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Adaptation to Quantitative Regulation of Agricultural Water Resources: Mosaic Cropping Pattern and Rotational Irrigation in China

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ABSTRACT: Quantitative regulation of agricultural water resources (QRW) is an effective means of reducing water demand and sustaining water development. Few studies, however, have investigated the mechanism underlying a region's adaptation to QRW. In this study, we first establish an adaptive mechanism framework which incorporates rotational irrigation and cropping patterns a means of solving the problems of inefficiency, inequality and costly coordination that result from adaptation to QRW. Next, in order to examine the applicability of the theoretical framework, we refer to the case study of Xuwen County, Guangdong Province, China, where QRW was implemented by the Central Government in 2011. We find that a mosaic cropping pattern can enable rotational irrigation on a regional scale, which can cost-effectively mitigate the problems of inefficiency and inequitable allocation caused by QRW. We find that a diverse cropping pattern can provide a form of spatial rotational irrigation that requires less water than the temporal rotational irrigation required for a heterogeneous cropping pattern. Our findings have implications for irrigated agriculture and water resource conservation; they reveal that it is possible to decouple agricultural water supplies from crop growth through the implementation of QRW.

KEYWORDS: Quantitative regulation, cropping pattern, agricultural water resource management, rotational irrigation, China

INTRODUCTION

Regulation of agricultural water resources, both surface water and groundwater, has been widely suggested as an effective demand-side solution to the problem of water overuse, enabling water resource development to be sustained (Molle, 2009). There are two ways of regulating agricultural water resources, one based on quantity and the other on price. The former, quantitative regulation of agricultural water resources (QRW), which focuses on controlling the amount of water used and sets constraints on water availability, can help achieve the goal of curtailing water demand (Molle, 2009; Drysdale and Hendricks, 2018). Some scholars have proposed that QRW is a precondition for the effective operation of other water-saving measures such as a direct cap on water usage or on the area under irrigation (Grafton et al., 2018; Perry et al., 2017; Wheeler et al., 2016; Debaere et al., 2014). Drysdale and Hendricks (2018) found that QRW resulted in a 26% reduction in groundwater use by farmers in the American state of Kansas. Studies of practices in the European Union and in the western United States have also found that it is difficult to achieve water saving at the basin scale without QRW (European Union, 2013; Milman et al., 2018). To prevent irrigators from increasing their water use, Australia enforced a basin-wide limit on surface and groundwater extraction in the Murray-Darling Basin; this was known as the sustainable diversion limits (Wheeler et al., 2020; Murray-Darling Basin Authority, 2019).

Similarly, since 2000, some regions in China have adopted measures to control water use with the aim of reducing total water demand (Li et al., 2015). In 2011, the Chinese government enacted a policy of stringent water resource management which established "*Three Red Lines*",[1] one element of which involved constraining total water use (Global Water Partnership, 2015). This policy marked the implementation of QRW across China (He et al., 2018), and it has been reinforced since 2020. Recent studies on QRW have focused on theoretical works exploring its potential effectiveness through the use of simulations of various scenarios using simulations of various scenarios. QRW has been found to be a much more effective water-saving measure than price regulation as it did not affect livelihoods or compromise the cropping area (Shi et al., 2014; Yi et al., 2019).

A seminal study by Wang et al. (2019) found that the influence of irrigation management policy depends on the local stakeholders' responses in the form of behaviour change. There are two ways to change behaviour: adjusting the irrigation strategy (including irrigation intensity and the irrigated acreage) and adjusting the cropping pattern (Li et al., 2015; Drysdale and Hendricks, 2018). Although scholars and policy makers have confirmed that QRW is an effective means of controlling agricultural water use, few studies have explored the local adaptation process and the underlying mechanism, in particular the behavioural changes. Furthermore, few studies have presented a generalisable framework of the mechanism underlying adaptation to QRW. This study aims to fill this gap by pursuing three key objectives. First, we explore the mechanism of adaptation to QRW through providing a framework based on the perspectives of rotational irrigation and cropping patterns. Second, we address the formation of a rotational irrigation regime at the regional scale through the introduction of a mosaic cropping pattern. Third, we use a case study to explain the process of adaptation to QRW and to reveal the pathway whereby QRW can enable the decoupling of agricultural water resources from crop growth.

The remainder of the paper is organised as follows. In the next section, after explaining the significance of the study, we review previous theoretical studies on the mechanism underlying adaptation to QRW through rotational irrigation and a changed cropping pattern. We then present a case study of Xuewen County as an example of a successful adaptation involving a dynamic decision-making process by the stakeholders. The final two sections present a discussion of the results and our conclusions.

THEORETICAL FRAMEWORK

Potential problems of adaptation to QRW and the way out through rotational irrigation

Water resources used for agricultural irrigation, both surface water and groundwater, are a typical example of a common pool resource (CPR) which has twin inbuilt dilemmas, namely inefficiency of water resource use and inequity of water resource allocation between different users (Albiac et al., 2020; Ostrom, 1990). Inefficiency results from water overuse; this occurs because of the CPR's attributes of subtractability and negative externalities, which result in a 'pumping race' (Gardner et al., 1997). Inequity occurs when an asymmetric distribution of locations enables farmers located nearer to the water source to withdraw more water than those whose farmland is more distant from it (Janssen et al., 2011).

QRW has the potential to worsen the twin problems of inefficiency and inequity. Regarding inefficient water withdrawal, when water availability is limited each farmer has more incentive to withdraw excessive amounts (Ostrom, 1990); farmers' simultaneous water withdrawal, however, is likely to cause a CPR externality. This captures the negative effect of adding an additional unit of area to the total weight for all irrigated crops, resulting in inefficient water use in the form of much longer appropriation time and the input of more efforts In particular, regarding groundwater, numerous wells simultaneously

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[1] The other aspects of the "*Three Red Lines*" are controlling water-use efficiency and restricting pollutants in water-use areas.

pumping water from an aquifer can lower the water level; it can even lead to water depletion wherein the rate of pumping exceeds the 'safe yield' (Molle et al., 2018). By this logic, QRW can have adverse effects, with highly inefficient water use resulting from overuse.

In addition, QRW may reinforce the inequity caused by the asymmetric locations of the various farmlands. With limited water availability and a 'first in time, first in right' approach, upstream users have an incentive to make full use of their priority access to water by withdrawing all the water available, leaving nothing for downstream users. Irrigation systems are exacerbating this situation, resulting in stationary bandit behaviour, with farmers in disadvantaged locations having to transition to rainfed agriculture (Cody, 2018). Even more severe outcomes, such as the destruction of the entire system, could also occur because those farmers who do not benefit from the system are not likely to provide the resources necessary to maintain the infrastructure (Ostrom and Gardner, 1993; see Wang and Cao, this issue).

If these two issues are not resolved, QRW is likely to fail, leading to the tragedy of the commons in the form of an unsustainable water supply. Adaptation in response to QRW must therefore focus on alleviating inefficiency and inequity in relation to water use. Ostrom and Gardner (1993) proposed a method involving rotational irrigation as an efficient and equitable irrigation strategy that is particularly suited to situations involving limited water availability. Rotational irrigation means that water delivery/pumping is undertaken by each farmer in turn based on a timetable that is designed to provide equitable access to water for irrigation (Cody, 2018; Ostrom and Gardner, 1993). By this rationale, rotational irrigation is likely to mitigate the two issues of inefficiency and inequity and has the potential to facilitate successful adaptation to QRW.

An irrigation strategy involves coordinating water use in terms of both timing and quantity in such a way as to counteract irrigators' tendency to overuse. Rotational irrigation has three more attributes. First, by imposing entry restrictions, it enables staggered water withdrawal periods to mitigate the 'pumping race'; at any given time, only part of the irrigated areas are able to access water, a system that is widely recognised as reducing or removing the incentive to exploit water availability (Ostrom, 1990; Gardner et al., 1997). Second, rotational irrigation emphasises duration of water use, which can affect the quantity of water used; in other words, the shorter the duration for which water withdrawal is permitted, the less water is used. Third, rotational irrigation can provide equitable access to water by equalising the allocation of times for water appropriation, with various crops being allocated positions in the irrigation schedule to enable equitable coordination of water use; rotation also provides equitable water appropriation opportunities for farms in different locations.

Rotational irrigation based on cropping patterns

The coordination costs of a rotational irrigation regime are positively correlated with the scale of jurisdiction. A rotational irrigation system requires coordination such that every farmer can withdraw water on an established schedule (Ostrom, 2014). Rotational irrigation can succeed at the community scale because the costs involved in coordinating a rotational irrigation scheme among farms in a community are moderate. As the size of the jurisdiction increases, however, there is less incentive to develop, agree to, or adhere to a rotational irrigation system because of the increased coordination costs required to organise the timing and duration of each farmer's access to water.

Even if a rotational irrigation system can be designed on a large scale, it is costly to monitor the farmers' behaviour to ensure that they do not withdraw water at unauthorised times or take more water than permitted. Thousands of farms would have numerous opportunities to take water at unauthorised times, and conflict would thus certainly occur (Ostrom, 1990). A farmer who is nearing the end of their scheduled period of access may want to continue beyond the cut-off time, while the next farmer in line may want to start withdrawing water earlier than permitted. A farmer who in this way violates the schedule can indeed obtain additional water, but the other farmers must bear the cost; furthermore, the cost of monitoring and applying penalties to prevent such behaviour is extremely high. The establishment and enforcement of a rotational irrigation regime at the regional scale thus has a high likelihood of failure.

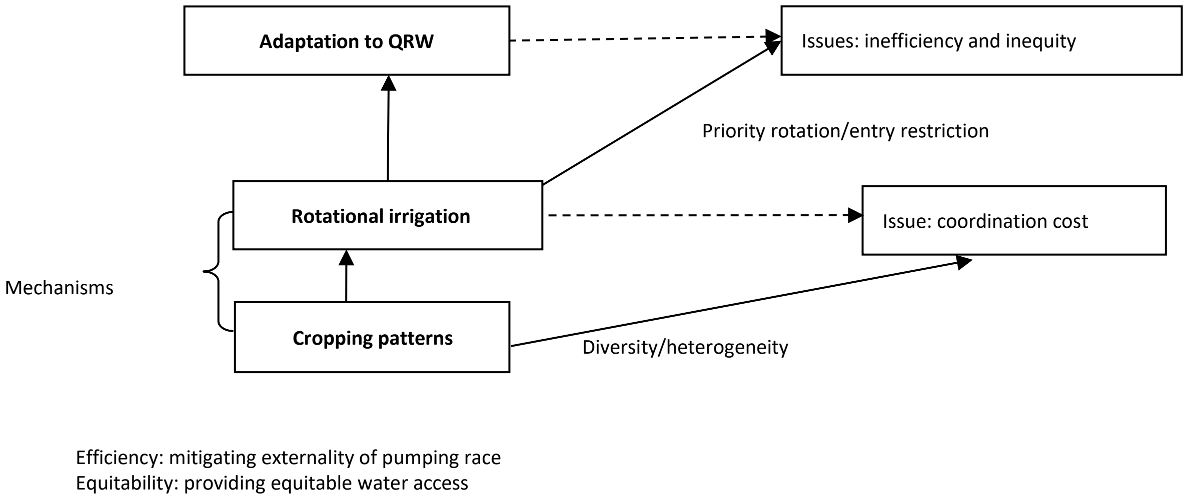
A rotational irrigation system can be economically implemented at the regional scale if a mosaic cropping pattern is in place, as it lowers coordination costs through providing an institutional foundation that facilitates interactions among farmers (Milman et al., 2018). Excessive water appropriation at any given time can be avoided because each crop has a different growing cycle and thus each has priority for water use at specific times. Previous studies, however, have paid little attention to the relationship between cropping patterns and rotational irrigation at the regional scale; in this study, we aim to fill that gap.

A mosaic cropping pattern involves two dimensions of crop rotation, namely spatial and temporal patterns; these lead to two corresponding types of rotational irrigation, that is, spatial and temporal rotation. Crop rotation in terms of the spatial dimension is classified into two types, specialisation and diversification; these are based on the composition of the cropping area in a given season. Specialisation means that all of the irrigated area in a village is used to grow the same crop and thus no rotational irrigation regime emerges at the village scale; specialisation is thus prone to causing water over-withdrawal. Empirical evidence from the world's largest funnel area, the North China Plain, provides a tragic lesson. The area is suffering from the aftermath of groundwater depletion because all of the farmers in that region grow winter wheat and all thus pump water at the same time (Wang et al., 2019; Deng et al., this issue). Diversification, on the other hand, means that the irrigated area in a village is used to grow various crops in a single season, which enables spatial rotational irrigation. The different growing seasons of the various crops enable the demand for water to be spread over time, and thus crop diversity is characterised by alternative periods of priority access in relation to water withdrawal and the problem of water over-withdrawal is avoided.

Temporal crop rotation is also classified into two types, namely, homogeneity and heterogeneity; these are based on the crop rotation that occurs during a given year. Homogeneity means that the same crop is grown throughout the given year, while heterogeneity means that different crops are grown successively in the same field in the course of a year. Heterogeneous crop rotation enables temporal rotational irrigation, with multiple periods of intense water requirements during the year. Because the length of the growing season varies among different crops, heterogeneous crop rotation enables different periods and quantities of water use, which can alleviate water stress. In the North China Plain, shifting from winter wheat to diverse crop cycles over a four-year cycle, such as sweet potato-cotton-sweet potato-winter wheat-summer maize, has been suggested as a highly successful means of reducing water use (Yang et al., 2015). Furthermore, implementing such cycles can lead to increased water infiltration rates, resulting in shorter periods of water use and less water being required; this contributes additionally to reductions in water use (Nel, 2005).

Summarising the above-mentioned studies, we can infer that rotational irrigation at the regional scale can achieve efficient and equitable water allocation, enabling farmers to adapt to QRW (see Figure 1). A mosaic cropping pattern allows a rotational irrigation regime that incurs negligible coordination costs in terms of rule establishment and enforcement. The order in which rotational irrigation occurs is based on the growth cycles of the crops; for instance, chive crops mature in February, which is when they need frequent watering, while banana crops germinate in February and do not need watering at that point. The variations in the timing of growing cycles and the corresponding staggering of peak water use for various crops automatically creates a rotational irrigation regime. The dual dimensions of diversity and heterogeneity in relation to the cropping pattern can enable the coordinated rotation of water withdrawal based on the characteristics of the various crops. Solving the problem of adapting to QRW is thus divided into solving the problem of inefficiency and inequity through rotational irrigation, and then solving the problem of coordination through the use of a mosaic cropping pattern.

Figure 1. A framework for successful adaptation to quantitative regulation of agricultural water resources (QRW) based on the mechanisms of rotational irrigation and a mosaic cropping pattern.



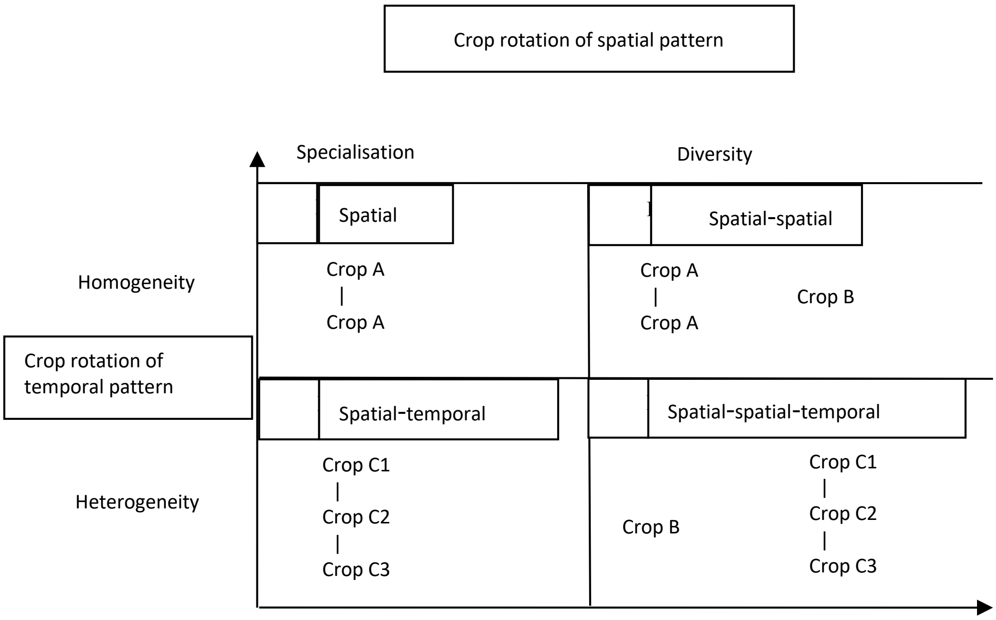
Classification and features of rotational irrigation

Based on the two dimensions of crop rotation at the village scale, plus the spatial aspect at the regional scale, we classify rotational irrigation into four styles (see Figure 2): spatial, spatial-spatial, spatial-temporal, and spatial-temporal-spatial.

We use a matrix based on the two dimensions of the cropping pattern – namely, crop rotations based on either spatial or temporal patterns – to present the four types of rotational irrigation. Type I, the spatial style, is the archetype located in the top-left corner of the matrix; it indicates rotational irrigation only at the regional scale. The spatial style of rotational irrigation involves a pattern of special and homogeneous cropping patterns, such as crop A-crop A. Normally, this type of village plants a traditional subsistence monoculture crop of grain, meaning that the crops all have a similar growing season and thus similar water demands. Farmers withdraw water at the same time, and thus it is difficult to establish a rotational irrigation regime at the village scale. Scaling up to the regional level, however, a mosaic cropping pattern emerges, with various villages needing water at different times; this enables the formation of a spatial rotational irrigation system.

Type II is the spatial-spatial style which involves crop rotation featuring diverse and homogeneous patterns; it is in the top-right corner of the matrix in Figure 2. This type of village is in the process of transitioning to semi-commercial agriculture, such as planting both crop A-crop A and crop B. At the village scale, crop A and crop B require water at different times, which creates a spatial style rotational irrigation system. When scaled up to the regional level, the mosaic cropping pattern forms a spatial-spatial rotational irrigation system.

Figure 2. Matrix of the four types of rotational irrigation at the regional scale.



Spatial: simultaneous partial water access
Temporal: water access for different amounts of time

Note: for instance Crop A = rice; Crop B = bananas; Crop C1 = chives; Crop C2 = leeks; Crop C3 = peppers.

Type III, the spatial-temporal style, involves crop rotations featuring both special and heterogeneous crops; it is located in the bottom-left quadrant of the Figure 2 matrix. This type of village has transitioned into commercial agriculture; it plants, for example, cash crop C, which includes multiple subtypes of crop C in a pattern of crop C1-crop C2-crop C3. The heterogeneous attributes of the different subtypes of crop C enable water to be withdrawn at different times; for instance, after crop C1 has been harvested, crop C2 starts to require water. Farmers thus engage in a temporal rotation system at the village scale. Scaling up to the county level, this type of village can engage in the spatial-temporal style of rotational irrigation.

Type IV, the spatial-spatial-temporal style, involves crop rotations featuring diverse and heterogeneous patterns; it is located in the bottom-right corner of the matrix. This type of village also engages in commercial agriculture, but the farmers grow different cash crops, such as crop B together with crop C1-crop C2-crop C3. The differing irrigation requirements for crop B and crops C1, C2 and C3 enable the farmers to engage in a spatial-temporal rotation system at the village scale and a spatial-spatial-temporal rotation at the regional scale.

Water rotation at the regional scale has three characteristics. First, it is a two-tier system involving both regional and village scales. Each of the four quadrants represents a form of crop rotation and a rotational irrigation regime at the village scale. The entire matrix represents the cropping pattern and rotational irrigation regime at the regional scale.

Second, the rotational irrigation regime at the regional scale includes a degree of flexibility. The order in which farmers receive water is more or less fixed, based on the growing seasons of their crops. Farmers can thus approximately predict when their turns will arrive and, even if water availability is limited, 'authorised' farms can make full use of the water.

Third, the rotational irrigation system operates automatically and requires no coordination. Farmers only withdraw water during the growing seasons of their crops and do not need to take water at other times. The cost of coordinating the rotational irrigation system is therefore very low.

METHOD

Case study: Xuwen County, Guangdong Province, China

We used a case study of Xuwen County, Guangdong Province, China to investigate the mechanism underlying adaptation to QRW. This county was chosen for three reasons. First, water is scarce there, with an annual precipitation of about 1400 mm, most of which is concentrated in July and August. The average annual volume of water per capita is 1829 m^3, which is less than the national annual average of 2355 m^3, and the county is said to experience "nine years' drought out of every ten years". Second, Xuwen County is a typical agricultural region and is highly dependent on irrigation to ensure food security. It includes 14 towns and 173 villages, and about 70% of the population lives in rural areas. Agriculture is one of its largest industries. Third, the county has achieved sustainable agricultural water use for many years. It has 117 reservoirs with a total water storage capacity of 442 million m^3; in addition, its allowable groundwater extraction is 410 million m^3/year, which accounts for 65% of the annual recharge volume. Its total groundwater storage is 205 million m^3/year, of which 70% is stored in shallow aquifers. By controlling the use of its water resources, Xuwen County has successfully transformed its agricultural development through cropping pattern adjustments and an appropriate rotational irrigation strategy.

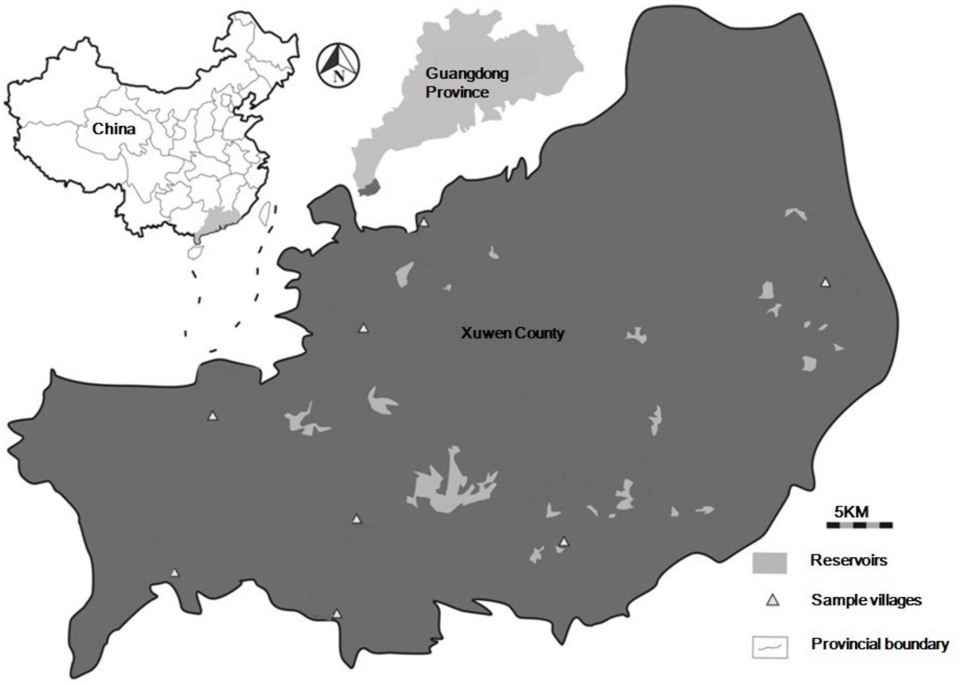
Xuwen County is located in Guangdong Province, at the southern extremity of the Chinese mainland (see Figure 3). The county's rotational irrigation regime commenced in 1998 and was intensified in 2011. Its agricultural department is responsible for planning and directing the development of the cropping pattern. The objective is to promote agricultural development in order to achieve increased production and income. Since 2011, the county's agricultural planners have had to consider the stringent regulatory constraints of an agricultural water-use policy that caps the annual volume of water available for irrigation at 370 million m^3. This cap is based on the quantity of groundwater that was being used for agriculture in Xuwen County in 2010. Given this red line, the planners could choose from three options: reducing water-use intensity, reducing the irrigated area, or changing the cropping pattern. The first two options would obviously result in reduced production, and so they understandably chose the third option. The heads of the villages adopted a leading role in shifting the cropping structure from purely rice to mixed cropping. Once farmers recognised the economic benefits provided by alternative crops, they followed the lead of the village heads and increased the area planted with alternative crops while reducing the area planted with rice.

The two most popular alternative crops are bananas and vegetables; they are highly productive and profitable, with bananas yielding 8000 kg/mu (120,000 kg/ha) and 1 yuan/kg (US$.16/kg), and vegetables yielding 4500 kg/mu (67,500 kg/ha) and 10 yuan/kg (US$ 1.57/kg). Rice, in comparison, yields only 900 kg/mu (13,500 kg/ha) and 2.77 yuan/kg (US$.43/kg). These three types of irrigated crops occupy a total farmland area of 54,000 ha, or about 75% of the total arable area, and are located in various parts of the county. In terms of water usage, farmers use water from canals to irrigate rice, and groundwater to irrigate bananas and vegetables. Rice requires six months of irrigation, while bananas require only five. Further, the banana-producing farmland is located above the aquifer, which enables higher levels of groundwater storage and recharge. Meanwhile, vegetables require 10 months of irrigation, and the aquifer above which the vegetable-producing farmland is located has lower levels of groundwater storage and recharge. Bananas thus enable higher production than rice, using less water, while vegetables enable the highest level of production but require more water than either rice or bananas.

Data collection

Multiple data sources were used for the case study for mutual verification purposes; they included policy documents, statistical yearbooks, participant observation and in-depth interviews (see Table 1).

Figure 3. Study area.



Source: from the surveying by our research team and with the help of Mapinfo software.

Table 1. Data sources and collection methods.

Data source	Methods of data collection	Data classification	Number
Primary materials	Interviews	Adaptive behaviours, rotational irrigation	236 people
	Semi-structured questionnaire and survey	Demographic characteristics, cropping patterns and adjustment, water demand and irrigation information, water-use evaluation	186 householders
	Field trips	Distribution of crop mix, operation of rotational irrigation	8 times
	Participant observation	Water use at peak times and different locations	8 times
Secondary materials	Policy documents	Planning of agricultural development, water management	30 copies
	Statistical yearbooks	Agricultural production, water demand and supply	10 copies

Note: The household characteristics included the age of the household head (55-59 years), area under irrigation of each household (0.35-0.93 ha), and the household head's average years of schooling (9).

General information at the county level included agricultural production, agricultural water supply and demand, and policy dynamics; this information was collected from policy documents and statistical yearbooks that were provided by the local government. Semi-structured questionnaires were used to provide a degree of structure while also providing respondents with sufficient flexibility to express opinions and ask questions. Interviewees included householders as well as 50 stakeholders such as public servants (from agricultural and hydrology departments) and village leaders. A random sample of 186 householders from 8 administrative villages were asked questions concerning demographic characteristics, cropping patterns and adjustment, water demand and irrigation methods, and water-use evaluation and comparison before and after 2011. Snowball sampling was used to collect information on how farmers had adapted to QRW and how they had changed their cropping patterns and embraced a rotational irrigation regime. Data from the county, village and household scales was then compared in an effort to explain the outcomes of the rotational irrigation regime at each scale.

Based on the area under cultivation and the market prices, the economic yield for rice, bananas and vegetables was approximately 2500 yuan/mu (US$ 5880/ha), 8000 yuan/mu (US$18,810/ha), and 45,000 yuan/mu (US$ 105,975/ha) respectively.

Analysis method

We used the proposed framework to design, conduct and analyse the case study. A case study was an appropriate methodology since adaptation to QRW involves various factors and their complex interrelationships, which are occurring in a contemporary environment that embodies institutional change (Yin, 2003). The results of the case study were able to illuminate the decisions made by the local stakeholders regarding changes to cropping patterns and the irrigation strategy that enabled them to adapt to QRW. The detailed observations undertaken in the case study enabled us to gain an understanding of why these decisions were taken and how they were enforced to solve the potential problems of inefficiency and inequity.

We used a mixture of subjective evaluation and objective indicators to measure adaptive performance. Wang et al. (2016) suggested that the amount of water available at peak times can be used to measure the efficiency of water use; we thus used a three-point Likert-type scale (1 = scarce; 2 = moderate; 3 = abundant) to measure the subjects' responses. Similarly, a two-point Likert-type scale (1 = inequitable; 2 = equitable) was used to measure the subjects' responses regarding equity of water allocation. Another three-point Likert-type scale (1 = reduction; 2 = no change; 3 = increase was used to measure the perceived difference in water availability before and after the implementation of QRW. In addition to these subjective indicators of environmental performance, we used statistical data and professional information regarding dynamic changes in the supply and demand of surface water and groundwater, including safe pumping levels from the aquifer.

Revenue from irrigated crops was used to measure economic performance. In Xuwen County, one household typically cultivates several small areas of farmland in different locations. No charge is levied for the use of water. Cash crops require more capital investment in items such as fertiliser, pesticides and machinery, but require less inputs in the form of labour than paddy rice. The subjects agreed that the total planting costs for each unit of irrigated farmland were similar for the different types of crops, that is, an annual average of about 2000 yuan/mu (US$ 4695/ha). Revenue per unit of irrigated farmland is thus an appropriate measure of economic performance.

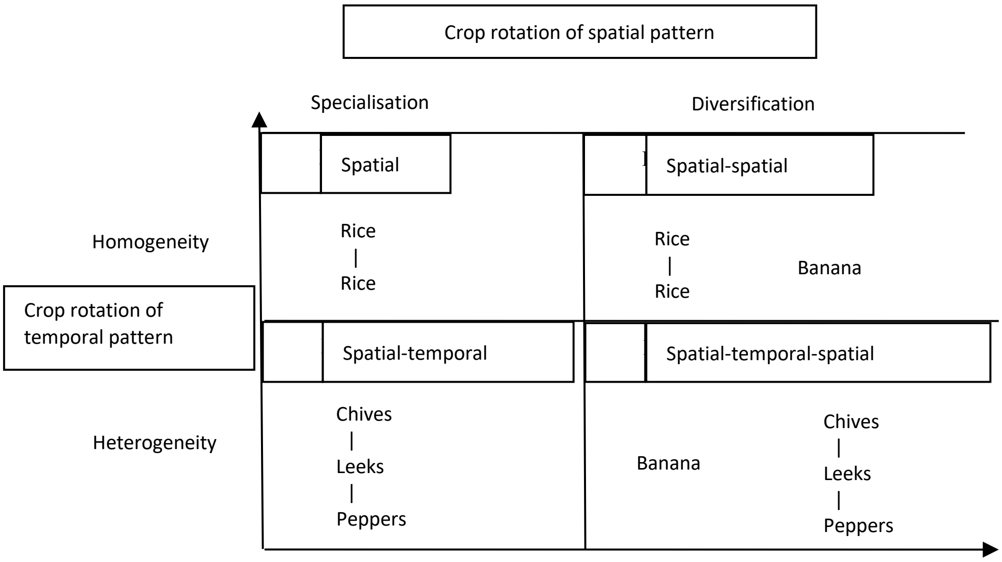
MAIN FINDINGS

Mosaic cropping patterns and rotational irrigation

A mosaic cropping pattern plays an important role in rotational irrigation regimes because different crops require irrigation at different times. At the county scale, a mosaic cropping pattern, which avoids synchronised water demands, provides the basis for a rotational irrigation schedule. The cropping pattern of irrigated agriculture in Xuwen County has transitioned from the traditional structure of rice to mixed cropping, with 75% of the irrigated farmland area now used to grow bananas and vegetables.

Based on the two dimensions of a cropping pattern, namely spatial and temporal patterns, these irrigated areas exhibit four types of crop mix: rice-rice, rice-rice and bananas, chives-leeks-peppers, and bananas and chives-leeks-peppers. Meanwhile the two dimensions of the cropping pattern are divided into four types of rotational irrigation: spatial, spatial-spatial, spatial-temporal, and spatial-temporal-spatial (see Figure 4). The percentage of each of the four types of cropping mix at the county level is 10%, 20%, 40% and 30%, respectively.

Figure 4. Matrix for analysing the four types of rotational irrigation at the regional scale.



Spatial: simultaneous partial water access
Temporal: water access for different amounts of time

At the county scale, the crop grown by a village forms a spatial rotational irrigation system in conjunction with the different crops grown by other villages, constituting a mosaic cropping pattern. Only those villages planting a particular crop need water at a given time, with other villages able to wait until their crops require irrigation. Different cropping patterns also mean that there are differences among villages in terms of water requirements, which also enables various types of rotational irrigation.

Types of rotational irrigation

In Xuwen County, no agency is responsible for allocating agricultural water resources at the village scale. In practice, under riparian rights and the flexible water-use rule, farmers can access both canal water and groundwater. Farmland at lower levels is used to grow rice, with irrigation water delivered from reservoirs via canals; meanwhile, upper-level farmlands are used to grow cash crops such as bananas and vegetables, with irrigation water pumped from aquifers. Farmers follow informal rules regarding water appropriation (such as withdrawing canal water sequentially), while groundwater is pumped at will based on the needs of the crop. In the traditionally wet months of July and August, rain is sufficient to meet the water needs of the crops, and thus irrigation is unnecessary.

Table 2 shows basic water-use information for the four types of rotational irrigation. We assume that each mu of farmland used for a particular crop needs the same amount of water, and so we use cells to indicate the amount of water required. Blue cells represent the amount of water required for irrigation; for example, one irrigated row of rice, bananas and vegetables requires 6, 5 and 10 cells of water respectively, per year. The plain blue cells and the blue cells with black stripes indicate off-peak and peak water requirements, respectively. Off-peak water requirements indicate that moderate watering is sufficient, while too much water can destroy the roots and reduce production. Water withdrawal, in practice, is equal to the theoretical water use divided by the irrigation efficiency (IE) of the crop; for example, rice uses canal irrigation with an IE of 0.5, and thus one row of rice needs 12 cells of water (6÷0.5). All of the cash crops use water-saving technology such as sprinklers, and thus the IE for both bananas and vegetables is 0.8. One row of bananas therefore requires 6.25 cells of water and one row of vegetables uses 12.5 cells of water.

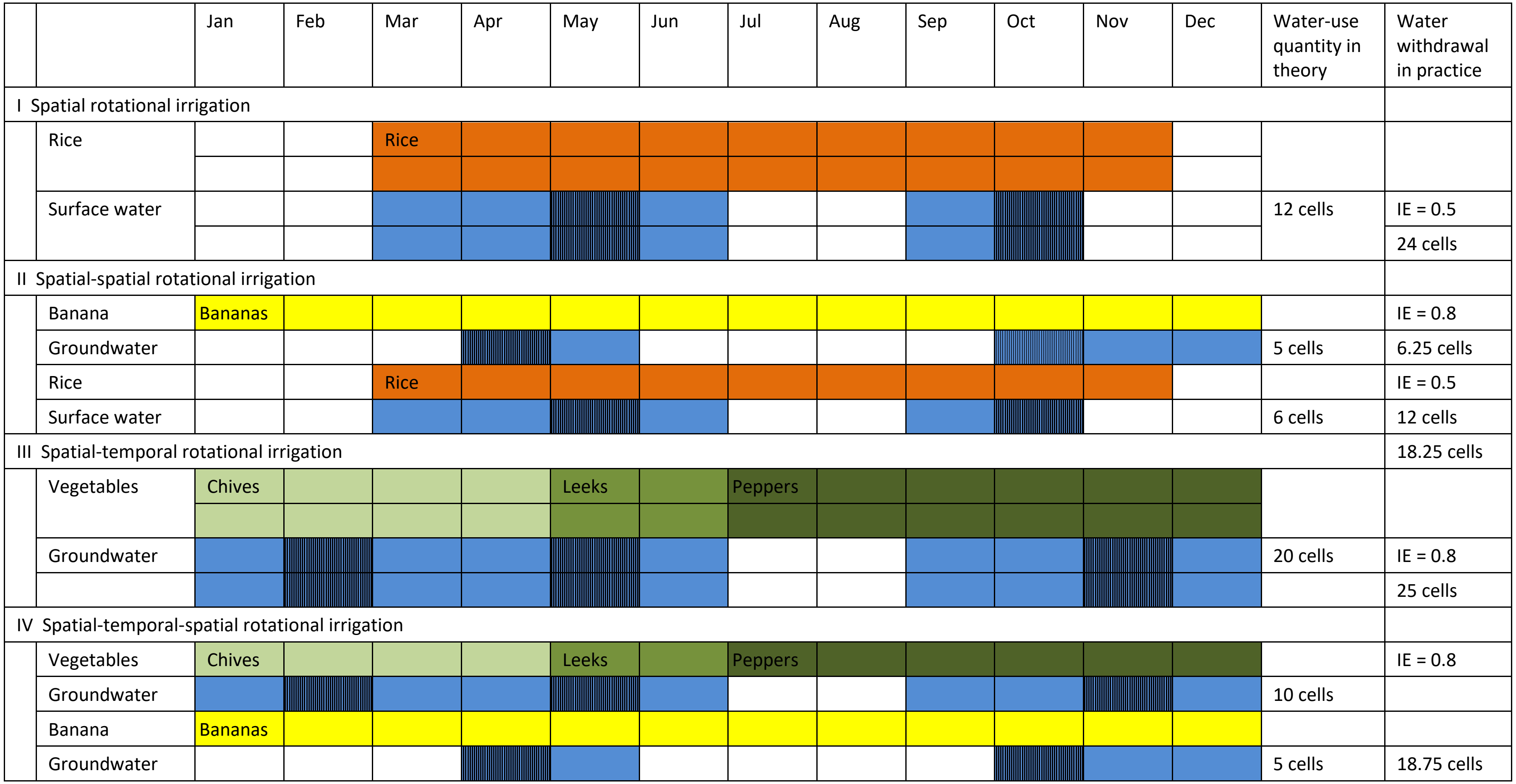
Regarding Type I, spatial rotational irrigation, the cropping pattern is exclusively rice with two crops grown each year. These types of villages, such as Beijie and Dongguan, practise traditional subsistence agriculture. The farmland on which rice is grown is located at lower levels where rice is much easier to grow than other crops. In addition, because rice production is unprofitable, almost all of the young people emigrate in search of off-farm work; the elderly farmers who are thus the people left in the village prefer to plant crops with a lower risk of failure, and thus they continue to plant rice.

One crop of rice requires six months of irrigation; thus, a rice-rice cropping pattern requires roughly 12 cells of water in theory and 24 cells in practice, given rice's IE of 0.5. May and October are the peak months in terms of water use. Growing two crops of rice each year means that there is no rotational irrigation at the village scale; at the county scale, however, these villages can participate in rotational irrigation in conjunction with other villages that grow other crops. Rice growers can thus take priority at times of peak water use. Because some of the farms in neighbouring villages have transitioned to planting crops other than rice, they do not withdraw water at the same time as the rice growers, and thus the rice-growing villages can obtain sufficient water and a stable harvest.

Type II, spatial-spatial rotational irrigation, includes homogeneous and diverse cropping patterns, that is, rice-rice and bananas. These types of villages, such as Hualin and Longjiangtang, are in the process of transitioning from traditional subsistence agriculture to semi-commercial agriculture. The rice-growing farmlands located at higher levels have difficulty in obtaining sufficient water and therefore production is reduced. The county government thus directed farmers whose farmlands were located in those areas to plant banana crops. Village leaders complied with this request and then, following their lead, some of the middle-aged farmers who were willing to take the risk of adjusting their cropping pattern also switched to growing bananas. These banana farms have since sunk new wells to enable them to pump groundwater for irrigation.

Bananas require relatively low levels of water over shorter periods and thus use the least water; they use about 5 cells in theory and 6.25 cells in practice given their IE of 0.8. The difference in peak water-use times for rice and bananas means that both crops can be appropriately prioritised in terms of water use, enabling spatial rotation at the village scale. The storage and recharge rates for the groundwater used to irrigate banana-growing farmlands are both high. Total practical water use for bananas is about 18.25 cells, which is less than that for Type I. In addition, the returns from the production of bananas [8000 kg/mu (120, 000 kg/ha) and 1 yuan/kg (US$.16/kg)] are more than three times those from the production of rice [900 kg/mu (13, 500 kg/ha) and 2.77 yuan/kg (US$.43/kg)], and thus farmers' incomes have increased. A cropping pattern of rice-rice and bananas has therefore helped farmers to achieve synergic development in terms of economic production and conservation of the environment.

Table 2. Rotational irrigation at the regional scale.



		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Water-use quantity in theory	Water withdrawal in practice
I Spatial rotational irrigation															
	Rice			🟧 Rice	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			
				🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			
	Surface water			🟦	🟦	▨	🟦			🟦	▨			12 cells	IE = 0.5
				🟦	🟦	▨	🟦			🟦	▨				24 cells
II Spatial-spatial rotational irrigation															
	Banana	🟨 Bananas	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		IE = 0.8
	Groundwater				▨	🟦					▨	🟦	🟦	5 cells	6.25 cells
	Rice			🟧 Rice	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			IE = 0.5
	Surface water			🟦	🟦	▨	🟦			🟦	▨			6 cells	12 cells
III Spatial-temporal rotational irrigation															18.25 cells
	Vegetables	🟩 Chives	🟩	🟩	🟩	🟩 Leeks	🟩	🟩 Peppers	🟩	🟩	🟩	🟩	🟩		
		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	Groundwater	🟦	▨	🟦	🟦	▨	🟦			🟦	🟦	▨	🟦	20 cells	IE = 0.8
		🟦	▨	🟦	🟦	▨	🟦			🟦	🟦	▨	🟦		25 cells
IV Spatial-temporal-spatial rotational irrigation															
	Vegetables	🟩 Chives	🟩	🟩	🟩	🟩 Leeks	🟩	🟩 Peppers	🟩	🟩	🟩	🟩	🟩		IE = 0.8
	Groundwater	🟦	▨	🟦	🟦	▨	🟦			🟦	🟦	▨	🟦	10 cells	
	Banana	🟨 Bananas	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		
	Groundwater				▨	🟦					▨	🟦	🟦	5 cells	18.75 cells

Note: Blue cells represent the amount of water required for irrigation. The plain blue cells and the blue cells with black stripes indicate off-peak and peak water requirements, respectively. Orange, yellow and green cells represent rice, banana and vegetables respectively.

Type III, spatial-temporal rotational irrigation, includes special and heterogeneous cropping patterns featuring vegetable cropping with three subtypes of vegetable crops in rotation, namely, chives, leeks and peppers. Village in this category, such as Manghai and Beitan, have transitioned to fully commercial agriculture. Almost all of the farms located a long distance from water sources have switched from rice to vegetable growing. Farmers pump groundwater to irrigate their vegetable crops, which require water almost year round.

Vegetable crops grown on dispersed farmlands have the same growing seasons and thus require simultaneous pumping of groundwater. The three-crop rotation involving chives, leeks and peppers extends the water-use period. This type of cropping pattern involves intensive and long-term water use, consuming 20 cells in theory and 25 cells in practice given the IE score of 0.8. At the village scale, the three types of vegetables take turns receiving water based on their growing seasons, resulting in temporal rotational irrigation. Priority in terms of water use is based on temporal considerations, with the three peak water-use periods being in February, May and November.[2] At the county scale, these farms participate in a spatial rotational irrigation regime in conjunction with farms growing other crops in neighbouring villages. Vegetables provide high levels of production and high prices, and thus farmers who grow vegetables earn significantly higher incomes than those who grow rice or bananas. Although vegetable-growing farms are in areas of moderate water availability, they consume slightly more water than rice-growing farms. This type of cropping pattern can thus promote economic development, but at the cost of slightly increased water use.

Type IV, spatial-temporal-spatial rotational irrigation, includes heterogeneous and diverse cropping patterns involving bananas and chives-leeks-peppers. These types of villages, such as Gaotian and Xiayang, practise fully commercial agriculture, with farmers having abandoned rice to grow bananas and vegetables.

The farmers pump groundwater to irrigate their crops of bananas and vegetables. At the village scale, water use is based on temporal-spatial rotation, with peak water requirements occurring in five different months. Although both rice and vegetables use groundwater for irrigation, this rotation enables the various crops to be irrigated in turn based on their various growing cycles, so that not all farmers are pumping water at the same time. This type of cropping pattern uses 15 cells of water in theory and 18.75 cells in practice. The spreading out of peak water-use periods means that Type IV uses less water than Type III. At both the village and county scales, the use of this cropping pattern enables a spatial-temporal-spatial rotational irrigation regime; thus farmers now experience a win-win and receive more income while achieving greater water-use efficiency.

Performance in terms of adaptation to QRW

Since the implementation of a stringent water resources management policy in 2011, Xuwen County has adapted successfully by introducing a rotational irrigation regime based on a mosaic cropping pattern. Compared with their performance prior to 2011, farmers have achieved greater efficiency and equity in relation to water use by adjusting their cropping patterns. In general, rotational irrigation produces technical and economic efficiency, allocation equity, sustainability and robustness, in the sense that agricultural water resources are allocated optimally to enhance crop production.

The interviewees reported that both canal water and groundwater were adequate for their irrigation requirements. As can be seen from Table 3, the scores for the amount of water available at peak times

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[2] Although May is the peak time of water use for rice and vegetables, they have two different water sources, surface water and groundwater, respectively. These two types of crops still can form a spatial rotation at the county level in terms of their peak water-use time. Furthermore, crops using groundwater – such as vegetables and bananas – can form a spatial style of rotational irrigation with rice, which uses surface water for irrigation. Requiring 10 months of irrigation, vegetables only overlap for a couple of months with bananas in terms of off-peak time of water use; hence, vegetables can still roughly embody the characteristic of spatial rotational irrigation at the county level.

were 1.58 to 1.8, which is a moderate level. The respondents also reported that the current water availability was similar to that in the years prior to 2011, when the scores were 2.1 to 3. Most of the farmers grow two or three different crops each year and even in dry seasons have sufficient water for irrigation. At times of peak water use, there is adequate water and they can use it at will, the 'pumping race' having been eliminated by the introduction of different crops. Farmers stated that they were no longer concerned about their neighbours' water use because they were growing different crops with staggered water requirements; even vegetable crops, which require large volumes of water, were not causing problems for farmers growing other crops.

Regarding economic efficiency, growing bananas and vegetables has delivered higher productivity and income than rice growing. Farms that grow these cash crops produce more per hectare than those growing rice given the constraint of water availability. On average, farms can produce 900 kg/mu (13,500 kg/ha) of rice, 8000 kg/mu (120,000 kg/ha) of bananas, and 4500 kg/mu (67, 500 kg/ha) of vegetables annually, and receive 2.77 yuan/kg (US$.43/kg), 1 yuan/kg (US$.16/kg), and 10 yuan/kg (US$ 1.57/kg), respectively. Farmers' incomes thus increased after they transitioned to growing cash crops of bananas and vegetables.

The 2019 Statistical Yearbook[3] also reported that Xuwen County had achieved increases in agricultural production and farmers' incomes while maintaining sustainable use of agricultural water resources. The process of transitioning to a mosaic cropping pattern has seen the traditional ubiquitous rice crop replaced by a mixture of rice, bananas and vegetables. The use of groundwater from the Xuwen Basin is within sustainable levels, the pumping rate being lower than the recharge rate; furthermore, hydrological information shows that the groundwater being pumped is from the shallow aquifer, which has the same water source as the water transported along canals. Over the last decade, the water level has remained almost constant, even though water use has increased as a result of the greater water requirement for more intensive irrigation of vegetable crops. The study by Liang (2018) confirms that the agricultural water resource is now sustainable because the groundwater in the Xuwen Basin is sufficient to meet the demands of the farms, with no sign of overuse.

Additionally, regarding equity of water allocation, farmers with land that is distant from reservoirs report that they now have adequate water because in certain seasons they have priority for water withdrawal. As Table 3 shows, the score of equitable water allocation is about 1.46 to 1.7, which is close to equal. Even farms distant from the water resource or at higher levels can access sufficient water by planting cash crops and pumping groundwater. Because cash crops attract higher prices, these farms can earn more revenue than they could by growing rice. The increase in farmers' incomes is proportional to the type of cash crop grown and its price. The difference between upstream and downstream production is negligible, confirming the equitable nature of the outcome.

Furthermore, the rotational irrigation regime ensures the robustness of the system at the county level in terms of economic production and sustainable use of agricultural water resources, even in the face of external disturbances. The water conservation techniques introduced to Xuwen County following the implementation of the stringent water resources management policy in 2011 mean that, in contrast to what was suggested by previous studies, these disturbances have not resulted in increased water use (Grafton et al., 2018). This study provides evidence that a mosaic cropping pattern and the resulting rotational irrigation regime at the county scale have resulted in more efficient water use.

DISCUSSION AND CONCLUSION

The findings of this paper improve our understanding of the mechanisms underlying adaptation to QRW, that is, how local governments and communities have responded to the stringent water resources management regulation introduced in 2011. We found that a strategy of rotational irrigation can alleviate

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[3] See http://stats.gd.gov.cn/gdnctjnj/index.html

the twin problems of inefficiency and inequity in agricultural water allocation caused by QRW. Using a framework based on cropping patterns and rotational irrigation, we showed that a mosaic cropping pattern which includes diversity and heterogeneity is the optimal means for achieving automatic rotational irrigation at regional scale in both the spatial and temporal dimensions. This finding provides useful input into the establishment of a low-cost rotational irrigation regime at the regional scale.

This paper examined the application of this theoretical adaptation mechanism using a case study of Xuwen County, Guangdong Province, China. The framework based on cropping patterns and rotational irrigation provides generalisable insights into the region's response to QRW, which has facilitated efficient and equitable agricultural water allocation despite the constraint of limited water availability. We also showed that the introduction of a mosaic cropping pattern leads to an automatic rotational irrigation regime at the regional scale. This provides an example of the successful adjustment of the cropping pattern, a process that can be implemented by agricultural departments during crop planning. The findings of this study provide evidence of a successful response to QRW in a region of water scarcity where agricultural production is particularly dependent on irrigation. This study also extends the body of research on QRW by providing evidence of the success of a mosaic cropping pattern, particularly one involving diverse crops.

The case study of Xuwen County shows a successful adaptation to QRW, which serves to limit water use to the cap specified by China's stringent water resources management system. Since the agricultural conditions in Xuwen County are representative of the conditions of southern China – that is, a small-farm economy involving scattered farm plots, which grows crops throughout most of the year and has a scarcity of surface water – the findings of this paper have scope for broad applicability. Regions adjacent to Xuwen County, both within and beyond Guangdong Province, are reported to have adopted similar cropping patterns following the implementation of the stringent water resources management policy in 2011.

Although this study provides a framework that is based on a cropping pattern used to adapt to QRW, its application to other regions will require adjustments based on specific local context. The formation of a mosaic cropping mix in a region takes time – in this case almost a decade – and the application of policies regarding adaptation to QRW thus also takes time. In regions such as northern China, with overlapping growing seasons and common water sources, the high costs of transformation may increase the difficulty of adapting to QRW; thus, alternative measures such as seasonal fallow cropland may have to play a similar role to that of rotational irrigation.

Furthermore, the framework provided by this study is at the macro scale, and if it is applied at the micro farm-plot level an additional factor must be considered, namely, the varying terrain of individual farm plots. Different crops cannot be mixed in the same area if each crop has its mutually exclusive requirements; for example, rice is planted in lower-level plots near canals, while bananas are planted higher and require groundwater to be pumped up for irrigation. This spatial distribution of crops is necessary to meet their different requirements in terms of soil and water. Future studies should examine a broader range of cases with the aim of widening the application of our framework.

Table 3. Study sample characteristics.

Town name	Village name	Number of household	Mean age of household head (years)	Mean area of irrigated crop for each household (mu)	Crop diversity and heterogeneity (type)	Water source (canal water or groundwater)	Water availability at peak time 1: scarce; 2: moderate; 3: abundant	Equitability of water allocation 1: inequitable; 2: equitable	Irrigated agriculture income (yuan/mu)	Water availability in comparison to pre-2011 1 = reduction; 2 = no change; 3 = increase
Maichen	Beijie Dongguan	42	58	5.4	Rice-rice	canal water	1.7	1.7	2500	2.1
Longtang Xiayang	Hualin Longjiangtang	56	55	14.2	Rice-rice bananas	canal water groundwater	1.8	1.7	2500-8000	3
Xiaqiao Xiayang	Gaotian Xiayang	50	59	11	bananas chives-leeks-peppers	groundwater	1.66	1.46	8000-45,000	2.9
Nanshan	Manghai Beitan	38	55	6.3	Chives-leeks-peppers	groundwater	1.58	1.59	45,000	2.7

Note: 1 mu = 1/15 (0.066) hectare; 1 yuan = US$.16.

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REFERENCES

Albiac, J.; Calvo, E.; Kahil, T. and Esteban, E. 2020. The challenge of irrigation water pricing in the Water Framework Directive. *Water Alternatives* 13(3): 674-690.

Cody, K.C. 2018. Flexible water allocations and rotational delivery combined adapt irrigation systems to drought. *Ecology and Society* 23(2): 47.

Debaere, P.; Richter, B.D. and Davis, K.F. and Duvall, M.S. 2014. Water markets as a response to scarcity. *Water Policy* 16: 625-649.

Drysdale, K.M. and Hendricks, N.P. 2018. Adaptation to an irrigation water restriction imposed through local governance. *Journal of Environmental Economics and Management* 91: 150-165.

European Union. 2013. Regulation on support for rural development by the European Agricultural Fund for Rural Development (EAFRD), vol. 17. Regulation of the European Parliament and the Council of December 2013, (EU) No 1305/2013.

Gardner, R.; Moore, M.R. and Walker, J.M. 1997. Governing a groundwater commons: A strategic and laboratory analysis of western water law. *Economic Inquiry* 35(2): 218-234.

Global Water Partnership. 2015. *China's water resources management challenge: The 'Three Red Lines*'. www.gwp.org.

Grafton, R.Q.; Williams, J.; Perry, C.J.; Molle, F.; Ringler, C.; Steduto, P.; Udall, B.; Wheeler, S.A.; Wang, Y.; Garrick, D. and Allen, R.G. 2018. The paradox of irrigation efficiency. *Science* 361(6404): 748-750.

He, Y.; Chen, X.; Sheng, Z.; Lin, K. and Gui, F. 2018. Water allocation under the constraint of total water-use quota: A case from Dongjiang River Basin, South China. *Hydrological Sciences Journal* 63(1): 154-167.

Janssen, M.A.; Anderies, J.M. and Cardenas, J.-C. 2011. Head-enders as stationary bandits in asymmetric commons: Comparing irrigation experiments in the laboratory and the field. *Ecological Economics* 70(9): 1590-1598.

Li, N.; Wang, X.; Shi, M. and Yang, H. 2015. Economic impacts of total water use control in the Heihe River Basin in Northwestern China - An integrated CGE-BEM modeling approach. *Sustainability* 7(3): 3460-3478.

Liang, J. 2018. Characteristics and potential assessment of groundwater resources in the Leizhou Peninsula. *East China Geology* 39(4): 299-304. (in Chinese)

Milman, A.; Galindo, L.; Blomquist, W. and Conrad, E. 2018. Establishment of agencies for local groundwater governance under California's Sustainable Groundwater Management Act. *Water Alternatives* 11(3): 458-480.

Molle, F. 2009. Water scarcity, prices and quotas: A review of evidence on irrigation volumetric pricing. *Irrigation Drainage System* 23: 43-58.

Molle, F.; López-Gunn, E. and van Steenbergen, F. 2018. The local and national politics of groundwater overexploitation. *Water Alternatives* 11(3): 445-457.

Nel, A.A. 2005. Crop rotation in the summer rainfall area of South Africa. *South African Journal of Plant and Soil* 22(4): 274-278.

Murray-Darling Basin Authority. 2019. *Transitioning from the Cap to sustainable diversion limits.* www.mdba.gov.au/basin-plan-roll-out/sustainable-diversion-limits/transitioning-cap-sustainable-diversion-limits

Ostrom, E. 1990. *Governing the commons: The evolution of institutions for collective action.* New York: Cambridge University Press.

Ostrom, E. 2014. Do institutions for collective action evolve? *Journal of Bioeconomics* 16: 3-30.

Ostrom, E. and Gardner, R. 1993. Coping with asymmetries in the commons: Self-governing irrigation systems can work. *Journal of Economic Perspectives* 7(1): 93-112.

Perry, C.; Steduto, P. and Karajeh, F. 2017. *Does improved irrigation technology improve water? A review of the evidence.* Food and Agriculture Organization. www.fao.org/3/I7090EN/i7090en.pdf.

Shi, M.; Wang, X.; Yang, H. and Wang, T. 2014. Pricing or quota? A solution to water scarcity in oasis regions in China: A case study in the Heihe River basin. *Sustainability* 6: 7601-7620.

Wang, J.; Zhu, Y.; Sun, T.; Huang, J.; Zhang, L.; Guan, B. and Huang, Q. 2019. Forty years of irrigation development and reform in China. *The Australian Journal of Agricultural and Resource Economics* 64: 126-149.

Wang, Y.; Chen, C. and Araral, E. 2016. The effect of migration on collective action in the commons: Evidence from rural China. *World Development* 88: 79-93.

Wheeler, S.A.; Schoengold, K. and Bjornlund, H. 2016. Lessons to be learned from groundwater trading in Australia and the United States. In Jakeman, A.J.; Barreteau, O.; Hunt, R.J.; Rinaudo, J.-D. and Ross, A. (Eds). *Integrated groundwater management: Concepts, approaches, and challenges, pp.* 493-517. Springer.

Wheeler, S.A.; Carmody, E.; Grafton, R.Q.; Kingsford, R.T. and Zou, A. 2020. The rebound effect on water extraction from subsidizing irrigation infrastructure in Australia. *Resources, Conservation and Recycling* 159: 104755.

Yang, X.L.; Chen, Y.Q.; Pacenka, S.; Gao, W.S.; Ma, L.; Wang, G.Y.; Yan, P.; Sui, P. and Steenhuis, T.S. 2015. Effect of diversified crop rotations on groundwater levels and crop water productivity in the North China Plain. *Journal of Hydrology* 522: 428-438.

Yi, F.; Rong, X. and Wang, J. 2019. Water price, quota or irrigated area tax? An examination of agricultural water policies in Haihe River Basin. *China Rural Survey* (1): 33-50. (in Chinese)

Yin, R.K. 2003. *Case study research: Design and methods.* London: Sage.

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