Optimal allocation of water resources with dual water environmental carrying capacity constraints of water quantity and quality based on multi-scenario analysis

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Abstract

Multiple dilemmas under the interaction of water quantity and water quality have become the primary problem of water resources allocation. The effects of climate change are also exacerbating uncertainty in the system. To overcome the uncertainty and coupling in regional water resources planning management, a comprehensive framework through integrated with interval fuzzy program, water quality model and water resources quantity model has been developed to obtain the "optimal" solution in this study. The model is a hybrid methodology of interval parameter programming (IPP), fuzzy programing (FP), a general one-dimensional water quality model and the Tennant method. The multiple scenario analysis has been conducted under different representative concentration paths (RCPs). The results suggested that the methodology was applicable for reflecting the complexities of the regional water resources planning and management systems within the planning period. The total regional water availability and water environmental capacity under the impact of climate change will be obtained. Furthermore, the decision-maker can obtain the reasonable allocation of limited water resources in different regions and different users, so as to achieve the sustainable utilization of water resources and the development of regional economy.

1. Introduction

As an essential resource for human survival and social development, the total annual water consumption is increasing rapidly. With the rapid development of the global economy and the advancement of urbanization and industrialization, this problem is becoming increasingly serious (Hoekstra et al., 2007; Song et al., 2016; Xie et al., 2018; Long et al., 2019). Recently, water resources have been severely depleted in Asia, South America and North America. As well as affecting natural circulation, this situation also threatens the health of ecosystems (Gleeson et al., 2012; Tao et al., 2020). At the same time, with the sharp decline of water availability per capita in many countries, the relationship between access and utilization of water resources is becoming increasingly tense (Cooley et al., 2021). The water environment is also gradually deteriorating, and the problem of water resources together with human survival. The shortage of available fresh water has caused global concern. Population growth, expansion of commercial activities, economic development, land use change, environmental degradation and other factors will also affect the balance between supply and demand of water resources. Several studies assessing the world's available water resources have concluded that more than 50 per cent of renewable and accessible water has already been allocated for human use (Gleick et al., 2010; Dawadi et al., 2013; Xie et al., 2013; Lv et al., 2020). Therefore, the optimal allocation of water resources has become an important means to achieve the reasonable allocation of limited water resources in different regions and different users, so as to achieve the sustainable utilization of water resources and the good development of regional economy (Liu et al., 2010; Kazemi et al., 2020; Li et al., 2021).

Optimal allocation of water resources is a process of rational allocation of various water resources among multiple users through various measures (engineering and non-engineering means). Thus, on the basis of realizing sustainable utilization of water resources, the maximum economic, social and environmental benefits can be obtained (Li et al., 2015; Abdulbaki et al., 2016; Dai et al., 2016; Zhang et al., 2020). The optimal allocation of water resources involves many subsystems such as water resources, economic system, social system and environmental system, and is affected by many factors such as hydrology, meteorology, population, industry, technological level and pollutants. The research on optimal allocation of water resources started from the optimal operation of reservoirs. In recent years, operational research and management concepts and methods have been widely applied to the study of optimal allocation of water resources (Velarde et al., 2019; Du et al., 2019; Liu et al., 2021). The introduction of different optimization techniques, computer analysis and other methods has also made great progress in the optimal allocation of water resources (Raul et al., 2012; Singh et al., 2013; Farhadi et al., 2016; Herman et al., 2018; Lalehzari et al., 2020; Liu et al., 2021). However, the parameters and their inter-relationship may appear uncertain in water resources systems. Such uncertainties would directly affect the related exercises for generating desired water resources management schemes. Therefore, it is urgent that the uncertainties should be considered in water allocation planning programming.

The total available water resources and water environmental capacity are the core elements that need to be given priority in the optimal allocation of water resources (Xie et al., 2017; Yang et al., 2019; Sun et al., 2020; Luo et al., 2021). They are the main factor determining the scale of regional population and economic development, and also an important scientific basis for formulating water resources allocation plan and sustainable development plan (Jia et al., 2018; Li et al., 2020; Naderi et al., 2021). Water resources availability refers to the largest one-time utilization quantity of local water resources within an expected time range based on the overall consideration of water consumption for life, production and ecological environment. It is the maximum available amount of water after deducting the ecological water demand in the river. Water resources availability is affected by many factors, such as physical and geographical conditions, meteorological and hydrological characteristics, and economic and social development. To evaluate the water availability for areas with water shortages and fragile ecology, the widely adapted method first satisfies the ecological water demand in river channels and further allocates the water for industrial production, domestic consumption and other requirements. Therefore, the determination of ecological water demand is the key to evaluating water resources availability. Currently, some acceptable methods for simulating ecological water demand in river channels can be divided into four categories, including the hydrological index method, hydraulic method, holistic method, and habitat method (Qiao et al., 2004; Si et al., 2013; Fan et al., 2018; Tramblay et al., 2018; Li et al., 2018; Sedighkia et al., 2021).

The calculation of water environmental capacity mainly includes mathematical model calculation method and pollution load calculation method (Sudjono et al., 2010; Doyle et al., 2010; Zhang et al., 2020; Jian et al., 2020). The pollution load calculation method can be divided into measurement method, investigation and statistics method and estimation method (Yi et al., 2017; Zhu et al., 2018). Water quality model is a mathematical equation used to describe the migration and mixing process of substances in water, that is, to describe the quantitative relationship between pollutants in water and time and space. There are many kinds of water quality models, so it is necessary to select appropriate models combining hydrology, hydrodynamic characteristics and pollutant degradation characteristics in the study area, so as to calculate water environmental capacity more accurately (Gao et al., 2014; 44. Smith et al., 2016; Ranjith et al., 2019; Boah et al., 2020).

Therefore, the aim of this study is to build a comprehensive framework through integrated with the calculation method of water resources availability, water environmental capacity and optimal allocation of water resources (Fig. 1). It is of great significance to carry out research on optimal allocation of water resources under dual constraints of water quantity and water quality based on multi-scenario analysis. For the framework, a general one-dimensional water quality model and the Tennant method were applied for calculating the water resources availability and water environmental capacity, the interval parameter programming (IPP) and fuzzy programing (FP) were advanced to develop inexact water resources programming model. Then, taking the "double index" of water quantity and water quality as the primary constraint of the optimization model, considering the influence of uncertainty, the optimal allocation model of water resources in the basin was established. In order to explore the effects of climate change, multiple scenario analysis has been conducted under different representative concentration paths (RCPs). Compared with the existing tools, this method can not only reflect multiple uncertainties expressed as interval values and fuzzy level, but can also make regional water resources planning under different water environmental carrying capacity with the impact of climate change. The evaluation results of water environmental carrying capacity are the key input parameters of the optimization model. The results of the distribution of water resources, industrial structure adjustment and total pollutant control in different scenarios in the future are obtained. Finally, it provides decision support for realizing rational allocation and efficient utilization of water resources and watershed scale water resources management.

2. Methodology

2.1 Calculation method of available water resources

Water environmental carrying capacity is the threshold which water system is able to endure activities of human society in the definite period from the perspective of quality and quantity. For the water quantity, the Tennant method determines different flow levels by assessing the environmental quality of fish habitat. For example, 10% of the annual average flow represents the poor or minimum ecological flow. At the same time, combined with hydrological conditions and fish growth cycle, each year will be divided into two periods of time for assessment. In practical applications, the characteristics of the study area will also be considered.

Table 1
range of basal flow division of Tennant ecological water demand (Unit: %)

Narrative description of flow	Recommended base flow regiments (October-March) (Percentages of Average Annual Flow)	Recommended base flow regiments (April-September) (Percentages of Average Annual Flow)
Flushing or Maximum	200	200
Optimal Range	60 ~ 100	60 ~ 100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or Degrading	10	30
Poor or Minimum	10	10
Severe Degradation	0 ~ 10	0 ~ 10

2.2 Qual-2k water environmental capacity calculation model

The Qual-2k water environmental capacity calculation model will be as follows:

$$\frac{dC}{dt} = -KC$$

1a
where K = the pollutant degradation coefficient.

$$K = \alpha Q^{-\beta}$$

1b

$$C = C_0 \cdot \exp\left(-\frac{KL}{u}\right)$$

1c
where C = Pollutant concentration; C_0= background concentration; u = mean velocity; L = the transmission distance.

$$W_I = W_R + K \cdot C_s \left(Q + \sum q\right)$$

1d

$$W_R = \left(W_P + K \cdot \sum q \cdot C_s - I\right) + \left[K \cdot Q\left(C_s - C_{ss}\right)\right]$$

1e

$$W_p = K \cdot C_s \cdot Q\left[1 - \exp\left(-\frac{K \cdot X_1}{86.4u}\right)\right] + K \cdot C_s \cdot \left(Q + \sum q\right) \cdot \left[1 - \exp\left(-\frac{K \cdot X_2}{86.4u}\right)\right]$$

1f

W_I= ideal water environmental carrying capacity ;W_R= real water environmental carrying capacity;W_p= self-purification capacity; C_s = the water quality target; C_{ss}= the water quality target for last computing unit; Q = stream discharge;X_1=the distance to the upstream section; X_2= the distance to the downstream section.

2.3 Assessment of water environmental carrying capacity

Based on quality and quantity evaluation results, two indexes of available water resources and water pollution carrying capacity (water environmental capacity) related to the development of population, resources and environment in the basin are selected. Combined with the calculation results of water resources availability obtained from the improved Tennant method and Qual-2k model, the water environmental carrying capacity in different planning periods under future climate change scenarios was obtained.

$$SW_t = \frac{WAV_t}{WAV_{t=0}}$$

2a

$$SE_t = \frac{WP_t}{WP_{t=0}}$$

2b

$$ST_t = \alpha \cdot SW_t + \beta \cdot SE_t$$

2c

whereSW_t= water resources availability index;WAV_t= available water resources in different periods;SE_t = water environmental capacity index;WP_t= water environmental capacity index in different periods;ST_t= water environmental carrying capacity index; α = weight of water resources availability index; β = weight of water environmental capacity index.

2.4 Interval-fuzzy linear programming

Consider an interval fuzzy programming model as follows (Fedrizzi et al., 1991; Li et al., 2015; Xie et al., 2018; Ezhilarasan et al., 2020):

$$\min f^{\pm} \underset{\sim}{=} C^{\pm} X^{\pm}$$

3a

subject to:

$$A^{\pm} X^{\pm} \underset{\sim}{\leqslant} B^{\pm}$$

3b

$$X^{\pm} \geqslant 0$$

3c

where \underset{\raise0.3em\hbox{$\smash{\scriptscriptstyle\thicksim}$}}{=} and \underset{\raise0.3em\hbox{$\smash{\scriptscriptstyle\thicksim}$}}{ \leqslant } represent fuzzy equality and fuzzy inequality, respectively. Based on the principle of fuzzy flexible programming, a connection between the value of{\lambda ^ \pm }and membership function would be established. Specifically, the flexibility of constraint conditions and the fuzziness of system objective would be denoted by fuzzy number set. \left[{{\lambda ^ \pm }} \right]as the degree of membership associated with the degree of satisfaction would represent the “fuzzy constraint” or “fuzzy object”. λ = min{$\mu_G, \mu_{C_1}, \mu_{C_2}, ^\wedge \mu_{C_m}$} denotes the membership level. Therefore, the interval fuzzy programming model would be converted as follows:

\hbox{max} {\lambda ^ \pm }

3d

subject to:

{C^ \pm }{X^ \pm } \leqslant {\lambda ^ \pm }{f^+}+(1 - {\lambda ^ \pm }){f^ - }

3e

{A^ \pm }{X^ \pm } \geqslant {B^ - }+(1 - {\lambda ^ \pm })({B^+} - {B^ - })

3f

{X^ \pm } \geqslant 0

3g

0 \leqslant {\lambda ^ \pm } \leqslant 1

3h

3. Case Study

The research object of this study is the Huangshui watershed (Fig. 2), with a total area of 10337 km^2. The basin is located in the northeast of Qinghai-Tibet Plateau and is an important tributary of the Yellow

River. The regional ecological environment is fragile, and the over-exploitation in recent years poses a serious threat to the water resources security in the middle and lower reaches of the Yellow River. The degradation of ecological environment not only affects the production and life of people around the region, but also restricts the sustainable development of regional economy and society. Both resource-based and quality-based water shortages exist in the region. With the further development of industry in the basin and the acceleration of urbanization, it is necessary to conduct in-depth research on how to plan and manage the utilization of water resources and reduce the discharge of water environment pollutants.

Place Fig. 2 here

According to previous studies, the representative concentration paths (RCPs) with stable concentration characteristics proposed in the IPCC Fifth Climate Change Projection report were selected as the basis for scenario setting. The RCPs climate scenarios used in this study can be divided into three scenarios, namely RCP26, RCP45 and RCP85, respectively representing high, medium and low carbon emission intensities (Arora et al., 2011; Yahya et al., 2017; Park et al., 2018). The obtained hydrological changes of the basin are shown in Table 2. Under the scenario of RCP26, the average runoff in the three planning periods was above 60 m^3/s. The average annual runoff in the first two planning periods of RCP45 scenario is more than 60 m^3/s, and only 47.25 m^3/s in the third planning period. The overall annual mean runoff in RCP85 scenario was low. It showed a trend of decline and then rise. The mean square deviation of annual average runoff under different scenarios was compared. The mean square error of RCP26 scenario was 5.77. The mean variance of RCP45 scenario is 10.18, indicating that the annual and seasonal average runoff fluctuates the most. The RCP85 scenario falls between the other two scenarios.

Table 2
Annual average flow under different scenarios (m^3/s)

	RCP26	**RCP45**	**RCP85**
period 1	64.03	62.28	50.86
period 2	60.17	68.07	45.91
period 3	69.58	47.25	52.05
total	64.59	59.20	49.61
Mean square deviation	5.77	10.18	7.12

In view of the regional geological conditions and the impact of human factors, serious soil erosion, high sediment content of the river characteristics. Additional water for sediment transport should be added on the basis of the assessment of the availability of raw water resources. According to the hydrological data mentioned above, the Tennant method is used to obtain the available water resources of the basin under different climate change scenarios in the future. Based on Qual-2k model, the results of water capacity under different climate change scenarios were obtained, as shown in Table 4. Using the interval fuzzy programming in the uncertain programming, the optimal allocation model of water resources based on water environmental carrying capacity was established. The time range of the model study starts from 2021, with three planning periods (2021–2025, 2026–2030, 2031–2035).

The model considers the cost of water consumption and pollutant treatment costs. At the same time, the constraints include water environmental carrying capacity constraints, water consumption satisfaction constraints, working population constraints, industrial development intention constraints, land use constraints, and so on.

Objective function:

The objective function considers the cost of water consumption and pollutant treatment costs in the process of production and takes maximization as the ultimate goal.

$$\max{\kern 1pt} {\kern 1pt} {\kern 1pt} {\kern 1pt} {f^ \pm }=\sum\limits_{{i=1}}^{I} {\sum\limits_{{t=1}}^{T} {W_{{it}}^{ \pm }} } - \sum\limits_{{i=1}}^{I} {\sum\limits_{{t=1}}^{T} {W_{{it}}^{ \pm } \cdot WC_{{it}}^{ \pm } \cdot WP_{{it}}^{ \pm }} } - \sum\limits_{{i=1}}^{I} {\sum\limits_{{t=1}}^{T} {\sum\limits_{{k=1}}^{K} {W_{{it}}^{ \pm } \cdot PE_{{itk}}^{ \pm } \cdot PC_{{itk}}^{ \pm }} } } - \sum\limits_{{t=1}}^{T} {\sum\limits_{{k=1}}^{K} {\left({UTP_{t}^{ \pm } \cdot UPE_{{tk}}^{ \pm } \cdot PUP_{{tk}}^{ \pm }} \right)} }$$

3a

Constrains:

(1) Constraints of water environmental carrying capacity

The constraint of water environmental carrying capacity mainly consists of two parts: water resources availability constraint and water environmental capacity constraint. The constraint refers to the calculation results of water resources availability and water environmental capacity in the basin.

$$\sum\limits_{{i=1}}^{I} {W_{{it}}^{ \pm } \cdot WC_{{it}}^{ \pm }} +PWT_{t}^{ \pm }+EWT_{t}^{ \pm } \leqslant TTW_{t}^{ \pm }+OW_{t}^{ \pm }$$

3b

$$\sum\limits_{{i=1}}^{I} {W_{{it}}^{ \pm } \cdot PE_{{itk}}^{ \pm } \cdot \left({1 - RP_{{itk}}^{ \pm }} \right)} {\text{+}}UTP_{t}^{ \pm } \cdot UPE_{{tk}}^{ \pm } \cdot (1 - UPR_{{tk}}^{ \pm }) \leqslant TP_{{tk}}^{ \pm }$$

3c

(2) Satisfactory degree constraints of water consumption per unit output value

The satisfaction value of water consumption with different output value was obtained by constructing membership function.

$$f\left({\alpha _{t}^{ \pm }} \right){\kern 1pt} {\kern 1pt} {\kern 1pt} {\kern 1pt} =\left\{ \begin{gathered} 1{\text{ if x}} \leqslant m \hfill \\ l\left(x \right){\text{ if }}m<x \leqslant n \hfill \\ 0{\text{ if }}n<x \hfill \\ \end{gathered} \right.$$

3d

$$\alpha _{t}^{ \pm }{\text{=}}\frac{{\sum\limits_{{i=1}}^{I} {\sum\limits_{{t=1}}^{T} {W_{{it}}^{ \pm } \cdot WC_{{it}}^{ \pm }} } }}{{\sum\limits_{{i=1}}^{I} {\sum\limits_{{t=1}}^{T} {W_{{it}}^{ \pm }} } }}$$

3e

$$\lambda _{t}^{ \pm }=f\left({\alpha _{t}^{ \pm }} \right){\kern 1pt} {\kern 1pt} \cdot {\beta _t}$$

3f

(3) Working population constraints

The working population constraints considered the supporting effect of population on economic development is considered

$$\sum\limits_{{i=1}}^{I} {W_{{it}}^{ \pm } \cdot WUP_{{it}}^{ \pm } \leqslant UTP_{t}^{ \pm }} \cdot Q_{t}^{ \pm }$$

3g

(4) Constraints on industrial development

This constraint condition is used to reflect the actual situation of production capacity change and ensure the relative stability of industrial structure to prevent the rapid growth or recession of each industry.

$${q_1}W_{{i,t - 1}}^{ \pm } \geqslant W_{{it}}^{ \pm } \geqslant {q_2}W_{{i,t - 1}}^{ \pm },{\kern 1pt} {\kern 1pt} {\kern 1pt} {\kern 1pt} \forall i,t$$

3h

$${q_1} \geqslant 1 \geqslant {q_2} \geqslant 0$$

(5) Output value constraints

The constraints ensure the sustainable development of the economy and avoid an excessive pursuit of growth by the decision-makers.

$$WTV_{t}^{ \pm } \geqslant \sum\limits_{{i=1}}^{I} {W_{{it}}^{ \pm }} \geqslant DTV_{t}^{ \pm },{\kern 1pt} {\kern 1pt} {\kern 1pt} {\kern 1pt} \forall t$$

3i

(6) Planting land area constraint

The constraint conditions are used to ensure that the planting land area meets the actual requirements.

$$SL_{t}^{ \pm } \cdot RL_{t}^{ \pm } \geqslant W_{{i=1,t}}^{ \pm } \geqslant ML_{t}^{ \pm } \cdot RL_{t}^{ \pm },{\kern 1pt} {\kern 1pt} {\kern 1pt} {\kern 1pt} \forall t$$

3j

4. Results Analysis And Discussion

4.1 Basin Water Availability Assessment and Prediction

Available water resources under different scenarios are shown in Fig. 3. From scenario 1 to scenario 3, the average available water resources in total planning period showed a downward trend, which were 6.40×10^8 m^3, 5.87×10^8 m^3 and 4.92×10^8 m^3, respectively. In the RCP26 scenario, the results of each year are relatively close, showing relatively low volatility. In the RCP85 scenario, water availability will have a sharp fluctuation, such as 2.63×10^8 m^3 in 2022 and 9.13×10^8 m^3 in 2023. These results indicate that with the increase of carbon dioxide concentration, regional water resources availability may decrease to a certain extent and produce greater volatility, which will bring great difficulties and challenges to regional water resources planning and utilization in the future.

Place Fig. 3 here

4.2 Prediction results of water environmental capacity

Taking the average annual runoff in different periods as input data, the water environmental capacity of the Huangshui watershed in different planning periods under different scenarios can be obtained through the Qual-2k model. In the baseline period, the results show that the water environmental capacity of COD, NH_3-N and TP are 42521.19t, 2194.42t and 119.90t, respectively. The water environmental capacity of the Huangshui watershed varies greatly under different climate scenarios and fluctuates in different planning periods. Under the scenario of RCP26, different pollutants have higher water environmental capacity, COD environmental capacity can reach 82619.41t, NH_3-N environmental capacity can reach 4133.4t, TP environmental capacity can reach 507.69t in the third planning period. Under RCP85 scenario, the water environmental capacity of different pollutants has been significantly reduced. In the first planning period of RCP85, COD environmental capacity is 45060.99 t, NH_3-N can reach 2315.18 t, TP can reach 144.05 t. Compare the water environmental capacity and pollutant discharge status of river basin under different scenarios in the future. Therefore, NH_3-N will be the key pollutant type to be controlled in the Huangshui watershed in the future, TP is the secondary pollutant to be controlled, and COD does not need additional control measures and means in the current prediction results.

Table 3
The results of water environmental capacity (tonne)

Scenarios		Pollution		
		COD	NH_3-N	TP
Base year		42521.19	2194.42	119.90
	Planning period 1	76603.07	3844.17	449.85
rcp26	Planning period 2	77427.44	3876.87	456.39
	Planning period 3	82619.41	4133.40	507.69
	Planning period 1	75848.58	3810.73	443.16
rcp45	Planning period 2	78856.32	3948.85	470.78
	Planning period 3	52805.60	2695.07	220.03
	Planning period 1	45060.99	2315.18	144.05
rcp85	Planning period 2	53919.43	2745.96	230.20
	Planning period 3	51221.41	2609.64	202.94

4.3 Water environmental carrying capacity assessment

The result of water environmental carrying capacity are shown in Fig. 4. The basin has the largest water resources availability index under RCP26 scenario. Under RCP85 scenario, the water resources availability index of the basin is close to the baseline period. Under RCP45 scenario, the water resources availability index of the basin decreased significantly in the third planning period, which needs to be taken into account in the future. By comparing the water environmental capacity index of different scenarios and planning periods, it can be seen that the water environmental capacity index of different basins has a certain increase compared with the baseline period. Under RCP26 scenario, the growth of the water environmental capacity index was obvious in different planning periods. Under RCP45 scenario, there was a significant decrease in the third planning period. The RCP85 scenario remains the worst-case scenario. The water environmental carrying capacity index of the Huangshui watershed is obtained based on water resources availability index and water environmental capacity index. Both RCP26 and RCP45 scenarios have large water environmental carrying capacity in the Huangshui watershed. In the third planning period, the water environmental carrying capacity under RCP45 scenario decreased significantly and was at the lowest value under different scenarios. Under RCP85 scenario, the water environmental carrying capacity of the Huangshui watershed was close to the baseline period, and was in a low state.

Place Fig. 4 here

4.4 The result of water resources allocation

4.4.1 High satisfaction scenario

The output values of different industries in planned periods in the case of high satisfaction are shown in Fig. 5. Under the upper bounds of the results, the tertiary industry will increase obviously and become the pillar industry of the Huangshui watershed in the future. Different planning periods will be 135.5 billion yuan, 231.261 billion yuan and 338.958 billion yuan respectively. There will also be significant growth in construction and pharmaceuticals. Smelting industry will see the most significant decline, with 134.975 billion yuan, 57.448 billion yuan and 22.979 billion yuan in different planning periods respectively. The output value of thermal power generation industry, chemical industry and manufacturing industry will increase in the first and second planning period, and decrease in the third planning period. In the primary industry, agricultural output value basically maintains stable, livestock and poultry breeding industry will drop significantly.

Under the low bounds of the results, the industry structure will produce greatly change with upper bounds of the results. Agriculture, livestock and poultry breeding industry in the primary industry did not produce larger changes. The manufacturing industry will also show a trend of first rise and then decline, but will still maintain a certain industrial scale of 23.885 billion yuan in the third planning period. Thermal power generation industry, chemical industry, smelting industry and textile industry will show a significant decline trend in different planning periods. Pharmaceutical manufacturing industry and construction industry will increase greatly in different planning periods, and surpass the tertiary industry in the third planning period to become the leading industry in the Huangshui watershed. The tertiary industry will rise first and then decline, and reach 122.541 billion yuan, 151.66 billion yuan and 130.715 billion yuan respectively in different planning periods.

Place Fig. 5 here

Figure 6 shows the upper and lower limits of water consumption. In the upper bounds of results, the agricultural water consumption will be the largest industry of water consumption, reaching 163 million m^3, 150 million m^3 and 137 million m^3 in different planning periods. The tertiary industry will be the second largest water consumption industry, with 51 million m^3, 87 million m^3 and 105 million m^3. In the lower bounds of results, the water consumption of the tertiary industry will increase first and then decrease, respectively 48 million m^3, 60 million m^3 and 43 million m^3 in different planning periods. The proportion of water consumed by construction, thermal power generation and manufacturing will increase significantly.

Place Fig. 6 here

Figure 7 shows water resources consumption in different water use fields. Under the upper and lower limits, the total domestic water consumption increased year by year, exceeding agricultural water consumption and becoming the largest water consumption mode in the Huangshui watershed, reaching 135 million m^3, 173 million m^3 and 213 million m^3 respectively in different planning periods. The upper limit of industrial water will show an upward trend and then a downward trend, which are 65 million m^3, 76 million m^3 and 59 million m^3 respectively in different planning periods. The lower limit results will decrease steadily and reach 85 million m^3, 79 million m^3 and 78 million m^3 in different planning periods, respectively. The upper limit of water consumption in the tertiary industry will increase year by year, reaching 51 million m^3, 87 million m^3 and 105 million m^3 respectively in different planning periods. The lower limit will increase first and then decrease, and reach 48 million m^3, 60 million m^3 and 43 million m^3 in different planning periods, respectively.

Place Fig. 7 here

Figure 8 shows the total amount and sources of each pollutant. In the upper limit results, the total COD discharge in the Huangshui watershed in different planning periods is 54025.45t, 55912.27t and 33,588.88 t, respectively. The total emissions of agricultural pollution and domestic pollution decreased year by year, while the total emissions of industrial pollution increased first and then decreased, and were 25099.37t, 29258.34t and 12137.28t respectively in different planning periods. The emissions of tertiary industry were 11615.41t, 13381.36t and 11767.78t respectively in different planning periods. Industrial pollution and tertiary industry pollution will become the main sources of COD emissions, and agricultural pollution will greatly reduce the proportion. In the lower limit results, the total COD discharge of the Huangshui watershed in different planning periods is 54281.15t, 37957.80t and 24564.29t, respectively. In different planning periods, agricultural pollution, industrial pollution, tertiary industry pollution and domestic pollution all show a decreasing trend, and industrial pollution will still be the main source of COD.

In the upper limit results, the total discharge of NH_3-N in different planning periods in the Huangshui watershed is 2591.07t, 2272.41t and 1682.84t, respectively. The total emission of agricultural pollution, industrial pollution and domestic pollution decreased year by year, while the tertiary industry pollution showed a rising trend, which were 289.34t, 355.55t and 351.77t respectively in different planning periods. Domestic pollution will still be the main source of NH_3-N emissions, and the proportion of industrial pollution has decreased significantly, approaching that of tertiary industry pollution. In the lower limit results, the total NH_3-N emissions in different planning periods are 2362.55t, 1858.84t and 1402.97t, respectively. In different planning periods, NH_3-N emissions of agricultural pollution, industrial pollution, tertiary industry pollution and domestic pollution all show a downward trend, and tertiary industry pollution has obvious changes compared with the upper limit result, and the proportion of total pollutant emissions will also be lower than the upper limit result, and domestic pollution will still be the main source of NH_3-N.

In the upper limit results, total TP emissions in different planning periods are 140.53t, 90.80t and 48.53t, respectively. Total emissions of agricultural pollution and domestic pollution decreased year by year, while pollution from tertiary industry remained basically stable, reaching 6.59t, 6.74t and 4.45t in different planning periods, respectively. Agricultural pollution will still be the main source of TP emissions, while the proportion of TP emissions from domestic pollution will decrease to a certain extent. In the lower limit results, the total TP emissions in different planning periods are 129.44t, 86.15t and 45.05t, respectively. In different planning periods, agricultural pollution, tertiary industry pollution and domestic pollution TP emissions all show a downward trend, tertiary industry pollution has significant changes compared with the upper limit results, and the proportion of total pollutant emissions will be lower than the upper limit results. Agricultural pollution will still be the main source of TP.

Place Fig. 8 here

4.4.2 Low satisfaction scenario

Figure 9 shows the upper and lower limits of output value of various industries under the low satisfaction scenario. The results show that under the upper limit, the tertiary industry will increase significantly and become the pillar industry of the Huangshui watershed in the future. Different planning periods will be 153.547 billion yuan, 228.641 billion yuan and 337.910 billion yuan respectively. There will also be significant growth in construction and pharmaceuticals. Smelting industry will see the most significant decline, with 76.547 billion yuan, 30.619 billion yuan and 12.248 billion yuan in different planning periods respectively. The output value of thermal power generation and manufacturing will increase in the first and second planning periods, and decrease in the third planning period. In the primary industry, agricultural output value basically maintains stable, livestock and poultry breeding industry will drop significantly. Under the lower limit, the industrial structure of the Huangshui watershed will change greatly with the upper limit. Agriculture and livestock and poultry breeding industry in the primary industry did not produce larger changes. The manufacturing industry and chemical industry will show a trend of first rise and then decline, but will still maintain a certain industrial scale, smelting industry will decrease significantly in the second planning period, but will basically keep stable in the later period, and become the fourth industry in the Huangshui watershed. Thermal power generation industry and textile industry will show a significant decline trend in different planning periods. Pharmaceutical manufacturing industry and construction industry will grow significantly in different planning periods. The tertiary industry will show an upward trend and reach 116.753 billion yuan, 168.956 billion yuan and 234.699 billion yuan respectively in different planning periods.

Place Fig. 9 here

Figure 10 shows the upper and lower limits of water consumption of various industries under the low satisfaction scenario. In the upper limit and lower limit results, agricultural water consumption shows a decreasing trend year by year, but it will still be the largest industry of water consumption in the Huangshui watershed. The tertiary industry will be the second largest consumption of water resources and will increase year by year in different planning periods. thermal power generation industry will grow first and then decline in the upper limit, but will decline year by year in the lower limit. The water consumption of chemical industry will be contrary to that of thermal power generation industry. In the upper limit, the water consumption will decrease year by year, but in the lower limit, it will increase first and then decrease. At the same time, in the lower limit result, the proportion of water consumption in construction industry will increase significantly, and is much higher than the upper limit result.

Place Fig. 10 here

Figure 11 shows water resources consumption in different water use areas under low satisfaction scenario. Under the upper limit and lower limit, domestic water consumption increased year by year and exceeded agricultural water consumption, becoming the largest water resources consumption mode in the Huangshui watershed. The upper limit and lower limit of industrial water use will increase first and then decrease. The upper limit and lower limit of water use in tertiary industry will increase year by year.

Place Fig. 11 here

Figure 12 shows the total amount and sources of each pollutant under the scenario of low satisfaction. In the upper limit results, the total COD discharge in different planning periods is 58452.54t, 45801.62t and 30429.18t, respectively. Total emissions of agricultural, industrial and household pollution have decreased year by year. The decrease rate of industrial pollution is the fastest, which is 27979.48t, 19299.31t and 9013.96t respectively in different planning periods. The emissions of the tertiary industry in different planning periods were 13162.38t, 13229.74t and 11731.40t, respectively. The tertiary industry pollution will become the main source of COD discharge, industrial pollution and domestic pollution will become the secondary source of COD. In the lower limit results, the total COD discharge in the Huangshui watershed in different planning periods is 56233.18t, 59831.83t and 32735.40t, respectively. In different planning periods, agricultural pollution, tertiary industry pollution and domestic pollution COD emissions all showed a decreasing trend. The industrial pollution will be the main source of COD in the Huangshui watershed, which will be 29567.43t, 37007.82t and 15154.70t in different planning periods.

In the upper limit results, the total NH_3-N emissions in different planning periods are 2569.04t, 2086.92t and 1628.43t, respectively. Total emissions of agricultural pollution, industrial pollution and domestic pollution decreased year by year, while tertiary industry pollution remained basically stable, reaching 327.88t, 351.53t and 350.68t respectively in different planning periods. Domestic pollution will still be the main source of NH_3-N emissions, and the proportion of industrial pollution will decrease significantly, which is basically the same as the tertiary industry pollution. In the lower limit results, total NH_3-N emissions in different planning periods are 2502.90t, 2316.31t and 1626.20t, respectively. In different planning periods, NH_3-N emissions of agricultural pollution, domestic pollution and domestic pollution all showed a decreasing trend, while industrial pollution showed a changing trend of rising first and then decreasing, and significantly decreased in the third planning period. The pollution of tertiary industry is basically stable, domestic pollution will still be the main source of NH_3-N, and industrial pollution will become the secondary source of NH_3-N.

In the upper limit results, total TP emissions in different planning periods are 141.41t, 90.73t and 48.51t, respectively. Total emissions of agricultural pollution, tertiary industry pollution and household pollution have decreased year by year. Agricultural pollution will continue to be the main source of TP emissions. In the lower limit results, total TP emissions in different planning periods are 128.05t, 82.05t and 43.91t, respectively. In different planning periods, TP emissions of agricultural pollution, tertiary industry pollution and domestic pollution all showed a downward trend, and pollutant emissions were close to the upper limit.

Place Fig. 12 here

5. Conclusions

In this study, to obtain optimal allocation of water resources schemes under climate change, a general one-dimensional water quality model, the Tennant method, the interval parameter programming (IPP) and fuzzy programing (FP) were integrated into a comprehensive framework.

The watershed water resources optimization method based on the dual water environmental carrying capacity constraints of water quantity and quality was established, and climate change factors were taken into account to conduct relevant research on optimal allocation of water resources. The calculation results of water environmental carrying capacity including water quantity and water quality will become the core constraint in the method of optimal allocation of water resources. The method system constructed in this study includes water resources availability accounting method, Qual-2k water environmental capacity accounting method, and water resources optimal allocation model based on interval fuzzy programming. This method system can provide a reference method for the calculation of water environmental carrying capacity and optimal allocation of water resources under climate change scenarios at watershed scale. Finally, the results of different scenarios of water resources allocation, industrial structure adjustment and total pollutant control at watershed scale are obtained, which can provide decision support for optimal water resources management at watershed scale. However, compared with other approaches, there is still much space for improvement of the proposed model. For example, the improved Tennant method is customized for the diversity of hydrological characteristics and high sediment concentration of the basin, but other attributes are not considered; the proposed optimization model would have difficulties in dealing with the uncertainties in the form of random variable.

Declarations

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

Zhenghui Fu: Conceptualization, Software application, original draft preparation. Manuscript writing, Methodology. Yang Zhang: Software application, Manuscript revision, Data collection. Xia Jiang: Manuscript writing, Manuscript revision, Data collection. Han Wang: Conceptualization, Manuscript revision, Methodology, Manuscript revision. Shuhang Wang: Conceptualization, Funding acquisition, Methodology, Manuscript revision.

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Competing Interests

The authors declare no competing interests.

Availability of data and materials

Not applicable.

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Figures

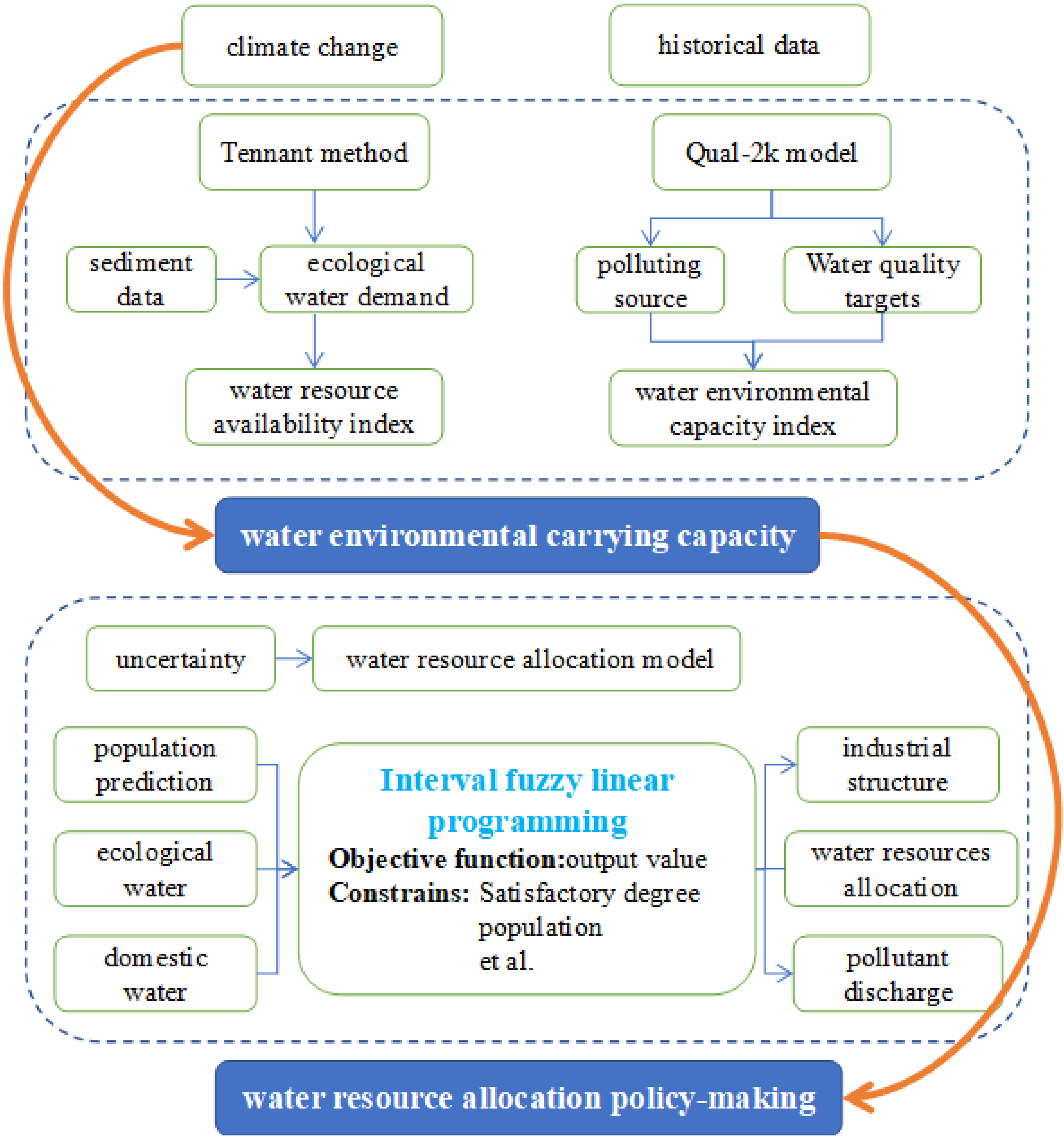


Figure 1

The framework of this study

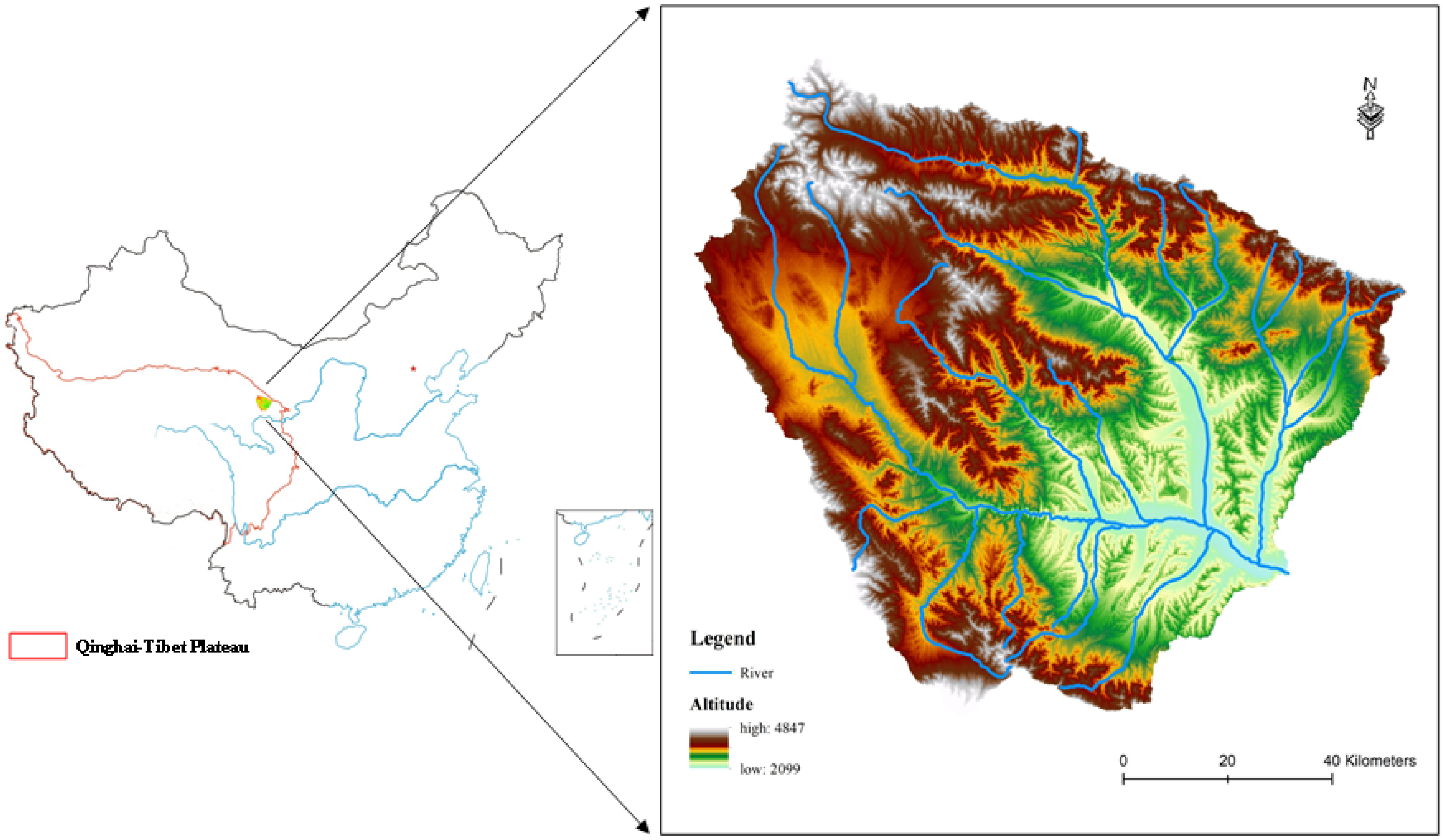


Figure 2

Geographical location of Huangshui Basin

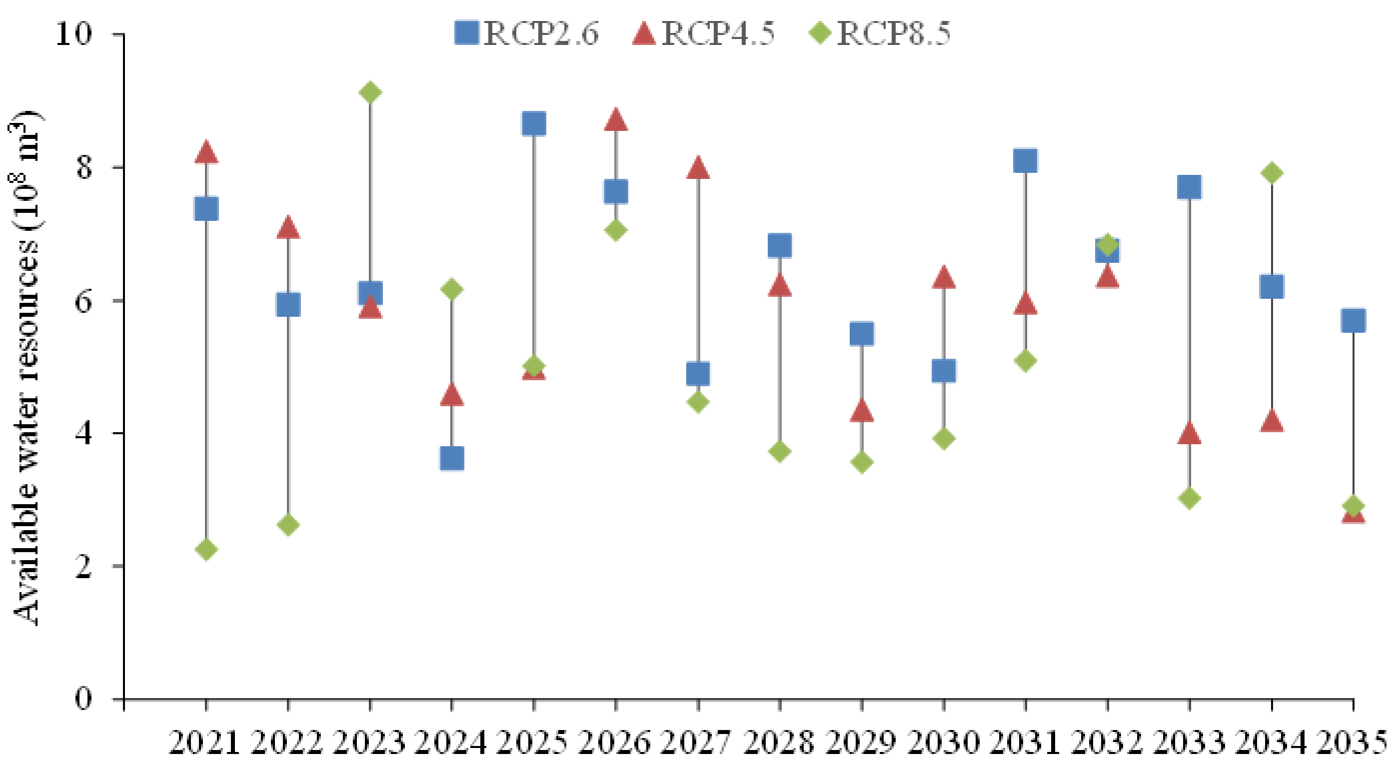


Figure 3

Annual average available water resources under different scenarios

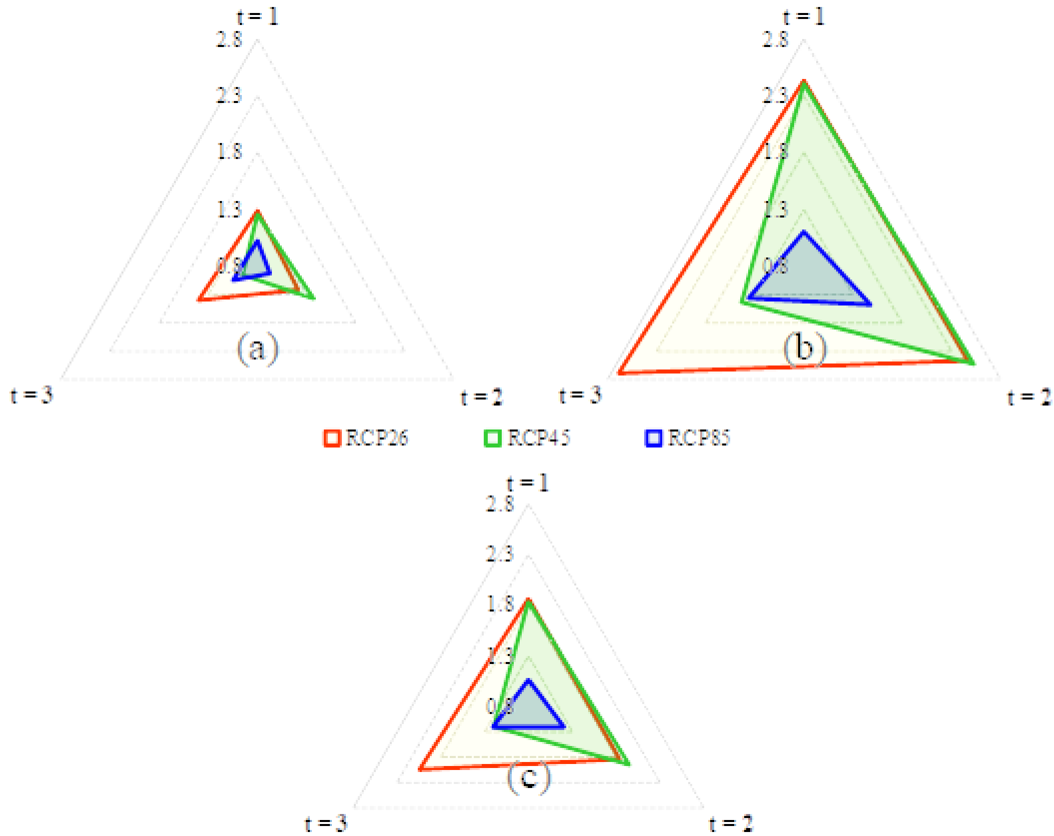


Figure 4

The result of water environmental carrying capacity

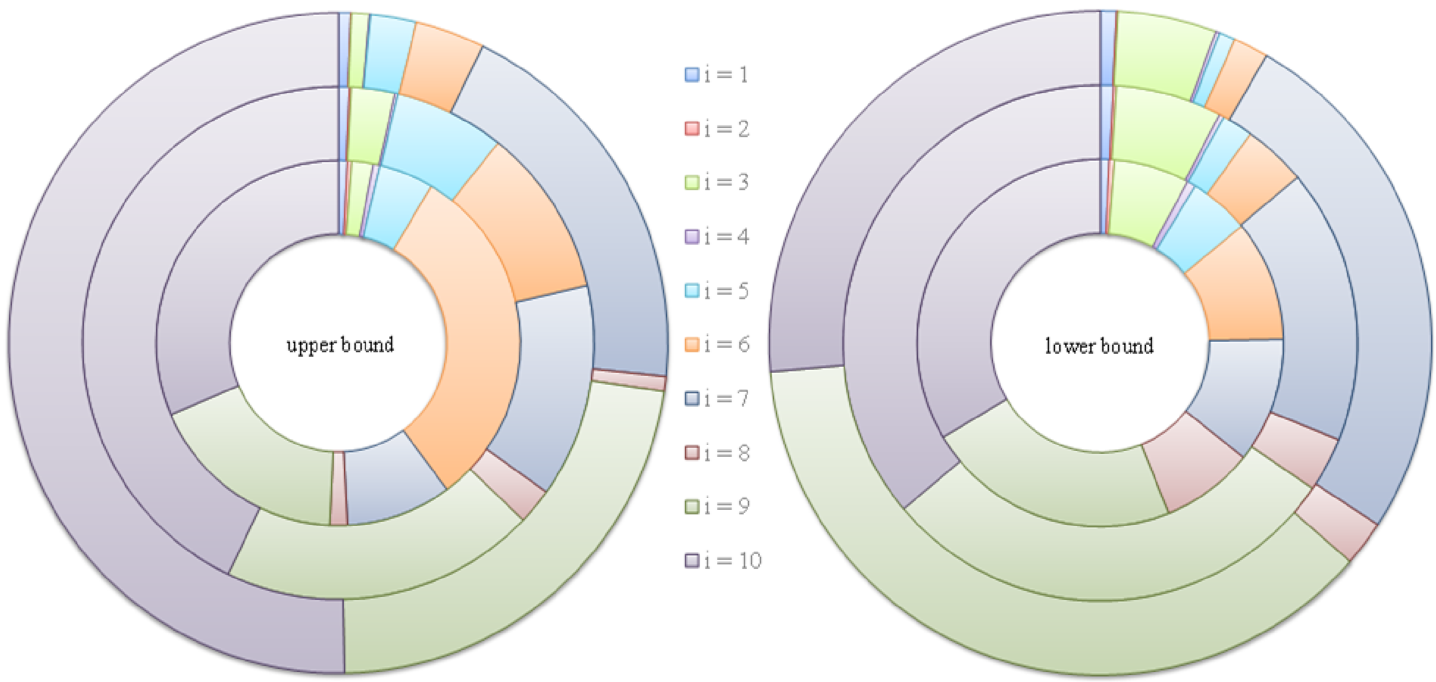


Figure 5

Output value of various industries in different planning periods under high satisfaction scenario

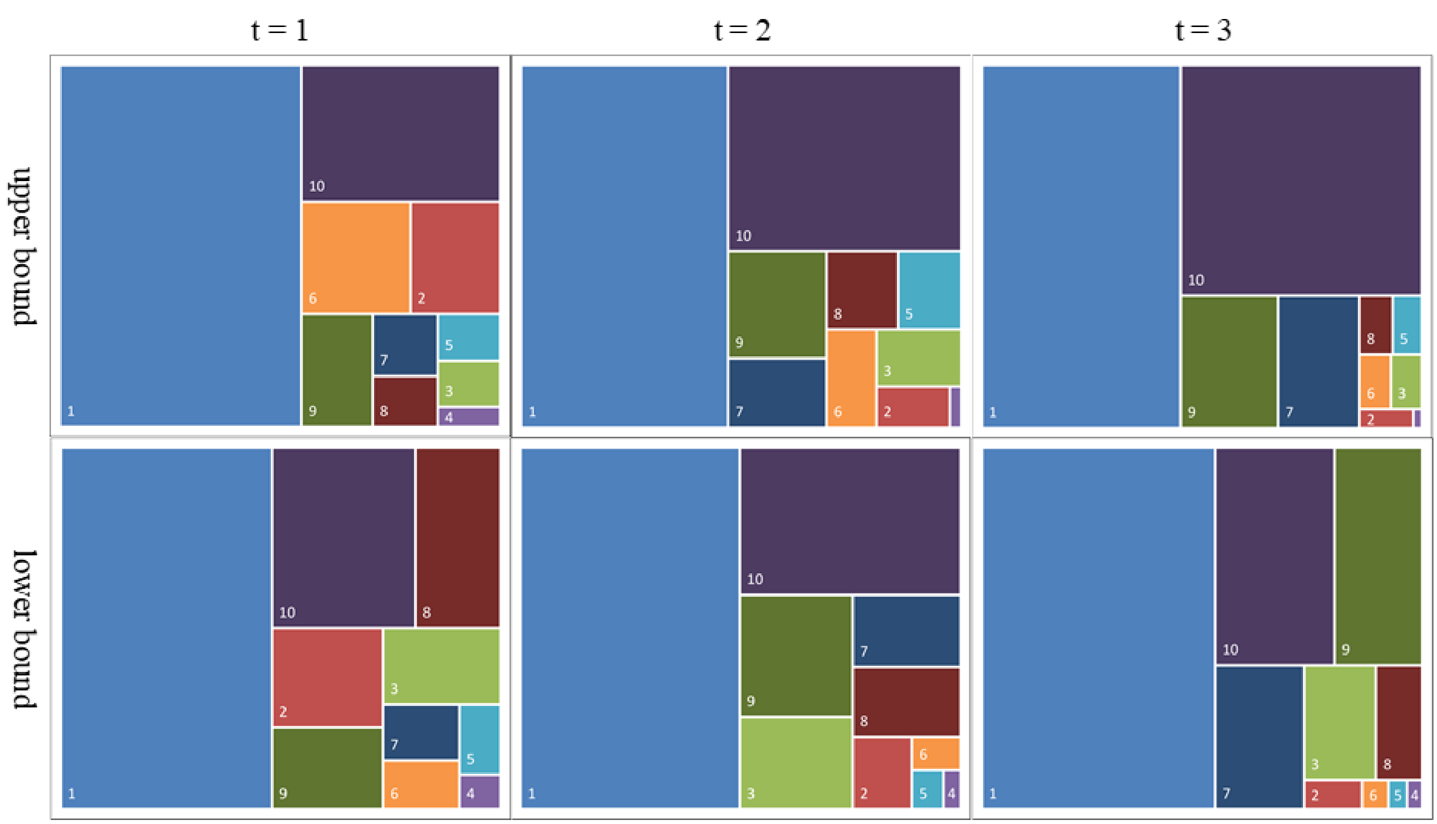


Figure 6

Water consumption of various industries in different planning periods under high satisfaction scenario

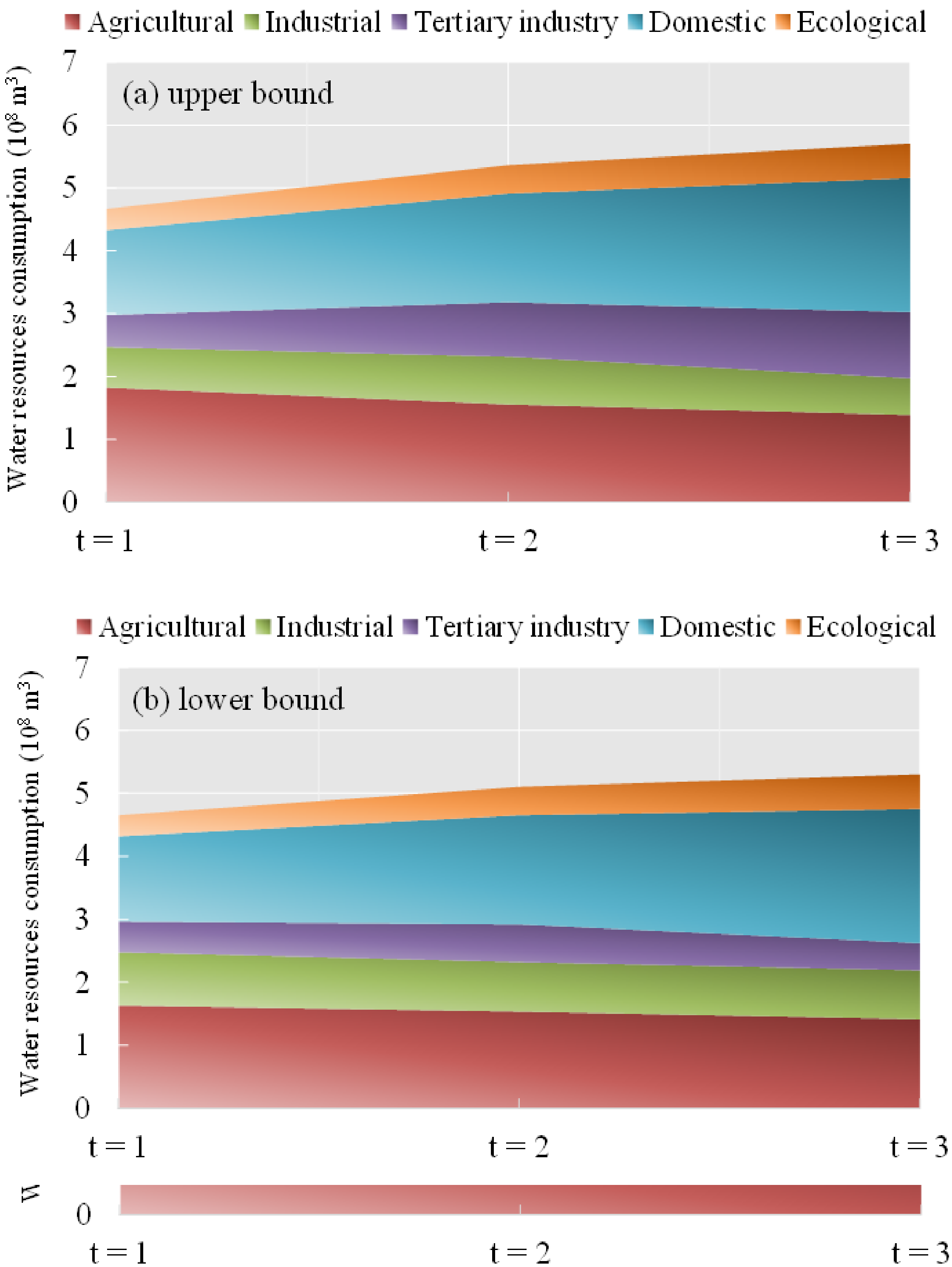


Figure 7

Water resources utilization in different planning periods under high satisfaction scenario

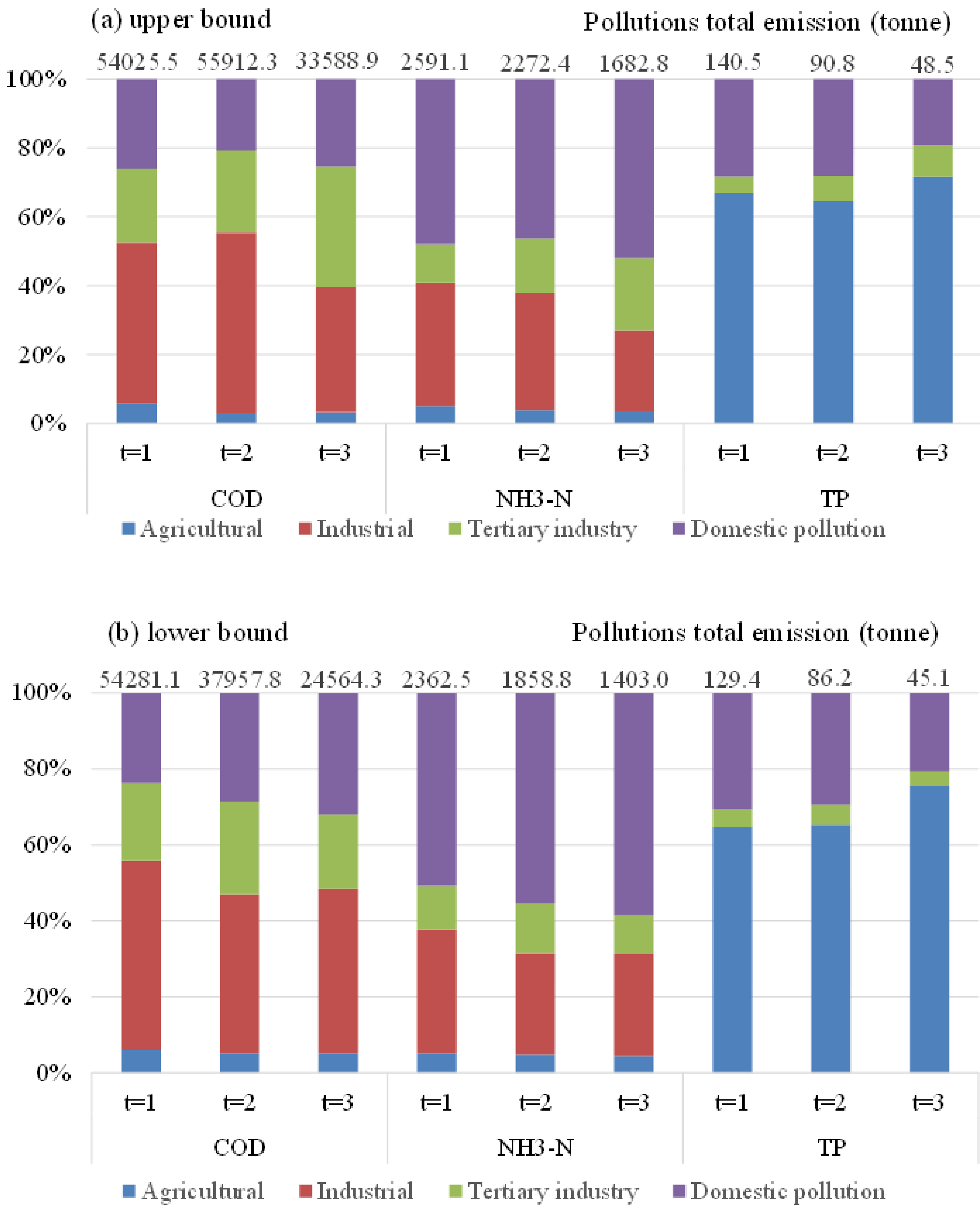


Figure 8

Total amount and sources of each pollutant in different planning periods under the scenario of high satisfaction

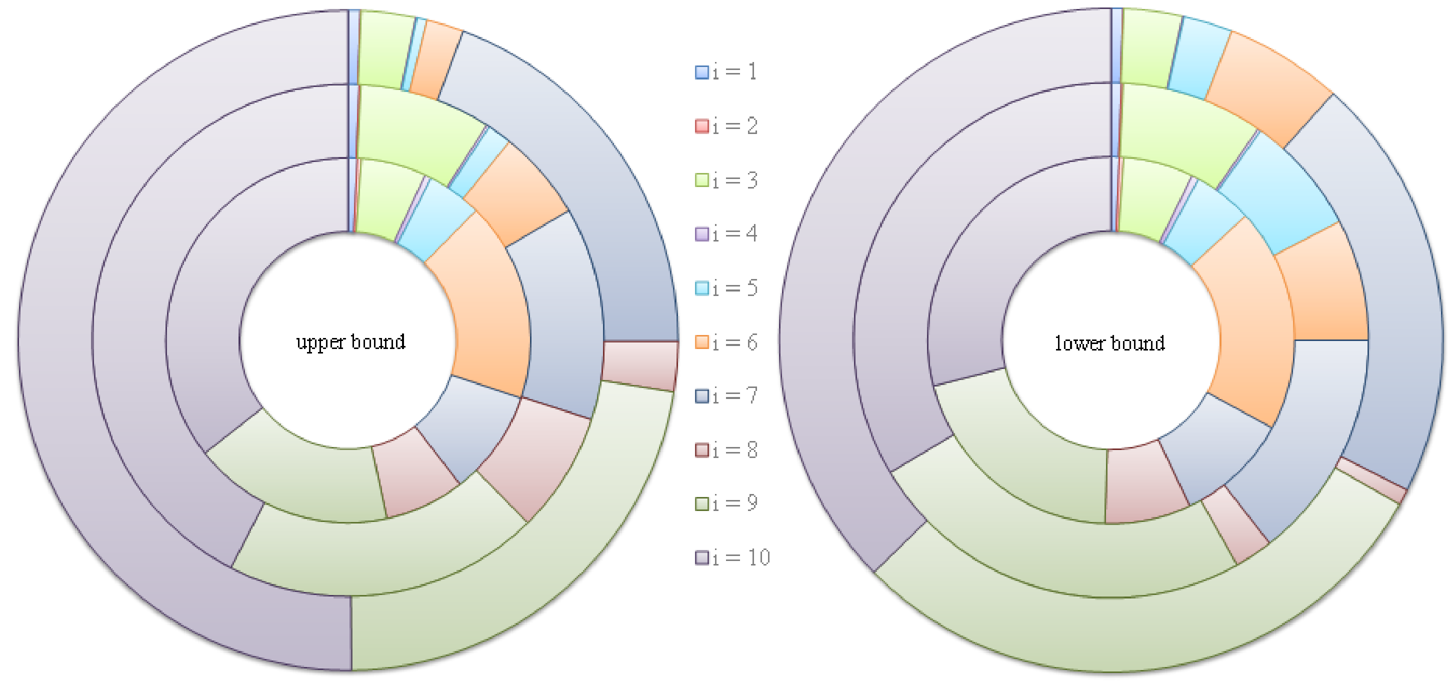


Figure 9

Water resources utilization in different planning periods under low satisfaction scenario

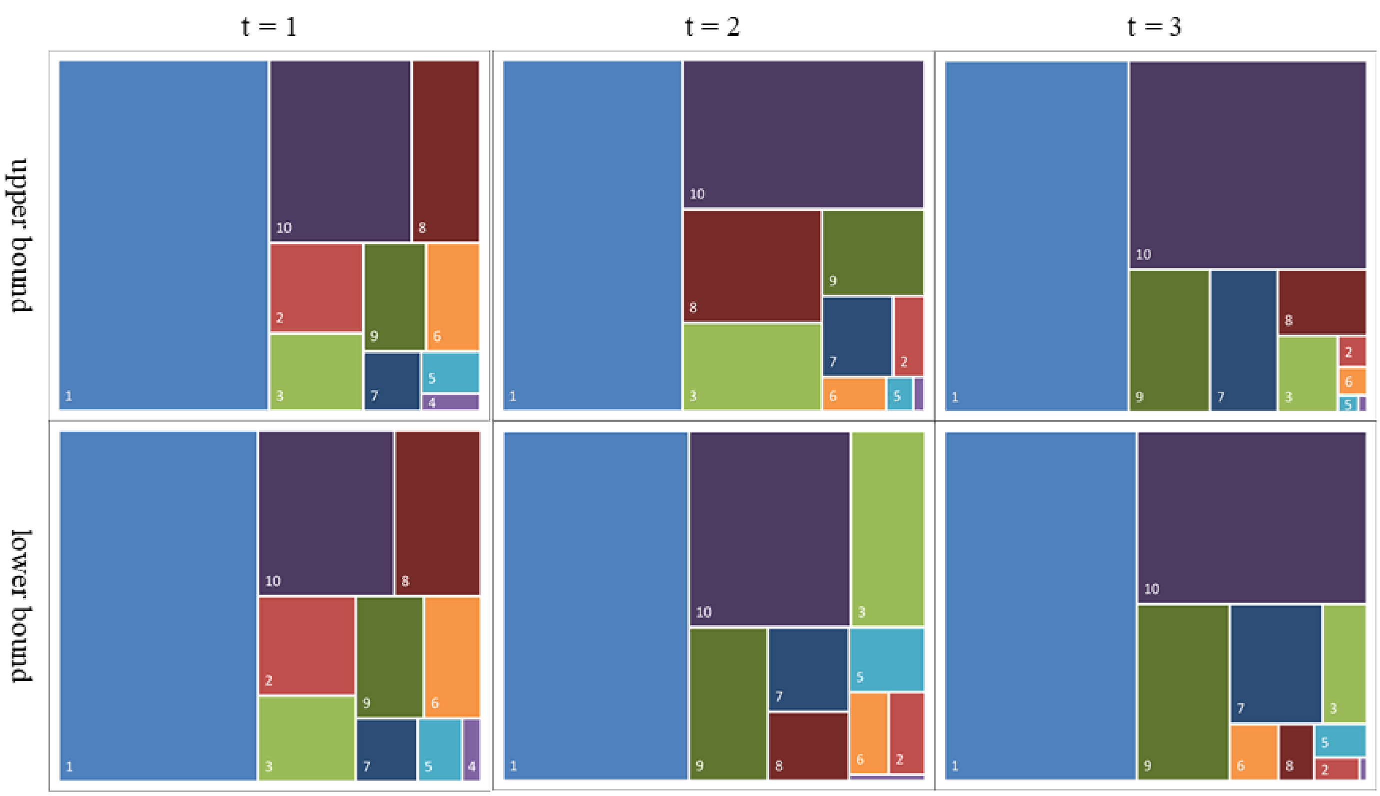


Figure 10

Water consumption of various industries in different planning periods under low satisfaction scenario

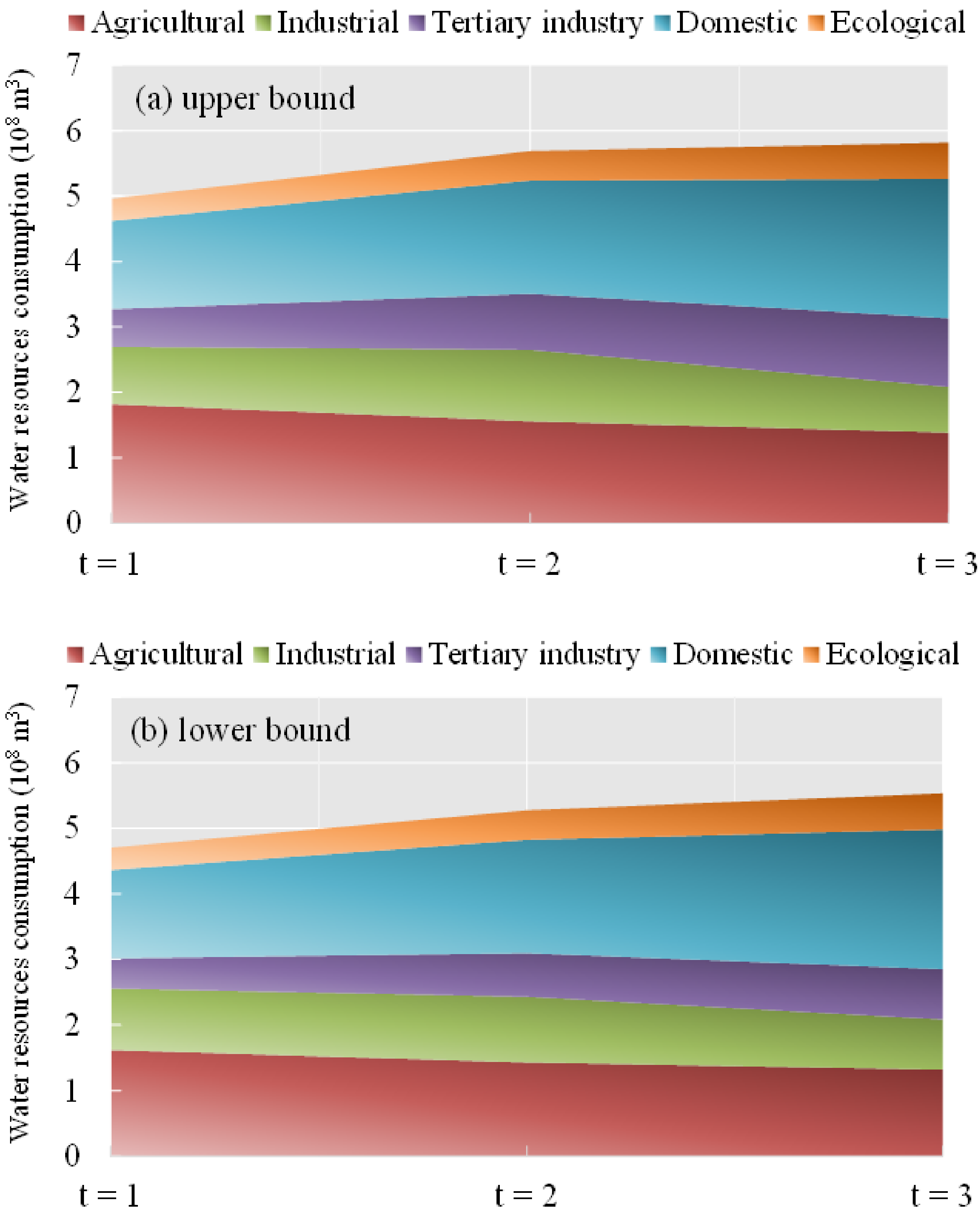
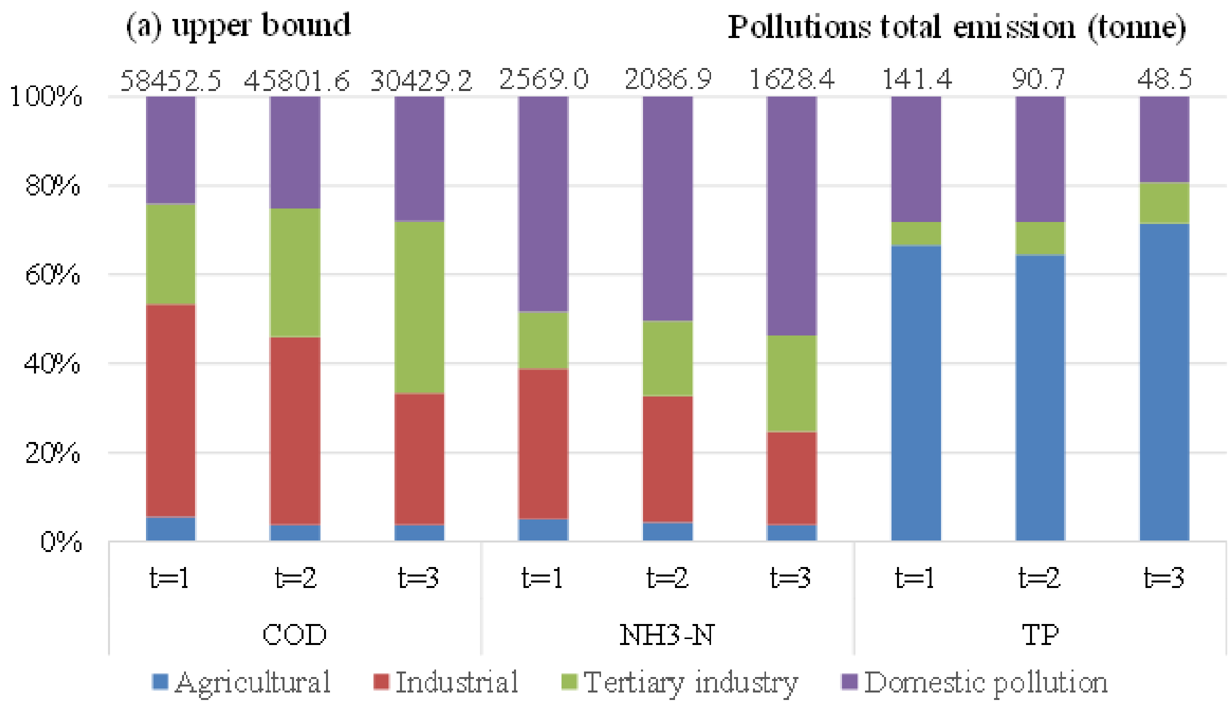


Figure 11

Water resources utilization in different planning periods under low satisfaction scenario



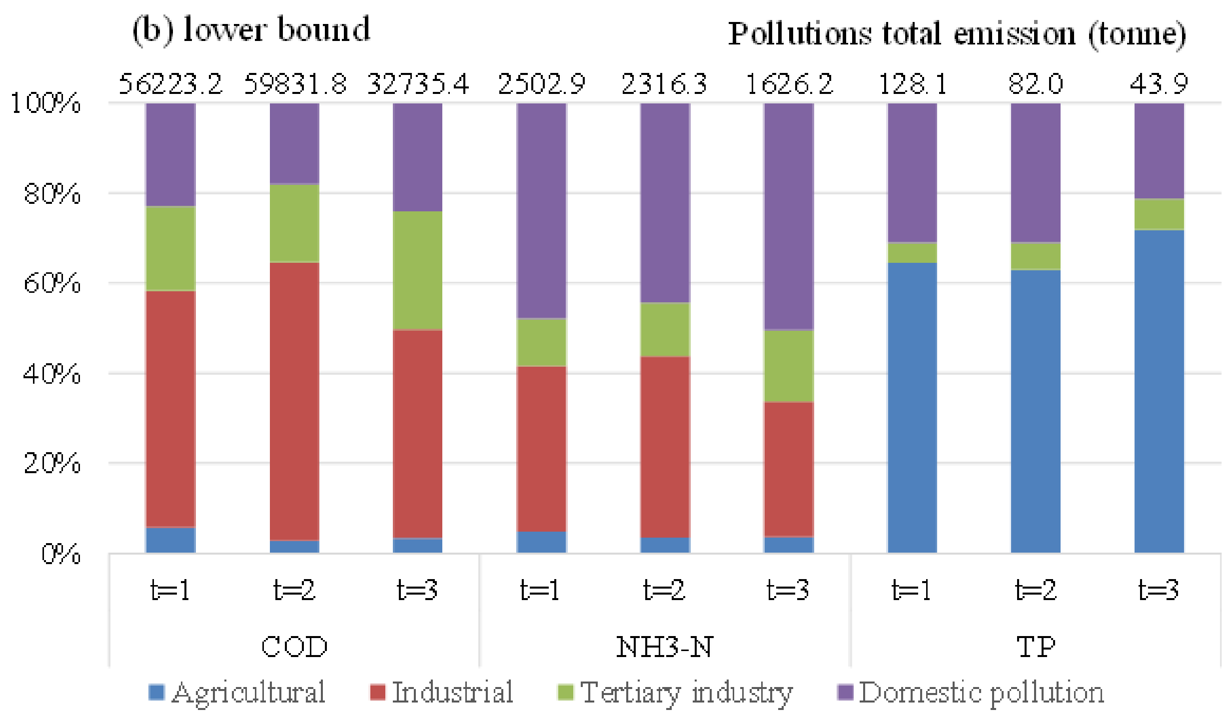


Figure 12

Total amount and sources of each pollutant in different planning periods under the scenario of low Satisfaction

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- AppendixA.docx