Research on Scale Demonstration Technology of Inter Basin Water Transfer Project in Agricultural Irrigation

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Research Article

Keywords: Water transfer project, Dynamic trial feedback, Scale demonstration, Despiking utilization, Water allocation, Sanjiang Plain

Posted Date: March 11th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-307277/v1

Version of Record: A version of this preprint was published at Water Resources Management on October 26th, 2021. See the published version at https://doi.org/10.1007/s11269-021-02999-w.

Abstract

Inter-basin water transfer projects are powerful measures for resolving the uneven distribution of water resources, but their scale directly affects the associated investment and income. Therefore, determining the scale of an inter-basin water transfer project is essential. Based on the inter-basin agricultural water transfer project in the Sanjiang Plain, Northeast China, combined with the suitable development scale of the irrigation area with the joint allocation of existing water sources, this research proposes a technique to demonstrate the scale of an inter-basin water transfer project based on dynamic trial feedback under the condition of the optimization method of despiking of the groundwater allocation; the water transfer project scale is demonstrated for each section in reverse order. According to the water demand prediction results in the study area, the scale of water transfer project BC is demonstrated, and the scale of water transfer project AB is demonstrated on the basis of the BC scale. The final AB and BC water transfer scales decrease by 15% and 13%, respectively, compared with the conventional method under the premise that the water supply guarantee rate is 75%. When the water is transferred, the process is stable, and the utilization rate of the canal is high, thereby saving investment funds and facilitating project scheduling and management.

Introduction

Water resource security is a fundamental concern that must be addressed to ensure economic and social development (Dutt and Manocha 2016). However, with the rapid socioeconomic development that coincides with urbanization, water resource security is becoming increasingly challenging due to a series of problems, such as serious overexploitation of surface water resources and groundwater resources and the pollution of the water environment in some areas (Saleth 2013; Hou et al. 2018).

To solve this problem, inter-basin water transfer projects have been widely implemented around the world to ensure the safety of regional water resources (Prichard & Scott, 2014). According to statistics, more than 350 water transfer projects have been constructed in at least 40 countries and regions around the world, and these projects play vital roles in ensuring the coordinated development and ecological security of the regional economy and society (Gupta and van der Zaag 2008).

Water transfer projects boast a long history. As early as 3400 B.C., Egypt initiated a water irrigation network around the Nile River (Haug 2017). In 3000, B.C., India developed a water irrigation system along both sides of the Indus River. In the Spring and Autumn period over 2400 years ago, the Han Ditch Project, which was built for military purposes (485 B.C.) and was connected to the Yangtze and Huai Rivers, constituted the beginning of an inter-basin water transfer project in China; subsequently, three famous water transfer projects, namely, the Dujiangyan (256 B.C.), Zhengguo canal (246 B.C.), and Ling canal (219 B.C.) were built in succession prior to and during the Qin dynasty, during which time these canals played vital roles in the unification of China (Zhang et al. 2013).

The number of water transfer projects began to increase on a global scale after the 1950s (Molina and Melgarejo 2016). The period from the 1940s to the 1980s represented a peak construction phase, and most water transfer projects, which were aimed at providing a water supply and an irrigation network, were built in this period. For example, the famous California State Water Transfer Project was initiated in 1957, and it was completed at the end of 1973 (Marston and Konar 2011). Furthermore, the Australian Snow Mountain project started in 1949 and was completed in 1974 (Lunney 2001). However, larger-scale water transfer projects, such as the joint North American hydropower project with an annual water volume of 136 billion m^3 and the water transfer project in North and Central America with an annual volume of 185 billion m^3, were proposed during the 1960s. In China, the South-to-North Water Transfer Project, which was intended to transfer water from the Yangtze River into the Huai River and Yimu River, began in 1961. The Dongshen Water Transfer Project, which transfers water from the Dong River into Hong Kong, was completed in 1965 (Cheung 2014). The Jingtaichuan power irrigation project, which transfers water from the Yellow River into the Shiyang River Basin was completed in 1974 (Xu et al. 2014).

Since the 1980s, the speed with which water transfer projects have been constructed in developed countries has slowed significantly, while building is still ongoing in developing countries (Wang et al. 2015). In addition to India and Pakistan, China, Egypt, South Africa and other countries are also energetically constructing water transfer projects (Turton et al. 2006; Thatte 2007). Among them, the water transfer projects in China include the Yellow River-to-Qingdao (1989), Yellow River-to-Wei River (1994), Yellow River-to-Hebei Province (1995), and Yellow River-to-Tianjin (1999) water transfer projects (Cai and Rosegrant 2004) in addition to the Luan River-to-Tianjin (1983) and Luan River-to-Tangshan (1983) projects, among others.

Since the twenty-first century, with the acceleration of urbanization in China, a number of urban water transfer projects with the primary goal of allocating water resources have been built, such as the Yellow River-to-Shanxi Province Water Transfer Project (2002), the Xijiang Water Transfer Project (2010), and the first phase of the South-to-North Water Transfer Project consisting of the East and Middle routes (2003) (Zhang et al. 2009). Simultaneously, the ecological and environmental problems caused by human activities and climate change are becoming increasingly prominent (Wen et al. 2018). Inter-basin ecological water transfer projects aimed at improving the water quality restoring the ecology are highly valued by the Chinese government (Wang et al. 2018). Examples of such large-scale urban water transfer projects include the Hei River and Tarim River Water Transfer Project (2000), the Yangtze River-to-Taihu Lake Water Transfer Project aimed at improving the water quality of Taihu Lake (2002), the Yellow River-to-Baiyangdian Water Transfer Project for replenishing the ecology of Baiyangdian (2004), and the Zhalong Wetland replenishment project (2008).

These water transfer networks serve many purposes, mainly including agricultural irrigation, providing urban and industrial water supplies, shipping, power generation, fishery and ecological environment replenishment (Sharifi et al. 2013). For example, the Central Valley Project and California State Water Project in the United States, which was mainly intended for providing an urban water supply and agricultural irrigation, generate power by hydraulic drop. Meanwhile, water transfer projects in Europe and

Japan are mostly aimed at providing an urban water supply. Similarly, numerous water transfer projects have been built in the former Soviet Union; in addition to providing an urban water supply and agricultural irrigation, the North-to-South Water Transfer Project therein also replenishes the Caspian Sea to raise its water level, help develop fisheries and improve the environment. In developing countries such as India and Pakistan, water transfer projects are mainly constructed to meet agricultural irrigation needs (Rani et al. 2016); water transfer techniques are also used for flood control, an example of which is the Tigris River-Searl Saar Lake-Euphrates River Water Transfer Project in Iraq, which greatly reduces the likelihood of flooding in the lower Tigris River Basin and is connected to the rich water resources of Searl Saar Lake (Odemis et al. 2010). As a consequence of this project, the formation and movement of sand dunes around the area, especially around Baki, have greatly slowed down, and this water transfer project has played an enormous role in flood control and in producing ecological benefits (Chen et al. 2011).

Synthetically, inter-basin water transfer projects are mainly characterized by the following aspects. (1) The water supply target often evolves from a single target to a comprehensive set of many targets, such as cities, industry and agriculture in addition to the shipping industry and ecological environment (Akron et al. 2017; Lei et al. 2018). (2) The water transfer route develops from a straight line to a network, that is, the linear development of a single project evolves into a network of multiple inter-basin and inter-region water transfer projects (Lynch et al. 2011). (3) The engineering planning and construction transition from being simple to complex through the formation of a connected system of water storage, diversion, extraction and transfer engineering elements (Peng et al. 2015). (4) The engineering benefits shift from water supply benefits to comprehensive water quantity, quality, and ecology benefits, thereby promoting the overall socioeconomic and societal development in water receiving areas (de Andrade et al. 2011).

The scale of a water transfer project directly affects the associated investment and income, and thus, determining its scale is essential (Ward et al. 2006; Li et al. 2014). Water transfer projects should take into account a multitude of factors, including the water intake, the ability to guarantee a water supply, and the technical and economic environment in the water receiving area (Yevjevich 2001; Lei et al. 2018). Based on the optimal allocation of water resources in the water receiving area, multiple schemes can be selected to determine the water transfer scale (Ez and Prat 2003). To determine the scale of a water transfer project based on agricultural irrigation, the conversion relationship between surface water and groundwater should be taken into consideration, and the project scale should accordingly be determined under the joint optimization of both surface water and groundwater (Shourian et al. 2017). In this paper, a new method for determining the scale of an inter-basin agricultural water transfer project is proposed based on the reality of an inter-basin agricultural water transfer project in the Sanjiang Plain, Northeast China, based on the concept of dynamic trial feedback. The final determination of the water transfer scale using the proposed technique is smaller than that using the conventional method. When water is truly transferred from one area to another, the process is stable, and the utilization of the transfer channel is high, which can save investment funds and facilitate project scheduling and management.

Methodology

The thought of scale demonstration of water transfer based on dynamic trial feedback

To reduce the scale of a water transfer project, the operation modes of local surface water, groundwater and external water should be used in conjunction. After the local surface water and groundwater are allocated, any water shortage in the irrigation area is supplemented by the provision of an external water source (Zhou et al. 2017). After the operation of a water transfer project is initiated, a large amount of irrigation water retreats back underground, recharging the aquifer and increasing the exploitable amount of groundwater. This recharge process can further increase the exploitation of groundwater and reduce the regulation of external water sources despite the need to avoid the over-exploitation of an aquifer. Therefore, dynamic trials should be carried out under the premise of jointly scheduling surface water and groundwater extraction to determine the scale of the water transfer project in an irrigation area (Wan et al. 2018).

The step of demonstrating the water transfer scale based on dynamic trial feedback

Based on dynamic trial feedback, the method of demonstrating the scale of a water transfer project is as follows.

(1) Determine the transferable water volume of the external water source and preliminarily formulate the water transfer route. Then, calculate the net agricultural water demand, the available local surface water and the exploitable amount of groundwater in each irrigation area along the water transfer route (assuming 6 irrigation areas, as shown in Fig. 1).

(2) Convert the net agricultural water demand of the irrigation area into the gross surface water demand (which can be determined by the net agricultural water demand divided by the effective utilization coefficient of the surface irrigation water), and then allocate the local surface water among each irrigation area (note that the general availability of local surface water is very small; thus, water shortages in large parts of the irrigation area are still serious) to obtain the surplus gross water demand in each time interval. Simultaneously, convert the surplus water demand into the gross groundwater demand (the surplus water demand is first converted into the net water demand and then the gross groundwater demand, that is, the surplus gross water demand is first multiplied by the effective utilization coefficient of the surface irrigation water, which is then divided by the effective utilization coefficient of underground irrigation water).

(3) Starting from the last irrigation area along the water transfer route, the groundwater is adopted for despiking; that is, the groundwater is used only during periods of large surplus water demand in that irrigation area. During the process of allocation, the starting line of groundwater allocation can be established; that is, groundwater is used only above the starting line. All of the water demand is accumulated as the exploitable amount of groundwater (i.e., the available amount of groundwater, which

equals the exploitable amount of groundwater multiplied by the exploitable coefficient), and the starting line of the groundwater allocation can be determined by a trial calculation; this process is discussed in detail hereafter.

In conventional groundwater allocation, the annual exploitable amount of groundwater is generally allocated to each period of time on average; the allocation process is relatively simple according to the demand during the given time period. However, when the surface water and groundwater are combined, this allocation method is not conducive to the scheduling of surface water, especially for an external water source. Therefore, this study proposes an optimal dispatching method for despiking the groundwater allocation, that is, the groundwater is used only during periods of large water demand, and a trial calculation method can be used to determine the starting line of the groundwater allocation for the specific allocation process. The groundwater is allocated only during periods in which the water demand is larger than the starting line value, and the allocation amount is the water demand minus the starting line value. In the end, the annual amount of allocated groundwater is equal to the annual exploitable amount of groundwater.

After despiking the groundwater allocation, a substantial water demand remains for the water allocation period, and thus, groundwater should not represent the last source of water employed for the allocation of water resources. The surplus water demand is relatively stable after despiking the groundwater allocation; this provides certain benefits for the allocation of water sources, especially external water sources, and it can increase the utilization of the canal. In addition, this method can effectively reduce the scale of water transfer when determining the external water transfer scale (as shown in Fig. 2).

(4) After a long period of groundwater allocation (according to relevant requirements, this period is generally not less than 30 years), the water shortage in the last irrigation area is obtained for the entire period. The water shortage is converted to the gross surface water shortage, and the new water shortage process is obtained by considering the losses in the canal system due to leakage and evaporation. The loss due to leakage is related to the length of the trunk canal, the construction material of the trunk canal, the permeability coefficient of the underground soil, and the depth of the groundwater level, among other factors. The loss due to the trunk canal can be determined through field observation experiments in combination with relevant standard specifications and empirical parameters, and it may be simplified by an empirical coefficient.

(5) According to the design guarantee rate of agricultural irrigation in an irrigation area (assumed to be 75%), the scale of the water diversion outlet in the last irrigation area along the water transfer route can be preliminarily determined. The design guarantee rate of agricultural irrigation is generally the annual guarantee rate calculated using an empirical frequency formula expressed as $P = m/(n + 1)\times 100\%$, where n is the total number of years, and m is the number of years fully satisfied within each period of time. The number of years of water supply can be calculated by a trial calculation. First, a numerical value is selected from the water shortage process to represent the initial water transfer scale (to reduce the number of trial calculations, all water shortage processes can be sorted from smallest to largest, after

which approximately 75% of the values are selected as the initial scale of the water diversion outlet). From the first year, the water shortage process and the initial scale of the water diversion outlet can be obtained. The initial scale of the water diversion outlet is compared with the water shortage process on a yearly basis. If the amount of water shortage in all time periods is less than or equal to the initial scale of the water diversion outlet, then m = 1; otherwise, m = 0 and is incremented as m = m + 1 and is compared over the entire period; finally, the m value is inserted into P = m/ (n + 1)×100%. If the P value is less than the design guarantee rate of agricultural irrigation, the initial scale of the water diversion outlet will be increased. If the P value is greater than the design guarantee rate of agricultural irrigation, the initial scale of the water diversion outlet is reduced, and the trial calculation is continued until the P value equals the design guarantee rate of agricultural irrigation or until the P value is slightly larger than the guarantee rate of the agricultural irrigation design; then, the trial calculation is considered complete, and the initial scale of the water diversion outlet is obtained.

(6) Replace the water shortage processes greater than the initial scale in the last irrigation area with the initial scale in each year, that is, with the initial water transfer process of the last water diversion outlet.

(7) Determine the coefficient of irrigation infiltration recharge in the last irrigation area through irrigation tests and relevant references. By multiplying the initial water transfer process by the irrigation infiltration recharge coefficient, the amount of groundwater recharged by irrigation water can be obtained, and the new amount of exploitable groundwater in the irrigation area can be obtained by adding the amount of groundwater recharged by irrigation water to the initial calculated amount of exploitable groundwater.

(8) Repeat steps (3) ~ (7) until the difference in the water transfer scale is sufficient small during the last two iterations to stop the trial calculation. The last initial water transfer scale is the final scale of the last irrigation area along the water transfer route.

(9) Determine the scale of the water diversion outlet in the second-to-last irrigation area of the water transfer project. The surplus water demand in the second-to-last irrigation area is superimposed onto the water transfer process of the last irrigation area along the route, after which the new surplus water demand is obtained and then converted into the gross groundwater demand.

(10) The despiking of the allocation of groundwater should also be applied to the second-to-last irrigation area. Note that the allocation of groundwater in each time interval should not be greater than the surplus gross water demand of the second-to-last irrigation area.

(11) The water shortage after despiking is converted into the gross surface water shortage. Furthermore, the loss of water transfer in the canal in this section is considered, and the net surface water shortage process of the second to last irrigation area with the loss is obtained.

(12) The water shortage process obtained in step (11) minus the water transfer process in the last irrigation area, which is the initial water transfer process in the second to last irrigation area.

(13) The same trial calculation will ultimately determine the water transfer scale and process of the second to last irrigation areas.

(14) The scale of water dividing outlet in other irrigation areas and the water transfer process in the irrigation area are determined to be similar to the second to last until the canal head of the water transfer project.

(15) Finally, the canal head scale of the water transfer project and the water dividing outlet scale along the irrigation area were obtained.

Based on dynamic trial feedback, the detailed block diagram of the water transfer scale demonstration is shown in Fig. 3.

Case Study

Study area

The case study area is located in the Sanjiang Plain, Northeast China. The superior conditions of the water, soil, climate and light greatly facilitate the growth of rice. Therefore, some large paddy fields have been developed. However, because of the flat terrain, the area is not suitable for the construction of large-scale reservoirs, and numerous river wetlands are scattered throughout the region (Wang et al. 2015). At the same time, most of these wetlands are national, provincial or municipal nature reserves, so water cannot be diverted from the rivers therein, and thus, farmland irrigation in the area mainly depends on groundwater (Wu et al. 2017). Consequently, long-term groundwater exploitation has led to a decline in the groundwater level, a reduction in the wetland area, a decline in the regional biodiversity, and a multitude of serious ecological and environmental problems. In some areas, a groundwater funnel has appeared, that is, the ground has slightly settled due to the overexploitation of groundwater (Guo 2016).

Although the local surface water resources are insufficient in this area, the amount of transferable water resources is abundant; three large rivers (A, B and C) flow to this area, which could potentially lead to the transfer of water resources for irrigation and simultaneously supplement the water resources of the wetlands and improve the regional ecological environment.

Rice security is especially important for China, which has a large population of 1.3 billion (Xiang et al. 2017). Therefore, 27 irrigation areas are planned for construction in this area, and rice will be mostly planted by 2030. Because of the large water demand, the water transfer project is intended to provide an inter-basin water supply to prevent further overexploitation of groundwater resources. According to the scope of the water supply, the study is divided into a water supply area and a non-water supply area. The water supply area covers 27 irrigation areas and 12 wetland nature reserves over a total area of 12.8 thousand km^2. The non-water supply area does not require a water transfer project, but it has a hydraulic connection to balance the water supply area that constitutes the boundary condition of the water supply area, including 12 watershed intervals. The area is 20.5 thousand km^2.

The planned water transfer project consists of two parts. Part one is the construction of water transfer project BC, which consists of the water transfer from river B to river C, and the 12 irrigation areas are irrigated along the route by project BC and river C. Part two is the construction of water transfer project AB, which consists of the water transfer from river A to river B to replenish the water in river B and the irrigation of 6 irrigation areas. A total of 9 irrigation areas are irrigated on both sides of river B. To restore the ecological environment of the study area, the water transfer project will simultaneously replenish the water in the wetland protection areas, but it will not account for the scale of the project, that is, the scale of the water transfer project is determined only by the irrigation of the farmland. A sketch of the study is shown in Fig. 4.

Water demand prediction

In accordance with the water saving priority, water management practices are strengthened throughout the irrigation area. The water use index of the irrigation area in 2030 is designed to reach the international advanced water use level to efficiently utilize water resources. Then, the water demand prediction can be carried out.

The prediction results (see Table 1) indicate that the research area for the year 2030 includes a total water demand of 9.33 billion m^3 after supplementing the water in the wetlands, and the total water demand of the water supply region will be 7.33 billion m^3.

Table 1

Water demand prediction results in the study area for the planned level in the year 2030 (million m^3)

Water-demanding agent			Water demand
Residential water demand			237.05
Production water demand	First industry	Total for first industry	7489.91
		Farmlands	7314.23
	Second industry	Total for second industry	1088.69
		Industry	1076.52
	Third industry		45.50
	Total production		8624.10
Ecological water demand	Ecological water demand outside the river channels		19.59
	Water supplement of wetland reserves		453.03
Total water demand			9333.77

Demonstration of the water transfer scale for project BC

The above methods will be used to quantitatively demonstrate the scale of project BC. From the above analysis, the groundwater water consumption directly affects the water transfer scale. Therefore, the scale of the groundwater exploitation rate will be established to demonstrate the scale. First, the groundwater exploitation rate is set to 80%, and a long series of monthly calculations are carried out.

The water transfer project operates only during the irrigation period from May to August, so only the monthly water shortage in the irrigation period is counted, as shown in Table 2; the data include the loss in the water transfer canal (loss coefficient of 0.12). The numbers in the table greater or equal to the design scale are listed in a bold italic format, indicating that this year is a destructive year (i.e., a water shortage appeared in this year), and in the last column (i.e., "destructive or not"), a value of 1 denotes destruction and a value of 0 denotes no destruction.

Based on the results in Table 2, according to the required annual guarantee rate of 75% in the paddy field, the monthly maximum water shortage is determined by a trial calculation, and the monthly water shortage represents the water transfer scale. According to the result of the trial calculation, with the groundwater exploitation rate set to 80%, the monthly design water transfer scale is approximately 358.5 m^3/s.

Table 2
Water shortage process of project BC under a groundwater exploitation coefficient of 0.8.

Year	May (m^3/s)	June (m^3/s)	July (m^3/s)	August (m^3/s)	Maximum value	Destruction or not
1956	324.8	319.3	284.3	239.7	324.8	0
1957	343.2	335.8	234.2	279.9	343.2	0
1958	349.0	364.9	322.0	274.8	364.9	1
1959	343.8	238.5	172.2	286.6	343.8	0
1960	317.7	323.9	324.4	310.7	324.4	0
1961	355.7	366.3	268.3	125.5	366.3	1
1962	340.0	350.9	263.5	302.4	350.9	0
1963	355.0	337.8	334.8	85.5	355.0	0
1964	355.2	298.3	342.0	245.7	355.2	0
1965	322.7	314.5	316.1	2.8	322.7	0
1966	348.6	342.2	320.9	191.5	348.6	0
1967	320.8	301.1	305.2	302.8	320.8	0
1968	332.1	380.5	375.3	285.2	380.5	1
1969	343.7	313.1	314.9	308.9	343.7	0
1970	324.8	341.4	320.7	316.1	341.4	0
1971	351.5	365.3	232.6	173.2	365.3	1
1972	362.4	366.9	258.3	231.5	366.9	1
1973	334.0	335.2	237.6	182.8	335.2	0
1974	357.4	342.3	323.0	264.1	357.4	0
1975	354.9	351.7	254.6	172.8	354.9	0
1976	329.2	335.2	315.0	122.4	335.2	0
1977	337.8	333.8	320.5	259.1	337.8	0
1978	329.0	339.3	299.3	231.9	339.3	0
1979	312.2	276.3	250.4	312.9	312.9	0
1980	338.8	356.1	319.2	331.9	356.1	0

Year	May	June	July	August	Maximum value	Destruction or not
	(m^3/s)	(m^3/s)	(m^3/s)	(m^3/s)		
1981	348.2	232.1	180.8	94.3	348.2	0
1982	340.5	358.5	337.2	230.0	358.5	1
1983	344.0	198.0	301.4	329.3	344.0	0
1984	357.8	341.5	345.9	261.1	357.8	1
1985	348.0	327.4	321.2	134.7	348.0	0
1986	338.9	319.0	320.3	234.8	338.9	0
1987	351.8	327.4	281.0	55.1	351.8	0
1988	358.5	355.8	301.9	343.2	358.5	1
1989	347.9	345.6	335.9	335.6	347.9	0
1990	342.6	342.3	344.6	117.8	344.6	0
1991	365.8	314.4	359.0	140.1	365.8	1
1992	336.9	333.4	324.5	307.6	336.9	0
1993	316.4	316.6	296.7	227.8	316.6	0
1994	365.1	370.9	169.9	64.0	370.9	1
1995	349.8	354.7	315.7	276.5	354.7	0
1996	354.2	351.0	325.3	246.5	354.2	0
1997	324.7	362.7	323.6	54.1	362.7	1
1998	350.4	337.7	293.2	252.6	350.4	0
1999	358.0	361.9	335.6	169.7	361.9	1
2000	319.3	394.8	383.0	291.9	394.8	1
2001	325.4	314.3	296.4	229.0	325.4	0
2002	337.9	324.4	333.2	243.4	337.9	0
2003	357.1	350.7	333.0	201.9	357.1	0
2004	328.7	321.0	314.2	326.7	328.7	0
2005	352.5	334.1	352.7	203.9	352.7	0
2006	343.5	351.9	259.0	177.2	351.9	0
2007	327.8	329.3	317.0	196.8	329.3	0

Year	May	June	July	August	Maximum value	Destruction or not
	(m^3/s)	(m^3/s)	(m^3/s)	(m^3/s)		
2008	373.0	387.5	332.2	184.6	387.5	1
2009	322.6	286.7	264.3	194.7	322.6	0
2010	331.0	344.7	314.9	165.2	344.7	0

The different scales of the groundwater exploitation coefficient can be used to obtain different scales of the canal head, as shown in Table 3.

Table 3
Results of project BC's canal head scale under different groundwater exploitation rates.

Groundwater exploitation rate	60%	65%	70%	75%	80%	85%
Canal head scale (m^3/s)	395.7	380.3	371.6	365.2	358.5	350.1

According to the above results, the groundwater consumption amount will directly determine the scale of the water transfer project. The study area is low and flat with a large area of cultivated land, and the wetland protection area is widely distributed with a large area. Thus, groundwater overexploitation will introduce more serious consequences to the land in this area. A small exploitation amount will cause waterlogging problems due to the high water level, while excessive exploitation will cause the declining groundwater problem to continue. According to relevant research results, the recovery of the water level is relatively slow when the groundwater exploitation rate in the water supply area is approximately 80%, and the groundwater level in some areas still maintains a downward trend. When the exploitation rate is approximately 75%, the groundwater depth is basically maintained at approximately 4 m ~ 6 m, which is a suitable burial depth. The amount of groundwater used in the comprehensive basin planning for the study area is basically maintained at approximately 75% of the exploitable amount. Based on the above results, it is recommended that the rate of exploitable groundwater is 75% of the canal head scale, that is, the scale of water transfer of the canal head of project BC is recommended to be 357.5 m^3/s.

Demonstration of the water transfer scale for project AB

Based on the above results, the scale of the groundwater extraction rate is recommended to be 75%. With a water transfer scale of 365.2 m^3/s for the BC canal head, the trial result of the AB canal head scale is 356.7 m^3/s.

Analysis of synchronous encounters of river A and river B

The above water transfer scale demonstration is carried out under the condition that the external water source is fully sufficient. In fact, it is restricted by the water from river A and river B. According to the above water transfer scale, there may not be a sufficient water transfer in some period of time, which will affect the guarantee rate of the agricultural irrigation water supply. In addition, the water of river A transferred into river B can make up for the lack of water in project BC due to the insufficient flow of river B, and thus, the inflow situation of river A will not only affect the water transfer of AB but also the process of the water transfer of BC together with the inflow of river B.

According to this analysis, during the 55 years of data for 1956 ~ 2010, there were 23 drought years, 3 relative drought years, 7 normal years, 6 relative flood years and 16 flood years for the river A transfer section. Among them, 1967 ~ 1971 was a drought period for 4 consecutive years, and 1999 ~ 2008 was a drought period for 10 consecutive years with 2 relative drought years.

During the 55 years of data, there were 22 drought years, 2 relative drought years, 10 normal years, 6 relative flood years and 15 flood years for the river B transfer section. Among them, 1974 ~ 1980 was a drought period for 7 consecutive years, and 1999 ~ 2010 (except for one normal year in 2009) was the other 11 drought years.

Evidently, river A and river B also experienced drought in the same year, i.e., the continuous 12-year drought period in 1999 ~ 2010 (except that river B was basically normal in 2004).

In addition, from the time interval analysis, when navigation flow in river A and river B and the upstream and downstream water consumption are further considered, the amount of water from the river A water transfer section from May to August 2008 was only 5.0×108 m^3, of which there was zero transferable water from May to July. The transferable water amounts of the river A water transfer section in August 1968, July 1979, June 1986, May 1987, May 1993, June 1996 and June 2000 were all 0, and thus, they were unable to meet the requirements of a water supply. The water amount of the river B water transfer section was also lower than the planning year navigation flow in some years and periods. Although the amount of water in the water source area was able to meet the demand for water transfer in most years and most of the period, there may not be any water supply in some periods of special years (i.e., drought years).

The nonparametric kernel density estimation method and Copula function were combined to calculate the river A and river B inflow in different months during the period of irrigation (Tu et al. 2017). Through this calculation, the two rivers always experience flooding or drought at the same time during the irrigation period and especially have the possibility of drought during the same period, which is more likely to be in May and July (see Fig. 5).

The above analysis shows that the inflow of river A and river B is very small in drought years, and there are multiple years and multiple periods of drought at the same time. Therefore, a demonstration of the water transfer project scale should consider the influence of inflow.

Analysis and determination of the water transfer scale

By comparing the initial water transfer scale with the inflow of rivers A and B, the total water transfer scales of projects AB and BC are determined to be 357 m^3/s and 366 m^3/s, respectively, under the premise that the water supply guarantee rate in the guaranteed irrigation area is 75%; these values are 15% and 13% of the water transfer scale of conventional methods.

Discussion

Discussion on the applicability of the method

This method is applicable to water transfer projects mainly based on agricultural irrigation in plain areas. Because the guarantee rate of agricultural irrigation in China is relatively low and the variation in the agricultural water demand is relatively large, if the agricultural water demand is fully met in an extraordinary drought year ($P > 90\%$), the water transfer scale will be very large. At the same time, the surface water irrigated by the water transfer project can supply groundwater with irrigation runoff and raise the groundwater level. For plain areas frequently afflicted by flooding, the water supply method with a combination of groundwater and surface water, that is, well - canal irrigation, can be used to reduce the water transfer scale, and the economy is relatively good. For an urban water supply, the water supply guarantee rate for urban life ($P > 95\%$) and urban industry ($P > 90\%$) is high, the relative change in the urban water demand is relatively small, and the influence of precipitation is relatively small. At the same time, there is little change in the supply between the urban water supply and the groundwater supply; therefore, the scale of water transfer can be directly determined by the urban water demand.

Influence of the water transfer source

The water transfer source, especially for rivers with substantial changes in flooding and drought and large water consumption both upstream and downstream, has a great influence on the scale of the water transfer project. According to the first order of the initial right to a water source, the demand of upstream water users takes priority. If the upstream water use increases suddenly, the transferable water amount will be reduced accordingly; however, the water intake should be guaranteed for the downstream users, who also have a right to the water, and their intake cannot be greatly affected by the water transfer, especially in a drought year. In addition, for some rivers with navigation requirements, the requirements of the water level and variation range of the river are relatively high, and thus, the water transfer project will not have a great impact on the navigation. On the one hand, to reduce the influences of changes in the flooding and drought of water sources on water transfer projects, the water transfer scale should be increased; on the other hand, to reduce the impacts on other users and navigation, the water transfer scale should be reduced appropriately, and thus, the effect of the water transfer source should be fully considered when the final water transfer scale is being determined.

Conclusions

Based on the inter-basin agricultural water transfer project in the Sanjiang Plain, Northeast China, combined with the suitable development scale of the irrigation area with the joint allocation of existing water sources, this research proposes a technique to demonstrate the scale of an inter-basin water transfer project based on dynamic trial feedback and the optimization method involving the despiking of the groundwater allocation; the water transfer project scale is demonstrated for each section along the route in reverse order.

First, the scale of the irrigation area at the last water diversion outlet of the water transfer project is determined. After the local surface water and groundwater are optimized, based on the water shortage in the irrigation area, the initial water transfer scale is assumed, the water supply guarantee rate is calculated, and the dynamic trial calculation is carried out until the water supply can meet the required water supply guarantee rate according to the assumed scale. The water transfer process is determined according to the initial scale, and the amount of groundwater recharged by irrigation runoff is assumed. The exploitable amount of groundwater is recalculated, and the optimized allocation of groundwater is carried out again. A dynamic trial of the water transfer scale is recalculated until the difference between two initial water transfer scales is sufficiently small. The water transfer process of the last water diversion outlet is combined with the total water demand of the second-to-last water diversion outlet. After the optimal utilization of the local surface water and groundwater (i.e., the utilization during any period of time is no greater than the water demand of the second-to-last water diversion outlet), the same dynamic trial feedback is used to determine the scale up to the canal head.

The results show that under the premise of a 75% guarantee rate for the water supply in the irrigation area, the total water transfer scales of routes AB and BC are finally determined to be 357 m^3/s and 366 m^3/s. The final water transfer scale obtained with the proposed method is relatively smaller than obtained with the conventional method. Compared with the conventional method, the water transfer scales for routes AB and BC decreased by 15% and 13%, respectively.

When the water is transferred, the process is stable, and the utilization rate of the canal is high, thereby saving investment funds and facilitating the project scheduling and management.

Declarations

Funding

This research was financially supported by the National Natural Science Foundation of China, grant numbers 51625904 and 51779271, and the IWHR Research & Development Support Program, grant numbers WR0145B522017 and WR0145B622017.

Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest or competing interests.

Availability of data and material

The data and material used in this research will be available on request from the corresponding author.

Code availability

The software code used in this research will be available on request from the corresponding author.

Authors' contributions

Conceptualization, Jianhua Wang and Baodeng Hou; Data curation, Baodeng Hou and Fan Lu; Formal analysis, Baodeng Hou, Yong Zhao and Weihua Xiao; Methodology, Jianhua Wang, Weihua Xiao and Fan Lu; Software, Jianhua Wang and Yong Zhao; Writing – original draft, Jianhua Wang, Baodeng Hou and Weihua Xiao; Writing – review & editing, Jianhua Wang and Baodeng Hou.

Ethics approval

This manuscript does not require ethical approval.

Consent to participate

No volunteers or animals were involved in the study.

Consent for publication

This manuscript will be published if accepted.

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Figures

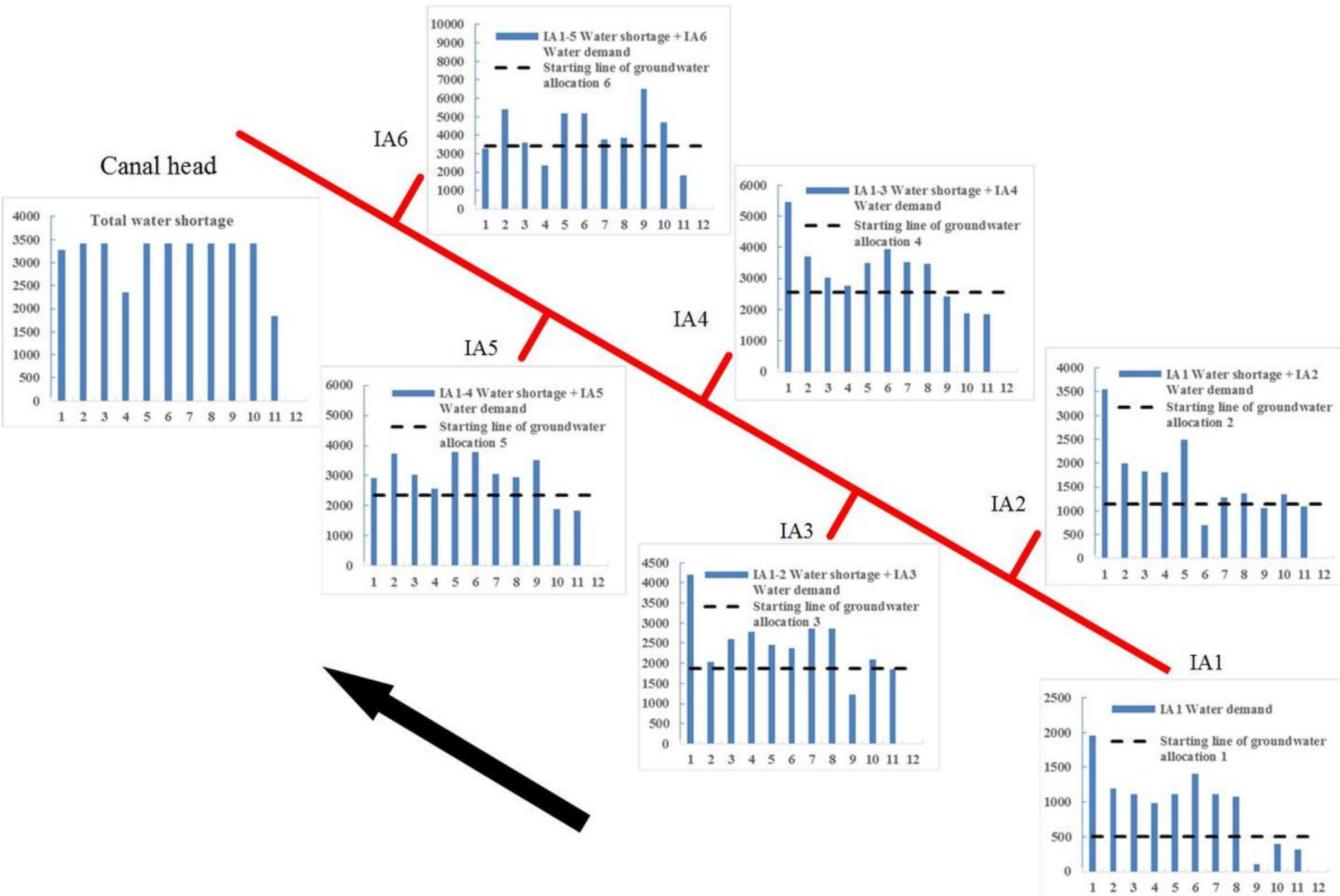

Figure 1

Schematic diagram of the scale of water transfer projects in 6 irrigation areas (one year).

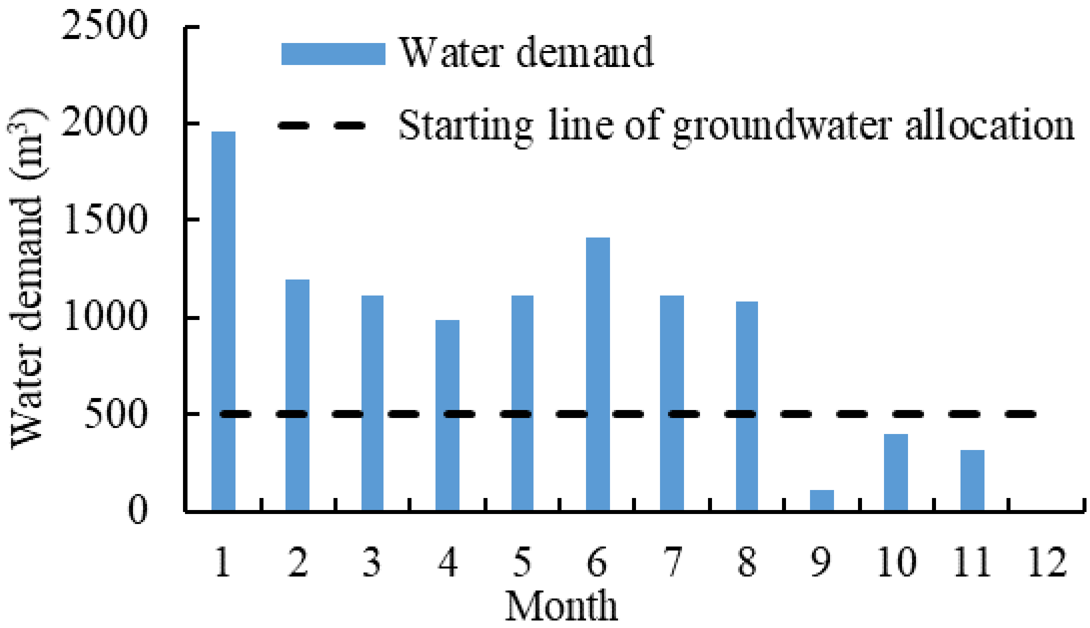

Figure 2

Schematic diagram of the despiking of groundwater allocation.

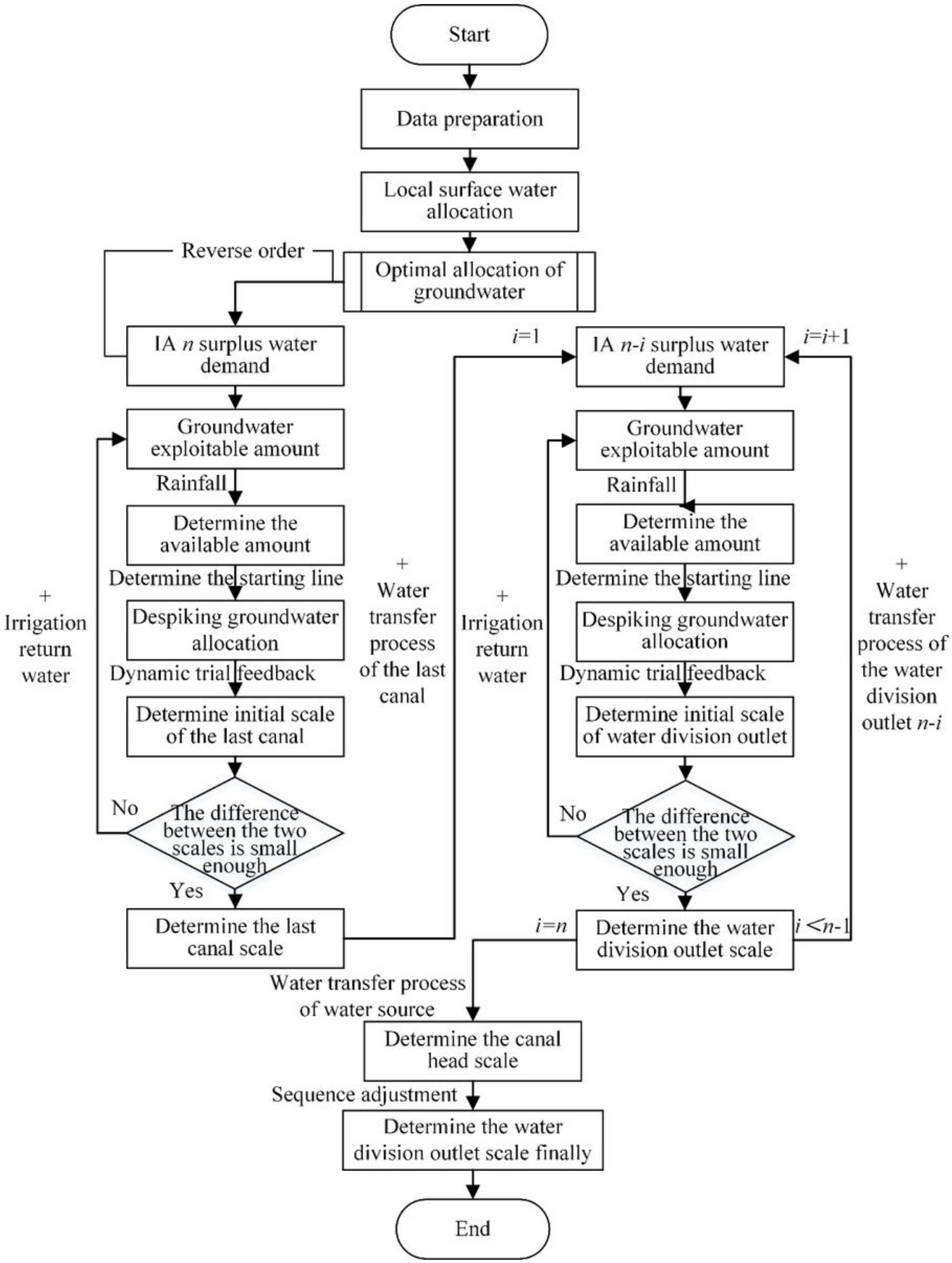

Figure 3

Implementation steps for examining the water transfer project scale.

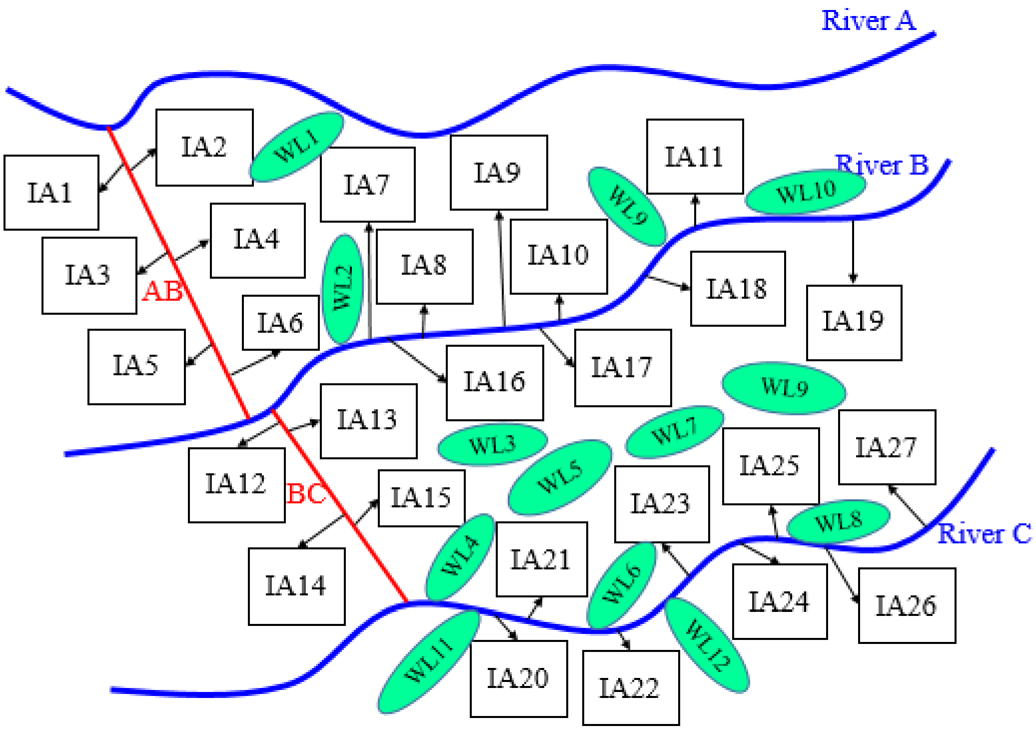

Figure 4

Sketch map of the study area (IA=irrigation area, WL=wetland).

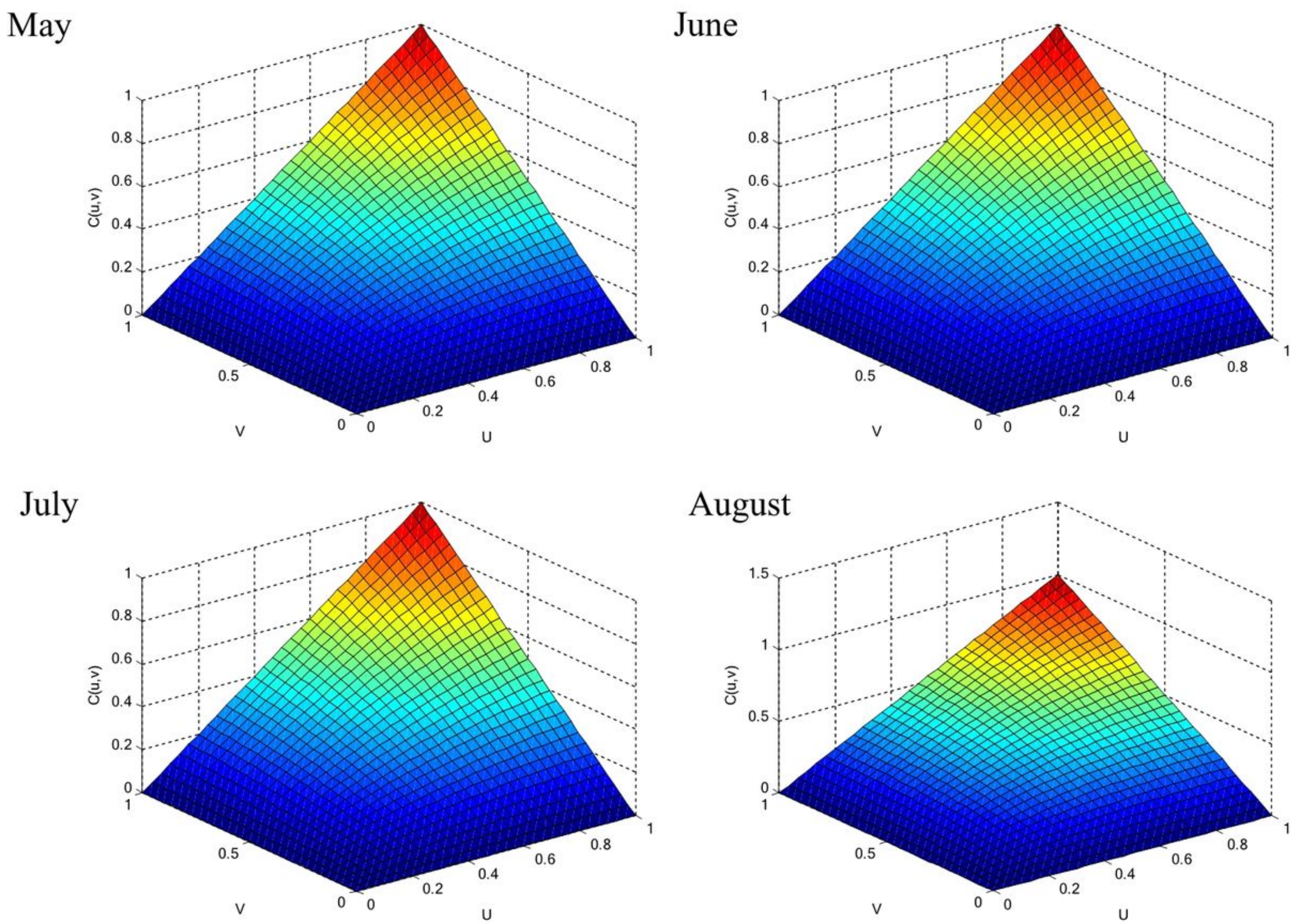

Figure 5