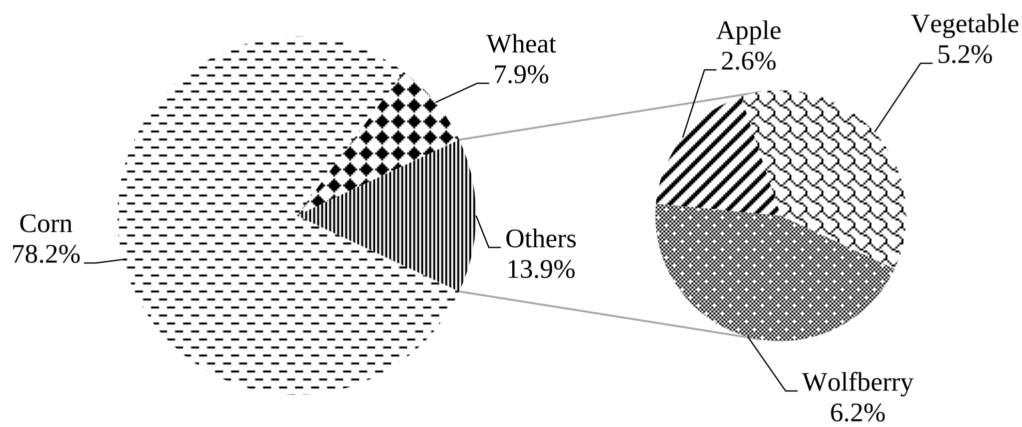

Figure 5.2 (a) Cropping pattern for the baseline year

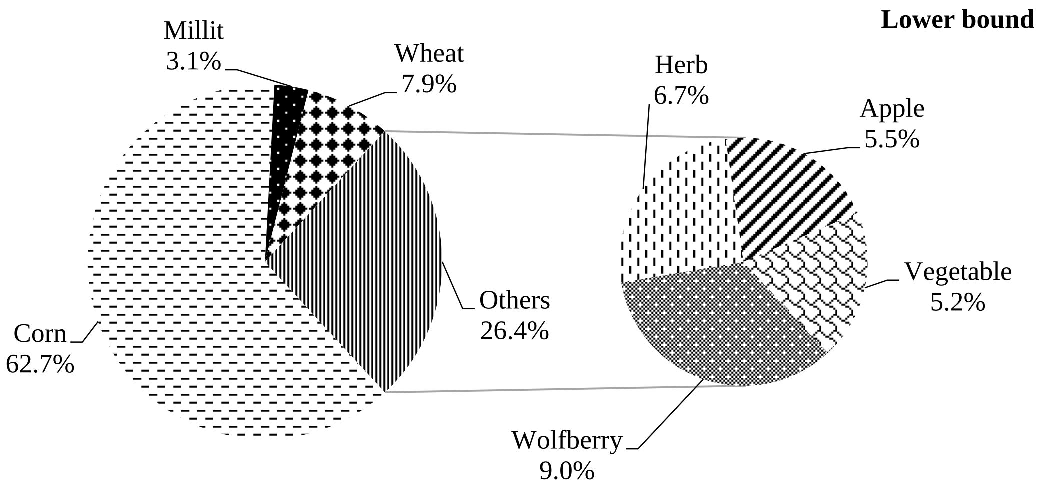

Figure 5.2 (b) Cropping pattern in 2017 under IDEP and PRAP-A scenarios (lower bound)

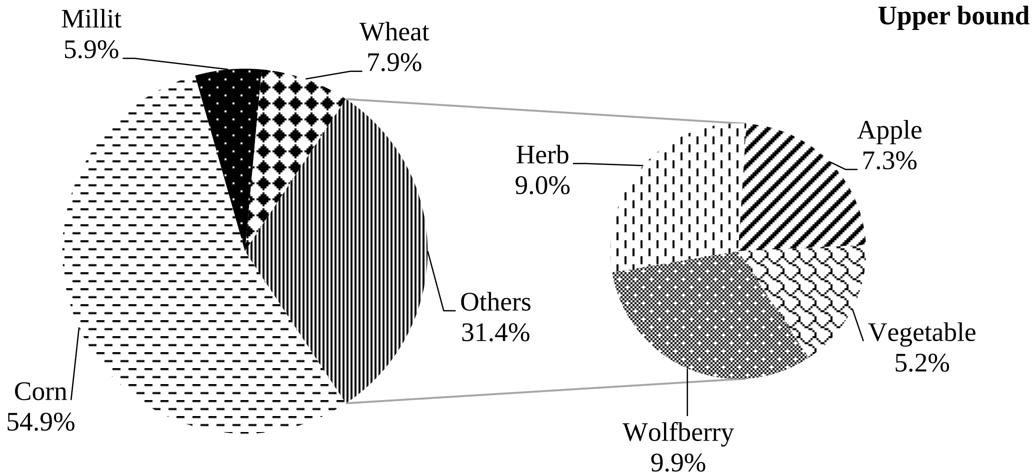

Figure 5.2 (c) Cropping pattern in 2017 under IDEP and PRAP-A scenarios (upper bound)

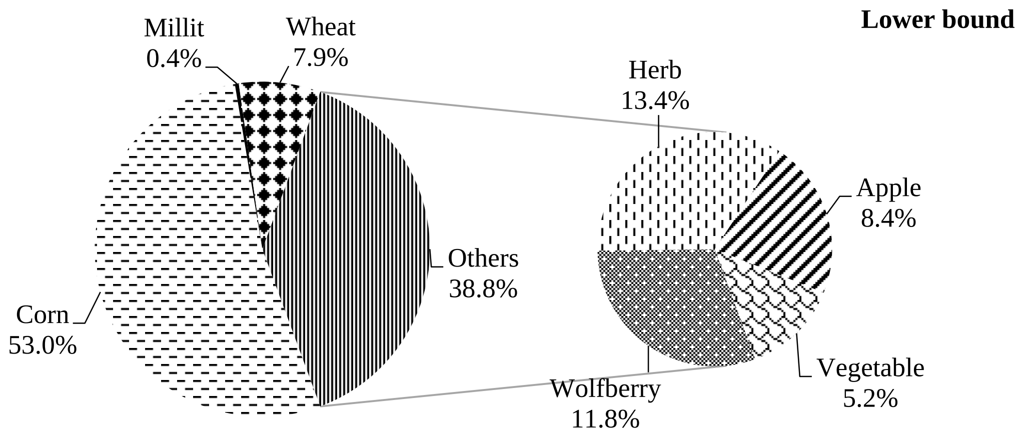

Figure 5.2 (d) Cropping pattern in 2020 under IDEP and PRAP-A scenarios (lower bound)

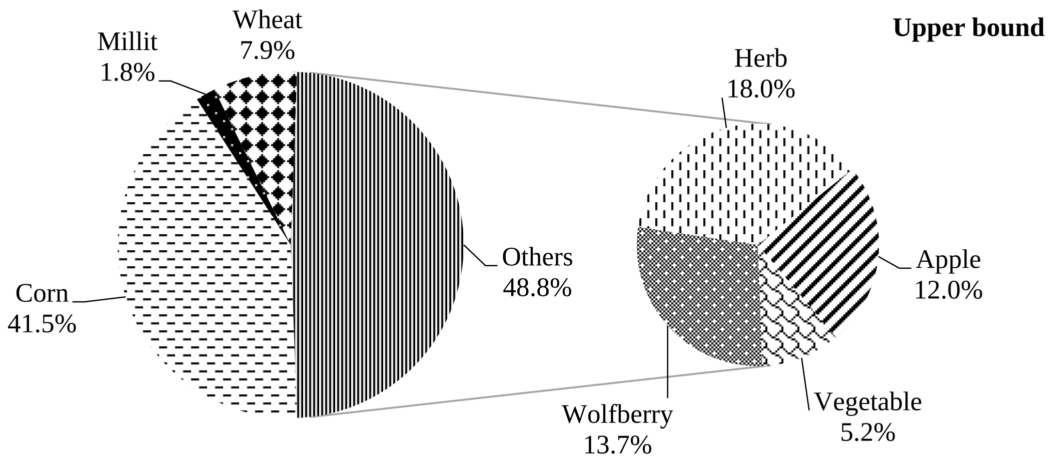

Figure 5.2 (e) Cropping pattern in 2020 under IDEP and PRAP-A scenarios (upper bound)

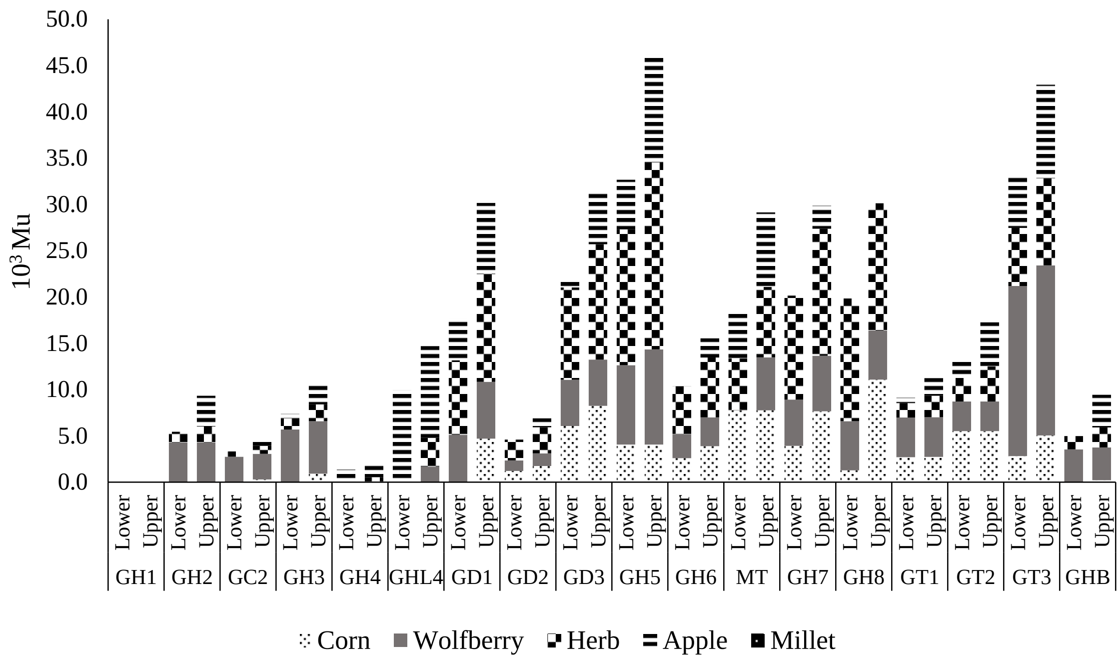

Figure 5.3 (a) Improved-infrastructure areas under IDEP scenario at 2020

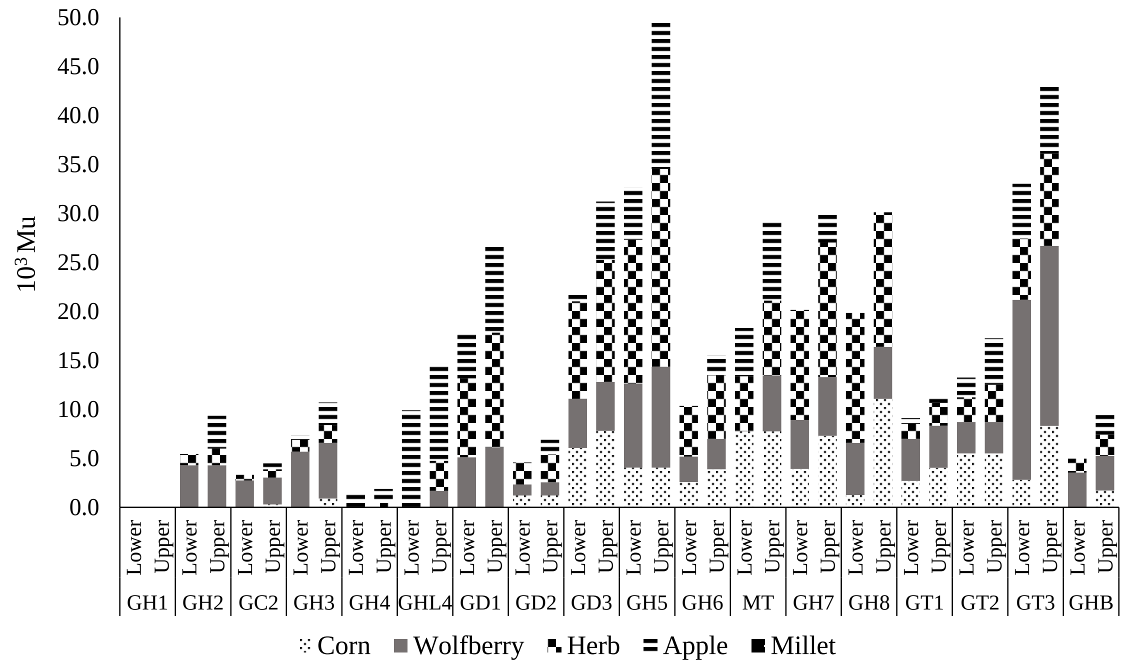

Figure 5.3 (b) Improved-infrastructure areas under PRAP-A scenario at 2020

make a few contributions to the unit water profit. Thus its impact on irrigation infrastructure improvements can be neglected. Table 5.1 indicates the crops with higher revenue and water consumption are first considered to improve the irrigation infrastructure. On the contrary, crops with lower revenue but higher volume water consumption will be considered at last. Figure 5.4 indicates the pumping head of the GWDS has a positive correlation with water use efficiency which is defined as the ratio of the water use by dripping and sprinkling irrigation against the total irrigation water. The correlation coefficients for the lower and upper bounds are 0.8 and 0.7, respectively. This suggests the optimal infrastructure-improved area and cropping patterns modification will to some extent contribute to agricultural sustainability by saving the system energy.

5.1.3. Water Allocation

The detailed water allocation for the study system is shown in Table 5.2. The results indicate the water will be transferred out of the original land and then reallocated to three sections: municipal, industrial and land reclamation. The municipal water use is required for increasing the local population and raising living standards in the study area. Given the current population growth of 1% and urbanization rate of 1.25%, the water demand for 2020 will be raised by [4, 5] million cubic meters of water. The industrial sector owns the highest unit water profit, so it has the highest priority access to conserved water. The promised water use for the industrial sector will be [4, 8] million cubic meters water by 2020 in both scenarios. The land reclamation has the biggest share of conserved water. Due to the adoption of advanced irrigation infrastructures, the reclaimed land have much higher water efficiency than lands with flood irrigation. This implies that various policy scenarios

Table 5.1 Crop water consumptions, profits and infrastructure improvement

Crop	Water consumption (m^3/Mu)		Profit (under full irrigation) (10^3 yuan/Mu)		Improved irrigation infrastructure area at the end of 2020
	Traditional	Advanced	Traditional	Advanced	
Corn	[400, 440]	[180, 200]	[1.5, 2.2]	[1.1, 1.7]	[11, 24]%
Wolfberry	[490, 520]	[320, 350]	[11.3, 17.9]	[11.9, 18.7]	100%
Herb	[400, 440]	[200, 220]	[2.2, 3.7]	[2.5, 4.1]	100%
Apple	[290, 300]	[180, 200]	[4.4, 8.3]	[4.8, 8.5]	[66, 100]%
Millet	[300, 320]	[230, 240]	[1.0, 2.5]	[1.0, 2.3]	0

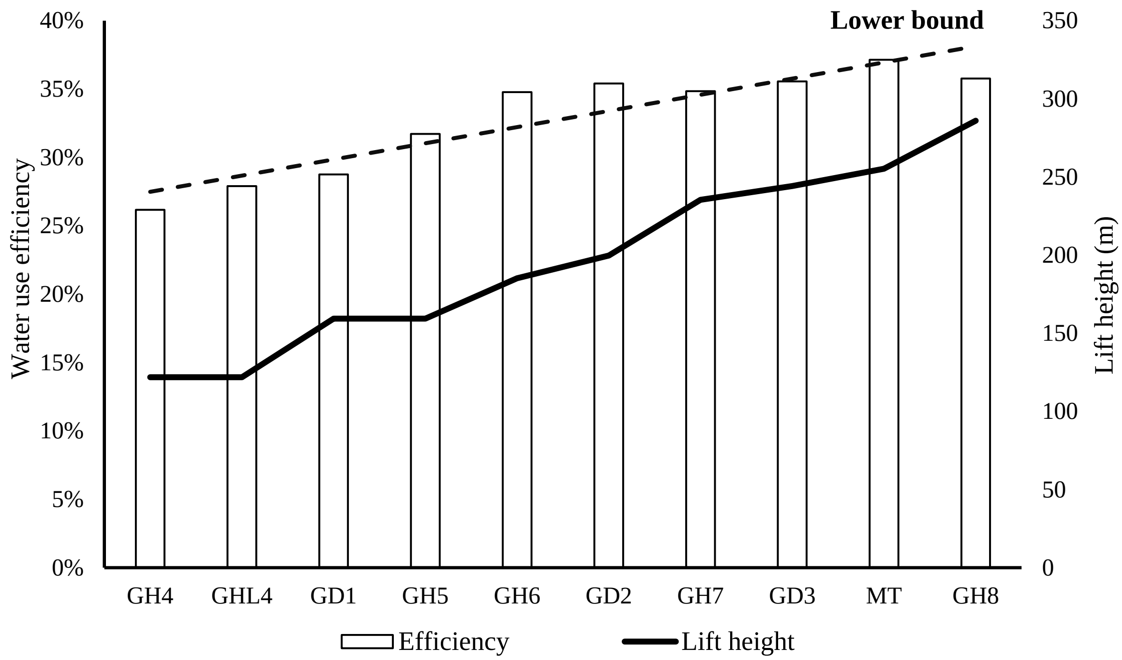

Figure 5.4 (a) Relations for pumping head and water use efficiency (lower bound)

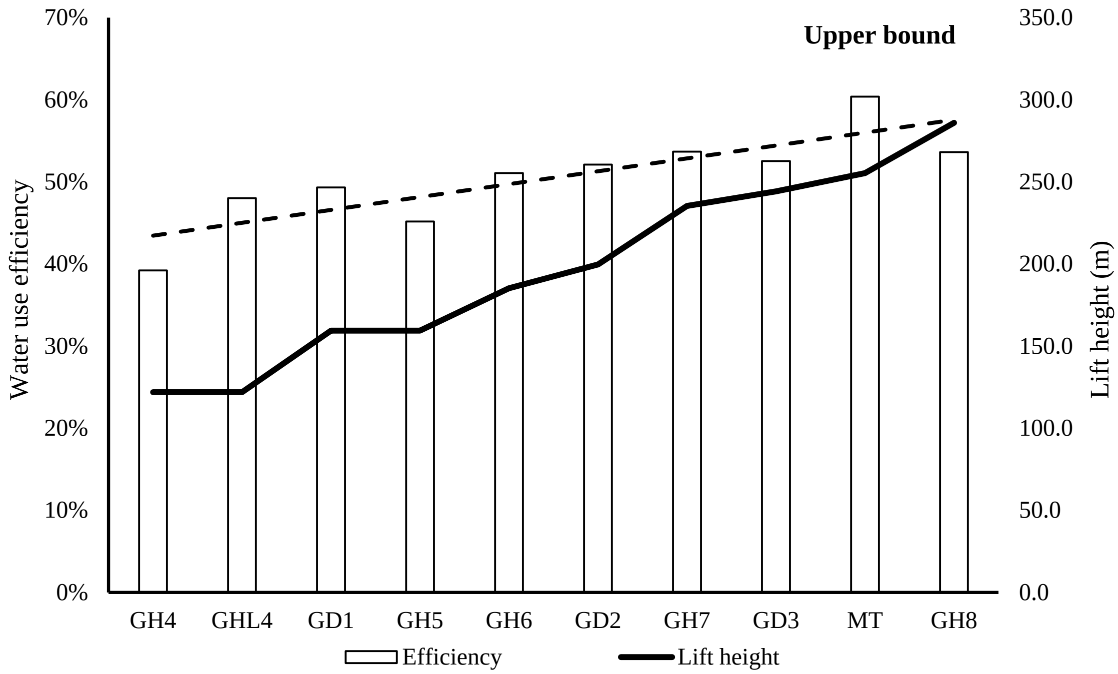

Figure 5.4 (b) Relations for pumping head and water use efficiency (upper bound)

Table 5.2 Water allocation for all sectors

Water Use	Baseline Year	IDEP		PRAP-A	
	2014 (10^6 m^3)	2017 (10^6 m^3)	2020 (10^6 m^3)	2017 (10^6 m^3)	2020 (10^6 m^3)
Original land & tradable water	230.8	[173.8, 192.6]	[142.8, 170.6]	[173.8, 192.4]	[142.7, 170.3]
Municipal	0	[1.8, 2.7]	[3.6, 5.4]	[1.8, 2.7]	[3.6, 5.4]
Industrial	0	[1.4, 3.6]	[3.8, 8.0]	[1.4, 3.6]	[3.8, 8.0]
Reclamation	0	[34.1, 51.6]	[50.9, 76.4]	[34.3, 51.6]	[51.2, 76.5]
Other	35.8	35.8	35.8	35.8	35.8
Total	266.6	266.6	266.6	266.6	266.6

Note: (1) The upper bound (lower bound) of the original land water use (including tradable water) is derived from the lower bound (upper bound) of the model solutions, respectively. (2) The value of municipal water use is pre-defined, its lower bound is used to produce the upper bound of the interval-valued solutions (i.e. water use for industrial and land reclamation).

do not have significant impacts on the water use in land reclamation.

5.1.4. Economic Targets

Figure 5.5 indicates the agricultural reformation will make a significant contribution to the local gross revenue (likely to be tripled by 2020). In detail, the net annual revenue for the emerging industrial sector will reach [25, 70] and [58, 119] million yuan in 2017 and 2020, respectively. Table 5.3 lists all the industrial expansions during the planning horizon. The lower and upper bounds represent the minimum and maximum phases of expansion, respectively. Land reclamation makes another remarkable contribution to the growth of local economy. The net benefit for land reclamation can reach [64,184] million yuan under IDEP scenario, which is 2% lower than PRAP-A scenario due to the different water price. Table 5.4 shows the detailed land reclamations for each period and in each county. By the end of 2020, the total reclaimed area for either scenario will reach [232, 336] thousands Mu, equivalent to [34, 49]% of the original irrigation area. Figure 5.6 and Table 5.5 specify the generated revenue and the water conserved in each subarea, respectively. The results imply that the water conservation dose not sacrifice the agricultural revenue of the original land. Rather, all the subareas have more or less increased revenues. At the meantime, there are remarkable increases in the profit per volume of water for each subarea. The mean value for agricultural product will be increased from [4.5, 7.4] yuan in 2013 to [6.6, 12.4] yuan in 2017, and then to [9.2, 19.6] yuan in 2020 under IDEP scenario. In comparison, the value for PRAP-A scenario would be [4.8, 7.7] yuan in 2014, [6.7, 12.5] yuan in 2017, and [9.2, 19.6] yuan in 2020, respectively.

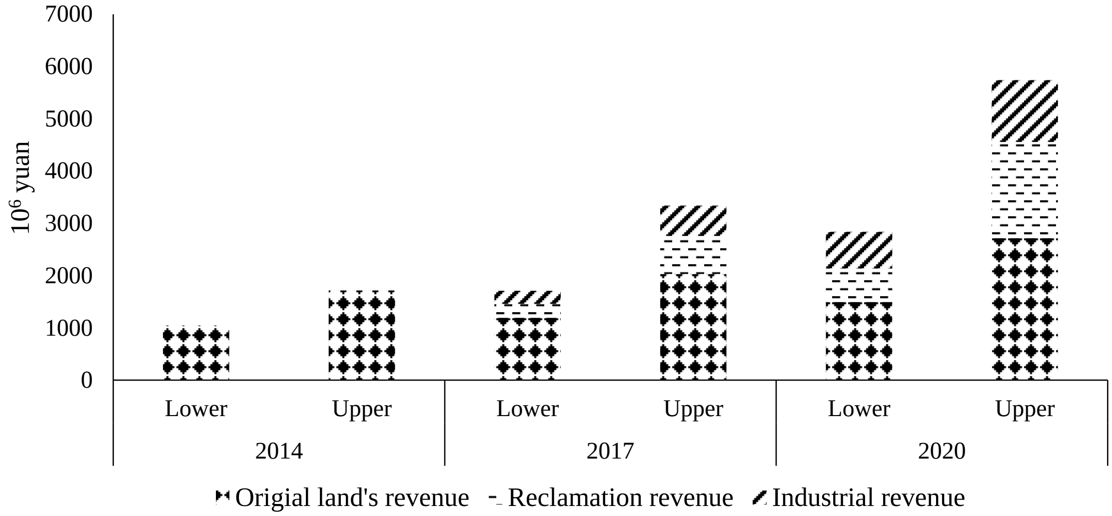

Figure 5.5 (a) Gross revenue under IDEP scenario

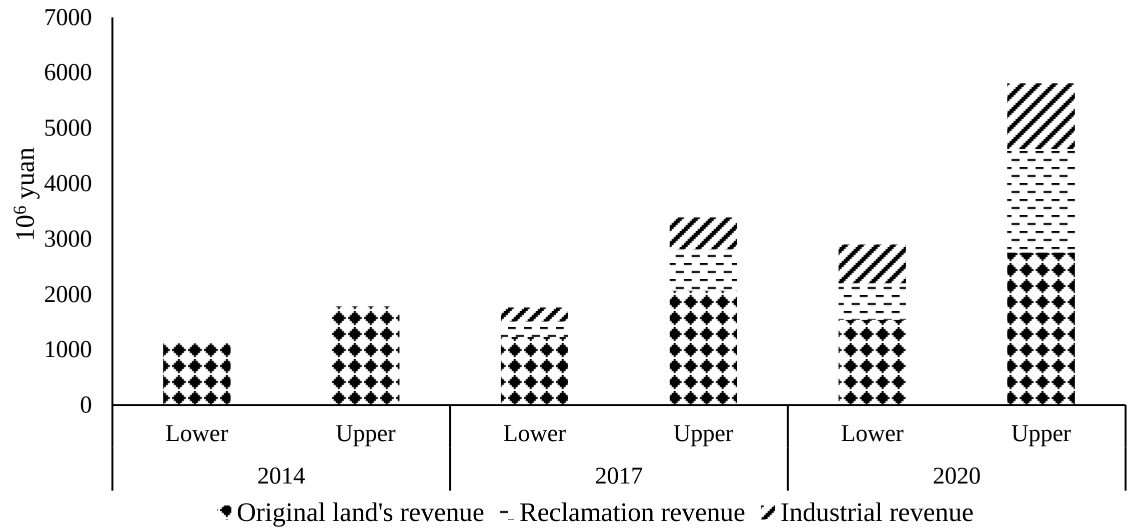

Figure 5.5 (b) Gross revenue under PRAP-A scenario

Table 5.3 Industrial expansions for each county

Industry	Year	ZN	CST	TX	HY
Gypsum powder	2017	[1,2]	0	0	0
	2020	[2,4]	0	0	0
Dry wall	2017	[1,2]	0	0	0
	2020	[2,4]	0	0	0
Cashmere	2017	0	0	[1,2]	0
	2020	0	0	[3,4]	0
Blanket	2017	0	0	[1,2]	0
	2020	0	0	[3,4]	0
Sheep fur	2017	0	0	[0,1]	[0,1]
	2020	0	0	[0,3]	[1,3]

Note: The interval-valued solutions denote expansion times

Table 5.4 Land reclamations for each county

	IDEP		PRAP-A	
	2017 (10^3 Mu)	2020 (10^3 Mu)	2017 (10^3 Mu)	2020 (10^3 Mu)
Corn				
ZN	[45.0,56.9]	[45.0,56.9]	[31.5,31.5]	[47.2,47.2]
CST	0	0	[15.3,15.3]	[15.3,15.3]
TX	[40.0,60.0]	[40.0,60.0]	[38.8,38.8]	[55.2,55.2]
HY	[0.0,10.9]	[0.0,10.9]	0	[10.6,10.6]
Wolfberry				
ZN	[8.0,11.9]	[11.9,18.6]	[3.9,6.3]	[5.9,9.4]
CST	0	0	[4.1,6.2]	[6.1,9.3]
TX	[15.2,29.0]	[22.8,43.4]	[15,29]	[23.0,28.9]
HY	[0.0,3.4]	[0.0,5.1]	0	0
Herb				
ZN	[17.8,26.8]	[26.7,40.2]	[12.0,15.3]	[18.0,13.0]
CST	0	0	[5.9,9.7]	[8.9,14.6]
TX	[13.1,25.1]	[19.6,37.6]	[13.2,26.8]	[19.7,40.2]
HY	[0.0,4.1]	[0.0,6.2]	[0.0,4.2]	[0.0,6.3]
Apple				
ZN	[7.6,11.8]	[11.4,17.6]	[0.6,4.2]	[0.9,6.2]
CST	0	0	[3.6,6.4]	[5.3,9.6]
TX	[7.8,21.8]	[11.8,32.7]	[11.3, 23.1]	[17.0, 34.7]
HY	0	0	0	0

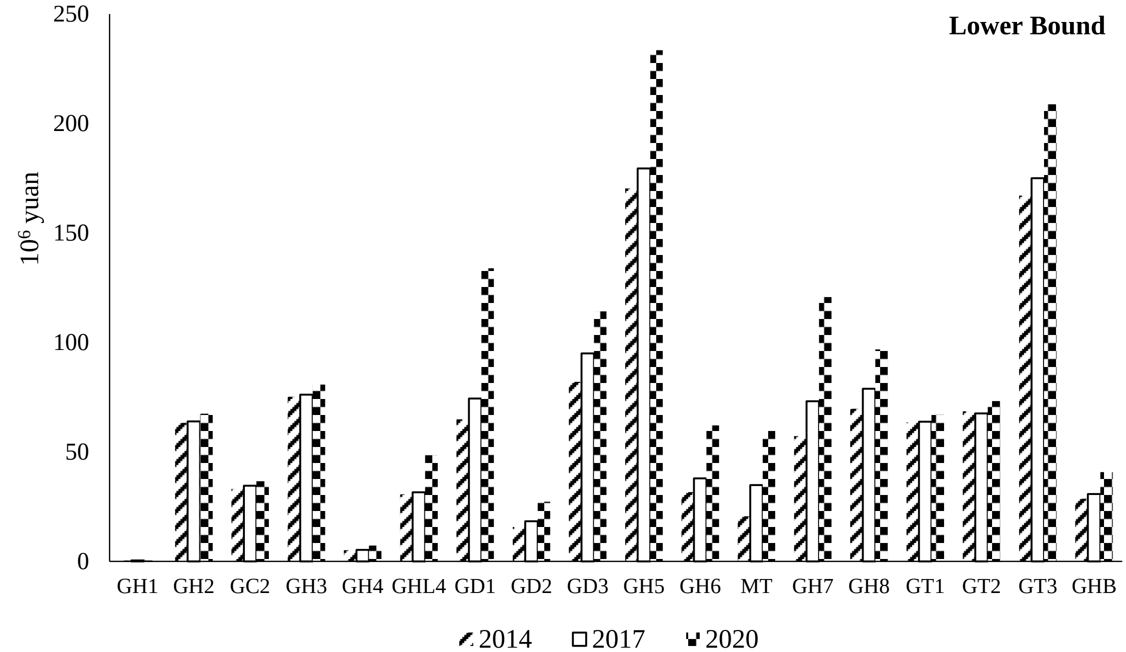

Figure 5.6 (a) Revenue for each subarea under IDEP scenario (lower bound)

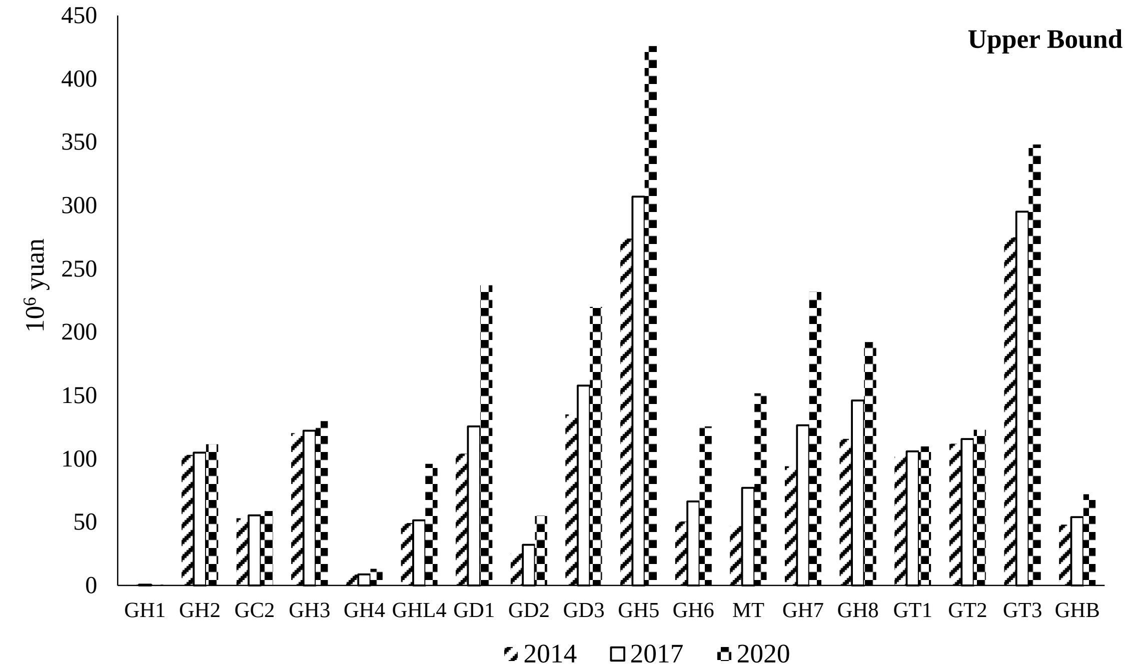

Figure 5.6 (b) Revenue for each subarea under IDEP scenario (upper bound)

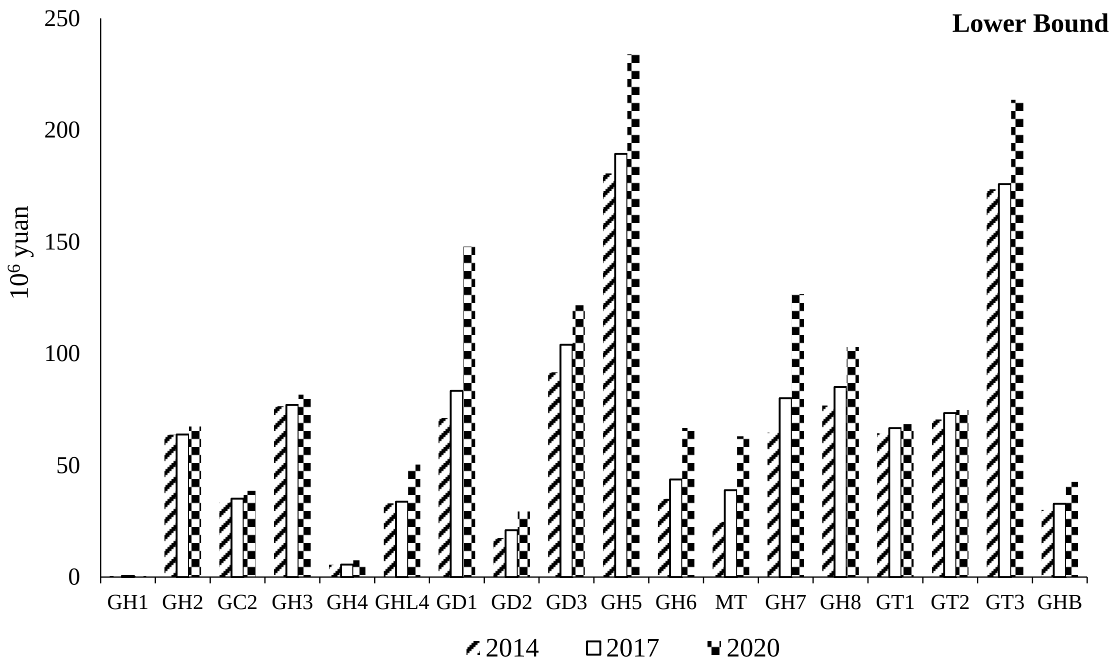

Figure 5.6 (c) Revenue for each subarea under PRAP-A scenario (lower bound)

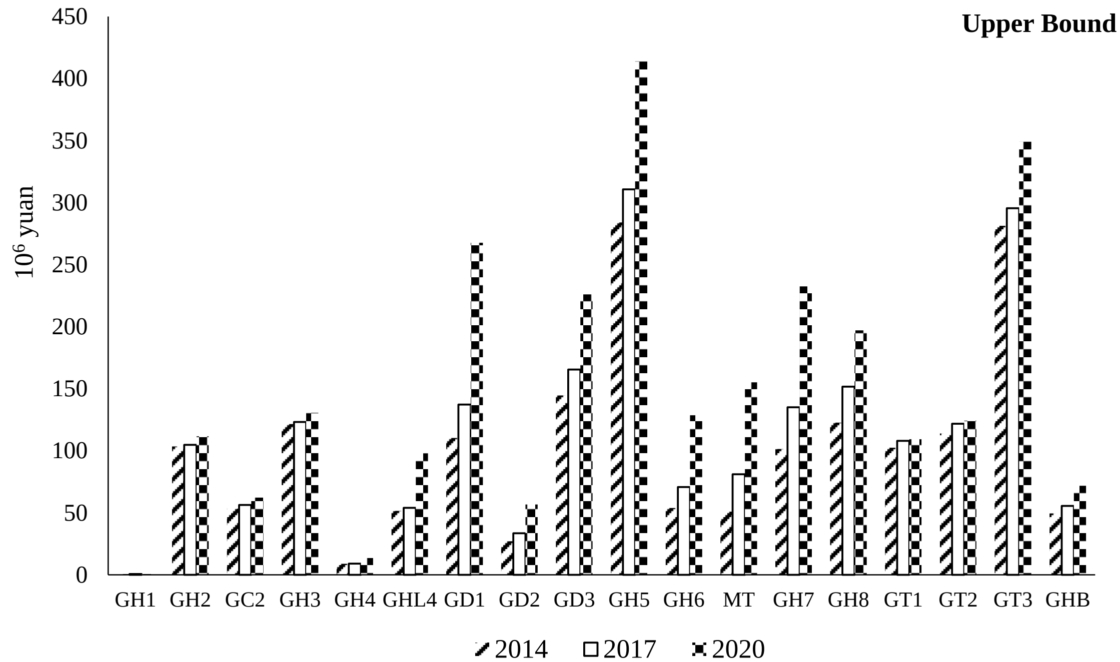

Figure 5.6 (d) Revenue for each subarea under PRAP-A scenario (upper bound)

Table 5.5 Water conservation potentials in each subarea

Subarea	Water can be delivered (10^6 m^3)	Water can be conserved in 2017 (10^6 m^3)		Water can be conserved in 2020 (10^6 m^3)	
		PRAP-A	IDEP	PRAP-A	IDEP
GH1	0.1	[0.0, 0.0]	[0.0, 0.0]	[0.0, 0.0]	[0.0, 0.0]
GH2	6.3	[1.2, 1.6]	[1.1, 1.6]	[1.3, 2.0]	[1.3, 2.0]
GC2	2.4	[0.4, 0.6]	[0.4, 0.5]	[0.5, 0.8]	[0.5, 0.8]
GH3	7.7	[2.0, 2.4]	[2.0, 2.5]	[2.3, 3.1]	[2.3, 3.1]
GH4	2.2	[0.5, 0.6]	[0.5, 0.6]	[0.6, 0.7]	[0.6, 0.7]
GHL4	11.8	[2.4, 3.1]	[2.6, 3.3]	[3.2, 4.2]	[3.4, 4.4]
GD1	25.5	[5.2, 7.5]	[6.3, 7.3]	[6.6, 9.1]	[7.5, 9.7]
GD2	5.6	[0.9, 1.5]	[1.4, 1.5]	[1.2, 1.9]	[1.6, 1.9]
GD3	23	[4.8, 7.0]	[5.5, 7.4]	[6.1, 8.1]	[6.6, 9.0]
GH5	41.4	[8.5, 11.5]	[10.3, 12.7]	[10.9, 15.1]	[12.2, 15.2]
GH6	11.4	[1.7, 2.7]	[2.8, 3.2]	[2.5, 3.8]	[3.3, 4.0]
MT	12.1	[0.0, 0.0]	[0.0, 0.0]	[0.0, 0.0]	[0.0, 0.0]
GH7	22	[3.4, 5.4]	[4.1, 6.0]	[4.6, 7.0]	[5.1, 7.3]
GH8	17.7	[1.8, 3.0]	[1.8, 3.3]	[1.8, 3.6]	[1.8, 3.8]
GT1	16.1	[3.8, 4.6]	[3.8, 4.7]	[4.8, 6.1]	[5.0, 6.2]
GT2	18.2	[4.3, 5.6]	[4.0, 5.4]	[6.0, 7.8]	[6.2, 7.9]
GT3	37.3	[8.8, 11.9]	[9.8, 12.8]	[11.1, 15.0]	[11.4, 15.2]
GHB	6	[0.4, 1.1]	[0.6, 1.2]	[0.5, 1.5]	[0.7, 1.5]
Total	266.6	[50.1, 70.0]	[56.8, 73.8]	[63.9, 90.3]	[69.2, 92.6]

Note: The water can be conserved includes seasonal tradable water, which is converted to the expected value.

5.2. Water Trading Analysis

5.2.1. Effectiveness of Seasonal Water Trading

The total water use by different scenarios and drought levels is summarized in Figure 5.7. The results illustrate that under IDEP and PRAP-A scenarios, if the irrigation can be well-scheduled and accompanied with timely precipitation, a considerable amount of water will be conserved and traded. According to the tradable water in Table 5.6, the design of different policy scenarios will have different influences on seasonal (temporary) water trading. In IDEP scenario, local governments have no intervention to the water market, so the trading prices of water is based on the full opportunity cost (market-driven price). Accordingly, the seasonal tradable water reaches [16.8, 18.7] million cubic meters (in expected value) in 2017, sharing about [6, 7]% of total available water. As mentioned previously, most water buyers cannot afford the full opportunity cost of water, so under the PRAP-A scenario, the government should lower the trading prices of water down to a subsidized opportunity cost, allowing more users to have access to water market. Nevertheless, the subsidized opportunity cost under PRAP-A scenario is still lower than the cost of IDEP scenario (shown in Table 4.8 and 4.9), indicating the seasonal water trading under PRAP-A scenario will only conserve [11.7, 13.0] million cubic meters (in expected value) water in 2017, sharing about [4, 5]% of total available water. The results suggest that the government controlled trading prices of water are effective in encouraging permit holders to perform water trading. The results also indicate that the effectiveness of seasonal water trading will be affected by irrigation infrastructure improvement and irrigation scheme enhancement. In the first period (2015-2017), about [55, 63]% irrigation area will grow corn without any enhancement on irrigation infrastructure. Such state

Table 5.6 Water use for original land and seasonal tradable water

Water Use		IDEP		PRAP-A	
		2017 (10^6 m^3)	2020 (10^6 m^3)	2017 (10^6 m^3)	2020 (10^6 m^3)
Original land					
	Wet year	[148.7, 165.5]	[133.4, 155.2]	[151.3, 172.1]	[135.0, 160.4]
	Normal year	[157.1, 172.1]	[138.2,160.3]	[163.6, 182.7]	[142.0, 168.3]
	Dry year	[165.0, 185.9]	[142.8, 170.6]	[164.7, 185.3]	[142.6, 170.3]
	Expected value	[157.0, 173.9]	[138.2, 161.6]	[160.8, 180.7]	[140.4, 166.8]
Seasonal tradable water					
	Wet year	[25.1, 27.1]	[9.4, 15.4]	[20.3, 22.5]*	[7.7, 9.9]
	Normal year	[16.7, 20.4]	[4.6, 10.4]	[9.7, 10.2]*	[0.6, 2.0]
	Dry year	[6.6, 8.8]*	[0, 0]	[7.1, 9.1]*	[0, 0]
	Expected value	[16.8,18.7]	[4.6, 9.0]	[11.7,13.0]	[2.2, 3.5]*
Total		[173.8, 192.6]	[142.8, 170.6]	[173.8, 192.4]	[142.7, 170.3]

Note: ‘*’ denotes the lower bound is generated from the upper level of the model.

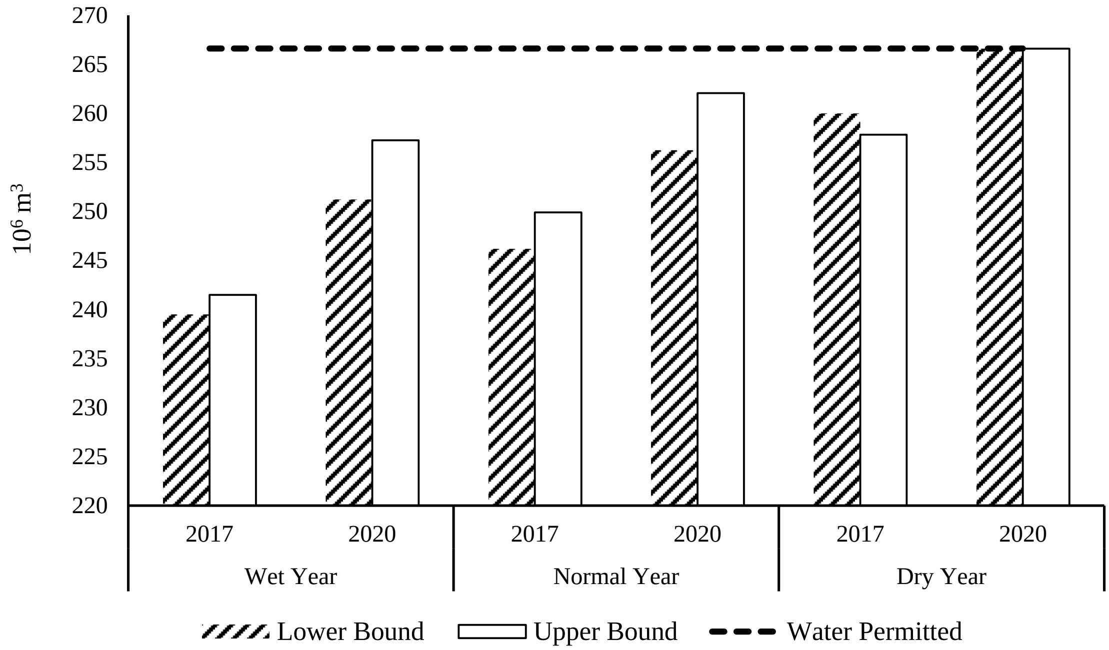

Figure 5.7 (a) Water use under IDEP scenario

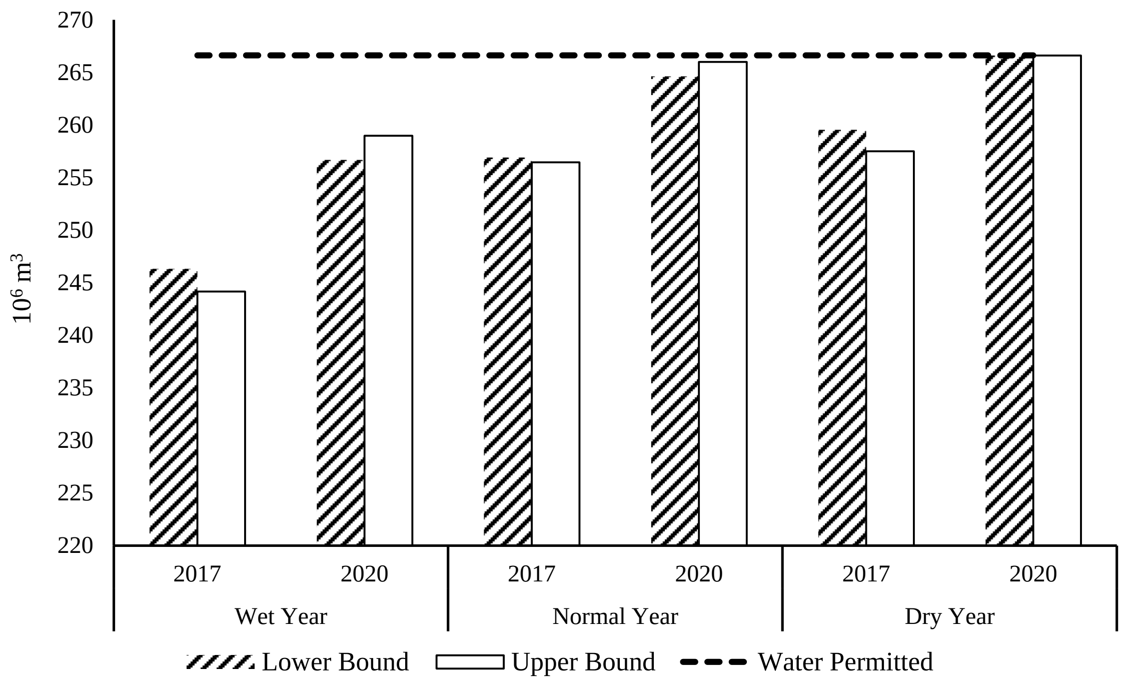

Figure 5.7 (b) Water use under PRAP-A scenario

can provide great potential for the seasonal water trading. For example, in the first period, it can contribute [3.9, 4.3]% and [1.6, 2.4]% to the annual original land's revenue under IDEP and PRAP-A scenarios, respectively; while in the second period, the corn growing area is likely to be gradually shrunk to [41, 53]% with [11, 24]% of its area being under improved irrigation infrastructure. The increased irrigation efficiency tends to greatly limit the seasonal water trading. Particularly, the original land's revenue from seasonal water trading will drop down to [0.8, 1.6] and [0.3, 0.3]% under IDEP and PRAP-A scenarios, respectively. Moreover, the ratio of seasonal water trading against long-term water trading will be reduced from [29.1, 35.9]% in the first period to [5.1, 10.9]% in the second period under IDEP scenario, while the ratio for PRAP-A scenario will drop from [22.4, 31.2]% to [2.5, 6.0]%.

5.2.2. Tradeoffs for Seasonal Tradable Water and Food Production

Table 5.7 shows the water deficit for the corn in original land. For the policy consistency, the initial water rights in each county of each subarea will stay the same during the optimization process. In the IDEP scenario, the high trading price of water will encourage irrigators to benefit from water trading from all drought levels. However, in the PRAP-A scenario, the low trading prices of water in wet and normal years will be less attractive to irrigators, thus causing a reduced volume of seasonal water transfer. So the water deficit in wet and normal years are considerably lessened in comparison with IDEP scenario. Figure 5.8 and Figure 5.9 show unit water profit and unit area revenue of corn for each subareas, respectively. The figures indicate the implication of the deficit irrigation scheme will lift the corn unit water profit from [2.7, 4.4] to [3.3, 5.7] yuan. In addition,

Table 5.7 Corn water deficit for each subarea

County & Subarea	2014 (share/Mu)	IDEP (share/Mu) Wet	Normal	Dry	PRAP-A (share/Mu) Wet	Normal	Dry
ZN							
GT1	0	[3,4]	[4,4]	[6,6]	[2,3]	[3,3]	[4,5]
GT2	0	[2,3]	[3,4]	[4,5]	[2,3]	[2,3]	[4,5]
GT3	0	[2,3]	[3,4]	[4,5]	[2,3]	[2,3]	[4,5]
GHB	5	[2,3]	[4,4]	[4,5]	[2,3]	[2,3]	[4,5]
GH1	6	[2,2]	[4,4]	[6,6]	[2,2]	[4,4]	[6,6]
GH2	3	[3,3]	[3,4]	[3,4]	[2,3]	[4,4]	[6,6]
GC2	7	[2,3]	[3,4]	[3,4]	[2,3]	[2,3]	[4,5]
GH3	0	[2,3]	[3,4]	[3,5]	[2,3]	[2,3]	[4,5]
GH4	0	[2,3]	[3,4]	[5,5]	[2,3]	[2,3]	[4,5]
MT	10	[6,6]	[8,8]	[10,10]	[6,6]	[8,8]	[10,10]
CST							
GH3	1	[2,3]	[4,5]	[6,7]	[3,3]	[5,5]	[7,7]
GH4	0	[3,3]	[3,4]	[3,5]	[2,3]	[2,3]	[4,5]
GHL	2	[3,3]	[3,4]	[3,5]	[2,3]	[2,3]	[4,5]
GD1	0	[3,3]	[4,4]	[5,5]	[2,3]	[2,3]	[4,5]
GH5	2	[3,3]	[4,4]	[5,5]	[2,3]	[2,3]	[4,5]
TX							
GD1	1	[2,3]	[4,4]	[3,5]	[1,3]	[2,3]	[4,5]
GD2	2	[3,3]	[4,4]	[6,6]	[1,3]	[2,4]	[4,5]
GD3	1	[2,4]	[3,4]	[4,4]	[2,3]	[2,3]	[3,5]
GH5	1	[2,3]	[4,4]	[3,5]	[1,3]	[2,3]	[4,5]
GH6	2	[3,3]	[4,4]	[6,6]	[1,2]	[2,3]	[4,5]
MT	10	[6,6]	[8,8]	[10,10]	[6,6]	[8,8]	[10,10]
GH7	3	[3,3]	[3,4]	[3,5]	[1,3]	[3,3]	[4,5]
HY							
GH7	0	[4,5]	[4,6]	[2,4]	[2,4]	[3,5]	[2,4]
GH8	4	[3,5]	[4,5]	[5,6]	[3,4]	[4,5]	[5,6]

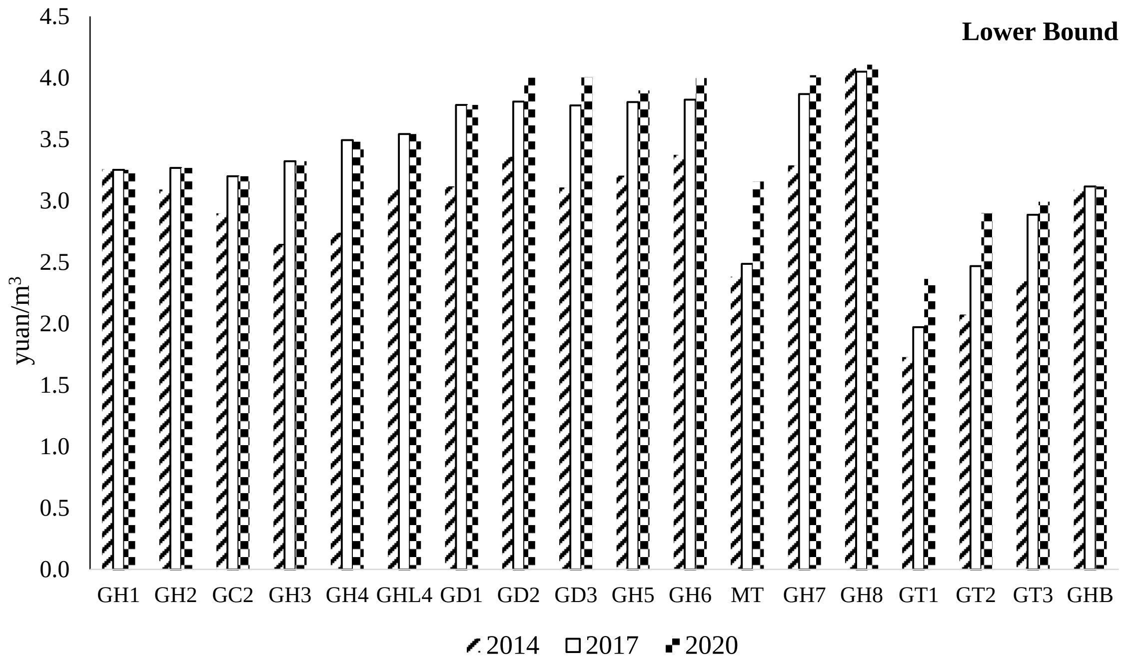

Figure 5.8 (a) Corn unit water profit under PRAP-A scenario (lower bound)

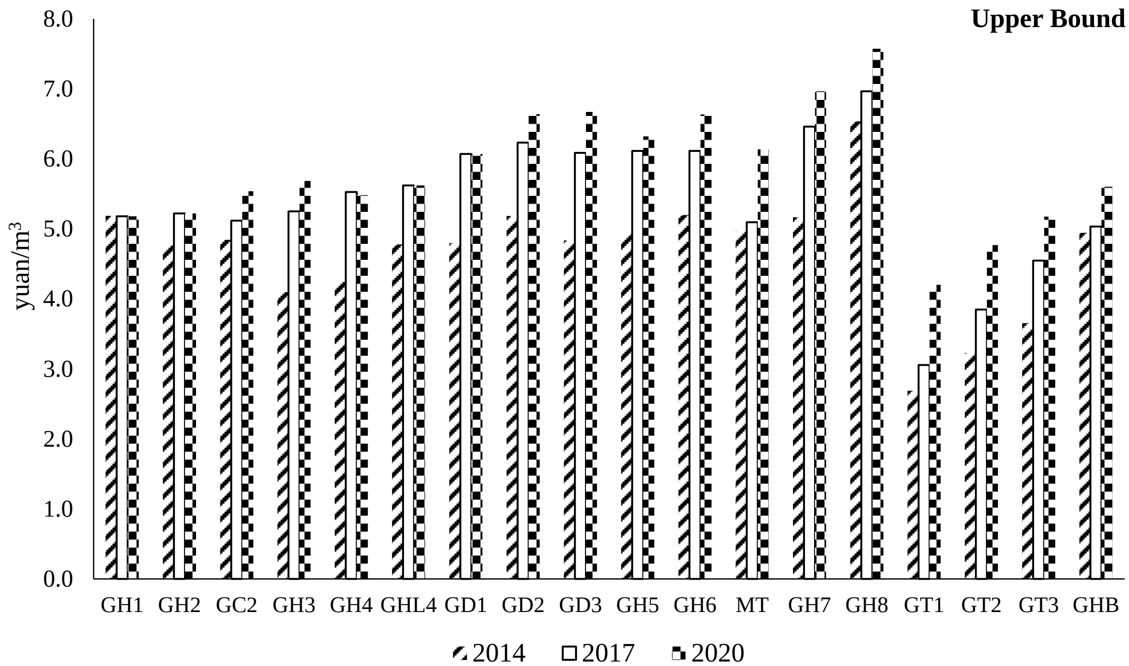

Figure 5.8 (b) Corn unit water profit under PRAP-A scenario (upper bound)

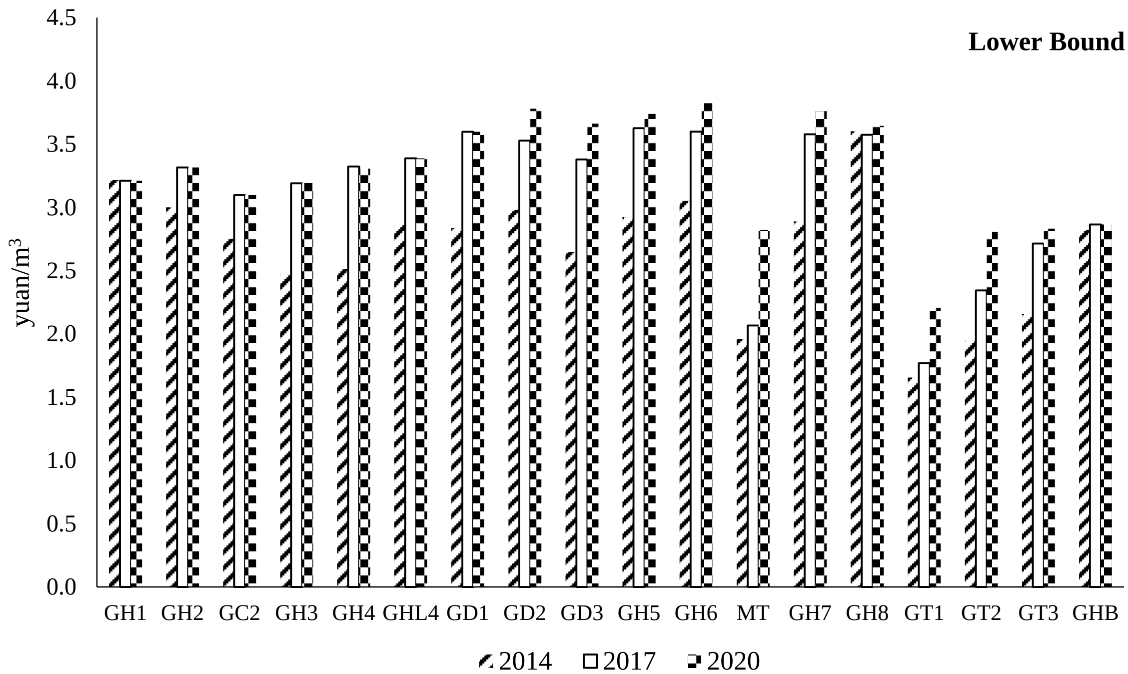

Figure 5.8 (c) Corn unit water profit under IDEP scenario (lower bound)

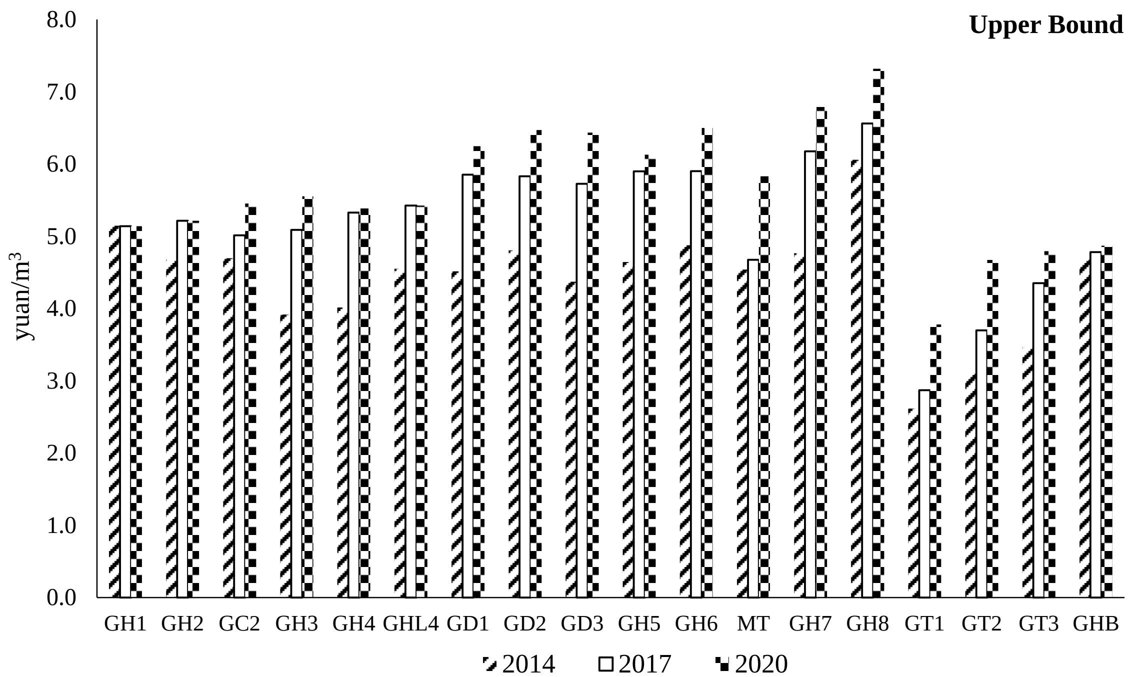

Figure 5.8 (d) Corn unit water profit under IDEP scenario (upper bound)

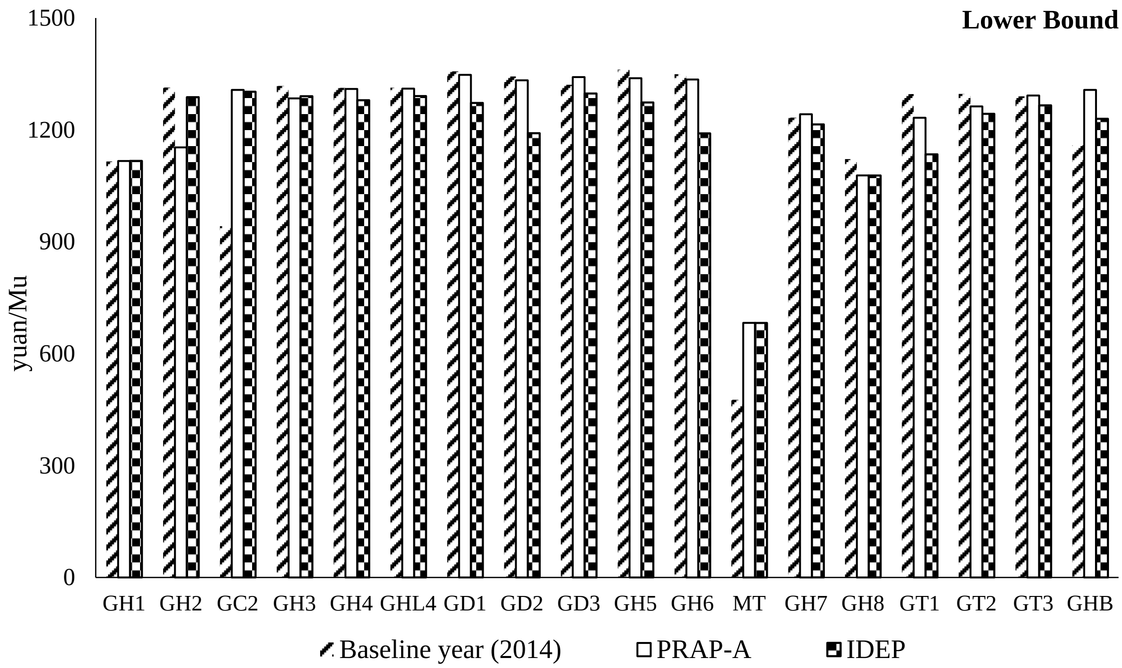

Figure 5.9 (a) Corn unit area revenue at 2020 (lower bound)

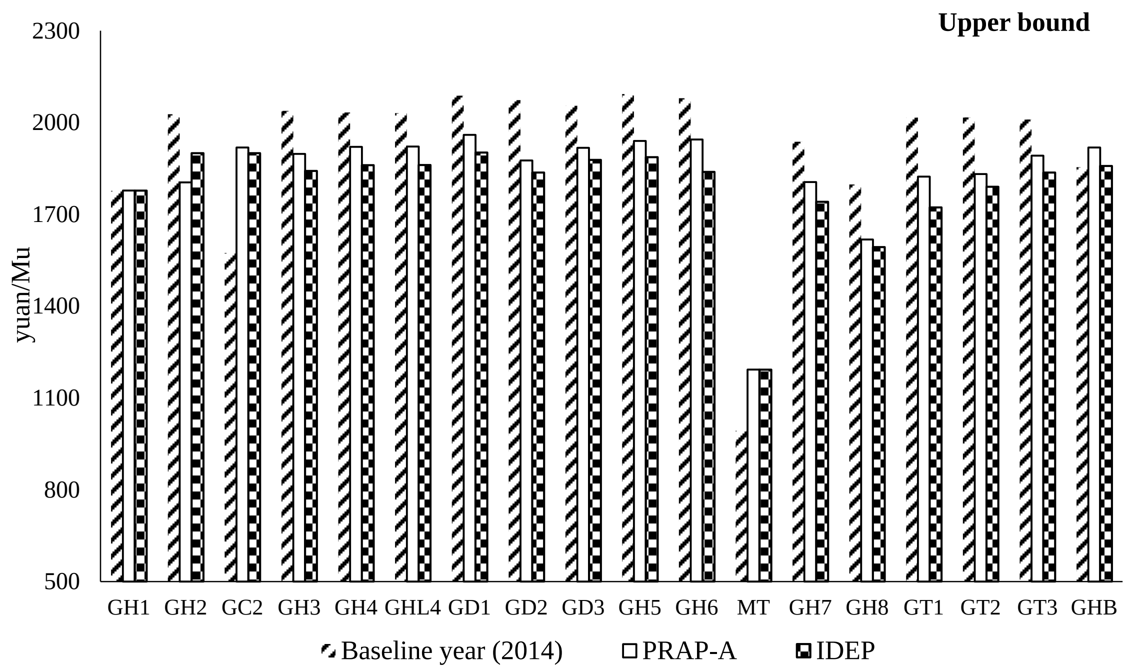

Figure 5.9 (b) Corn unit area revenue at 2020 (upper bound)

the tradeoffs between food production and the effectiveness of water trading will be observed as: the higher (or lower) trading prices of water reflected by different policy scenarios will lead to a lower (or higher) corn production. Moreover, Figure 5.9 reveals the relationship between food production and food security. Specifically, the unit area revenue of corn will stay at the same level with the baseline year (2014) if 90% of corn yield rates (lower bound) is ensured. In comparison, the upper bound of the model (85% corn yield rates) will sacrifice an average amount of 4% (under PRAP-A) and 7% (under IDEP) of the corn revenue per unit area for the higher overall benefit. Table 5.8 shows the average corn irrigation quotas for each county and at each drought level. The result suggests that, in the MAWRP model, the average corn irrigation quotas are responsive to the temporal and spatial distributions of the local precipitation. In compare with the uniformed irrigation quota that currently adopted, the optimized corn irrigation quotas is more adaptable and flexible, and thus should be ideal for sustainable agriculture.

5.3. Subsidization Policy Analysis

5.3.1. Effectiveness of Subsidization Policies

To disclose the effectiveness of the subsidization policies, social net value is used as the indicator to demonstrate the economic impacts under different water subsidization policy scenarios. According to Figure 5.10, the original irrigation land's revenue generated under PRAP-A scenario is higher than that of in the IDEP scenario. However, the social net value of the PRAP-A scenario is less than the IDEP scenario. This is because some of the revenue generated under PRAP-A scenario comes from government subsidy. To

Table 5.8 Average corn irrigation quotas

County Name	2014 (share/Mu)	Bound	Wet Year (share/Mu)		Normal Year (share/Mu)		Dry Year (share/Mu)	
			IDEP	PRAP-A	IDEP	PRAP-A	IDEP	PRAP-A
ZN	18.3	Lower	14.3	14.4	15.0	15.7	15.8	15.8
		Upper	13.6	13.7	14.4	15.1	15.1	15.1
CST	17.3	Lower	12.0	13.0	13.5	15.0	15.1	15.0
		Upper	12.0	12.0	13.0	14.0	14.0	14.0
TX	15.8	Lower	11.6	12.6	12.2	13.7	14.1	14.0
		Upper	10.7	11.0	11.9	12.8	12.9	12.8
HY	12.7	Lower	9.7	10.3	10.0	10.3	11.0	11.0
		Upper	8.0	9.0	8.7	9.0	9.6	9.6

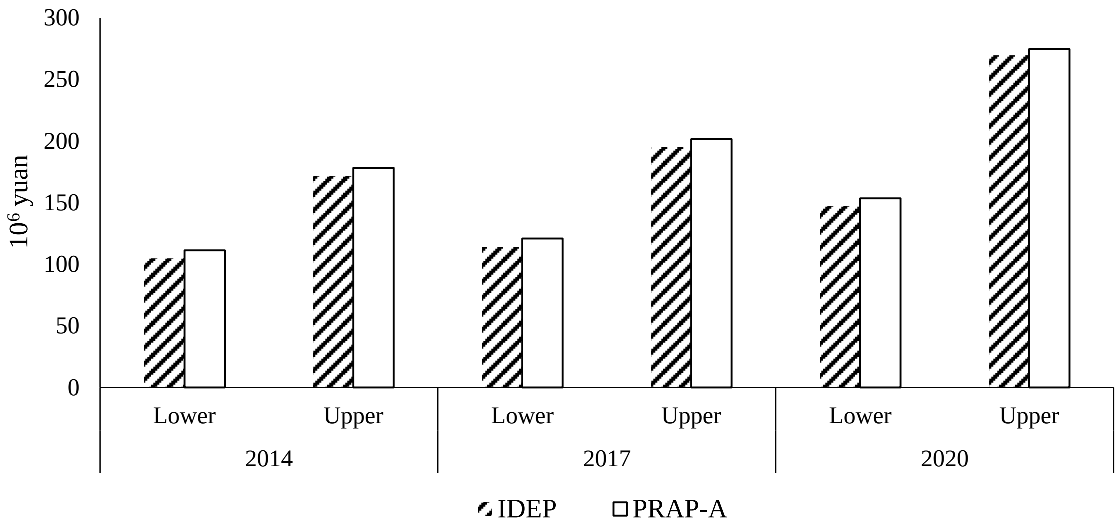

Figure 5.10 Revenue for the original land

investigate the effectiveness of different policy subsidies, a neutral policy (no water trading and no government subsidy) is used as the zero point for the other four policy scenarios (i.e. IDEP, PRAP-A PRAP-B and baseline scenario), and the results are shown in Figure 5.11. It illustrates the subsidized water trading and/or water price can benefit water users in direct and indirect manners and thus generate more revenue in comparison with the neutral scenario. In detail, the PRAP-B policy generates [80, 128] million yuan more than Neutral scenario does in first period and ranks the first among all scenarios. The other three scenarios (i.e., PRAP-A, baseline and IDEP scenario) will make the annual contribution of [73, 115], [69, 101] and [23, 65] million yuan, respectively. Due to the reduced trading effects in second planning horizon, the trading-generated revenue from the model's upper level will be less than it from the model's lower level. As it illustrated in Figure 5.11, the interval-valued lower bounds for the revenue under IDEP, PRAP-A and PRAP-B scenarios will be 17, 13 and 7 million higher than those of the model's upper bound during the second period. The total government subsidy for each policy scenario is listed in Table 5.9. It shows the Baseline scenario owns the biggest government subsidy for [92, 95] and [96, 101] million yuan in 2017 and 2020, respectively, followed by the PRAP-B and PRAP-A scenarios. The social net value is shown in Figure 5.12, which use the neutral scenario as the zero point of the social net value. The figure illustrates only the IDEP and PRAP-A scenarios will have all positive values for the social net value, while the two remaining scenarios (PRAP-B and baseline scenario) are more or less lower than the social benefit generated by the neutral scenario in some circumstances.

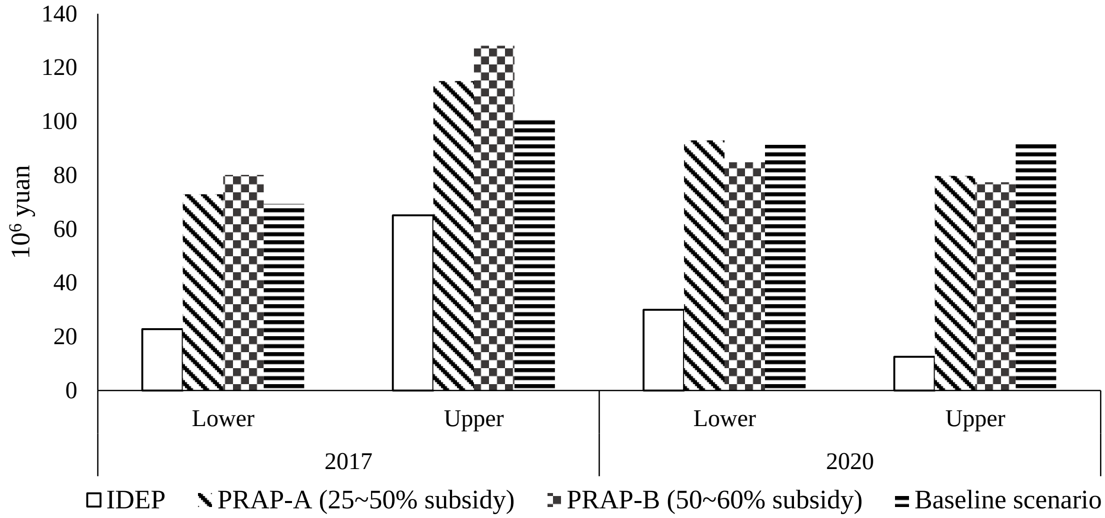

Figure 5.11 System gross revenue (compared with neutral scenario)

Table 5.9 Government subsidies under different scenarios

Scenario	2017 (10^6 yuan)	2020 (10^6 yuan)
PRAP-A	[68.3, 88.6]	[67.1, 72.1]
PRAP-B	[86.3, 111.2]	[76.0, 80.5]
Baseline	[92.0, 95.1]	[95.8, 101.1]
Neutral	0.0	0.0
IDEP	0.0	0.0

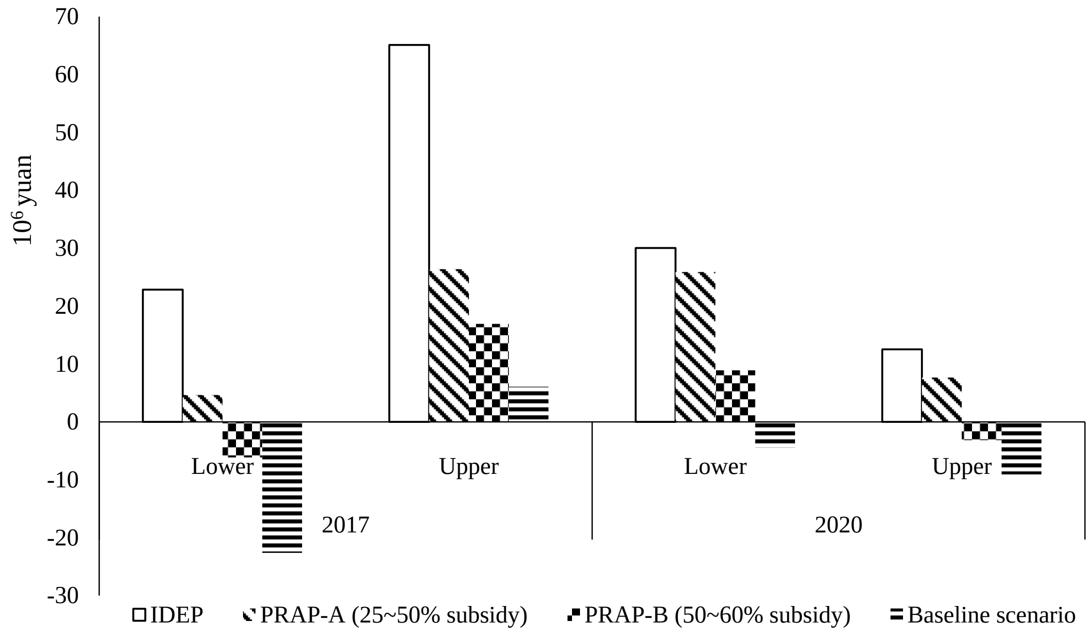

Figure 5.12 Social net value (compared with neutral scenario)

5.3.2. Relationship of Subsidization Policy and Local Economy

The results indicate the adoption of water trading in the study region is significantly enhanced with the aid of government subsides. In comparison with the subsidized trading prices of water, the subsidized water price can be a direct approach to benefit irrigators in GWDS. However, the 'devalued' water price does not provide any contribution to the formulation of the water market. On the contrary, it will become a financial burden for local government. In comparison with the subsidized water price, the subsidized opportunity cost of water shows more promise to the local economy. This form of subsidy can create more opportunities for irrigators with poor technology to gain more revenue if they plan their irrigation properly. The outcomes from the PRAP-A and PRAP-B scenarios suggest that appropriate water trading subsidies will increase social net value and reduce the overall government subsidy compared with baseline scenario. According to the two PRAP scenarios, it can also be found that more subsidized opportunity cost of water does not necessary yield a higher social net value. As the PRAP-B has a [13, 16] million yuan subsidy more than the PRAP-A, but the social net value of PRAP-B is only [0, 5] million yuan more than the PRAP-A scenario.

CHAPTER 6

CONCLUSIONS

6.1. Summary

In this study, the MAWRP model was developed and applied to the Guhai Water Distribution System (GWDS) in the Arid Zone of Ningxia Hui Autonomous Region (AZN), China. Due to the complexities of Ningxia's natural, social and economic conditions, the MAWRP model is delicately crafted for the implementation of water resources planning strategies of AZN region. The most highlighted feature of the proposed model was the integration of a water market, which in detail, encompassed water trading in the long-term and short-term (seasonal). In comparison with other water resources planning models developed in recent years, the proposed model is able to reflect the changes in irrigation technological innovation and water trading under policy intervention. By employing the deficit irrigation and corn water-production simulation module, the model can have more advantages when applying to a rain-fed agriculture.

In the MAWRP model, the seasonal water trading is achieved using an improved TSP model built upon deficit irrigation scheme. Compared with the conventional TSP model, the improved TSP model can tackle the randomness in precipitation and the associated penalties. Furthermore, in order to address the uncertainties presenting in interval and probabilistic formats, the TISP model is proposed through the improved TSP framework. The developed MAWRP model can address not only the uncertainties existing in natural, social and economic contexts within GWDS, but also lots of pre-defined local policies with consideration of the past experience of policy enforcement.

The results obtained from MAWRP model can help decision makers manage the risk of uncertain climate and improve irrigation efficiency. In detail, the interval solutions from MAWRP model indicate that the total revenue of study area can be tripled in six years (two periods) under the increased water use in the municipal and industrial sector. In addition, the MAWRP method is able to explore the full potential for water conservation in the irrigation system. By the end of the planning horizon, [34, 52]% of the original land's irrigation infrastructure will be improved, along with [59, 89] million cubic meters of water (sharing [20, 30]% of the total available water) will be traded and transferred to industrial sector permanently or in long-term contracts. The results indicate the MAWRP model will substantially shift the water from lower profit crops to higher profit water users without compromising the interests of the original land. This information is indispensable for determining the scale of new farm land and the associated water supplementary systems. The optimal cropping patterns and irrigation infrastructure improvement will support the decision makers to plan proper investments and implement water trading plans to satisfy the water demand from the industrial and municipal sectors.

The MAWPR model is proved to be effective in dealing with seasonal water trading. The deficit irrigation scheme and the presence of a water market will become an effective tool for irrigators to help manage their licensed water and revolutionarily change the famers' irrigation behavior, as they will seek the maximum benefit rather than maximum food production. Some characteristics of the seasonal water trading are revealed from the comparison between the IDEP and PRAP policy scenarios. First, seasonal water trading is price responsive. The subsidized trading prices of water enlarged the scale of potential water users. The controlled (reduced) trading prices of water to some extent limits the trading performance in terms of transaction volumes. Secondly, the tradeoff for seasonal water trading and local food production is analyzed. The more volume of water traded, the more gross revenue is generated, and the less food is produced. The revealed tradeoffs between the food production and gross revenue can support the design of tradable water rights and secure the basic food production level. Thirdly, seasonal water trading is significantly affected by irrigation technology. The adaptation of innovative irrigation methods will directly increase the unit water profit. As a result, the government subsidized trading prices of water become less attractive to water permit holders.

The relationship between government subsidy and social net value is also revealed from the comparison of different subsidization policies. An appropriate subsidization policy (i.e. under the PRAP-A scenario) can bring direct benefits to water users and reduce the government's financial burden. On the contrary, excessive water trading subsidy (i.e. under the PRAP-B scenario) or inadequate water trading subsidy (i.e. under the baseline scenario) will increase the government's financial burden and impede formulation of the water market. The comparisons between different policy scenarios generated from the MAWRP model can help the local government establish a more transparent trading environment along with well-defined water rights with more trading opportunities and less barriers for all water related stakeholders.

6.2. Research Achievements

The development MAWRP model is a pioneer study integrating the water market into a system optimization with consideration of technological innovation and institutional reformation. The proposed model is applied to the GWDS in the AZN, located in northwestern China. Based on the complexity of the natural, social and economic conditions in the study region, the MAWRP model is able to reflect the effectiveness of water trading under various policy scenarios. The solution provided from the MAWRP model can support the formulation of the optimal subsidization policy to achieve the maximum social net value. As a growing trend for the water market, water trading will become a more effective means in the AZN to achieve a sustainable water community. In addition, the experiences and lessons learned through this research can be extended to a number of other regions with arid climatic conditions, based on the proposed MAWRP framework and the associated deficit irrigation and water trading approaches.

The result from MAWRP model revealed a number of phenomena that help decision makers to better design and conduct water policies. Firstly, water-saving strategies would not compromise the revenue for each subarea, on the contrary, all the subareas would see revenue increases. Secondly, an appropriated deficit irrigation scheme along with the infrastructure enhancement would maintain the food crop yields at a desired level. Thirdly, seasonal water trading could create more revenue than no seasonal water trading practice. Finally, appropriate water trading subsidy will help reduce the government financial burden and realize the local agricultural sustainability. These disclosed findings could also be generalized to other regions to help generate value-added benefits.

6.3. Recommendations for the Future Study

The capacity of the MAWRP model is limited because corn is the only crop chosen in this study for exploring deficit irrigation. When the corn's growing area becomes smaller, the space for seasonal water trading becomes narrower. As shown in the results, there is a growing trend of permanent water trading (water-saving from irrigation infrastructure improvement) and a diminishing trend of seasonal water trading. This phenomena may put seasonal water trading in a challenging situation if the temporary water demands from industry and other high profit water users increase significantly. This strong desire taking place in temporary water resources is creating a great challenge for this model. In order to tackle these challenges, further research needs to be undertaken to obtain a more comprehensive deficit irrigation scheme involving more crops.

To obtain a precise and accurate deficit irrigation scheme, non-liner functions are used to represent the water-production relationships but there are still some discrepancies between the observed data and simulated functions. Moreover, another model simplification is that the deficit irrigation uses the limited sites and water-production functions to represent the entire irrigation area even though the three sites can geographically represent the water-production relationship. However, there still exist some extreme cases that may disturb the model performance. This aspect also needs to be improved in future studies.

The comparison results from multiple scenarios reveal the necessity of subsidization policies. However, one concern raised from irrigators is whether or not the subsidized opportunity cost of water can be profitable under the changing climate. Unlike the subsidized water price, for which irrigators would enjoy a stable subsidy every year, the benefit from the subsidized trading prices of water will vary with different drought levels, thus reducing the chance of gaining more benefit. Even though the MAWRP model demonstrates the long-term benefit from the subsidized trading prices of water can be much greater than the current subsidized water price, irrigators still may not be convinced of transferring the uncertain ‘risk’ to their own interests. Therefore, further studies need to be performed with respect to designing a water subsidization policy favored by both governments and irrigators.

In the MAWRP model, the revenue contributed by the seasonal transferred water is not being considered in the modelling process. More advanced optimization approaches need to be developed in the future to reflect the whole picture of seasonal water trading.

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