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A Hybrid Life-Cycle Analysis and Two-Stage Stochastic Programming Model for Low-Carbon Management upon Urban Water Resources

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Abstract

Due to population growth and economic development, water demands for municipal, industrial, and agricultural users are increasing. It is a challenging and critical issue in water resources system to properly allocate and utilize water resources to satisfy the goals of different stakeholders and greenhouse gases mitigation. In this study, a hybrid life-cycle analysis and two-stage stochastic programming model was proposed to analyze the water-allocation strategies based on complicated urban water resource system. The hybrid model can effectively assess the low-carbon performance of an urban water resources system in the framework of life-cycle analysis. The environmental impacts and GHGs reduction of urban water resources were firstly considered as the objective and constraint for solving the water allocation problems. The results indicated that the first-stage solutions of surface water conveyance of Dalian could be [3.83×10^8, 8.25×10^8] in 2015, and [3.83×10^8, 9.21×10^8] in 2020; Meanwhile, the first-stage solutions of surface water conveyance of Dalian could be [4.26×10^8, 8.68×10^8] in 2015, and [5.35×10^8, 10.7×10^8] in 2020.

***Keywords**: Life-cycle analysis; Two-stage stochastic programming; urban; water resources*

1. Introduction

Fresh water is fundamental for maintaining environmental sustainability of human communities [1]. Over the past decades, due to population and economic growth, water demand by municipal, industrial, and agricultural users has continuously increased. Potential conflicts over water resources can then arise from water demand for limited water supplies [2, 3]. Particularly, in many cities across the world, high reliance on fresh water resources and rapid population growth has resulted in severe water stresses [4]. However, many processes and factors need to be considered and addressed within a urban water resources system (UWRS), such as water resources protection measures, infrastructure capital and operational costs, electricity supporting, and water-related service allocation [1, 5].

In many previous studies, water is firstly set in a product level. For example, water footprint assessment can be utilized to assess the effects of products or businesses on

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aquatic environments during life cycle stages [6]. However, it is still difficult for governments, businesses, and individuals to apply the results of water footprints in decision-making activities [7]. In real UWRS, water is mainly comprised of supply, production, transport networks, water distribution to consumers, and urban drainage and sewer systems where electricity is one of main inputs [8]. Thus, the research of UWRS should be first conducted by the division of multi-attribute system.

Conventionally, many system analysis methods were developed for supporting urban water resource management, such as life cycle analysis (LCA), operational research, and system dynamics (SD) modeling. Among them, LCA was widely used to evaluate water footprints and the corresponding environmental performances of many water-related activities such as water extraction, conveyance, and consumption [9-11]. According to ISO [12], LCA can be used for systematic evaluation of two or more products and/or processes/services in terms of both economic and environmental implications. For example, many scholars assessed environmental performances of many processes related to water supply [13, 14]. Additionally, more recently, the scope of LCA has broadened from product to multiple product-service levels for identifying solutions of water resource allocation. For example, Chung and Lee [15] developed a social-economic-engineering combined framework for decision making in water resource planning. Joore and Brezet [16] developed a multilevel design model based on LCA, which divided urban social system into product technology, product service, and social technology. Sigel, *et al*. [17] proposed a conceptual framework for perceiving and describing uncertainties in environmental and water-related decision-making. However, there was also one challenge that made the traditional LCA framework ineffective. At the stage of life cycle interpretation, the accounting results cannot directly support decisions for future without any applicability, representing merely evaluation results.

Comparatively, many optimization tools can be used to remedy such disadvantages. To solve the problem of water allocation, optimization management tools need to be integrated into an LCA framework for robustly supporting decision making. There were numerous attempts on optimization models for decision-making within a UWRS. For example, Carmona, *et al*. [18] developed a methodological framework to support decision making in water management under uncertain conditions. In particular, two-stage stochastic programming (TSP) was considered as an effective tool that supports decision making under the condition that recourse decisions are required for correcting original decisions under the occurrences of stochastic events. The method was applied into many fields such as eco-resilience improvements under floods [19], sustainable water supply systems [20], and agricultural non-point source water pollution control [21]. Specifically, most related research considered economic performance as the only objective function and did not consider environmental impacts of UWRS in the optimization framework [22].

Therefore, the objective of this study is to develop an integrated approach for supporting comprehensive decision-making in urban water resources system for low carbon management through the incorporation of life-cycle analysis and two-stage stochastic programming. This method will improve the capabilities of conventional LCA in terms of applicability and robust decision-making supporting. It is particularly useful for strengthening the applicability of LCA in generating comprehensive decision alternatives. The methodology can (a) systematically reflect and address complexities of UWRS, and facilitate the evaluation of environmental impacts in multiple product-service levels, and (b) identify water allocation and manage adaptation action for low-carbon-oriented water supply system design. The developed method will then be demonstrated in a water-stressed city (*i.e*., Dalian) in northeastern China.

2. Methodology

2.1. Life Cycle Analysis

The UWRS are composed by surface, underground, and ocean water. In urban area, water re-sources are supplied to water users through the following stages: (1) the water-service level in consideration of the water supply, water treatment, and wastewater treatment; (2) the water-product level in consideration of the different users in different districts; and (3) the water-management level in consideration of the solution of water allocation from an environmental perspective, such as LCA, uncertainty analysis, and TSP model, should be introduced into the framework to support decision-making activities. The system boundary of a UWRS for low-carbon management includes the process of water extraction, production, use, treatment and discharge/reuse m (Figure 1). The production of pipelines and related chemicals are not included in the system boundary. Electricity production for water conveyance and treatment is included in the system boundary.

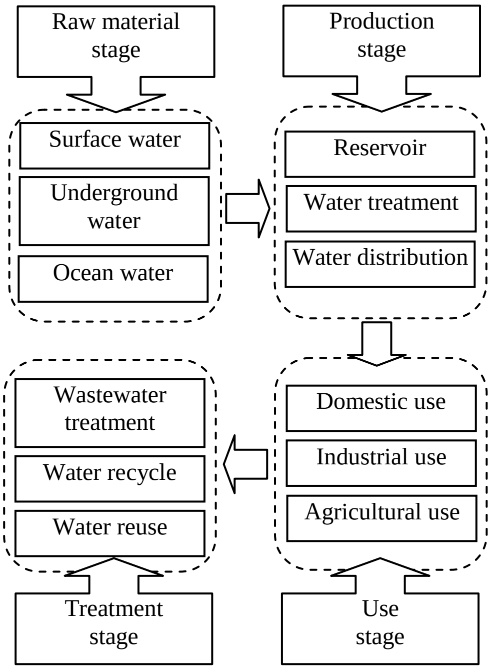

Figure 1. Life Cycle Stages of Water based on Multiple Levels

2.2 Two-Stage Stochastic Programming

Consider a problem in which a water manager is in charge of supplying water to multiple users from a number of water sources during dry and wet seasons[23, 24]. The users are expanding their activities and need to know how much water they can expect. The water manager can formulate the problem by minimizing the environmental impacts in the process of servicing water for certain regions. Given a quantity of water that is pre-promised to a user, if this water is diverted, it will definitely result in a cascade of environmental impacts. However, if the promised water is not diverted in a dry season, a certain amount of water needs to be obtained from alternative water sources and imported from external regions with enhanced expenses [23]. Because the total available water [23, 24] and the trends of the economy are random variables, this problem can thus be formulated as a two-stage stochastic programming (TSP) model [3] based on multi-level LCA.

In this study, the first-stage decision of the UWRS is the water distribution targets before the random change on seasonal flows; when the uncertainty of the variables are uncovered, a second-stage recourse action for the first-stage water allocation targets can be taken to analyze the extent of the added environmental impacts.

$$\min f \;=\; \sum_{l=1}^{k}\sum_{i=1}^{n} e_{il}T_{il} + \sum_{l=1}^{k}\sum_{i=1}^{n}\left[e'_{il}\,E(D_{iQl})\right] + \sum_{r=1}^{p}\sum_{i=1}^{n} e''_{ir}T_{ir} \tag{1a}$$

s.t.

$$T_{il} \;\geq\; \sum_{r=1}^{n'} D_{iQl} \;\geq\; 0,\ \forall i,\ l \tag{1b}$$

$$C_l \;\geq\; \sum_{i=1}^{m}\left(T_{il} - D_{iQl}\right),\ \forall l \tag{1c}$$

$$T_{i\max} \;\geq\; T_{il} + T_{ir},\ \forall i,\ l,\ r \tag{1d}$$

$$\frac{\sum_{l=1}^{k}\sum_{i=1}^{n}\psi(T_{il}) + \sum_{l=1}^{k}\sum_{i=1}^{n}\psi(D_{iQl})}{\sum_{l=1}^{k}\sum_{i=1}^{n}\psi(T_{il0})} \leq \Delta GDP \times L \tag{1e}$$

$$T_{il},\ T_{ir},\ D_{iQl} \;\geq\; 0,\ \forall i,\ l,\ r \tag{1f}$$

where

f: Environmental impact;

e_{il}: Environmental impact from the supply of 1 m^3 surface water to the i^{th} district from the l^{th} water source of the first stage;

e'_{il}: Added environmental impact from the supply of 1 m^3 surface water to the i^{th} district from the l^{th} water source of the second stage;

T_{il}: Fixed allocation target for surface water that is promised to district i from water source l (m^3/year) (the first-stage decision variable);

D_{iQl}: Amount of surface water delivered of which water-allocation target T_i is not met when the inflow is Q (unit/d) in the l^{th} water source (the second-stage decision variable);

e''_{ir}: Environmental impact from the supply of 1 m^3 other types of water (*i.e.*, ground water, desalinated water, and recycled water) to the i^{th} district from the r^{th} water source;

T_{ir}: Fixed allocation target for other types of water that is promised to district i from water source r;

$\psi(T_{il})$: Amount of greenhouse gases for supplying 1 m^3 surface water to the i^{th} district from the l^{th} water source of the first stage;

$\psi(D_{iQl})$: Amount of greenhouse gases for supplying 1 m^3 surface water to the i^{th} district from the l^{th} water source of the second stage;

ΔGDP: The change rate of GDP in planning year compared with GDP in base year;

L: Government mitigation target of GHGs in planning year (Unit: %);

i: districts of a city, $i = 1, 2, 3, \ldots, n$;

l: Surface water sources of a city, $l = 1, 2, 3, \ldots, k$;

r: Other types of water resources to a city, $r = 1, 2, 3, \ldots, p$;

T_{imax}: Maximum allowable allocations of water for district i (m^3/year);

C_l: Water supply capacity of l^{th} river.

To solve the above problem, the distribution of each Q must be converted to an equivalent set of discrete values. Letting each Q take values q_j with probabilities p_j (j=1, 2, ..., n):

$$E(D_{iQl})=\sum_{j=1}^{n} p_{jl} D_{ijl} \quad (2)$$

3. Case Study

3.1. Overview of the Study Area

As an important port and tourist city in northern China, Dalian is located at the southern tip of the Liaodong Peninsula, with the Yellow Sea to the east and the Bo Sea to the west. The city is composed of eight districts (*i.e*., Municipal Zone, Jinzhou, Pulandian, Wafangdian, Changxingdao, Zhuanghe, Huayuankou, and Changhai). Its annual average rainfall is from 600 to 800 mm. However, there is a natural shortage of fresh water sources to the city. The per capita water resource supply (10000 yuan) in Dalian was about 6.54 m^3 in 2013, which is not only for domestic consumption, but also for agriculture, industry, environment [25]. It is no more than a quarter of per capita supply of China. Not only is the water scarcity severe, the water resources distribution is uneven in Dalian, descending from the northeast to the southwest. In Municipal Zone of Dalian, the per-capita water resource is only 164 m^3. The problem of urban water supply shortage is always the main factor hindering the development of Dalian's economy [26]. According to the water supply plan for Dalian, the water supply is only 16.1 to 29.4×10^8 m^3, and is mainly supplied by surface water. Thus, the limited water supply cannot satisfy the constantly increasing water demand and will gradually influence the development of Dalian [26].

3.2 The Low-Carbon Management System (LCMS) for Water Resources

Dalian has a maritime climate and an inherently small fresh water supply. The Biliu River is one of the largest rivers in southern Liaoning, with a total length of 156 km, and is the primary water source for Dalian [27]. In past years, surface water mostly came from rivers flowing through the city, such as Yingna, Biliu, and Dasha Rivers. With the development of the population and economy, however, local water sources cannot fulfill the demands of the city. The system boundary of the LCMS for water resources in Dalian includes the following parts: electricity consumption in the stage of water transfer from reservoirs to the water treatment plants, electricity consumption in the stage of water and the wastewater treatment plants. The functional units of the LCMS in Dalian are 1000kg of product level and supplying 1000kg water to users of service level. The distance between the reservoir and the WTP of Dalian City is described in Table 1. The parameters of the reservoirs for Dalian City are listed in Table 2. Water demands of the two planning years are described in Table 3.

Table 1. The Distance between Reservoir and WTP of Dalian

Unit: km

Area*	First stage		Second stage	
	Rivers (reservoirs)	Distance	Rivers (reservoirs)	Distance
$I_{1\text{-}a}$	Yingna River (Yingnahe)	121	Hun River (Dahuofang)	190.5
$I_{1\text{-}b}$	Biliu River (Biliuhe)			
$I_{2\text{-}a}$	Yingna River (Yingnahe),	121		190.5

$I_{2\text{-}b}$	Biliu River (Biliuhe)			
I_3	Dasha River (Liuda)	31		197
$I_{4\text{-}c}$	Fuzhou River (Songshu,)	19		165.1
$I_{4\text{-}d}$	Fuzhou River (Dongfeng)			
I_5	Fuzhou River (Dongfeng)	59		242
I_6	Zhuang River (Zhuwei)	17		244
I_7	Yingna River (Yingnahe)	71		280
I_8	Yingna River (Yingnahe)	108		317

*Note: I_1 means Municipal Zone of Dalian. Similarly, I_2 means Jinzhou, I_3 means Pulandian , I_4 means Wafangdian, I_5 means Changxingdao, I_6 means Zhuanghe, I_7 means Huayuankou, and I_8 means Changhai.

Table 2. The Related Hydrologic Parameters of Dalian*

Unit: 10^8 m^3

Reservoirs and rivers	Water availability (q_j) in different probabilities			Water supply capacity
	20%	55%	25%	
Biliuhe and above river	10.98	5.97	1.73	4.5
Yingnahe and above river	6.66	3.12	1.04	2.41
Dongfeng and above river	4.47	1.33	0.35	0.67
Songshu and above river	3.47	0.66	0.17	0.47
Liuda and above river	3.29	0.58	0.19	0.49
Zhuwei and above river	3.97	1.09	0.35	0.81

*Note: The values of capacity in Biliuhe and above river are from Liu [28]; The values of water supply capacity in Biliuhe, Dongfeng, Songshu, Liuda, and Zhuwei with their above rivers are from Lu [29]; The values of capacity and water supply capacity in Yingnahe and above river are from Zhang [30]; The values of capacity in Songshu, Liuda, and Zhuwei with their above rivers are from Liu and Li [31], Liu, *et al.* [32], Tan and Zhang [33], Song and Ye [34].

Table 3. Water Demand Prediction of Dalian in 2015 and 2020

Unit: 10^5 m^3

	2015			2020		
	S	D	R	S	D	R
I_1	3490	165	1170	4000	39	1570
I_2	2050	53	539	2330	372	861
I_3	1780	266	193	1810	399	286
I_4	1190	119	133	1540	239	245
I_5	1070	543	162	1380	664	433
I_6	2660	112	140	3060	159	240
I_7	216	13	54	342	27	111
I_8	58	6	9	96	6	17
Total	12514	1277	2400	14558	1905	3763

*Note: S- Surface water; D- Desalinated water; R- Recycled water.

3.3 Life Cycle Inventory of LCMS in Dalian

(1) Activity emission factor of energy consumption

According to relevant research results from IPCC [35] and Cui, *et al.* [36], the activity emission inventory of electricity in China are listed in Table 4.

Table 4. The LCI of Electricity Generated by Power Stations of China in 2009

Unit: kg/kWh

Item		Amount
Raw material	Coal	6.60E-01
	Fuel oil	2.50E-04
	H_2SO_4	2.30E-04
	HCl	6.22E-05
	NaOH	5.82E-05
	Limestone	4.96E-03
	Freshwater	8.47E-02
Direct emissions	CO_2	8.00E-01
	SO_2	1.67E-03
	NOx	8.05E-03
	Particulates	2.00E-05
	CO	1.04E-03
	CH_4	7.90E-06
	NMVOC	2.40E-04
	As	1.86E-08
	Cr	1.42E-09
	Cd	2.40E-10
	Ni	1.83E-09
	Pb	4.81E-08
	V	2.42E-08
	Zn	6.51E-08
	Hg	4.13E-08
Waste disposal	Wastewater	8.47E-02
	Landfill	2.64E-01
GHGs	GWP	3.3

*Source: [36]

(2) Energy consumption of UWRS in Dalian

The amount of energy consumption in different areas of Dalian is described in Table 5.

Table 5. Energy Consumption for the Service of Water Conveyance in Dalian*

Unit: 10^{-3} MWh/1000kg

Area	Rivers (reservoirs)	S	D	R	2th stage
I_{1-a}	Yingna River (Yingnahe)	1.05	7.50	4.72	167
I_{1-b}	Biliu River (Biliuhe)	0.59			
I_{2-a}	Yingna River (Yingnahe)	1.05	7.50	4.72	167
I_{2-b}	Biliu River (Biliuhe)	0.59			
I_3	Dasha River (Liuda)	0.27	7.50	4.72	172
I_{4-c} I_{4-d}	Fuzhou River (Songshu)	0.17	7.50	4.72	145
	Fuzhou River	0.16			

	(Dongfeng)				
I_5	Fuzhou River (Dongfeng)	0.51	7.50	4.72	212
I_6	Zhuang River (Zhuwei)	0.15	7.50	4.72	214
I_7	Yingna River (Yingnahe)	0.62	7.50	4.72	246
I_8	Yingna River (Yingnahe)	4.67	7.50	4.72	278

*The data is calculated through the secondary data from [37]

4. Results and Discussion

4.1 Environmental Impacts

The Eco-indicator 99 method is chosen to assess the environmental impacts of the LCMS for water resources of Dalian. The Environmental impacts of 1000kg surface water conveyance in Dalian are showed in Table 6.

Table 6. Environmental Impacts of 1000kg Surface Water Conveyance in Dalian

Unit: $\times 10^{-6}$

Area	e	e'	e''_{i1}	e''_{i2}
$I_{1\text{-}a}$	30.7	4850.1	220	138
$I_{1\text{-}b}$	17.4	4863.5		
$I_{2\text{-}a}$	30.7	4850.1		
$I_{2\text{-}b}$	17.4	4863.5		
I_3	8.0	5047.5		
$I_{4\text{-}c}$	4.9	4232.6		
$I_{4\text{-}d}$	4.6	4232.8		
I_5	14.9	6189.9		
I_6	4.4	6247.1		
I_7	18.0	7164.8		
I_8	136.5	8008.5		

4.2 Water Supply Strategy

Referred to the Chinese government's targets in GHG reduction in the 12^{th} five year plan, per unit of GDP carbon emissions in 2015 should account for 83% of the one in 2010. The annual growth of GDP will be reach around 8~9%. Assuming that the mitigation plan for GHGs emissions in the 13^{th} year would be the same with the one in the 12^{th} five year plan, the solutions for water conveyance upon two stages of river in 2015 and 2020 are showed in Tables 7 and 8.

Table 7. First-Stage Solutions of Surface Water Conveyance in Dalian

Unit: m^3

Year		q_1 = 20%	q_1 = 55%	q_1 = 25%
Biliuhe and above river	2015	1.31E+08	1.31E+08	1.04E+08
	2020	4.50E+08	4.50E+08	1.73E+08
Yingnahe and above river	2015	4.50E+08	4.50E+08	1.73E+08
	2020	2.27E+08	2.27E+08	1.04E+08
Dongfeng and above river	2015	4.90E+07	4.90E+07	1.90E+07
	2020	6.70E+07	6.70E+07	3.50E+07
Songshu and above river	2015	4.70E+07	4.70E+07	1.70E+07
	2020	4.70E+07	4.70E+07	1.70E+07
Liuda and above river	2015	6.70E+07	6.70E+07	3.50E+07
	2020	4.90E+07	4.90E+07	1.90E+07
Zhuwei and above river	2015	8.10E+07	8.10E+07	3.50E+07
	2020	8.10E+07	8.10E+07	3.50E+07
Total	2015	8.25E+08	8.25E+08	3.83E+08
	2020	9.21E+08	9.21E+08	3.83E+08

Table 8. Second-Stage Solutions of Surface Water Conveyance

Unit: m^3

		q = 20%	q = 55%	q = 25%
I_{1-a}	2015	0	0	0
	2020	0	0	0
I_{1-b}	2015	0	0	1.76E+08
	2020	0	0	2.77E+08
I_{2-a}	2015	0	0	2.74E+07
	2020	0	0	1.23E+08
I_{2-b}	2015	0	0	1.01E+08
	2020	0	0	0
I_3	2015	1.29E+08	1.29E+08	1.59E+08
	2020	1.32E+08	1.32E+08	1.62E+08
I_{4-c}	2015	0	0	3.00E+07
	2020	0	0	3.00E+07
I_{4-d}	2015	7.20E+07	7.20E+07	7.20E+07
	2020	1.07E+08	1.07E+08	1.07E+08
I_5	2015	4.00E+07	4.00E+07	7.20E+07
	2020	7.10E+07	7.10E+07	1.03E+08
I_6	2015	1.85E+08	1.85E+08	2.31E+08
	2020	2.25E+08	2.25E+08	2.71E+08
I_7	2015	0	0	0
	2020	0	0	0
I_8	2015	0	0	0
	2020	0	0	0
Total	2015	4.26E+08	4.26E+08	8.68E+08
	2020	5.35E+08	5.35E+08	1.07E+09

5. Conclusions

The hybrid life-cycle analysis (LCA) and adaptation optimization approach, proposed in this paper, could systematically explore the variation in low-carbon management system (LCMS) for urban water resources. In detail, a hybrid LCA and two-stage stochastic programming (TSP) models were proposed to analyze the environmental impacts based on a complicated low-carbon management system (LCMS) for urban water resources. The improved methodology could optimize water allocation in consideration of adapting national GHGs mitigation targets. The study was an early attempt to introduce the LCA framework into an optimization model to solve the problems of water allocation from a low-carbon perspective. A case study illustrated the applicability of the improved methodology in a LCMS. The results indicated that the first-stage solutions of surface water conveyance of Dalian could be [3.83×10^8, 8.25×10^8] in 2015, and [3.83×10^8, 9.21×10^8] in 2020; Meanwhile, the first-stage solutions of surface water conveyance of Dalian could be [4.26×10^8, 8.68×10^8] in 2015, and [5.35×10^8, 10.7×10^8] in 2020. Further work is required in terms of collecting related data on underground water services and incorporating related chemical production into the system boundary.

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