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The Decline of Canal Irrigation in China: Causes, Impacts and Implications

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ABSTRACT: Irrigation is key for agricultural production and public affairs in China. Canal irrigation has been the dominant form of irrigation in China for over two thousand years, but this is changing dramatically in contemporary China. Official government data and observational studies prove that canal irrigation has sharply declined in China in the past several decades. This paper explores the causes and influences associated with this decline. We use the social-ecological systems (SES) framework to diagnose the causes of the decline of canal irrigation and identify the significant influences on it. The broader contextual variables of industrialisation, urbanisation, policy, marketisation and technological progress influence resource systems, farmers and governance systems, which, in turn, have jointly led to the decline of canal irrigation. This study also considers the economic, social and ecological consequences of such a shift in irrigation pattern. The decline of canal irrigation may be inevitable in the transformation from a rural to a modern society. However, we must be aware of its costs and risks. To maintain the effectiveness of rural irrigation during the transformation to a modern society, we propose three implications of the decline of canal irrigation.

KEYWORDS: Irrigation transformation, commons, social-ecological systems (SES) framework, rural governance, public systems, China

INTRODUCTION

As the earliest irrigation facilities, canals were invented in Mesopotamia circa 4000 BCE. Later, sophisticated irrigation and storage systems appeared in India, Egypt and China (Rodda and Ubertini, 2004; Hadfield, 1986; Wang et al., 2016a). In comparison to earlier flood irrigation, canal systems are more effective in agriculture, laying the foundation for the development of agricultural production, and have therefore played an important role in agriculture. However, with socioeconomic development, the use of canal irrigation is declining worldwide. This is reflected in China's irrigation structure, both in the communal irrigation within villages and in the large-scale irrigation systems that used canal irrigation, i.e. irrigation districts. Communal canal irrigation within villages has been gradually replaced by other irrigation methods. In official data from the Ministry of Water Resources (MWR), the proportion of farmland irrigated by wells and water-saving irrigation techniques has been increasing since the 2000s at the expense of canal irrigation (MWR, 2019). Some scholars have identified the same trend. A series of studies by Wang et al. (2007a, 2007b, 2008, 2009, 2020) found that groundwater irrigation had continued to spread to more villages, whereas canal irrigation had not. Hu et al.'s (2010) field research in northern China found that water for crops accounted for 70% of groundwater withdrawals in floodplains and more than 87% in mountain regions. Wang et al. (2016a) found that the proportion of households relying on canal irrigation in China had declined to one third of farming households based on a nationwide survey. For large-scale canal irrigation systems, wells are supplementary to canals in irrigation districts. In northern China, where water is scarce, some irrigation districts have gradually developed a combined well-and-canal irrigation model from the original single-canal irrigation of the 1970s, realising the conjunctive use of surface water and groundwater (Jing, 2010).

Other countries have also seen a decline of canal irrigation in relative terms. In Egypt, due to the expansion of land reclamation and the lightness of the soil in the newly reclaimed land, sprinklers and drip irrigation systems have complemented canal systems or been used with groundwater-based irrigation (Abu-Zeid, 1995). In India public canal irrigation systems are losing their position of dominance, while private pump irrigation is spreading faster than anticipated (Shah, 2011). From 1960 to 2001 the proportion of land irrigated by canals decreased from 42% to 28%, while well irrigation rose dramatically, from 30% to 62% (Gandhi and Namboodiri, 2009). In Pakistan wells have long appeared within the large public irrigation schemes (Qureshi, 2020; van Steenbergen, 2020) but also around Karez-based communal systems, where tube wells have undermined these traditional canal irrigation systems (Mustafa and Qazi, 2007).[1]

The relative decline of canal irrigation in these countries means that canals have been replaced or complemented by other methods such as well, sprinkler and drip irrigation, which presents a worldwide transformation of irrigation methods. The reasons for this transition vary from country to country, depending on the socio-ecological context. In India private wells took precedence over canal irrigation systems because these systems gradually proved to be unable to service their areas and meet farmers' water needs, in some cases leading to their eventual disregard, while the number of individual wells soared (Shah, 2011). An inability to meet the demand for irrigation water with existing irrigation methods lies behind the use of alternative water sources and methods in Pakistan (Mustafa and Qazi, 2007) and more recently in the Nile Delta (Ezzat et al., 2017). On the margins of the delta the spread of groundwater-based irrigation goes hand in hand with a shift from traditional to market-oriented production.

The decline of canal irrigation also leads to socio-ecological changes. On one hand the most immediate impact has been on the environment, in the form of a decline in the water table due to the over-abstraction of groundwater (Zektser and Loáiciga, 2005); on the other there has been a decline in cooperation between villagers and a gradual loss of social capital, which has in turn undermined the collective use of canal irrigation in villages (Mustafa and Qazi, 2007).

The reasons behind, and impacts of, the decline of canal irrigation have been addressed in the literature, yet few studies have been carried out that focus on this phenomenon. The research contribution of this paper is twofold. First, it offers a pioneering study of canal irrigation decline in China. Previous studies have noted the decline in China, such as Wang et al. (2007a, 2007b, 2008, 2009, 2020). Hu et al. (2010) and Wang et al. (2016a) mentioned it but without providing a systematic analysis. Second, this paper uses the SES framework to tackle the complexity of irrigation transition issues.

This paper draws on official government data, our own research data from the China Institute for Rural Studies (CIRS) and research by other academics to confirm the major transformation in China in terms of abandoned canal facilities, the rise of groundwater use and the pervasive use of new irrigation options. Based on these facts, we investigate the influencing factors and the relationships between them. We use the social-ecological systems (SES) framework to analyse the broader contextual factors in the decline of canal irrigation, identifying industrialisation, urbanisation, policy, marketisation and technological progress as the most fundamental drivers, which in turn influence resources, actors and governance, and ultimately lead to transformation. We also focus on the economic, social and ecological impacts of the phenomenon. We argue that these are both positive and negative, making it difficult to judge whether the transition as a whole is good or not, but there is no denying that the decline is irreversible. Finally, based on the above analysis, we recommend encouraging water-saving agriculture, a combination of well

[1] Karez irrigation is an ancient system of underground water channels where water flows by gravity.

and canal irrigation and the development of collective economies in villages to offset the negative effects of the transition.

THE DECLINE OF CANAL IRRIGATION IN CHINA

Canals for irrigation are defined as open watercourses that use gravity to convey water from surface water bodies such as lakes, rivers and reservoirs to its users (Jorgensen and Fath, 2014; Gil, 2018). Canal systems normally include five levels, with the lower levels being branches of the upper levels and the water from the last level flowing directly to the farmland. Hence, for canal irrigation, the water source is surface water, the conveyance is through open canals and by gravity, and the field irrigation method is surface irrigation. It is only when these four characteristics are met that it can be called canal irrigation. Well irrigation, by contrast, relies on groundwater that must be lifted, commonly by pump. In most cases the water is distributed through pressurised systems and applied to the plot level through new irrigation technology, such as sprinkler irrigation, micro-irrigation and low-pressure tubing. This distinguishes these irrigation methods from canal irrigation.

Canal irrigation using surface water has always played an important role in agricultural production and is the oldest, most traditional and most widely used method of irrigation in China. However, there is a new trend in irrigation: canal irrigation is declining; water increasingly comes from wells instead; and new methods of irrigation such as sprinkler and drip are being increasingly adopted. These three aspects are described in turn below.

Abandoned canal facilities

During the planned-economy period the government invested massively in irrigation facilities, especially canals which were widely used at the time. But with the establishment of the market economy and other factors (discussed in detail in later sections) the canals fell into disuse.

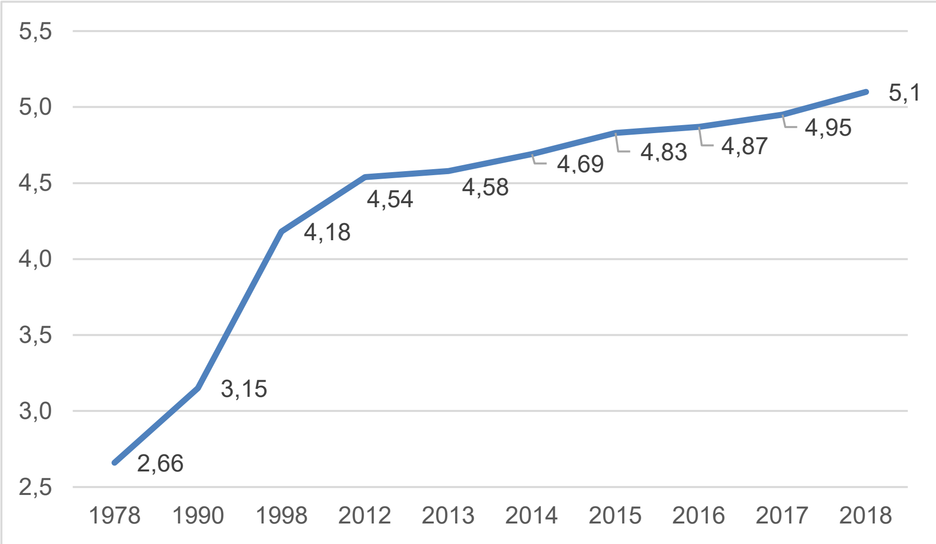
The CIRS at Tsinghua University found, for example, that the proportion of rural households using canals for irrigation dropped from 39% in 2012 to 30% in 2017. Neglect has brought increasing damage to the canals, concentrated in the three lowest levels (Liu et al., 2013). A study of the Wuzhong irrigation district in Guizhou Province found that the damage rate of the canal facilities in five branch irrigation districts ranged from 50% to 64%. The damaged canals were mainly in the last level and some had become completely inoperable (Liu et al., 2012). Lu (2011) also found that in the Ningxia irrigation district, one of the oldest in China and vital for farming in the Ningxia Plain, 7.5% of the fourth-level canals were lined, against 57% for secondary canals.

Neglect and damage are leading to an overall decline in the length of canals. Those in Wuzhong irrigation district have been shortened by amounts ranging from 6.8 km to 16.8 km (Liu et al., 2012). This is because the pool at the end of the canal used for flood drainage was damaged during the summer floods and not repaired in time, resulting in the flooding of farmland in the middle and lower reaches of the irrigation district and washed-out canals. This is an example of how the failure to repair infrastructure in a timely manner may contribute to the decline of a canal system.

Rise of groundwater use

Prior to the 1990s surface water bodies were by far the most common source of water for irrigation. But because of the policy change (discussed in detail in later sections), and although most of the water used in agriculture still comes from surface water bodies, the importance of groundwater (water from wells) has gradually increased. The most straightforward and generalised data is from the MWR, and shows that the area of farmland with electromechanical well irrigation increased from 11 million hectares to 18 million hectares between 1987 and 2012. Also, from 1978 to 2018 the number of electromechanical wells in China nearly doubled, from 2.7 million to 5.1 million (MWR, 2019) (see figure 1).[2]

Figure 1. Number of electromechanical wells used for irrigation in China, 1978 to 2018 (MWR, 2019).



Looking more closely, we see that the increase in well irrigation was more pronounced in the northern regions. For example, Wang et al. (2007b) surveyed 48 villages in Hebei and Henan provinces in 1995 and again in 2004. These two provinces in northern China are highly dependent on groundwater due to insufficient surface water resources. Of the effectively irrigated farmland, the proportion dependent on groundwater increased from 60% to 68% between 1995 and 2004.

Since the 1970s some canal irrigation districts in northern China have added well water to the original canal irrigation, providing insurance with the combined use of surface water and groundwater, effectively solving the problem of insufficient irrigation water and even expanding the irrigation area (Xu, 1991). Since the 1980s such combined areas have gradually expanded, and some areas even have greatly reduced the amount of surface water used, or even abandoned their canals and relied entirely on well water (Xing, 2003). Nowadays the large irrigation districts in China, including Hetao, the People's Victory Canal and the Ningxia irrigation districts, have all changed from canal irrigation to combined well and canal irrigation. Typifying this is the Ningxia irrigation district, where there were two periods of large-scale well drilling in 1977 and 2003 (Ma and Liu, 2014). In 2003, to encourage the combination of canal and well irrigation, the government subsidised the cost of electricity for the wells. Thus, the use of public wells to provide groundwater for irrigation expanded in irrigation districts.

The spread of new irrigation technologies

Canal irrigation is also being displaced by newer methods that use water more efficiently. Traditional canals are exposed to the air and are mostly earthen, so they suffer from large water losses, low irrigation efficiency, difficulty in improving distribution uniformity, and soil compaction. China first began to use water-saving irrigation technology in the 1980s, and since then it has developed significantly. The National Agricultural Water Conservation Programme (2012-2020) of the General Office of the State Council (2012) requires the active promotion of efficient water-saving irrigation and water – fertiliser

[2] The ownership of electromechanical wells can be either private (individuals) or public (village collectives), and individuals include single or multiple households.

integration technologies, such as sprinkler irrigation, micro-irrigation and sub-membrane drip irrigation in areas where water resources are in short supply, where cash crops are grown and where large-scale agricultural operations are carried out. Water-saving irrigation includes seepage-control canal irrigation, which is based on existing canals and means farmland using this technology is still irrigated by canals.[3] Other water-saving techniques such as sprinkler irrigation replace canal irrigation or are used to irrigate additional arable land. The proportion of irrigated area under new water-saving agriculture has been increasing year by year and grew by 137% between 1998 and 2018.[4] In 2000 it accounted for 30% of all arable land, and in 2018, 53%. The proportion of irrigated arable land using canal seepage-control technology rose from 12% to 20% between 2000 and 2012, but since 2013 this figure has been classified as 'others' in the official statistics. The proportion of irrigated arable land in this category rose by only 1% between 2013 and 2018, probably due to decreased canal irrigation, limiting seepage-control technology. However, the other three separate statistics on water-efficient irrigation include sprinkler, micro-irrigation and low-pressure tubing, which together accounted for 11% of irrigated farming land in 2000 and 32% in 2018 (MWR, 2019). Both national policy and observations indicate that the further spread of water-saving agricultural technologies is unstoppable, with a gradually increasing proportion of irrigated area under new irrigation methods, and traditional canal irrigation declining.

CAUSES FOR THE TRANSFORMATION OF IRRIGATION

Communal canal irrigation is a typical common as well as a social-ecological system, which is complex and affected by several variables. Ostrom created the SES framework which allows comparisons between them as well as the study of a system over time (Guevara, 2016). This paper uses the SES framework to explain the decline of canal irrigation in China. The framework provides a set of detailed variables in the social-ecological system to help identify the key factors and interactions. It proposes a conceptual map with eight components in the first tier: Social, economic and political settings (S), Related ecosystems (ECO), Resource systems (RS), Resource units (RU), Governance systems (GS), Actors (A), Interactions (I) and Outcomes (O) (McGinnis and Ostrom, 2014; Ostrom, 2007, 2009) (see Figure 2). Of these, S and ECO include broader contextual variables which influence the others. These components can be divided into sub-categories represented by a cluster of variables, which in turn can also be subdivided, depending on the SES framework being studied and the aim of the research.

To analyse the causes of the decline of canal irrigation in China, we use second-tier variables in the SES framework. We examine the relationship between broader contextual (S) and micro-situational variables. The SES framework is inclusive, with over 50 second-tier variables. It is not necessary to refer to all of these but merely to select those fitting the study. For our purposes we identified key second-tier variables based on the literature. Those relating to China’s irrigation system in the Social, economic and political settings (S), Resource systems (RS), Governance systems (GS) and Actors (A) were selected for detailed analysis as shown in Table 1.[5]

[3] Seepage-control canal irrigation is used to reduce infiltration at the plot level.

[4] In the statistics of water-saving irrigation area, the government classifies it as 'sprinkler irrigation', 'micro-irrigation', 'low-pressure tubing', 'seepage-control canal irrigation' and 'others'. Since 2013 'seepage-control canal irrigation' has not been recorded as a separate figure.

[5] In Social, economic and political settings (S), political stability (S3) was not selected because China's political stability has not changed significantly during the irrigation transition, and media organisations (S6) were not selected because the mainstream media in China are regulated and censored by the central government, and public information may be filtered and released in a biased way (Tai, 2014). The other second-tier variables of the SES framework were not selected in this paper because they are not directly related to the decline of canal irrigation.

Figure 2. SES framework with first-tier components (McGinnis and Ostrom, 2014).

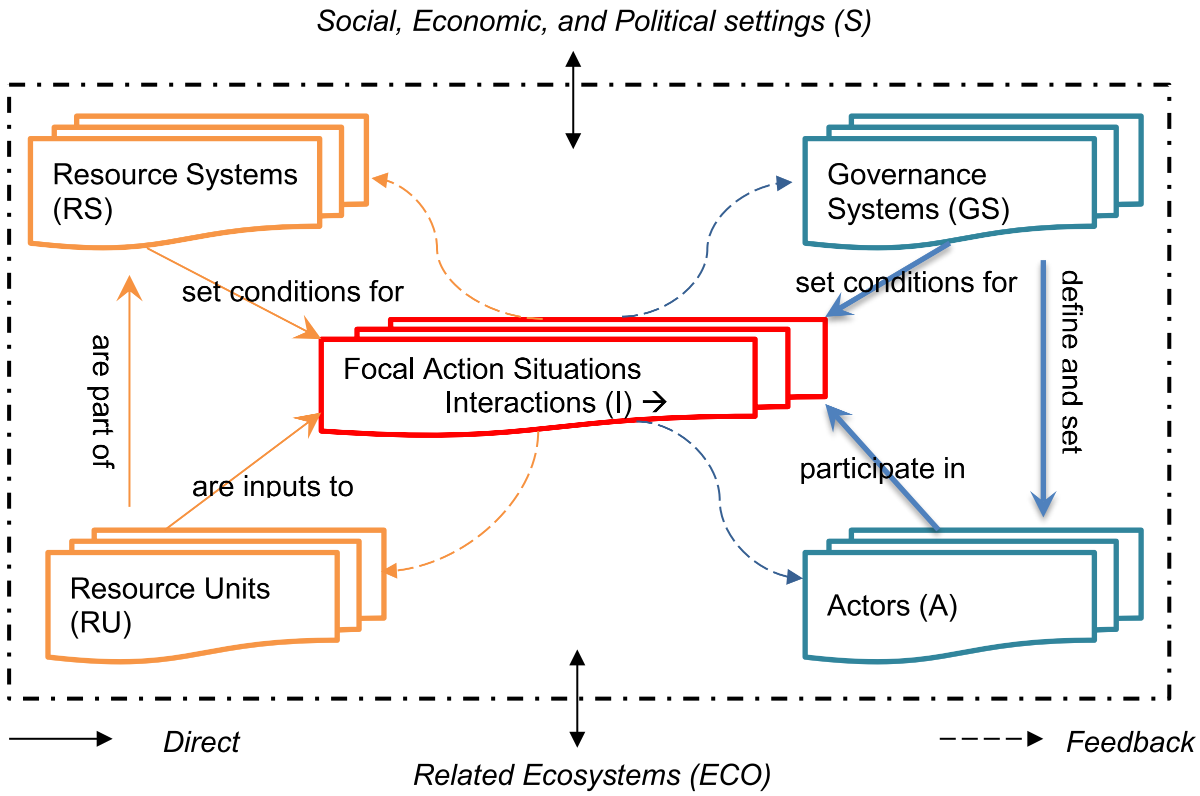


Table 1. Second-tier variables of a social-ecological system of canal irrigation in China (McGinnis and Ostrom, 2014).

Social, economic and political settings (S)	S1- industrialisation (economic development) S2- urbanisation (demographic trends) S4- policy (other governance systems) S5- marketisation (markets) S7- technological progress (technology)
Resource systems (RS)	RS3- scarcity of surface water (size of resource systems)
Governance systems (GS)	GS4- privatisation of use rights (property-rights systems) GS6- decline of village's ability to self-govern (collective-choice rules)
Actors (A)	A5- loss of leadership (leadership/entrepreneurship) A8- less dependence on irrigation systems (importance of resource [dependence]) A9- adoption of new technology in irrigation (technologies available)

Social, economic and political settings (S)

The dotted-and-dashed line surrounding the interior elements in Figure 2 indicates that the focal SES can be regarded as a logical whole, while the exogenous influences from relevant ecological systems or social-economic-political settings can affect any component of it (McGinnis and Ostrom, 2014). In this study social-economic-political settings are important factors that indirectly influence the SES by affecting S, RS, GS and A. They are more macro-level and more fundamental causes than the components in the dashed box. In irrigation systems, industrialisation (S1), urbanisation (S2), policy (S4), marketisation (S5) and technological progress (S7) all have an impact on the micro-situational variables that further contribute to the decline of canal irrigation.

Industrialisation (S1) is a trend in current global and Chinese economic development that provides a great deal of employment. It manifests in a shift from a traditional agrarian society to an industrial society, with a growing secondary sector. This is accompanied by urbanisation (S2), which refers to a process where the population becomes concentrated in cities, causing their expansion, and a whole series of related socio-economic changes. Since the late 1980s rapid urbanisation has been one of the social characteristics of China. In 1982 only 21% of the population lived in urban areas; in 2018 it was 59.58% (NBS, 2020). Policies (S4) may be directly related to water facilities or may indirectly influence the choice of irrigation method. Market-based reforms are one way China has been able to stimulate economic growth. China's marketisation (S5) has its roots in the economic reforms that began in the 1990s. Since then the coverage of the planned economy has been gradually reduced and a market economy has taken shape, which in agriculture is reflected in farmers enjoying more autonomy in production and marketing and less government intervention. Technology (S7) is a trend that concerns all sectors. Advances in irrigation technology on the one hand facilitate the development of agricultural production, but they may also pose challenges to traditional canal irrigation.

We begin with a brief explanation of how the broader contextual factors play out in China. More detail of how the above factors indirectly influence RS, A and GS is presented below in the analysis of the direct influences in the dashed boxes (see Figure 2).

Resource systems: Scarcity of surface water (RS3)

Although China is among the best-endowed countries in terms of total water resources, when these are measured per capita China has less than a third of the world average. When we measure water resources per mu of arable land - 1440 cubic metres, China has about half of the world average.[6] The available resource has decreased over the past several decades, particularly in northern China, where there has been a significant reduction in surface water resources since the beginning of the 21st century. Comparing the 2001-2009 multi-year average to 1956-2000, there was a reduction of 2.8% in precipitation and 5.2% in surface water resources across the country (CDA, 2013). The most significant reduction was in the Haihe River Basin, where precipitation decreased by 9%, surface water resources by 49% and total water resources by 31% (CDA, 2013).

Conversely, over the last seven decades China's total water use has witnessed a dramatic increase. Industrialisation (S1) has led to an increase in non-agricultural water use. From 1949 to 2014 industrial water withdrawals rose from 2 billion to 135 billion cubic metres, while agricultural water use began to decline after peaking in the 1980s (Wang et al., 2017). Despite a small decrease in industrial water consumption from 2015 onwards due to technological innovations, water scarcity is still a problem that cannot be overstated with the rapid industrialisation ahead (MWR, 2015-2019).

When water resources are extremely scarce relative to use it is difficult for farmers to come together and use open channels for irrigation. This is because water availability generally has an inverted-U relationship with willingness to use canals for irrigation (Uphoff et al., 1990; Bardhan, 1993; Dayton-

[6] 1 mu is equivalent to 667 square metres.

Johnson and Bardhan, 2002; Araral, 2009; Ito, 2012; Wang el al.; 2016a). In other words, when water resources shift from moderately scarce to extremely scarce there is a likely decrease in collective action and capacity to manage the system. Moderate water scarcity can enhance farmers' motivation to cooperate over canal irrigation, but when it is extremely scarce cooperation is unlikely and the benefits from using canals decrease. If they have alternative sources of water, farmers will therefore be unwilling to use canals and will turn to other sources.

Actors

Loss of leadership (A5)

Authority plays a key role in China's grass-roots governance networks and is often supplied by leaders of grass-roots organisations (Shu et al., 2018). However, rapid urbanisation (S2) has led to a declining number of better-educated and more active young adults in the village workforce. A lack of capable people to lead collective economic projects and provide advice in the governance of public affairs in the village also contributes to a loss of leadership in the village (Wang and Yang, 2021). For instance, in Yongjia county of Zhejiang province the proportion of people with university degrees and above working in agriculture in the villages is only 1%, while the proportion with an education level of primary and below is 66% (Zhou, 2019). The involvement of a charismatic or trusted individual can reduce the transaction cost of organising and makes individuals more willing to participate in collective action (Kolavalli, 1995; Baland and Platteau, 1999). When leadership is lacking, the vitality of the various organisations (including governmental, self-governing and market organisations) is limited and the overall governance capacity reduced (Wang and Gao, 2015; Meinzen-Dick et al., 2002).

The use of canal irrigation is a form of collective action that requires an external authority to organise the farmers where they are not sufficiently motivated to organise themselves (Ostrom, 1990). Leadership loss leads to a lack of endogenous leadership in the village, namely a reduction in the village's own organisational capacity, making the collective use of canals more difficult. Shu et al. (2018) suggest that China has taken measures to import exogenous leadership into villages by sending first secretaries from the public sector in to manage them. The results of the study showed that those villages lacking leadership eventually agreed to the common use of canal irrigation with the introduction of exogenous leadership. However, the policy of external leadership input is not permanent. In the future villages will continue to face the problem of leadership loss and the resulting difficulty in using irrigation canals.

Less dependence of irrigation systems (A8)

The development of industry (S1) in China started with, and is still dominated by, labour-intensive industries. These provide employment on a large scale. Young adults moved from the country to the cities for higher incomes, which has met the demand for labour in the secondary sector and led to urbanisation (S2) (Zhang et al., 2019). Both industrialisation (S1) and the associated urbanisation (S2) have led to decreasing dependence on agriculture and irrigation systems in rural areas, where people are increasingly inclined to engage in non-farm work, meaning the share of agriculture in production activities has decreased (Wang and Zang, 2020). The proportion of pure farming households, part-time farming households and non-farm households in China shifted from 11%, 56% and 33% to 3%, 33% and 64%, respectively between 2003 and 2016 (Zhang et al., 2019).[7] The data show that the dominant type of farm household has shifted from pure farming to part-time farming to non-farm, which means the importance of agriculture and irrigation systems is declining in relative terms.

Reduced dependence on agriculture leads to reduced incentives for cooperation within villages (Runge, 1986; Ostrom, 2000). This is reflected in irrigation as rural people become less dependent on

[7] Pure farming households are those in which agricultural income accounts for more than 80% of the total household income; non-farm households are those in which it accounts for less than 20%.

agricultural production, leading to reduced reliance on irrigation systems and a consequent reduction in their willingness to invest financially and physically in canal irrigation (Wang et al., 2016). An empirical study in Gansu Province also found that rural migration was negatively correlated with water use per unit of cultivated area (Castro et al., 2010). Thus, the declining relative economic importance of agriculture has contributed to a decrease in the use of canal irrigation in China. New technology adoption in irrigation (A9)

The lower-level ('on-farm') canals have modest technical requirements and are relatively cheap and easy to build, which is one of the reasons gravity irrigation has been adopted by China's smallholder-dominated agricultural society. On one hand, with the progress of technology (S7), the mechanisation of agriculture is improving, and this includes irrigation machinery and equipment. The manufacture of agricultural water pumps in China started in the 1960s, and today over 20 types of pump are produced with more than 3000 specifications. Locally produced pumps are currently much cheaper than imported pumps. The widespread use of electromechanical pumps for well irrigation has increased the efficiency of agricultural irrigation and reduced the need for human input. Small farmers freed from human-powered water lifting or the cooperative maintenance of irrigation canals can devote their labour to more profitable activities (Pingali, 2007). On the other hand, policies (S4) also encourage the use of electromechanical pumps. In 2009 agricultural water pumps (as drainage and irrigation equipment) were officially included in the central financial agricultural equipment purchase subsidies list, further reducing the threshold for farmers to use them.

Moreover, against a backdrop of increasing water scarcity, government policies and funding (S4) have encouraged the adoption of new water-saving technologies for agricultural development. This has led to the wider use of new water-saving technologies, such as sprinkler and drip. The area of farmland irrigated with water-saving equipment was 16.7 million hectares in 2018, an increase of 3% year on year, and the number of water-saving irrigation devices was 2.4 million, an increase of 5% year on year (MARA, 2019). Agricultural mechanisation has promoted the development of well irrigation and new irrigation methods and reduced the use of canal irrigation.

Governance systems

Privatisation of use rights (GS4)

Until the 1980s canals and irrigation wells were mostly collectively owned, and there were few privately owned irrigation facilities. From the 1980s onwards, with the marketisation of agricultural production, the trade in agricultural products (S5) and the government's fiscal reforms (S4) that reduced investment in public resources for agriculture, many villages had no access to funds or labour to invest in irrigation facilities, creating a need for private investment (Wang et al., 2020). At the same time, with the system of household contract responsibility (S4), farmers were allowed to independently manage distributed land and earn profits from agricultural production. This land reform transferred land-use rights from collectives to individuals, which sharpened farmers' motivation to engage in agriculture. To earn more, they needed to increase their productivity by using more reliable irrigation methods. They preferred wells to canals because they provide a more stable water supply and are easier to maintain. Despite the existence of public wells, excessive withdrawals and falling water tables meant additional investment was needed to deepen tube wells. As the village lacked the funds, more and more farmers drilled private wells for irrigation water(Wang et al., 2007a).

In addition to the reform of land-use rights, new allocation systems (S4) for water-use rights were introduced to facilitate the division of responsibilities and transactions. In rural areas water-use rights are allocated to each household and can be traded between households (Liu et al., 2016). This privatisation-oriented reform was originally intended to provide incentives and address the tragedy of the commons, but it led to the fragmentation of water-use rights, weakening the villages' capacity for collective action and making it more difficult for farmers to use canals cooperatively (Wang et al., 2016b). Thus, the privatisation of both land-use and water-use rights discouraged farmers from using canals.

Decline of village's ability to self-govern (GS6)

China's 2003 rural tax and fee reform (S4) (State Council, 2003) abolished the 'two labours' (*lianggong*) system in the countryside and replaced it with the 'one project, one discussion' (*yishiyiyi*) system.[8] The reform reduced confusion over fees, fundraising, fines and the distribution of work, and eased the conflict between villagers and village cadres. This helped the government regain the trust and support of farmers but not without problems. With the abolition of the 'two labours' system village groups are gradually declining and disintegrating, village committees are finding it more difficult to group farmers for the construction of canals and other irrigation facilities, and the relationship between village committees and farmers is further weakening. Although the 'one project, one discussion' system is in place, it has trouble organising meetings of the villagers to discuss and implement decisions. Without a basis for compulsory cooperation it is becoming increasingly difficult for farmers to use open channels for irrigation on a collective basis, and more and more are opting for individualistic solutions such as drilling their own wells, building weirs and purchasing irrigation equipment (Wang and Gao, 2015).

Figure 3 shows the relationship between broader contextual (S) and micro-situational variables in more detail. Social, economic and political factors are fundamental in irrigation transformation, and they indirectly influence irrigation management through micro-situational variables. In the resource systems the side effect of industrialisation (S1) is the overuse and pollution of water resources, leading to a scarcity of surface water (RS3), which forced farmers to give up collective canal irrigation. For actors, rural-urban migration (S2) has led to a loss of village leadership (A5); industrialisation (S1) and urbanisation (S2) have resulted in less dependence on irrigation systems (A8); and water conservation policies (S4) and rapid technological advances (S7) have facilitated the adoption of new irrigation technologies (A9). All these changes in farmer attributes in the villages have reduced the use of canal irrigation. As for the governance system, the fragmentation of land- and water-use rights (GS4) as a result of marketisation (S5) and fiscal reform (S4), and insufficient self-governance (GS6) to organise collective action in villages as a result of tax and fee reform (S4), have made it difficult to sustain the use of canal irrigation.

IMPACT OF THE DECLINE OF CANAL IRRIGATION

Not only did the external environment – social, economic and political features and related ecosystems – have an impact on China's irrigation system, but the decline of irrigation in turn influences the economic, social and ecological spheres. In this section we examine how irrigation transformation affects these different aspects – for better or worse.

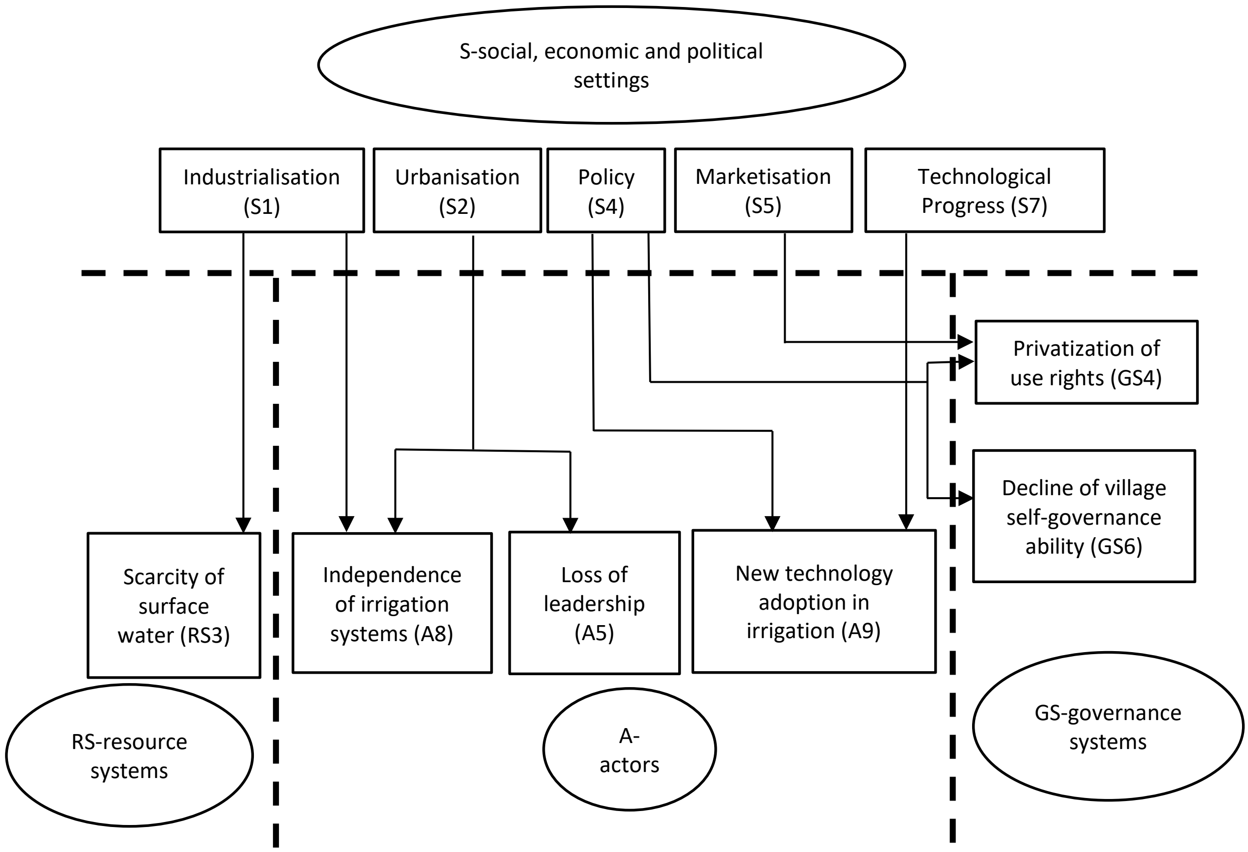
Economic impact

Ensuring the stability of agricultural production

Traditional irrigation methods, which are highly dependent on canals, are unstable, and new trends indicate that other water sources are becoming more widely used in China to compensate for this. The trend is particularly pronounced in the northern regions, where there is less rainfall and it is less

[8] The 'two labours' *(lianggong)* system is a generic term for both compulsory rural labour and labour with the need to accumulate working hours. The former involves flood control and tree planting, and the latter includes the construction and maintenance of irrigation facilities and village roads, both of which require a compulsory number of hours of work per year from each labourer in the village. In the case of the 'one project, one discussion' *(yishiyiyi)* system labour is no longer compulsory for projects in the village and the village does not charge villagers a fixed amount of money. Instead, each issue is discussed individually to decide whether or not to enforce labour or charge money.

Figure 3. The relationship between broader contextual (S) and micro-situational variables.



predictable. The dry season in the north lasts for eight months, from early winter to midsummer, and during this time – the growing season for wheat, just when water is needed – precipitation is only a third of the annual average (Guo, 1995). As an irrigation source, groundwater is not affected by the dry season and can provide a continuous supply to the farm throughout the year. The same role can be played by the conjunctive use of well and canal irrigation, providing more security and flexibility. The regulating effect of groundwater reservoirs can thus be used to address irrigation needs when the surface irrigation system is not functioning, when the river is low or when crop demand is at its peak (Xing, 2003). This effectively improves the stability of agricultural production.

Increasing cost of agricultural production

Although the use of other water sources and irrigation methods has improved the stability of agricultural production to some extent, it has also increased production costs for farmers. Many are choosing to purchase irrigation equipment and drill wells, but the cost of such equipment is ten times or more that of traditional large- and medium-scale irrigation (based on the cost of equipment per mu), and they need replacing periodically (He and Guo, 2010). Ma and Liu (2014) found that the cost of water from wells in Ningxia irrigation district is 0.08-0.12 yuan/m^3 (0.0234-0.0156 euro/m^3), while from canals it is only 0.03 yuan/m^3 (0.039 euro/m^3) – about a third. Farmers without access to canals are forced to maintain agricultural production at higher cost.[9]

[9] 1 yuan is equivalent to 0.13 euro.

Relying on groundwater not only increases the burden on farmers but also raises the future cost of water. The over-exploitation of groundwater has become one of the most difficult water resource problems in China – and around the world. As the water table continues to fall, the cost of digging wells and pumping water rises. According to Wang et al. (2007b), for every additional metre down to the water table, the pumping cost rises by 0.005 yuan/m³ (about 2% of the mean pumping cost in 2004); and digging each well another metre deeper costs another 120 yuan (15.6 euro). As the water table continues to drop, farmers will have to keep spending more on irrigation.

Social impact

Facilitating the watering of crops

One of the basic conditions of canal irrigation is the need for collective participation in the maintenance and use of the facilities, which means the cooperation of a significant labour force for the canals to function properly. However, with the exodus of labour from villages due to urbanisation there is a shortage of young men to work in small-scale agricultural production. This has left most of the jobs to be done by women or elderly men, but they are not physically strong enough for construction or maintenance. Well irrigation and other water-saving irrigation methods are much more convenient and require less physical labour. Wells are usually located near the farmland and can be used to pump water for irrigation directly, and water-saving materials are equipped with switches, making them easier to use. These methods are also privately owned and involve less cooperation than the use of canals.

Weakening rural collective action

The reduction in the use of canals has led to a rapid increase in irrigation independence, with households no longer having to share the cost of water or cooperate to maintain the canals. A 2012 survey by CIRS found that in 69% of the villages sampled in China irrigation facilities were either functioning but in disrepair or not functioning at all, while 68% of the farmers sampled had not participated in the construction or maintenance of collective irrigation facilities (Wang and Gao, 2015). In China's rural areas villager cooperation is usually required for the provision of public goods, including irrigation and the joint breeding of cattle for arable land (He, 2003a). But the penetration of the market economy into the countryside has undermined the foundation of the traditional village order and left farmers increasingly atomised (He, 2003b). Cooperation for irrigation is a kind of traditional village order which has been undermined by the market economy. However, the economic marketisation of China is irreversible, meaning that in the future collective action in general will be more difficult in villages in China.

Ecological impact

Saving water

In canal irrigation water is distributed to farmland through canals cut into the ground's bare surface. The transfer process usually involves multiple levels of canals, long distances and high losses (Wu et al., 2003). Canal irrigation is also surface irrigation, which relies entirely on gravity to transport water to the field. It requires precise engineering and a level field. If fields are on a slope or uneven, water cannot be evenly distributed. Some of the land will get too much water and some too little; the irrigation water will be under-utilised, and agricultural productivity will be limited.

In addition, climate warming and rising surface temperatures pose a major threat and challenge to agricultural production. On one hand, river runoff and surface water resources will be reduced; on the other, the rigidity of water demand will increase in various sectors, especially agriculture.

With the growing crisis of water scarcity and traditional canals being gradually replaced by advanced technologies such as lined canals and low-pressure pipelines, the efficiency of irrigation is improving. The spread of these new irrigation technologies has led to a gradual decrease in the water needed per unit area, so the effective irrigated land area can increase year on year, even though the total amount of water decreases (Wu and Zhao, 2010). The popularity of groundwater irrigation has also given rise to groundwater markets, which significantly increase the productivity of agricultural water use, as farmers buying water from groundwater markets have higher irrigation costs and thus have an incentive to use less water and be more productive (Wang and Zhang, 2009).

Environmental consequences

An over-reliance on groundwater for irrigation results in overdraft, and environmental problems can arise when the extraction of groundwater exceeds a threshold. Land subsidence is a common result (Zektser and Loáiciga, 2005). The over-exploitation of groundwater over a long period causes the water table to drop, which reduces the pressure between the upper and lower rock layers and deforms them as they are squeezed by gravity. This destabilises the ground surface, which can then collapse. The North China Plain is one of the regions with a water resource shortage and a typical sensitive groundwater zone, but it has used groundwater extensively (Yu and Liao, 2018; Guo et al., 1995). It is reported that as of 2014, due to this over-extraction, the North China Plain was the largest groundwater funnel area in the world, which not only changed the landforms but also affected people's lives. Groundwater over-exploitation degrades water quality. First, land subsidence breaks the water barrier so that polluted surface water infiltrates the ground through the subsidence area. Second, a lowered water table leads to shorter purification times for underground water. Third, in coastal areas the over-exploitation of groundwater has led to fresh groundwater levels being lower than seawater levels, triggering seawater back-up and ultimately causing groundwater salinisation. The sum of the environmental problems resulting from the over-exploitation of groundwater also jeopardises agricultural production.

CONCLUSION AND IMPLICATIONS

As the earliest irrigation technology to emerge in China, canals are now being superseded by other water sources and irrigation technologies. In this study we demonstrate the decline of canal irrigation in three aspects. First, farmers have neglected canal irrigation facilities, resulting in poor maintenance and shorter canals. Second, the use of groundwater and wells is growing, and the combination of canals and wells in canal districts is increasingly common. Third, new irrigation methods, such as micro-irrigation, sprinkler irrigation and low-pressure tubing, substitute canal irrigation to some extent.

We find this transformation of irrigation is the result of multiple factors. Industrialisation, urbanisation, marketisation, policy changes and continued advances in technology are all prominent social-economic features of contemporary China. These factors can be regarded as the root of the irrigation transition, affecting the attributes of water systems, the farmers who use irrigation facilities and village governance. They manifest in the increasing scarcity of surface water resources, less dependence on irrigation systems, a loss of leadership, the replacement of irrigation technology, the privatisation of land- and water-use rights and a decline in village self-governance. These shifts in villages and resource systems are the direct causes of the decline of canal irrigation.

We find the decline of canal irrigation to have multiple impacts. Economically, the spread of well irrigation has improved the stability of the water supply for agricultural irrigation but has increased the cost of water for farmers. The social impact is that it is easier for farmers to obtain water for irrigation, but the decline of canal irrigation makes future cooperation more difficult and thus weakens rural social capital. Ecologically, the efficiency of water use has improved, but new problems have emerged, including land subsidence and degraded water quality.

We posit that the consequences of the decline of canal irrigation are both positive and negative and that it is difficult to judge the overall impact. What is certain is that the trend is irreversible. This is because industrialisation, urbanisation, marketisation, technological progress and water policy reform, as the root causes of canal irrigation decline, are fundamental trends in the development and reform of contemporary China. These trends are set to continue and will therefore drive further transformation of irrigation patterns. This is essentially a structural shift in water use from surface water to multiple sources, especially groundwater, a shift in technology adoption from traditional canals to water-saving methods, and a shift in irrigation management from intensive collective action to a more individual mode.

Given that the process seems irreversible, we need to build a clearer understanding of its economic and social impacts to cope better with the transition. We acknowledge and welcome the positive effects of the decline of canal irrigation, but its negative effects cannot be ignored. Thus what should be discussed are the measures to be taken to enhance the positive effects and reduce the negative effects to make the transition smoother. To this end, three main implications have been summarised as follows.

First, the decline of canal irrigation means a change in the structure of water supply. China has more than five times as much surface water as groundwater, so the rapid expansion of groundwater for irrigation is unbalanced and has brought many environmental problems. More efficient use of groundwater is the key to reducing the quantities extracted and reducing environmental harm. Although water-saving agriculture has been promoted in China, only about half of the farmland had adopted the necessary technology by 2018 (MWR, 2019). The agricultural water conservation policy system should be further improved, encouraging input from the beneficiaries and private capital. At the same time water-saving projects should be implemented. There are limitations, however, to the amount of water-saving that can be effectively achieved because reductions in water 'losses' by infiltration actually reduce the recharge of the aquifer, which, as shown above, is a key and already overexploited resource (Kendy et al., 2004; Zhou, 2021).

Second, the irrigation shift implies a change in technology adoption. It is embodied in the move from low-technology canal irrigation, needing no external equipment, to well irrigation, which requires the purchase of electric pumps and often-associated micro-irrigation technology. This has resulted in the decay of existing canal irrigation facilities funded by government or collectives, while farmers spend extra money to dig wells, to install and maintain water-saving equipment and pay the electricity fees for pumping. The emergence of new technologies does not mean the elimination of traditional methods. Rather, canal irrigation, with its low-cost advantage, can complement well irrigation. Therefore, it is better to use a combination of well and canal irrigation than to use a single irrigation method. A large proportion of China's rural labour force is still engaged in farming during the busy season and leaving during the idle season, so it is feasible to organise the return of migrant workers to participate in collective canal irrigation during the busy season (Chen, 2019). When the village is short of labour, farmers could rely on the wells for irrigation water. With such a combination, existing canal irrigation facilities would not be wasted, while irrigation costs would be reduced during peak farming periods.

Thirdly, the shift from canal to well irrigation is also a shift from collective to individual irrigation management. The decline in the use of canals is a sign of a decline in the provision of public goods or commons in villages, making collective action more difficult to achieve. At present, the Chinese government is encouraging the development of collective economies in villages, offering new opportunities to improve village self-governance. Along with the development of collective industries, attracting migrant labour to participate in the production and management of the collective economy is an effective way to re-establish village cooperation. These measures could help people cope to some extent with the shift in irrigation.

In summary, this paper provides an overview of the decline of canal irrigation in China's irrigation transition with a systematic study of this transformation along with its causes, impacts and implications. However, we provide only limited evidence of the decline of canal irrigation, and preliminary explorations on the causes, effects and responses. In future work, deeper field research and data collection are necessary to provide further evidence of the decline of canal irrigation as well as a more systematic analysis of irrigation transformation towards a modern society in China. Furthermore, cross-national studies can be further explored to deepen the understanding of the phenomenon of canal irrigation decline worldwide.

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