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Article

Optimal Water Resources Allocation under the Constraint of Land Use in the Heihe River Basin of China

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Abstract: In recent years, water scarcity and irrational utilization have become the pivotal issues for the sustainable development of river basins in China. This paper attempts to propose a new perspective for the optimization of water resources allocation in a typical river basin. In order to conduct an accurate and feasible program for water resources allocation in the water-deficient river basin, a multi-objective and multi-constraint programming model was developed by embedding land use effect as a constraint on water allocation, which was currently solely decided by water resources demand in different water use sectors. The program includes two layers, namely water allocation among different counties located in the middle reaches of the Heihe River Basin and among domestic, industrial, agricultural and ecological uses within one county. Empirical analysis shows that the structural change of land use has an important influence and restriction on the water resources allocation in the river basin. The least cultivated areas that ensure food security and the constraint of construction land quota have great impact on agricultural and industrial water allocation. Moreover, the quantitative change of ecological land greatly affects ecological water allocation. The results demonstrate that the optimal program calculated from land use embedded model can well predicate the actual situation of water allocation in the future. To ensure regional sustainable development, it is vital that reasonable water-saving measures in each water use sector and ecological protection policies be taken.

Keywords: water resources allocation; land use; sustainable water use; optimal allocation model; Heihe river basin

1. Introduction

Recent decades, rapid urbanization, industrialization, population growth, and the increasing competition for scarce natural resources has made China face great water management challenges, especially in river basins with fragile ecologies [1,2]. Water resources scarcity has become one of the determinants which restricts social and economic sustainable development in these regions. Improving water use efficiency by means of optimizing water resources allocation nowadays has been considered as the fundamental method for solving water scarcity in river basin [3]. However, the problem of insufficient or excessive water allocation within each sector may occur in the traditional water allocation pattern, which distributes water resources based on the current situation and trend of water use. In addition, insufficient knowledge of available water resources, lack of coordination in water resources allocation and management, and drought episodes in the river basin often result in water deficits which have hampered the harmonious development and destroyed the ecological balance [4–6] in the basin. Therefore, water allocation decisions that consider equity, efficiency, and sustainability in every water sector should be treated as the main goal of decision-makers in the river basin.

Land is the carrier of social and economic development and human activities. Each type of land use area, such as agricultural land and construction land, directly influences the scale of each industry and the population supporting capacity. Meanwhile, the main aim of water resources allocation is to find a balance for allocation methods among different water use sectors, such as domestic water, agricultural water and industrial water to ensure the sustainable development of society and economy. It is obvious that land use plays an enormously important role in water resources allocation. Especially in integrated river basin management, water and land resources have been closely linked together. Thus, it is of great significance to take land use as a critical factor in water allocation in river basins.

Heihe river basin is a typical region of water shortage. With the rapid population and economy growth, unreasonable water allocation, disordered water resources exploitation has put Heihe River Basin facing serious ecological problems for nearly half a century. Thereby, it is crucially important to make scientific water allocation policy for balancing economic development and environmental protection of every county in Heihe River Basin. Conventional water allocation researches that only concentrates on water demand and supply but ignores the interplay between water resources and land use, cannot reveal the impacts of land use on water resources utilization and allocation [7,8].

This paper attempts to solve the problem of insufficient or excessive water allocation, which may occur under the traditional way of water allocation and propose a water resources allocation scheme that can well match water requirements of various competing sectors including domestic water demand, industrial water demand, agricultural water demand and ecological water demand in the middle reaches of Heihe River Basin. To achieve this aim, we construct a multi-objective optimal water allocation model under the constraint of land use to attain both economic and ecological sustainability. The paper is structured as follows: A literature review on optimal water resources allocation is summarized in Section 2.

The study area and data collection are described in Section 3. Section 4 shows the methodology of optimal water resources allocation under the constraint of land use in detail. Meanwhile, in Section 5, the derived optimal water resources allocation scheme that includes water allocation strategy among counties, as well as among sectors within each county in the middle reaches of Heihe River Basin is discussed. Finally, we conclude our study and suggest the possible issues for future study in optimal water resources allocation of river basin in Section 6.

2. Literature Review

The aim of optimal water resources allocation is to reallocate the limited water resources scientifically among different water use sectors based on a fair, effective and sustainable principle in a given region through measures such as restraining water demand reasonably , increasing water supply effectively, and protecting the ecological environment positively [9,10]. In terms of this field, the current research either focuses on agricultural irrigation water allocation, regional water resources allocation in different water use sectors or new methodology. Agricultural irrigation water allocation is a concern of most literatures because it accounts for most of the water consumption. Paul used a multi-level approach which consists of seasonal and intraseasonal levels to solve irrigation water resources allocation problem in semiarid region [11]. Salman designed an agricultural water allocation system (SAWAS) model for quantitatively and qualitatively analyzing inter-seasonal allocation of irrigation water and its impact on agricultural production and income [12]. In the modern agricultural development stage, the optimization of water resources allocation is an important premise for the development of efficient agriculture. Under the principle of maximum efficiency and decomposition harmonization, Shangguan presented a model for regional optimal allocation of irrigation water resources [13]. In addition, Ortega described the MOPECO model for irrigation water management in a semi-arid area of Spain and drew a conclusion that the irrigation depth for maximum benefits is lower than that necessary to obtain maximum production [14].

With the rapid social and economic development, the water demand in every industry keeps growing. How to allocate the limited water resources reasonably among different water use sectors to ensure the sustained economic growth becomes increasingly significant. Juan proposed an economic optimization model based on crop, irrigation district, and basin level for water planning in deficit irrigation systems [15]. Chakravorty suggested that market power of each micro-market should be taken into consideration in water allocation [16]. Wang developed an optimal water allocation model based on water resources security assessment [17]. Nikoo combined water with waste-load as a whole and optimized them with a fuzzy transformation technique [18]. Frank provided a framework for identifying, designing, and implementing water allocation rules for food security in the developing world's irrigated areas [19]. Besides, Fotakis integrated land-use and water allocation planning to maximize economic benefit, while minimizing water extraction and transportation cost under ecological constraints [20].

The optimization of water resources allocation is a complex process. Improving the existing methodology or creating new methodology to make the water allocation program more accurate is always the emphasis. Babel introduced a simple interactive integrated water allocation model which consists of three modules, *i.e.*, a reservoir operation module, an economic analysis module and a water allocation module [21]. Jeniffer applied water evaluation and planning model to evaluate water resources development based on an equilibrium scenario of the current water demand in the Upper Ewaso Ng'iro

North Basin, the results showed that high water irrigation demand was the main reason for a regional water shortage [22]. A methodology based on crisp and fuzzy shapley games to reallocate water resources in different users in Karoon river basin was proposed by Mojtaba Sadegh [23]. Lu constructed the IRFLP model, and conducted a comparison between the IRFLP model and the interval-valued fuzzy linear programming model in water allocation [24]. Moreover, Fotakis put forward an innovative evolutionary algorithm for treating combined land use planning and resource allocation problems by means of multi-objective self-organizing optimization algorithm (MOSOA) [25]. Aerts demonstrated how simulated annealing can be applied to a case study in Galicia, Spain, using an SDSS for supporting the restoration of a former mining area for new land use [26].

However, land use is overlooked in the above research, although it is the most significant factor that affects regional hydrology and water resources allocation. It is generally known that land use change will directly cause land cover change which in turn influences hydrologic cycle and water balance (e.g., available water resources, surface water flow, groundwater recharge, fluviatile deposit and water storage capacity), as well as peak flow, time to peak and flood volume [27,28]. Moreover, the transformation of agricultural or ecological land into construction land caused by rapid urbanization is irreversible, which make urban industrial and residential water demand keep increasing. Meanwhile a certain amount of cultivated land to guarantee food security would also affect the agricultural water demand. Especially the latter will directly affect water resources allocation between different water consumption sectors. Hence, a water allocation program that ignores land use constraint is doomed to lack of accuracy and feasibility. To make the water resources optimal allocation results more accurate and scientific, the researchers has developed a multi-objective restriction water resources allocation model, in which land use is embedded as a constraint, and has conducted an empirical study in the middle reaches of the Heihe River Basin. This research can provide decision support for river basin water resource management.

3. Materials

3.1. Study Area

The Heihe River Basin is located in the arid northwest region of China and is the second largest interior territorial river of China, with a mainstream of 928 km length and a drainage area of 11.6×10^4 km^2. Heihe originates from Qilian Mountain, flows across hinter land of northwest inland of China and ends at Ejina at the border between the northern Inner Mongolia and Mongolia. The multi-year average annual precipitation of the Heihe River Basin is 12.26×10^9 m^3 in which approximately 77% is consumed of evaporation, and only 23% convert into surface water and groundwater. The mean annual runoff of the Heihe main stream is only 15.8×10^8 m^3. The upper reaches of the Heihe River Basin is a runoff formation area and the alpine cold desert accounts for 22%, while the lower reaches is a runoff fade area with a huge evaporation capacity, which water yield is 0.95×10^9 m^3.The middle reaches of the Heihe River Basin discontinuous distribution of oasis, wilderness, gobi and desert, and is an important part of Hexi Corridor. The area is abundant with solar energy resources and there is a significant temperature gap between day and night. The middle reaches where concentrates 95% of the cultivated land, 91% of the population and more than 80% of the GDP, consumes most runoff. The middle reaches of the Heihe River Basin are also the main irrigated agricultural zone of Gansu province, and hence play a vital role in regional food security. For these reasons, the middle reaches of Heihe River Basin were chosen as a pilot study area. The middle reaches of Heihe River Basin ranges approximately from 97°20′E to 102°12′E, 37°28′N to 39°57′N, and is composed of nine counties or districts: Jinta County, Jiayuguan City, Suzhou District, Gaotai County, Sunan Yugur Autonomous County, Linze County, Ganzhou District, Shandan County and Minle County, as shown in Figure 1. The Heihe River is the primary water source supply for domestic water, ecological water, agricultural water and industrial water of all of the above nine areas, and each of them is in a state of critical water balance. Conflicts over water use between them are becoming much more severe and enduring, thus hampering their sustainable development.

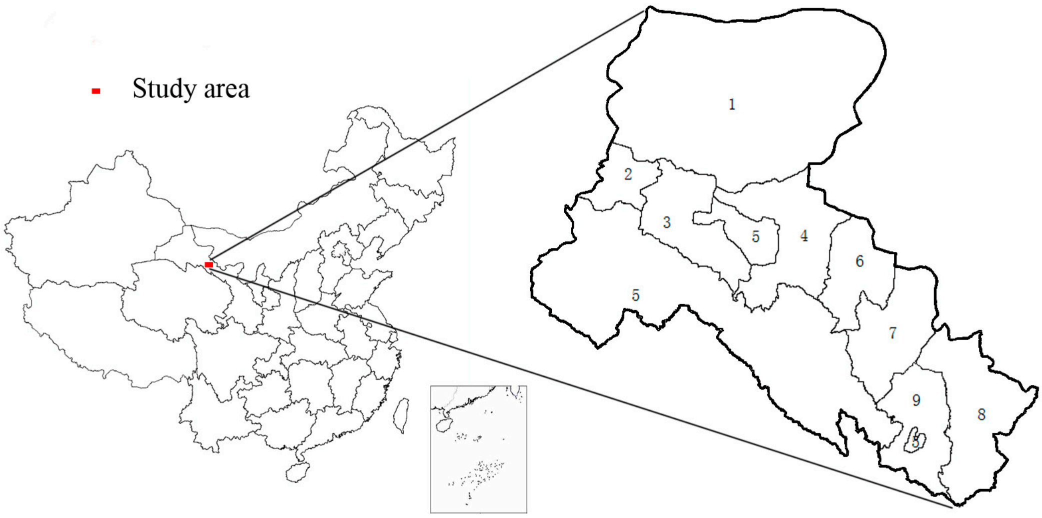

Figure 1. Location of study area. The administrative divisions are: 1: Jinta County; 2: Jiayuguan City; 3: Suzhou District; 4: Gaotai County; 5: Sunan Yugur Autonomous County; 6: Linze County; 7: Ganzhou District; 8: Shandan County; 9: Minle County.

3.2. Data

Data employed in this research mainly includes socio-economic data, land use data, and water resources data. The socio-economic data all come from the Statistics Yearbook of Gansu province published by National Bureau of Statistics of China, 1988–2009. The land use data are extracted from TM data of the Heihe River Basin from the years 1988, 1995, 2000, 2005 and 2008, and the general plans for the land use of every county. The water resources data are all acquired mainly from the official reports on water resources of Gansu province published by Gansu Provincial Water Resources Bureau. The other essential data are computed according to Partial-Survey data in the study area.

4. Methodology

An optimal water resources allocation model based on land use constraint is proposed in reference to the previous studies for the optimal use of river basin water resources [29–31]. The model employed primarily includes two aspects: one is the objective function, which is designed to allocate water to maximize the economic, social and ecological benefits of different water consumption sectors, and the other is constraint equation which is designed to set up the constraints according to the local resource condition and socio-economic development level [32,33]. In particular, the land use factor was embedded into the model to improve accuracy and practical applicability of the model. Figure 2 shows a flowchart for constructing the optimal water resource allocation model based on land use constraint. (Here, construction land includes residential land, industrial land, storage space land, public facilities land and so on).

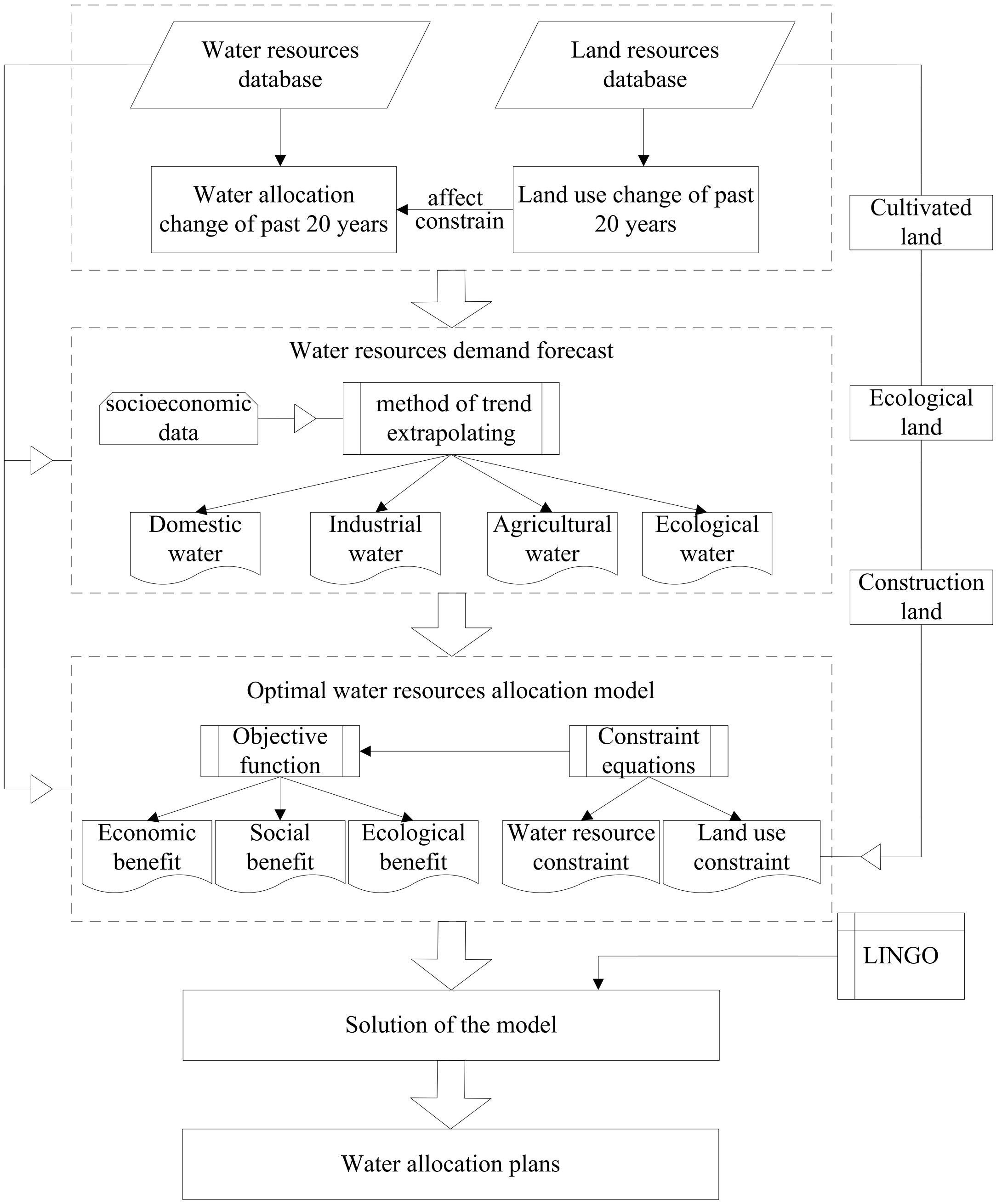

Figure 2. Flowchart of the research.

4.1. Land Use Change Depiction Method

In order to explore the relationship between land use change and water resources allocation in the river basin, we depict the process of land use change during the past several years. First, the index of Rate of Single Type Land Use Change was employed.

The Rate of Single Type Land Use Change is expressed as:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \tag{1}$$

where K is The Rate of Single Type Land Use Change; U_a and U_b represent the beginning and end areas of a specific land use type in a sub-district of the study area during the study period, respectively; T is the study period.

The Rate of Single Type Land Use Change can reflect land use change in a sub-district during the study period. By this indicator of land use change and water resources allocation change among different water use sectors, the changing rules and coupling relationship between the two can be seen and revealed.

4.2. Water Resources Demand Predication Method

In this paper, water resources demands were classified as follows: (a) domestic water demand, mainly including urban residents' daily water consumption and rural residents' daily water consumption; (b) industrial water demand, mainly including water use by thermal power industry, nuclear power industry and general industry; (c) agricultural water demand, mainly including farmland irrigation water requirement, forest and fruit land use, and livestock husbandry water use; (d) ecological water demand, mainly including water use of graze, water and soil conservation, sand-fixing forest. The four types of water demand were predicated as follows [34].

4.2.1. Domestic Water Demand Predication

The domestic water demand was calculated as:

$$DWD = \sum_{sd=1}^{sd} \left[\left[P_{sd}^{U} (1+\mu_{sd}^{U})^{n} + P_{sd}^{R} \sigma_{sd} \right] K_{sd}^{U} \right] + \left[\left[P_{sd}^{R} (1+\mu_{sd}^{R})^{n} - P_{sd}^{R} \sigma_{sd} \right] K_{sd}^{R} \right] \tag{2}$$

where DWD is domestic water demand of the whole study area in the forecast year; P_{sd}^{U} and P_{sd}^{R} present urban and rural population in one sub-district; μ_{sd}^{U} and μ_{sd}^{R} represent natural urban and rural population growth rate; n is the time interval between forecast base year and the forecast year; σ_{sd} is the rate of rural population emigration; K_{sd}^{U} and K_{sd}^{R} are the urban and rural per capita water use quota in the forecast year of one sub-district which can be speculated through the change of specified standards of water use quota during the past several years.

4.2.2. Industrial Water Demand Predication

The industrial water demand was calculated as:

$$IWD = \sum_{sd=1}^{sd} W_{sd}(1 + r_{sd})^n \quad (3)$$

where IWD is industrial water demand of the whole study area in the forecast year; W_{sd} represent industrial water use of one sub-district in the forecast base year; r_{sd} is the average annual growth rate of industrial water use in the sub-district which can be calculated by the change tendency of industrial water use in the past several years; n is the time interval between forecast base year and the forecast year.

4.2.3. Agricultural Water Demand Predication

The agricultural water demand was calculated as:

$$AWD = \sum_{sd=1}^{sd} \left[\left(\frac{S_{sd}^{F}\alpha_{sd} + S_{sd}^{O}\beta_{sd}}{\eta_{sd}} \right) + Q_{sd}\xi_{sd} \right] \quad (4)$$

where AWD is agricultural water demand of the whole study area in the forecast year; S_{sd}^{F} and S_{sd}^{O} are the area under irrigation farmland and forest and fruit land irrigation area of one sub-district in the forecast year, which can be acquired by curve fitting of the existing irrigation area data in the past years; α_{sd} and β_{sd} represent water use quota of area under irrigation farmland, and forest and fruit land irrigation respectively in the forecast year of the sub-district which can be acquired like K_{sd}^{U}, K_{sd}^{R} in Formula (3); η_{sd} is the water utilization coefficient of irrigation of the sub-district, which means the percentage of effective irrigation water utilization in the total supply of irrigation water; Q_{sd} is livestock number of the sub-district in the forecast year, and ξ_{sd} is the livestock water use quota in the forecast year of the sub-district.

4.2.4. Ecological Water Demand Predication

The ecological water demand was calculated as:

$$EWD = \sum_{sd=1}^{sd} A_{sd}\delta_{sd} \quad (5)$$

where EWD is ecological water demand of the whole study area in the forecast year; A_{sd} is the area of ecological land including forest land, grassland and water area in the forecast year of the sub-district; δ_{sd} is the ecological water use quota in the forecast year of one sub-district, which also can be acquired like K_{sd}^{U}, K_{sd}^{R} in Formula (3).

4.3. Optimal Water Resources Allocation Model Construction

An optimal water resources allocation model was constructed to achieve the maximum comprehensive benefit for the river basin socio-economic and eco-environmental systems through allocating limited water resources under the constraint of land use reasonably and scientifically The optimal water resources allocation model consists of two parts, *i.e.*, the objective function including economic objective, social objective, and ecological objective function and constraint equations which embed land use factor. The water consumption of all water use sectors were chosen as independent variables in this model.

4.3.1. Objective Function

(1) Economic function

$$f(x) = \max\left(\sum_{sd=1}^{sd}\sum_{i=1}^{i} B_i^{sd} X_i^{sd} - \sum_{sd=1}^{sd}\sum_{i=1}^{i} C_i^{sd} X_i^{sd}\right) \quad (6)$$

where $f(x)$ represents economic benefits of water resources use as the GDP of whole river basin. B_i^{sd} is the output of per water unit of sector i in sub-district sd; X_i^{sd} is the total water supply of sector i in sub-district sd; C_i^{sd} is the cost of per water unit of sector i in sub-district sd.

(2) Social function

The social benefits of water use include many aspects. It is hard to quantify social benefits. Limited by data availability, we chose min water deficit as a proxy to reflect max social benefits.

$$f(y) = \min\left(\sum_{sd=1}^{sd}\sum_{i=1}^{i} (D_i^{sd} - X_i^{sd})\right) \quad (7)$$

where $f(y)$ represents social benefits of water resources use, *i.e.*, the totality of min water deficit of all water use sectors in the river basin; D_i^{sd} is the water demand of sector i in sub-district sd.

(3) Ecological function

Existing research commonly adopts the minimization of pollution, which is caused by water resource utilization as ecological objective. Considering the researchers didn't acquire the relevant data, this paper used a more global index "ecological water deficit" to measure ecological objective.

$$f(z) = \min\left(\sum_{sd=1}^{sd} (D_{ec}^{sd} - X_{ec}^{sd})\right) \quad (8)$$

where $f(z)$ represents ecological benefits of water resources use, *i.e.*, the totality of min ecological water deficit of the river basin; D_{ec}^{sd} is the ecological water demand in sub-district sd; X_{ec}^{sd} is the ecological water supply in sub-district sd.

Hence our objective function which is designed to achieve the maximum integrated benefit can be expressed as the following equation:

$$OF = f(x) + f(y) + f(z) \quad (9)$$

4.3.2. Constraint Equations

(1) Exploitation ratio of water resources

$$\frac{\sum_{sd=1}^{sd}\sum_{i=1}^{i} X_i^{sd}}{TAWR} \le ER \quad (10)$$

where ER indicates the safety water resources exploitation and utilization ratio; $TAWR$ is the total amount of water resources of research area.

(2) Domestic water supply per capita

$$X_{pd}^{sd} \geq DS \tag{11}$$

where X_{pd}^{sd} is the domestic water supply per capita in sub-district sd, while DS stands for the standard of domestic water supply per capita.

(3) Industrial water supply

$$X_{in}^{sd} \geq MI \tag{12}$$

where X_{in}^{sd} is the industrial water supply in sub-district sd, and MI is the minimum demand for industrial water in sub-district sd.

(4) Agricultural water supply

$$X_{ag}^{sd} \geq MA \tag{13}$$

where X_{ag}^{sd} stands for the agricultural water supply in sub-district sd, and MA is the minimum demand for agricultural water in sub-district sd.

(5) Cultivated land quantity restrict

To guarantee food security of the study area, a certain amount of cultivated land resources must be strictly reserved. Correspondingly, in water resources supply, the portion of agricultural irrigation water should be matched with the cultivated land.

$$X_{cl}^{sd} \geq CI \tag{14}$$

where X_{cl}^{sd} is the cultivated land irrigation water supply in sub-district sd, and CI is the water demand for the minimum cultivated land irrigation in sub-district sd.

(6) Ecological land restrict

To maintain regional ecological security, and to ensure the ecosystem balance, ecological land such as forest land, grassland and water area must be controlled within limits.

$$X_{ec}^{sd} \geq ME \tag{15}$$

where X_{ec}^{sd} stands for the ecological water supply in sub-district sd, and ME is the minimum demand for ecological water in sub-district sd.

(7) Positive constraints

$$X_{i}^{sd} \geq 0 \tag{16}$$

4.3.3. Model Solution

The proposed optimal water resources allocation model under the constraint of land use involves multiple objectives, constraints, and decision variables related to socio-economical and eco-environmental systems. Generally speaking, the most conventional method to solve such a complex optimal model is to change the multi-objective problem into a single objective problem by using the system analysis theory. In this paper, we choose linear programming software LINGO to solve the allocation model.

5. Results and Discussion

5.1. Land Use and Water Allocation Change

The rate of single type land use change in the middle reaches of the Heihe River Basin between the years 1988 to 2008 were calculated according to Formula (1). As for cultivated land, the biggest change was in Linze County, which increased by 2.10%. Followed by Jinta County, Sunan Yugur Autonomous County and Ganzhou District, yielding increases of 1.27%, 1.06% and 0.89% respectively; the largest forest land change was in Jiayuguan City and Gaotai County, in which Jiayuguan City decreased by 3.00%, while Gaotai County increased by 0.97%; as for grassland, the most significant change comes from Linze County, which was reduced by 1.42%; the diminishing phenomenon of water area and unused land was appeared in almost every sub-district. For example, the water area decreased by 1.11% for Linze County and 0.93% for Ganzhou District, while the unused land decreased by 0.46%, 0.35%, 0.32% for Minle County, Jiayuguan City and Suzhou District, respectively; in contrast to water area and unused land, all the sub-districts had a different degree of increase construction land. Especially in Suzhou District, Linze County and Jiayuguan City, the corresponding growth rate was 3.55%, 3.41% and 3.13%, respectively.

The change of water allocation among different water use sectors can be acquired and calculated from the Water Resources Bureau. In Suzhou District and Jiayuguan City, the domestic water consumption increased most significantly, reaching 15.95% and 13.01%, respectively; Sunan Yugur Autonomous County industrial water increased by 22.26% due to the booming secondary industry, and Suzhou District followed with a rate of 5.57%; as for agricultural water, the maximum growth rate was in Linze County (5.73%), Sunan Yugur Autonomous County (4.75%) and Ganzhou District (4.62%); the highest decreasing districts of ecological water were Ganzhou District (5.68%), Jiayuguan City (5.60%) and Gotai County (5.26%).

Compared land use change with water allocation change, we can find that there was an obvious consistency between the domestic and industrial water allocation change and the construction land change; the change of agricultural water allocation corresponded to cultivated land variation in one district over the same period; the decrease of ecological water is often accompanied by the reduction of ecological water consumption. In consequence, land use has a pronounced effects and constraints on water resources allocation of river basin. Embedding land use factors into allocation model is enormously essential and will greatly improve the accuracy and application value of the model.

5.2. Forecasted Water Resources Demand

The domestic water demand, industrial water demand, agricultural water demand and ecological water demand in every sub-district of the middle reaches of the Heihe River Basin in 2020 were forecasted according to Formulas (2)–(5), and the results are shown in Table 1.

Table 1. Water demand predication in 2020 (unit: 10^4 m^3).

Sub-District	Domestic Water Demand	Industrial Water Demand	Agricultural Water Demand	Ecological Water Demand
Jinta County	529.69	73.05	54,316.43	283.83
Jiayuguan City	1241.50	6350.25	3201.97	986.43
Suzhou District	1132.38	354.08	53,195.96	76.71
Gaotai County	360.57	261.92	30,098.00	147.65
Sunan Yugur Autonomous County	132.29	955.18	5034.97	951.28
Linze County	1195.23	577.37	30,232.01	323.18
Ganzhou District	1710.78	1158.74	75,135.72	124.72
Shandan County	584.30	350.19	24,372.53	211.20
Minle County	545.09	308.53	31,840.16	442.35

There was an enormous difference on water demand among different water use sectors and each sub-district (Table 1). The main reason for this difference was the discrepancies in the level of economic development, dominant policy, natural conditions, populations and life styles. As is shown, Ganzhou District has the greatest total water demand probably because of the dense population and the relatively higher level of economic development. Furthermore, the huge agricultural water demand in Ganzhou District can be attributed to its role as China's key commodity grain base. In addition, agriculture is the main economic development mode in this region, and correspondingly the agricultural water demand is far larger than other water demand type in most counties except for Jiayuguan City which is an "industry priority" district. The biggest territory area but with the least domestic water demand in Sunan Yugur Autonomous County indicated that population is the most critical factor to determine domestic water demand. The population density of Sunan Yugur Autonomous County is only 1.5 person per km^2. Additionally, the industrial structure and functional orientation determine the lower industrial water demand and the higher agricultural water demand in Jinta County. The ecological water demand in Suzhou District was at a quite low level no matter compared to ecological water demand in other sub-districts or to other water use sectors of this region. This was mainly related to regional land use structure. The ecological land just occupied a small proportion in Suzhou District.

Agriculture being the leading industry of the middle reaches of the Heihe River Basin, agricultural land accounts for nearly 40% of total areas, with low water utilization coefficient of irrigation. For this reason, this region has more agricultural water demand. Ecological water demand accounts for only a very small part of all water resources demand mainly because the percentage of ecological land itself is much lower compared with agricultural land and construction land, and part of them was occupied and transformed into construction land every year.

5.3. Optimal Water Resource Allocation

Based on the water demand forecast for each sub-district of the middle reaches of the Heihe River Basin, we obtained the water allocation planning according to the insertion of Formulas (9)–(16) into LINGO. Water consumption allocations for each sub-district under the maximum exploitation degree of regional water resources under the constraint of land use are shown in Table 2.

Table 2. The optimal water resource allocation result in 2020 (unit: 10^4 m^3).

Sub-District	Domestic Water	Industrial Water	Agricultural Water	Ecological Water
Jinta County	1469.76	94.18	54,387.61	283.83
Jiayuguan City	3813.62	11,703.90	3204.99	986.42
Suzhou District	3969.64	650.36	53,226.08	76.71
Gaotai County	1036.64	401.08	30,136.36	147.65
Sunan Yugur Autonomous County	417.02	1934.44	5039.71	951.27
Linze County	3267.76	960.49	30,266.49	323.18
Ganzhou District	6092.95	2288.33	75,215.51	124.72
Shandan County	1741.91	543.22	24,385.49	211.20
Minle County	1618.30	506.70	31,855.16	442.35

The comparison of the forecasted water demand (Table 1) with the water consumption reallocated by the model designed under the constraint of land use (Table 2) is shown in Figure 3.

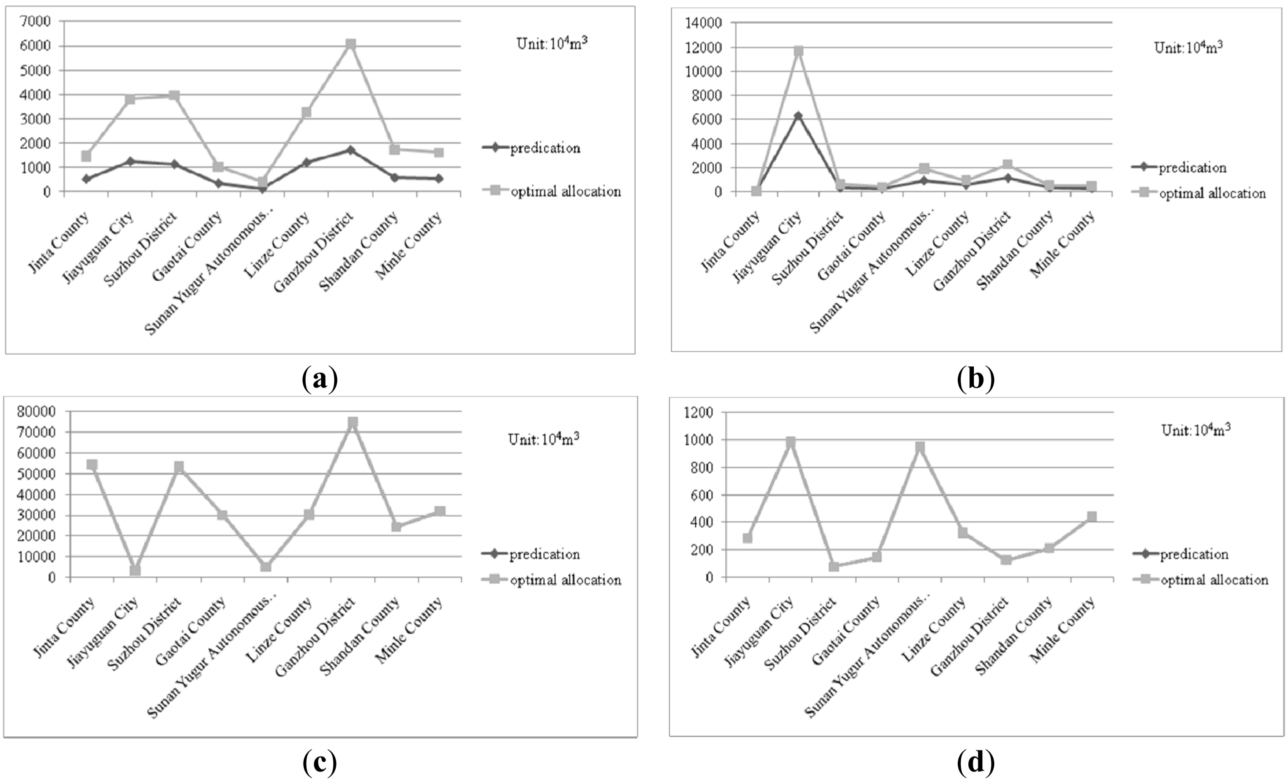

Figure 3. Comparison of water consumption reallocated with forecasted water demand of each sub-district. (**a**) Domestic water; (**b**) Industrial water; (**c**) Agricultural water; (**d**) Ecological water.

It is important to note that water resources demand was forecasted by trend extrapolation method according to the status of water resources utilization, while optimal water resources allocation was made on the premise that regional water resources were in the upper exploitation limit. Therefore, optimal allocation involves more water than predictions, but water utilization structure is more reasonable. The comparison results revealed that the domestic water increment was the most prominent compared to other water use type, especially in Ganzhou District, Suzhou District, and Jiayuguan City, and the sustained improvement of living standards and the ever-increasing of population particularly in those districts with relatively good economic development levels were considered as the main reasons. Though the economic return per industrial water use unit was much higher than others, it did not increase as much as domestic water. This was probably because the leading industry in the middle reaches of the Heihe River Basin is agriculture, and it accounted for most of the water allocation. From the view of land use constraint, the limitation of construction land quota is also an important factor. However, in Jiayuguan City, Sunan Yugur Autonomous County, and Ganzhou District, industrial water after reallocation increased more because secondary industry kept growth quickly in above districts; as for agricultural water, the predication curve was almost coincided with that of optimal allocation which reveals that the scheme satisfied each sub-district's demand in spite of the surge in demand. From the view of our model design, this is due to that we choose a certain number of cultivated land quota as a constraint; for ecological water, the quantity supplied in the allocation program just reached the forecast demand of each sub-district. It was because ecological water consumption did not result in economic benefits ostensibly in our model, and it only needed to satisfy the minimum ecological land water demand we set in constraint equation.

Though industrial water can bring high economic benefits while agricultural water present high consume and low output, industrial water did not increase much while the case did not happen that agricultural water could not meet the demand in the allocation scheme made by our model. Hence, taking land use constraint into consideration in optimal water resources allocation model can make the allocation program more in line with the actual situation of regional social and economic development in the future, and improve water allocation and utilization efficiency.

According to our research results, the water supply can meet the predicted water demand in the allocation program, but the result calculated based on that water resources were in the upper exploitation limit. Therefore, taking effective measures to relieve the pressure of water resources exploitation and supply in the river basin is imminently needed. As for the aspect of agriculture, each county should make use of water-saving measures or adjust agricultural planting structure properly to lower irrigation water loss rate and improve irrigation efficiency to alleviate the pressure of agricultural water use [35]. For ecological water, we should minimize its occupation but improve the degree of construction land intensity, and transform construction land expansion into exploitation from its own potentialities to guarantee sufficient ecological water supply for maintaining ecological security of river basin. In order to make a more harmonious relationship among water, eco-environment and human-being, an ecological civilization mode of economic development instead of a disordered exploitation should be adopted in river basin.

6. Conclusions

This study addresses that water resources allocation in a river basin should be optimized from the view of integrated river basin management and regional sustainable development, and land use must be taken into account as a significant constraint of the optimal water resources allocation plan. Taking the middle reaches of the Heihe River Basin of China as an example, we developed a multi-objective programming model which comprehensively considers the economic, social, ecological benefits, and the general constraint conditions of water resources utilization. In addition, an optimal water resources allocation program for the middle reaches of the Heihe River Basin in 2020 was calculated through particularly emphasizing the effects of land use on water utilization. The empirical analysis results indicated that land use change has an important influence on regional water resources utilization; a certain amount of cultivated land to ensure regional food security made agricultural water should be guaranteed instead of reduction even though it is considered as "high input but low output"; industrial water did not appear massive increase because regional construction land quota and leading industry constraint; the weak ecological environment protection consciousness may lead to a part of ecological land would convert to construction land in the future, which further caused ecological water in jeopardy. Additionally, the allocation program was calculated based on that water resources were in the upper exploitation limit. Therefore, there is a hidden contradiction between domestic water, industrial water, agricultural water and ecological water. Some water saving technical measures should be taken in time and people's awareness of protecting ecological land and water of the river basin should be raised through education, community engagement, and policy promotion.

The optimal model which embeds land use constraint can improve water allocation reasonableness, and this multi-objective programming model is easy to operate using LINGO. Besides, because all types of land-uses must be strictly controlled by the general plans for land use in every district of China, so the model has widespread applicability in solving similar water resources allocation problems. However, how to monetize the benefit of ecological water use and reflect it in the objective function and use integrated model to settle optimal water resources allocation from multiple perspectives would be considered as a next research direction of integrated water management in river basins and regional sustainable development. This is because different foci such as different objectives or different constraints may produce different research results. Additionally, how to balance the interests of different aspects to conduct the allocation program under limited water resources would also be an interesting research topic.

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Author Contributions

Zhanqi Wang, Jun Yang, Xiangzheng Deng and Xi Lan designed research; Zhanqi Wang and Jun Yang performed research; Zhanqi Wang, Jun Yang, Xiangzheng Deng and Xi Lan analyzed data; and Zhanqi Wang, Jun Yang, and Xiangzheng Deng wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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