*Desalination and Water Treatment*
www.deswater.com
doi: 10.1080/19443994.2013.874722

52 (2014) 2778–2785
March

# Optimal allocation model of river emission rights based on water environment capacity limits

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Received 12 July 2012; Accepted 3 December 2013

ABSTRACT

China implements the most strict water resources management policy in 2009. The water resources management policy is controlled by three red limits: total water use amount cannot exceed the available water resources, water use efficiency must be higher than the efficiency red limits formulated by government, pollution capacity cannot exceed the pollutant-holding capacity. To implement the pollution red limits policy in the river basin, it must control the total amount of pollution discharged in the river. The initial water pollution allocation scenario is one of the most important systems in the total pollution control. This paper based on water function districts that for different water use purpose, divided the river to different segments by different water use, then allocated the initial emission permits to different water function districts. According to this allocation mode, the emission rights should firstly be allocated to the respective water function districts by the environmental management agency (vertical configuration), and then the emission rights are allocated to the dischargers from the water function districts (horizontal configuration). In the allocation model, fairness, efficiency and production continuity of the dischargers are regarded as the objective functions. The concentration and total quantity of pollutant are considered as the constraints of the model. At last, we get an example and solve it with multi-objective evolutionary algorithm to verify that the model is viable.

*Keywords:* River emission rights; Multi-objective optimization; Fairness; Efficiency; Total pollutant quantity control

## 1. Introduction

Currently, rivers are polluted seriously in China and it is becoming the worst of all problems relating to the water pollution. In all the 1,200 survey, more than 850 rivers are polluted in varying degrees and it is becoming more and more serious. Among the largest seven river basins in China, nearly 40% water in the branch rivers are not suitable for drinking, especially in the developed industrial towns, whose polluted river reach to 78%. From light to heavy, the pollution level of

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*Presented at the Second International Conference on Water Resources Management and Engineering (ICWRME 2012) Zhengzhou, China, 14–16 August 2012.*

the seven river systems is as following: Hai River, Liao River, Huai River, Yellow River, Songhua River, Zhu River, and Yangtze River [1,2]. Therefore, it is urgent to treat the pollution of the river basins in China.

In 2009, Chen Lei, the Minister of Water Resource put forward that China will strengthen the management on the water resources and the strictest system would be carried out. He also delimits three red limits so as to promote the sustainable development of our society. The third limit is the water environment capacity limit, namely a study will be carried out to set a limit to control the total pollution with several stages after calculating the pollution capacity in the water areas in accordance with the national overall target for emissions cuts.

The liquidity of the water makes the whole river in a dynamic state. Whether it is the upstream, midstream or downstream, branch river or mainstream, left bank or right bank, if only the river basins are managed from overall perspective, the pollution can be controlled efficiency [3,4]. The emission permits exchange based on the total control is an effective way to reduce the emission volume. It was first started in 1960s, and American scholar Dales was the first to put forward it [5], and then was spread to some other countries [6–8]. The emission permit exchange refers to the control over the total emission by setting the legal emission right and permitting that it can be traded so as to control the environment quality in the given area under the condition that the total volume and the environment are fixed. On the basis of limited resources, for the sewage and all the society, only by reasonable allocation of the emission right can the recognition on the right use of the water resources as well as its nature is enhanced. Meanwhile, the water resources management and water environment protection should be put into force by the way of economic measures [9,10]. Therefore, for all the rivers, it is of great significance to study the reasonable allocation of the pollutant emission properly based on the different water function districts.

This paper is aimed to establish a horizontal plus vertical allocation model for the river emission rights. And using the fairness, efficiency and production continuity of the dischargers as the target function and the water quality as well as the total volume as the restriction, it is also hoped to set up an optimum multi-target allocation model so as to resolve the existing problems in the present study. A finishing example is to testify their accessibility and operation.

## 2. Horizontal and vertical management model on the basis of river water function districts

Water function district is based on the current situation of water resources in the areas of a river and the requirement of water quality and quantity from the development of society as well as the exploration of water resources. It is fixed in certain given area so as to utilize and protect the water resources reasonably and make it produce the optimum interests. In 9 April 2002, ministry of water resources published a notice about the division of water function districts in China, in which it is required that all the organizations relating to the river areas should read it carefully and put it into the real practice. This notice marked by the Division of Water Function districts in China has been carried out nationally [11].

The water function district is divided into two grades (Fig. 1), namely the first graded and the second graded function districts. Among the first graded function district, there are protection zone, reservation zone, exploration and utilization zone and buffer zones. The second graded function district mainly covers the following seven zones: drinking water zone, industrial water zone, farming water zone, fishing water zone, entertainment water zone, transition zone and emission controlling zone. The first graded vision is hoped to settle the problems between water resources utilization and protection so as to build up a harmonious relationship between different areas and to satisfy the requirements of the sustainable development. The second graded division is mainly hoped to adjust the relationship among different water departments.

### 2.1. Protection zone, reservation zone and part buffer zone

As for the protection and reservation zones, it is stipulated that the basic rule is to maintain the current water quality, keeping its acceptance to the pollutions that equals to the emission sent into this zone. As for parts, the buffer zones, because of its good quality and less demand, it is also hoped to maintain its current quality using the current pollutant in this zone as its acceptance. Therefore, as for the protection, reser-

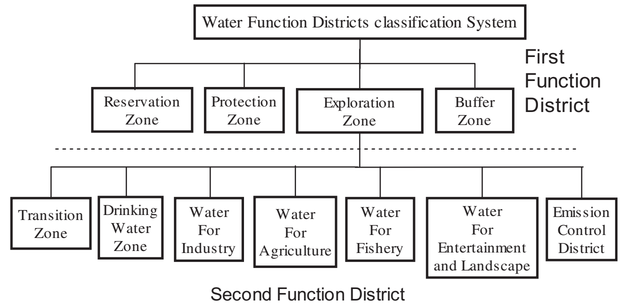


Fig. 1. Division system of water function district.

vation and part buffer zones whose acceptance of the pollutants equals to its inflow emission, their inflow emission amount is just their current acceptance of the pollutants. That is to say, these zones should be controlled and managed on the basis of current inflow emissions. If the water quality in certain zones needs to be improved, special treatment is needed then. The inflow emission should be controlled or reduced if needed for the interests of improving the water quality in that given zone. The concrete method is determined by the reduced amount and controlled amount in that given zone.

### 2.2. Exploration and utilization zone

For different parts in the exploration and utilization zone, when the current inflow emissions and the reduction need to be calculated, the current pollutant amount should be worked out first. After comparing it with the maximum pollutant capacity of second grade zones, the following three results can be obtained.

(1) If the current inflow pollution is larger than the capacity of the second graded water function zones, the pollution capacity is the current inflow volume of this function district. The current pollution reduction amount equals to the minus between the current inflow pollution and its current capacity.
(2) If the current inflow pollution is the same or a little smaller than the capacity of the second graded zones, it shows this zone achieves the quality target of the water in the function district. Namely, the current controlled inflow pollution in this second graded zone is its current inflow amount and no current inflow emission is to be cut.
(3) If the current inflow pollutant is smaller than the capacity of the second graded areas, it means its water quality reaches the standard and can be explored for further use. This kind of zone usually locates in areas which cover the less developed economy, abundant water resources and well water quality. The current controlled inflow volume can be set smaller than the inflow capacity. So no reduced cut is produced.

The horizontal plus vertical allocation model of the river emission rights means that the water environment protection department firstly distributes it to different water function districts. And then, certain related environment management organization horizontally distributes it to different dischargers. In this whole process of allocation, the water function district is just a bridge, limiting the emission amount distributed from the total emission rights. The ultimate purpose of distributing the emission rights is to make sure of the planned emission amount from the dischargers. This process should be under the supervision of river environment protection department. When vertically distributing the river emission right, part of it can be reserved in order to deal with the uncertain factors in the social economy development and to be in favour of the sustainable development of water environment protection and water resources.

## 3. Multi target allocation model of river emission rights

The allocation of the property will directly influence the fairness of wealth allocation and economy efficiency. In this way, the allocation of the initial emission right will have an effect on the fairness and efficiency of the wealth. The allocation of the initial emission rights should carry the spirit of fairness. It should also show the outlook on the ecology from the demand of natural resources as well the optimal allocation of the water resources.

Therefore, when establishing the initial emission right horizontal and vertical model, the demand of the environment quality in the water function district should be guaranteed and the fairness and efficiency should be taken into account. At the same time, the extra water environment capacity should be saved as much as possible for the sustainable development of water resources. By using the multi target allocation model, the balance point between the fairness and efficiency should be found so as to harmoniously deal with them.

### 3.1. Objective function

#### 3.1.1. Objective function based on fairness

When setting the initial emission right, one of the social interests needed to be considered is the maximum fairness of the emission right in the given areas. Every pollution company enjoys the equal right when dealing with the initial emission right. Such equality can surely arouse these companies to produce cleanly and improve their techniques to treat the pollution.

Assume there are $n$ water function districts in a river and $m$ professions in $j$-controlled areas. The $i$th profession occupies $b(i)$ companies. So, there are altogether $N = \sum_{i=1}^{m} b(i)$ companies in this controlled area, and the $f_1$ is the objective function based on fairness.

$$f_1 = \min f_1' \tag{1}$$

In Eq. (1), Gini Coefficient is based on the allocation of emission right. It is mainly used to show the fairness of the initial emission right among different companies. The smaller the Gini Coefficient is, the fairer it will be. The calculating equation of it is as follows [12]:

$$G = \frac{1}{N}\sum_{i=1}^{N}\sum_{j=2,j>i}^{N}\left(\frac{I_i}{I}-\frac{I_j}{I}\right) = \frac{I}{NI}\sum_{i=1}^{N}\sum_{j=2,j>i}^{N}(I_i - I_j) \tag{2}$$

In Eq. (2), G refers to the Gini Coefficient; $N$ refers to all the members in the society or the total strata of the society; $I$ refers to the total income of all the members or strata in the society; $I_i$, $I_j$, respectively, means income of the numbered $i$, $j$ member of stratum. The economic meaning of the Eq. (2) is the difference of income ratio between any two members or strata in all the society. So, it can be employed to observe the varying degrees of income allocation. The value scale of the Gini Coefficient is between 0 and 1. The smaller the value is, the more chances the income allocation towards the equality and vice versa.

The Gini Coefficient of emission right allocation for the companies mentioned in this paper is:

$$f_1' = \frac{1}{m}\sum_{j=1}^{m}\sum_{i'=2,i'>i}^{m}\left(\frac{Q_{ij}-Q_{kj}}{Q_j}\right) = \frac{1}{mQ_j}\sum_{j=1}^{m}\sum_{i'=2,i'>i}^{m}(Q_{ij}-Q_{kj}) \tag{3}$$

In Eq. (3), $f_1'$ is the Gini Coefficient of emission right allocation for the companies. The smaller the value is, the more tendency it shows for the fairness of emission right allocation among different companies, m refers to the total number of the companies taking part in the emission right trade system. $Q_{ij}$ and $Q_{kj}$ are the allocation amount of initial emission right acquired by $i$, $k$ companies in the $j$ water function districts. $Q_j$ means the total amount of initial emission right which can be distributed in $j$ water function districts.

#### 3.1.2. Objective function based on efficiency

All the same, for the allocation of emission right, the economy interest can finally be demonstrated by the maximum welfare to the utilization of all the resources in the whole society. For the m companies in the water function district, the interest $R_i(Q_{ij})$ of the $i$ numbered company is a function of the emission right allocation $Q_{ij}$.

The total social cost consists of two parts. One of it is the investment in the materials. No difference of material cost in the same profession is assumed in this paper. Another one is the cost on the pollution treatment. Suppose the i numbered company produces pollutant $e_{ij}$, then the amount of the pollution treatment for this company is $e_{ij} - Q_{ij}$, and the treatment cost will be $T_i(e_{ij} - Q_{ij})$. Therefore, if the social environment resources want to be maximized, namely:

$$\begin{aligned}\text{Max } f_2 = {} & R_1(Q_{1j}) + R_2(Q_{2j}) \\ & + \ldots + R_m(Q_{mj}) - [T_1(e_{1j} - Q_{1j}) + T_2(e_{2j} - Q_{2j}) \\ & + \ldots + T_m(e_{mj} - Q_{mj})],\ j = 1, 2, \ldots n\end{aligned} \tag{4}$$

#### 3.1.3. Objective function based on the production continuity of dischargers

When certain environmental policies need to be carried out in certain areas, the distributed amount of initial emission right should be kept stable. That is to say, the varying scale should be as small as possible when comparing the distributed emission right of each company with its prior average amount. This can guarantee the continuity of production for each company. Namely;

$$\min f_3 = \sum_{i=1}^{m}\left(Q_{ij} - \overline{Q_{ij}}\right)^2,\ j = 1, 2, \ldots n \tag{5}$$

In Eq. (5), $\overline{Q_{ij}}$ is the average of the annual emission right amount for the pollution producers.

### 3.2. Restriction conditions

#### 3.2.1. Restriction over the total pollution

The total emission amount from every discharger should be limited lower than the acceptance capacity in the water function districts. The entire planned emission amount should not be higher than the total amount of river emission right.

$$\sum_{i=1}^{m} Q_{ij} \le Q_j,\ j = 1, 2, \ldots n \tag{6}$$

$$\sum_{j=1}^{n} Q_j \le Q \tag{7}$$

In Eq. (7), $Q$ refers to the total emission amount distributed to the whole river, namely the total amount of the initial emission right acquired by all the companies in the environment management area that should not be more than the total amount of the distributed emission amount.

### 3.2.2. Restriction over density

In the water function districts, the planned emission density should be controlled under the supposed water quality target.

$$M_{j0} + \sum_{i=1}^{m} Q_{ij}\ b_{ij} \leq E_{js} \tag{8}$$

In Eq. (8), $M_{j0}$ means the density contribution value in the downstream-controlled section of the $j$-numbered water function district and $b_{ij}$ is the density transmission function of the controlled section by discharger $i$ in the $j$-numbered water function district. It is related to the distance from the controlled section to the drain outlet, the characteristics of water body and pollutant and so on. $E_{js}$ is the management target of water quality in the $j$-numbered water function district.

## 4. Example of an application

### 4.1. Introduction to the example

The river is a first level branch of Yangtze River which covers the 140 km total length and 4,300 km$^2$ area. With the economic development in its covered area, a lot of pollutants are poured into the river directly without any treatment, causing the water quality worsen more and more. Therefore, the total emission amount is supposed to be controlled in this river so as to adjust the relationship between economic development and deteriorating environment. This area is divided into $H_1$, $H_2$, $H_3$, $H_4$ and $H_5$; altogether five first-graded function districts and nine-simplified sewage outlets (P1–P9). The diagram of the function district and location of simplified drain outlet are shown in the following Fig. 2. The length and the water quality target of the function district are shown in Table 1.

The numerical example sets the COD as the research object and assumes the emission amount of COD is highly over standard. The governmental environment supervisor distributed the permitted amount of COD to each company. The water quality requirement of the function district can be inversed by one-dimensional water transport equation. The lower profile pollution concentration must be smaller than the water quality object of the next function district. Thereby, we can get the pollution concentration object $E_{js}$ in every function district. The lower profile pollution concentration caused by other polluters can be calculated by Yang [13]. The concentration transfer function $f_{ij}$ is computed by one-dimensional water transport equation.

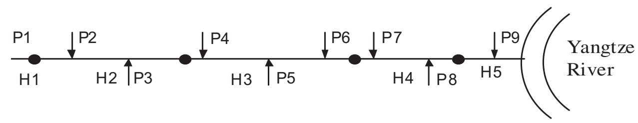


Fig. 2. Division system of water function district.

Table 1
The length and the water quality target of the function district

| Water function district | Length | Water quality target |
|---|---|---|
| $H_1$ | 32.1 | II |
| $H_2$ | 25.4 | III |
| $H_3$ | 57.9 | III |
| $H_4$ | 21.5 | II |
| $H_5$ | 3.1 | III |

$$f_{ij} = \exp\ (-Kx_{ij}/u_j)/Q_j \tag{9}$$

In Eq. (9), $K$ is the integrated pollution degradation coefficient. $x_{ij}$ is the distance from the $i$th polluter in the $j$th function district to the control profile of the function district. $u_j$ is the average flow velocity of $j$th function district. $Q_j$ is the design flow of $j$th function district.

The pollution capacity can be computed by the pollution concentration control target in every function district. The water character, water quality target and pollution character can influence the pollution capacity of the function district. Firstly, we can get the pollution concentration of the control profiled by water quality transfer equation, and then treat the pollution outfalls in the computed river length as a centralized outfall. The actual self-purification length of the centralized outfall is half of the river length [14]. So, the pollution capacity computed by the river length is calculated by Eq. (10).

$$W = 31.536\{C_s(Q_0 + Q_W)\exp[-KL/(172.8 \times u)] - C_0 Q_0 \exp[-KL/(172.8 \times u)]\} \tag{10}$$

In Eq. (10), $W$ donate the function capacity of the function district. $Q_0$ is the design flow. $Q_w$ is the discharged pollution water flow of the function district. $C_s$ is the water quality target of the function district. $C_0$ is pollution concentration of the upper profile in the function district. $L$ is the length of the function district and $u$ is the average velocity under the design flow in the function district.

According to the current river emission, economic level, further development plan and the river water environment capacity as well as the total-controlled emission amount for the river from Yangtze river is 5,000 t/a. The total-controlled amount target in each water function district can be determined through the emission capacity based on the controlled density target. The emission capacity is related to the characteristics of water body, target of water quality as well as the characteristics of pollutant. The emission allocation results of each function district can be seen in Table 2.

### *4.2. Solution*

The paper uses particle swarm optimization algorithm to solve the constrained multi-objective decision-making model. The key point of the algorithm is to design rational techniques handling the constraints, select appropriate global and local extremum. The algorithm not only fastens close to the feasible region, but also finds a good distribution Pareto optimal front. The basic idea of the algorithm is evaluating the objective function value of each particle. With random perturbation, the history and group optimal location decide the next step of the particle. Finally, the solution which satisfies the stop condition is the globally optimal solution. Specific calculation steps are as follows:

Step 1: Initialize the population.
Step 2: Calculate the fitness of particles in the populations.

Table 2
Emission right allocation results of function district

| Function district | Upstream background density (mg/L) | Downstream controlled section density (mg/L) | Planned pollution (t/a) |
|---|---|---|---|
| $H_1$ | 1.1 | 1.3 | 96.11 |
| $H_2$ | 1.3 | 1.7 | 204.89 |
| $H_3$ | 1.5 | 3.0 | 340.65 |
| $H_4$ | 3.5 | 3.0 | 181.09 |
| $H_5$ | 2.6 | 3.5 | 96.91 |

Step 3: Evaluate the fitness value and update the extremum.
Step 4: Work on the evolutionary algorithm to form a new population

(1) Selection
(2) Recombination
(3) Mutation

Step 5: If the ending condition is satisfied, the iterative algorithm is to be ended or else it will return to Step 2.

### 4.3. Results

The parameter of evolutionary algorithm can be set as follows: the initial population scale $N = 100$ and the iveration times are 200. The operator is selected optionally and crossover operator uses one-point crossover. The crossover rate is 0.65 and mutation rate is 0. With the aid of evolutionary algorithm, the result can be obtained by the multi-target decision patter, namely the non-inferior solution set (equivalently Pareto optimal) is obtained, as is seen in Fig. 3. At this moment, the environment manager needs to do the selection among these solutions.

Suppose that the decision-maker thinks the environment quality is the best and environment saving capacity is the largest, namely:

$$\max f_4 = Q - \sum_{j=1}^{n}\sum_{i=1}^{m} Q_{ij} \tag{11}$$

Compared the results of this paper with the results got from reference [19], it provides a multi-target decision model of emission right allocation, in which the optimum economy is the first target, the fairness and continuality is the second target. The results of both models can be seen in Table 2.

From Table 3, it can be found that the total amount of emission right from the dischargers calculated by this model reaches 874.16 t/a, the treatment fee of dealing with the pollutants reaches RMB 619,600 Yuan and the water environment saving capacity of the river is 45.49 t/a. However, the total amount of emission right from the dischargers calculated by reference [9] reaches 898.48 t/a and the treatment fee of dealing with the pollutants reaches RMB 636,900 yuan, water environment saving capacity is 21.17 t/a. By comparing these two methods, the result of the total amount of emission right acquired by this model is much less, and treatment fee for the pollutants is much less too and the water environment saving capacity is much

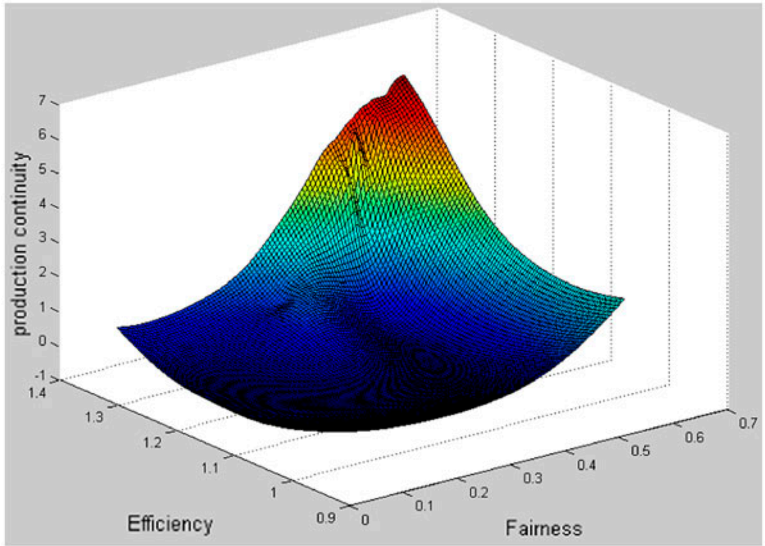


Fig. 3. Non-inferior solution set (equivalently Pareto optimal).

Table 3
Result of emission right allocation to discharger

| Discharger | Distance to the outlet (km) | Results of this paper (t/a) | Results of Ref. [13] (t/a) |
|---|---|---|---|
| $P_1$ | 135 | 87.09 | 91.55 |
| $P_2$ | 103 | 92.48 | 100.75 |
| $P_3$ | 90 | 102.87 | 101.87 |
| $P_4$ | 78 | 91.24 | 96.12 |
| $P_5$ | 72 | 120.53 | 114.89 |
| $P_6$ | 65 | 113.26 | 111.66 |
| $P_7$ | 54 | 74.11 | 85.44 |
| $P_8$ | 27 | 97.88 | 98.11 |
| $P_9$ | 2 | 94.70 | 98.09 |
| Total | | 874.16 | 898.48 |

more. Therefore, by this numerical example, this model favours the management and control of the water environment of the water and solves effectively the contradictions between different river areas, different river streams of the river. It can also adjust the contradiction between efficiency and fairness.

## 5. Conclusions

The paper introduces the water function zone to the initial emission rights allocation of the river. On the basis of the division of water function district, the environment protection department can draft the total emission rights of the river by the following two steps. First, the emission right should be distributed vertically to different water function districts. Second, the initial emission right can be distributed horizontally to the horizontal plus vertical distribution model which is distributed to the dischargers. The method that connects water function zone with pollutant emission is propitious to the basin environment management on the whole. Based on this, the fairness, efficiency and continuity of production are employed as the objective function, water quality and total amount are used as the restriction conditions, and the multi-target allocation optimal model is established. At last, a numerical example is given to illuminate the feasibility of the model. This method enjoys certain application prospect to solve the serious water pollution in China basin and the conflict between economic development and environmental protection. However, due to the allocation of river emission rights which is large-scale system engineering, the need to consider many factors and collect large amount of data, the model contains only the difference of initial emission rights between polluters in fairness. In future studies, we must take into account the regional characteristics of discharges, industry characteristics and other factors that can influence the allocation result.

## Acknowledgements

This work was supported by NSFC (51309129, 51109224), Ministry of Water Resources' Special Funds for Scientific Research on Public Causes (201201016), Foundation of Jiang'xi Science and Technology Department (20123BBG70215).

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