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# A robust optimization for agricultural crops area planning and industrial production level in the presence of effluent trading

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ABSTRACT

Suitable cropland use is not only beneficial for satisfying human daily demand, but also for controlling non-point source pollution leaks into adjacent rivers. Optimal industrial production levels are economical, and they also avoid water deterioration. With the promise of being lower than the total allowed emission cap, water use participants have to balance trade-offs between optimal production levels and emission amounts. Effluent trading seems to be a cost-effective method to reduce effluent emission as it allows effluent reallocation among different sectors. Because of changing hydrological information and continuous development of treatment technology, the effluent production ratio is regarded as uncertain and is characterized as polygonal budget sets. This study tries to control the total emission quantity by optimizing cropland use and non-agricultural production levels using effluent trading under uncertain future environments. To illustrate the feasibility of the proposed model, an application is conducted in Indonisian Citarum River. The application finds that the proposed model is able to (1) identify an optimal effluent trading scheme that balances various production plans from multiple water users; (2) balance the trade-off between total emission reduction and total benefit maximization by changing budget levels; and (3) ease the decision makers burden, avoid information losses or distortions, and guide them in adjusting farmland planning, production levels, and effluent trading results under uncertainty. Based on the results, managerial implications are analyzed in terms of (1) the optimal crop area planning in the agricultural sector and the optimal production level in non-agricultural sectors; and (2) the optimal effluent trading pattern that expands economic development without deteriorating water environments. Finally, the comparison analysis with a traditional deterministic model, verify that with the incorporation of robust parameters, flexible solutions are offered to decision makers that have different attitudes toward constraints-violation risks.



## 1. Introduction

Due to increasing amounts of high concentrations of untreated pollutants flowing into water bodies, water purification capacities become extremely limited. To help alleviated this problem, market-based controls have been introduced (De Lange et al., 2016). Among which, effluent trading is regarded as an efficient economic tool for pollution reduction (Nguyen et al., 2013). In real-world policies, effluent trading has been successfully carried out in the European Union (Wurzel, 2006), USA (Steinman et al., 2012), and other countries (Tietenberg, 2010; Narassimhan et al., 2018). One of the recent examples is the nutrient trading program for point and non-point sources initiated in Pennsylvania and the Greater Miami River watershed in Ohio (Nguyen et al., 2013).This method is likely to be copied by others if a global waste water emission limiting regime is implemented.

Different from additional effluent taxes, effluent trading has long-term impacts on economic growth and environmental protection (Xiong and Li, 2019). Effluent trading enables effluent rights reallocation among water users, and improves the economic efficiency of effluent emissions within a watershed (Zhang et al., 2017). Similar to groundwater transfer (Skurray et al., 2013), effluent trading rights can be considered as a type of cap and trade policy, as

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governments allocate the initial effluent emission rights and participants' interactive trading processes. In this way, under the cap given by the government, the emission participants make a trade-off between production levels and effluent trading, as production levels affect total effluent amounts. To achieve water use sustainability, water quality and quantity are two factors should be considered (Marzullo and Morita, 2018). To be specific, the quantity of freshwater is largely influenced by the water quality, which is further related to effluent amounts (Weidner et al., 2019). If they are not solved appropriately, the earth could become unsustainable (Soltani and Kerachian, 2018). It is, therefore, pivotal to optimize the trade-off between production levels and pollutant control using effluent trading.

A number of studies have been conducted to determine the optimal effluent trading patterns (Rong et al., 2017). Cai et al. (2018) identified agricultural nonpoint source (NPS) effluent trading planning in northern China. Zhang et al. (2014) applied NPS effluent trading planning to Xiangxi watershed, and found that the trading scheme can successfully mitigate agricultural NPS pollution with an increased system benefit. Zhang et al. (2015) studied optimal effluent trading schemes for NPS pollution control. However, there are still two remaining problems in the research discussing above. The first is determining whether it is necessary to allow effluent trading between NPS effluent and point source (PS) effluent. The other is determining how to deal with existing uncertainty in the pollutant emission processes, and determining whether the promised solution is robust.

For the first problem, NPS and PS pollutants caused by agricultural or non-agricultural sectors should be considered together. In the effluent discharge and trading process, water users (e.g., agricultural sector, domestic sector, and industrial sector) usually obtain initial effluent rights based on their historical production levels. However, the production varies from planning year to planning year, and initial effluent rights given by the government cannot usually satisfy the production demand. For example, industrial sectors' managers are inclined to get more economic benefits and to pay the additional money for effluent emission rights. On the other hand, with the implementation of the Grain for Green Project (GGP), future food security can be promised via imports. There may, therefore, be some redundant effluent emission rights for the agricultural sector in the future. Hence, it is necessary to consider effluent trading between NPS effluents and PS effluents within a watershed. Under the effluent trading mechanism, participants can cooperatively use effluent rights. Meanwhile, the environmental authorities mainly play the supervisory role in trading process, while the water users are sellers/buyers. During the trading process, optimum production plans should be the focus as they have an effect on the pollutant discharge amount. After considering the production level optimization, the participants with excess effluent emission rights can sell them to those who have insufficient emission rights (Zhang et al., 2017). Consequently, sellers increase their economic benefits, and the buyer will reconsider their production plan within the set environmental standards. In this study, the agricultural and non-agricultural sectors are considered, with the aim of optimizing their sectoral production levels using effluent trading.

Identifying the participants' effluent quantities and the water environmental capacity is the first step before proposing a mathematical model. Some studies have evaluated effluent emission. For example, Han et al. (2011) adopted an export coefficient model to calculate the production of NPS pollution. Dong et al. (2018) developed a water quality-constrained targeting framework to simulate NPS diffusion. In terms of PS pollution, Gunawardena et al. (2018) recorded daily wastewater discharge and pollution loads from firms and industrial parks, which were estimated based on industry type, water usage, and treatment facility availability. Gunawardena et al. (2017) estimated the relative contribution from point (industrial and domestic) to river water quality. The water environmental capacity can be measured with observed parameters, such as the pollutant concentration (mg/L), flow rate ($m^3$), and the time period (d/a). We know that waste water from agricultural or non-agricultural sectors will flow into the same river around them, so it is necessary to qualify different kinds of pollutants from different sectors. Besides, pollutant emission amounts are largely influenced by their production level, hence, a trade-off exists between optimal production levels for each sector, so pollution reduction should be considered when conducting cap and trade control. In this study, NPS and PS pollutants are considered together and are used to balance a trade-off between different kinds of participants based on their optimal production levels.

In terms of the second problem, it is worth noting that if uncertainty were ignored or not analyzed in depth, it would increase the difficulty in constructing an effluent trading mechanism (Yamout et al., 2007). Three methods are widely used to deal with uncertainty, that is, fuzzy (Cai et al., 2018), robust (Mulvey et al., 1995), and stochastic optimization methods (Santoso et al., 2005). Further, Rong et al. (2017) proposed a two-stage stochastic credibility constrained program for addressing uncertainties expressed as random variables. Li et al. (2014) tackled uncertainties expressed as fuzzy, interval, and/or probabilistic forms. However, the fuzzy or stochastic programming models needed to know the true probability distribution or membership function information (Birge and Louveaux, 2011; Heitsch and Römisch, 2003); however, in pollutant emission and effluent trading processes, it is difficult to determine the pollutant emission quantity because of precipitation amounts, soil types, crop types, the geomorphology of the watershed, and treatment technique improvements. Instead, a polygonal uncertainty set is suitable to describe this kind of variable with little historical data, as it does not assume that probability distribution or membership function are known. Moreover, a set of robust solutions can be determined by changing the robust parameters based random mathematics. In this study, polyhedral uncertainty set is applied to characterize pollutant production ratios when calculating total pollutants.

In 2018, Citarum river was regarded as the dirtiest river in the world by the World Bank, as shown in Fig. 1. The river not only supply fresh water for 80% of Bandung and Jakarta's domestic demand, but also irrigate 22,260 ha of rice and non-rice fields. As we know, NPS pollutants from farmlands flow directly into the river under the impact of topographic inequality and concentrated rainfall (Bank, 0000; Leimona et al., 2010). The river also supplies for up to 40% of Indonesia's textile industry water demands. After water use and industrial production, 280 t of toxic waste per day are pouring into Citarum river. Even worse, only 10% of factories along the river put their waste through a wastewater management plant. Which is called a vicious circle that, with the destruction of water environment, water productivity decrease. Hence, it is necessary to apply the proposed model to the Citarum river for optimizing farmland use planning and textile production levels in a planning year, which helps to balance trade-offs between economic and sustainable development.

Over all, this study is the first attempt to plan PS-NPS effluent trading under uncertain future environments using a robust optimization model. This should help decision makers decide whether it is worth the revenue to expand production levels or sell redundant effluent rights. Differences from the existing related studies (as shown in Table 1) and the following main contributions are summarized as follows:

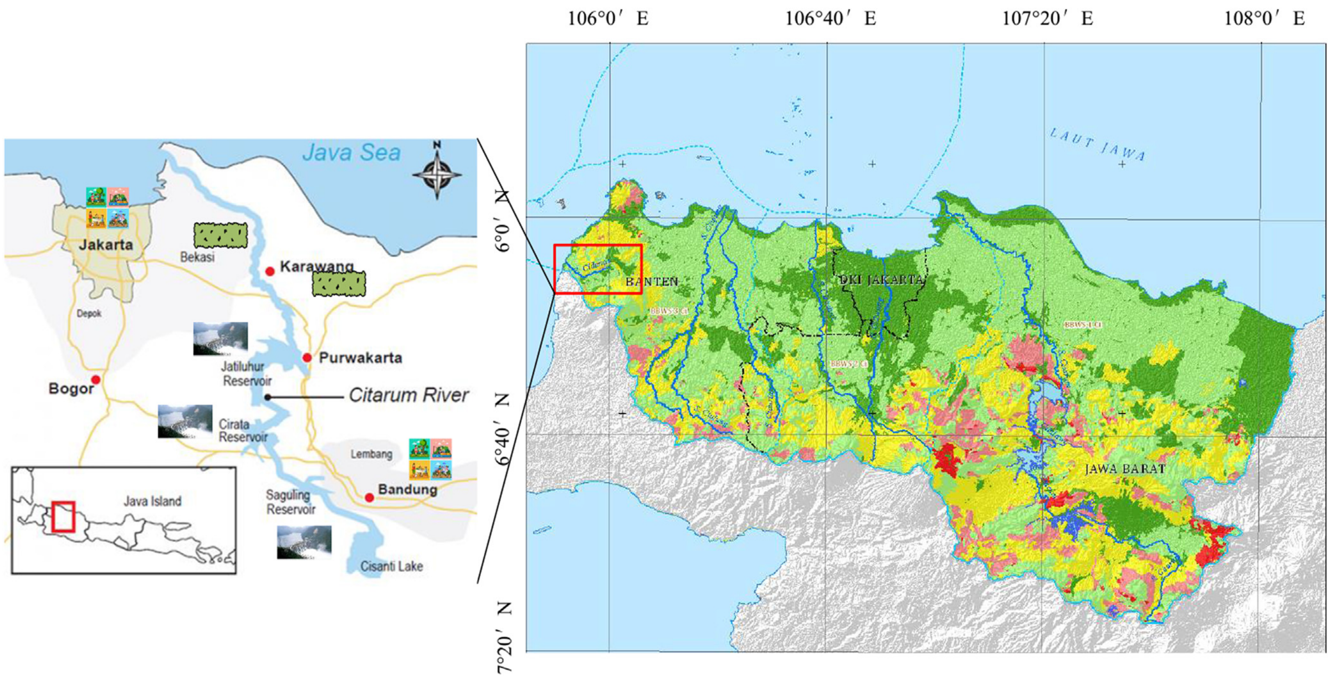



**Fig. 1.** Location of the study area.

**Table 1**
Literature review

| Articles | Problem statement | Methodologies | Difference in technical strategy point |
|---|---|---|---|
| Rong et al. (2017) | Determining the optimal effluent trading patterns | An enhanced export coefficient based optimization model | Ignoring the necessary of robust solutions |
| Zhang et al. (2014) | Supporting agricultural NPS effluent trading planning | A model combing two-stage stochastic programming with interval programming | |
| Zhang et al. (2015) | Identifying effluent trading strategies of agricultural nonpoint source | An inexact simulation-based stochastic optimization method | |
| Han et al. (2011) | Calculating the production of NPS pollution | An export coefficient model | Ignoring the trading activities between NPS and PS pollutants |
| Dong et al. (2018) | Simulate NPS diffusionn | A water quality-constrained targeting framework | |
| Gunawardena et al. (2018) | Recorded daily wastewater discharge and pollution loads from firms and industrial parks | An coefficient multiplication model | |
| Rong et al. (2017) | Addressing uncertainties expressed as random variables | A two-stage stochastic credibility constrained program | The need to know the true probability distribution or membership function information |
| Li et al. (2014) | Tacking uncertainties expressed as fuzzy, interval, and/or probabilistic forms | An interval fuzzy programming model | |

(1) A two-stage management paradigm was constructed including sectoral production and effluent trading processes, where effluent emissions are highly related to production levels. Thus, the management paradigm enables decision makers to have comprehensive optimization abilities on effluent emissions and trading.
(2) Effluent trading between NPS and PS is considered where pollution equivalency is applied to unify different kinds of pollutants. Based on this, this model is able to balance trade-offs between optimal production and total emission control.
(3) Polyhedral uncertainty sets were used to characterize pollutant production ratios, and with the application of robust optimization, different sets of solutions can be obtained under different robustness parameters that reflect different environment constraints-violation risks and avoid decision-making information losses.
(4) The Indonesian Citarum River is used as an example for optimizing farmland use planning and textile production levels in a planning year. Some of the findings and managerial insights are represented.

The remaining paper is organized as follows: section 2 illustrates the methodology, section 3 analyzes the application in Cidanau catchment, and section 4 concludes the paper.

## 2. Problem statement and methodology

This section introduces the background of the studied problem, the preliminary and the proposed model. The study plans to balance a trade-off between the effluent emission and trading processes, and then a robust optimization model is proposed, which is firstly applied with a case application in Citarum river.

### 2.1. Problem statement

In 2018, Citarum river was regarded as the dirtiest river in the world by the World Bank, as shown in Fig. 1. Textile industry is to be blamed, which is one of the oldest industries in Indonesia, with about 10,000 garment manufactures and 2100 bleaching and dyeing setups. In textile factories, bleaching and coloring are two major processes with wastewater generation of about 40–120 $m^3$/t. It is regretful to know that larger amounts of pollutants need to be poured into the river annually because of the existing behindhand treatment technology in Indonesia. Over the years, successive governments have vowed to clean the Citarum, but they have failed, mainly because such efforts were only done separately (Leal Filho, 2012).

In February 2018, President Joko declared a seven-year Citarum cleansing program with a final goal of making Citarum water drinkable by 2025. The program will also be supported by the International Monetary Fund ( IMF) and Asian Development Bank(-ADB), which, in 2009, had already committed to provide $500 million for funding the Citarum's rehabilitation. However, efforts to clean up the river will be wasted if the government does not immediately act against rogue businessmen who create dumping holes containing industrial wastewater that pollute the river. The authorities should go straight to the source to seal-off dumping holes and explicitly remove business permits for those who remain ignorant of the rules.

To ensure sustainable positive development in Indonesia, and simultaneously promote industrial development and pollutants control, effluent emission and trading processes need to be analyzed. Hence, we propose a two-stage system paradigm as shown in Fig. 2. In industrial development process, optimum production level for agriculture and non-agricultural industries is determined. During this process, effluent emission is highly related to its production level. In pollutants control process, effluent trading is allowed to increase participants' initiative to control production and effluent efficiently. It is worth noting that predetermined water quality standards over the length of a river can't be violated during a planning year. Effluent trading is applied to allow effluent rights reallocation from one field to another in a watershed.

Finally, aiming to balance a trade-off between the effluent emission and trading processes, this study proposes a robust optimization model, which is firstly applied to the Citarum river.

### 2.2. Preliminary

In real-world process, the effluent production ratios in agriculture and non-agricultural industries are sometimes imprecise and vague because of varying rainfall, river velocity, and changing treatment technology, and then the untreated pollutants poured into the river are uncertain. To deal with this uncertainty, random parameters are used to characterize the imperfect data/information in effluent emission process.

It is difficult to define the distribution probability; however, it is easy to determine the range of variation based on the historical data sets. Hence, interval uncertain sets are used to describe the effluent production ratios. Besides, robust counterpart problem can be obtained optimization method to solve a problem with uncertain data. Hence, interval uncertain parameters are applied to present the standard of water environmental capacity. In addition, by adjusting robustness parameters, the trade-off between conservation and optimality of robust solutions is obtained, which offers more information to decision makers.

**Definition 1.** *A interval random variable* $\overline{\lambda}_i = \lambda_i + \xi\widehat{\lambda}_i, i = 1, 2, \cdots, I$*, where* $\lambda_i$ *is the mean value,* $\widehat{\lambda}_i$ *is the variation, and* $\sum \xi_i \le \Gamma$.

**Definition 2.** A robustness parameter $\Gamma$ is applied to present the maximum number for random variable λ to violate the mean value, and $\Gamma \in [0, I]$. In this way, a constraint for robust adjustment is reformed, $\eta = \sum_{i=1}^{I} \frac{|\overline{\lambda}_i - \lambda_i|}{\widehat{\lambda}_i} \le \Gamma$. η presents the deviation degree between the actual value $\overline{\lambda}_i$ and the mean value $\lambda_i$, which is in $[-1, 1]$. When Γ is equal to 0, it presents that there is no $\overline{\lambda}_i$ can deviate, that is the value of $\overline{\lambda}_i$ is equal to 0. This is similar to the determined situation. When $\overline{\lambda}_i$ is equal to I, it means there are ith $\overline{\lambda}_i, \forall i$ to deviate from the mean value. It is similar to the most conservative situation.

**Definition 3.** Bertsimas and Sim (2004) Given a constraint with a polyhedral uncertainty set in $\sum|\xi_i| \le \Gamma$. A robust counterpart problem is present in the following,

$$\sum_j \theta_j x_j + \max_{\xi_j \in U}\left\{\sum_j \xi_j \widehat{\theta}_j x_j\right\} \le b$$

where $x_j$ are non-negative, $\xi_i$ are random variables distributed in

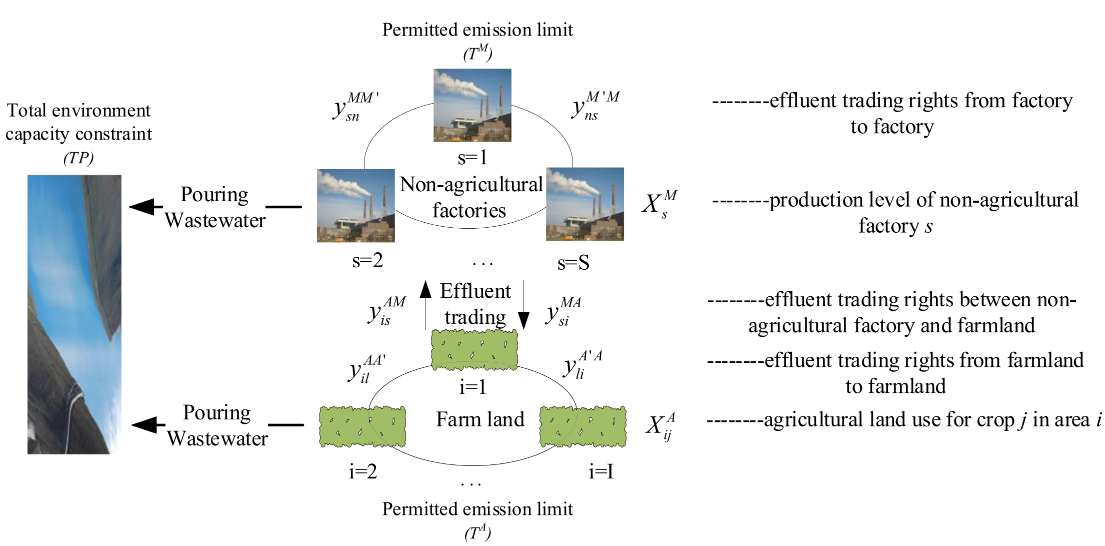



**Fig. 2.** A two-stage system paradigm considering effluent discharge and trading process.

the interval [-1,1], and $\Gamma$ is the robustness parameter. The equivalent linear formulation can be transformed by incorporating dual variables c and $q_j$, that is:

$$\sum_j \theta_j x_j + c\Gamma + \sum_j q_j \le b,$$
$$c + q_j \ge \widehat{\theta}_j x_j \forall j,$$
$$c \ge 0, q_j \ge 0 \forall j$$

### 2.3. Proposed model

This study aims to balance a trade-off between the effluent emission and trading processes from the perspective of economy and ecology. Fig. 3 depicts the framework of the study problem. There are different water users (including agricultural farm land and non-agricultural factories) along a watershed who discharge wastewater.

#### 2.3.1. Notation

Before modelling, some indexes are present at first.

##### 2.3.1.1. Sets

$i$: the farmland $i$, $i = 1, 2, \ldots, I$

$j$: the crop $j$, $j = 1, 2, \ldots, J$

$s$: the non-agricultural factory $s$, $s = 1, 2, \ldots, S$

##### 2.3.1.2. Constant

$b_j^A$, $b^M$: net economic benefit coefficients in agricultural and non-agricultural sectors, Rp/kg

$c^A$, $c^M$: emission trading costs among agricultural and non-agricultural sectors, million Rp/t

$TP$: total permitted effluent emission, t

$T^A$, $T^M$: upper limits for agricultural and non-agricultural sectors, t

##### 2.3.1.3. Uncertain parameters

$\overline{\alpha}_{ij}$: effluent production ratio of crop $j$ from agricultural farmland $i$

$\overline{\gamma}_s$: effluent production ratio from non-agricultural factory $s$

$\lambda$: the treated coefficient of wastewater because of production

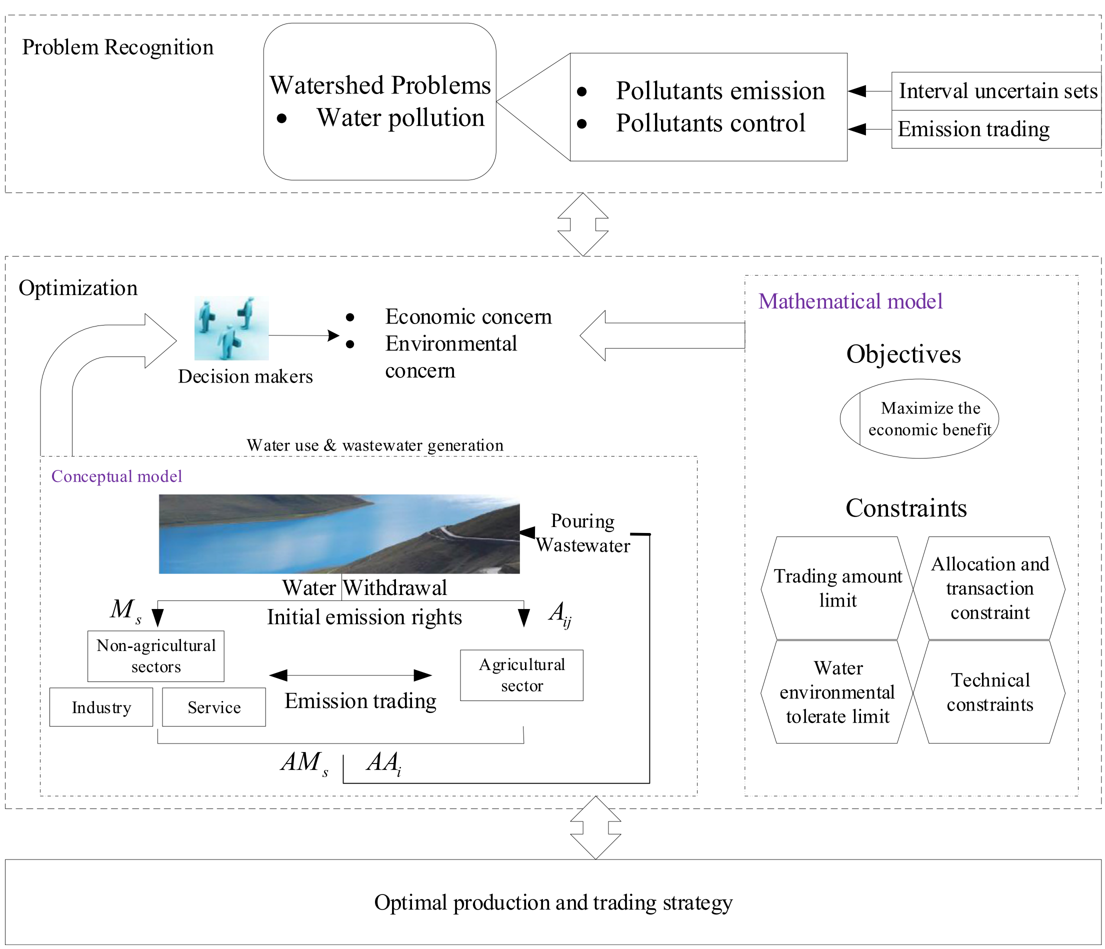



**Fig. 3.** An optimization framework considering effluent discharge and trading process.

#### 2.3.1.4. Auxiliary variables

$A_{ij}$: initial emission right for crop $j$ in agricultural farmland $i$ allowed by the government based on historical data, t

$M_s$: initial emission right for non-agricultural factory $s$ allowed by the government based on historical data, t

$AA_i$: emission right after transaction in agricultural farmland $i$, t

$AM_s$: emission right after transaction for non-agricultural factory $s$, t

#### 2.3.1.5. Decision variables

$X_{ij}^{A}$: agricultural land use for crop $j$ in area $i$, ha

$X_s^M$: production level of non-agricultural factory $s$, t/a

$y_{li}^{A'A}$: effluent trading rights from farmland $l$ to farmland $i$, t

$y_{si}^{MA}$: effluent trading rights from non-agricultural factory $s$ to farmland $i$, t

$y_{is}^{AM}$: effluent trading rights from farmland $i$ to non-agricultural factory $s$, t

$y_{il}^{AA'}$: effluent trading rights from farmland $i$ to farmland $l$, t

$y_{ns}^{M'M}$: effluent trading rights from non-agricultural factory $n$ to non-agricultural factory $s$, t

$y_{sn}^{MM'}$: effluent trading rights from non-agricultural factory $s$ to non-agricultural factory $n$, t

### 2.3.2. Hypothetical condition

1. The effluent production ratio in different sectors are uncertain.

### 2.3.3. Objective function

Environment sustainability and economic development remain two of the most contentious issues around the world. It is noticeable that production level accompanied by effluent emission and effluent trading have an great influence on economy and environment. To make an optimal strategy for effluent emission and transaction, this study aims to maximize the economic benefits with the constraints of water quality standards, which is beneficial to developing countries.

Model (1) is to maximize the economic benefit caused by production level and effluent trading, by which agricultural crops area planning and non-agricultural production level can be optimized.

$$\max f^A + f^M \tag{1}$$

where $f^A, f^M$ present agricultural and non-agricultural economic benefits respectively.

$$f^A = \sum_{i=1}^{I}\left(\sum_{j=1}^{J} X_{ij}^{A} b_j^A - \left(\sum_{l=1}^{I} y_{il}^{A'A} + \sum_{s=1}^{S} y_{si}^{MA} - \sum_{s=1}^{S} y_{is}^{AM} - \sum_{l=1}^{I} y_{il}^{AA'}\right) c^A\right),$$

$$f^M = \sum_{s=1}^{S}\left(X_s^M b^M - \left(\sum_{n=1}^{S} y_{sn}^{M'M} + \sum_{i=1}^{I} y_{is}^{AM} - \sum_{i=1}^{I} y_{si}^{MA} - \sum_{n=1}^{S} y_{sn}^{MM'}\right) c^M\right).$$

$\sum_{j=1}^{J} X_{ij}^{A} b_j^A$ and $\sum_{s=1}^{S} X_s^M b^M$ are net economic benefits derived from crops and products selling. Net economic benefits considering selling benefits minus production costs and wastewater treatment costs before pouring into river. However, in this paper, to reduce computing complexity, a kind of coefficients ($b_j^A$, $b^M$) is applied to directly calculate the net benefits. $(\sum_{l=1}^{I} y_{il}^{A'A} + \sum_{s=1}^{S} y_{si}^{MA} - \sum_{s=1}^{S} y_{is}^{AM})$ $(-\sum_{l=1}^{I} y_{il}^{AA'}) c^A$ and $(\sum_{n=1}^{S} y_{sn}^{M'M} + \sum_{i=1}^{I} y_{is}^{AM} - \sum_{i=1}^{I} y_{si}^{MA})$ $(-\sum_{n=1}^{S} y_{sn}^{MM'}) c^M$ are additional costs because of effluent trading from one sector to another.

### 2.3.4. Constraints

The following constraints construct a feasible region for the optimization model.

(1) Effluent trading limit.

Constraints (2)–(3) regulate the trading amount that can be sold. They imply a potential condition that if the initial emission rights are larger than the effluent demand, the participant can sell their excess rights. Otherwise, the participants should buy excess effluent emission rights from the market. It is worth noting that $(1-\lambda)X_s^M\overline{\gamma}_s$ is the untreated wastewater to be poured into the river after the factories' initial treatment. Constraint (4) presents the buy-sell equation.

$$\max\left\{0, \sum_{j=1}^{J} A_{ij} - \sum_{j=1}^{J} X_{ij}^{A}\overline{\alpha}_{ij}\right\} \geq \sum_{s=1}^{S} y_{is}^{AM} + \sum_{l=1}^{I} y_{il}^{AA'}, \tag{2}$$

$$\max\left\{0, M_s - X_s^M \overline{\gamma_s}(1-\lambda)\right\} \geq \sum_{i=1}^{I} y_{si}^{MA} + \sum_{n=1}^{S} y_{sn}^{MM'}, \tag{3}$$

$$\begin{aligned}&\sum_{s=1}^{S} y_{is}^{AM} + \sum_{l=1}^{I} y_{il}^{AA'} + \sum_{i=1}^{I} y_{si}^{MA} + \sum_{n=1}^{S} y_{sn}^{MM'}\\ &= \sum_{l=1}^{I} y_{il}^{A'A} + \sum_{i=1}^{I} y_{si}^{MA} + \sum_{s=1}^{S} y_{is}^{AM} + \sum_{n=1}^{S} y_{sn}^{M'M}.\end{aligned} \tag{4}$$

(2) Allocation and transaction constraint.

The emission rights after effluent trading are no less than the effluent emission caused by land use or industrial production, as shown in Constraints (5)–(6).

$$\sum_{j=1}^{J} X_{ij}^{A}\overline{\alpha}_{ij} \leq AA_i \tag{5}$$

$$X_s^M \overline{\gamma_s}(1-\lambda) \leq AM_s \tag{6}$$

where emission rights for farmland and factory after transaction is calculated as. $AA_i = \sum_{j=1}^{J} A_{ij} + \sum_{l=1}^{I} y_{li}^{A'A} + \sum_{s=1}^{S} y_{si}^{MA} - \sum_{s=1}^{S} y_{is}^{AM} - \sum_{l=1}^{I} y_{il}^{AA'}$, $AM_s = M_s + \sum_{n=1}^{S} y_{ns}^{M'M} + \sum_{i=1}^{I} y_{ist}^{AM} - \sum_{i=1}^{I} y_{si}^{MA} - \sum_{n=1}^{S} y_{sn}^{MM'}$.

(3) Water environmental tolerate limit.

Actual effluent emission amounts among different sectors are strictly controlled below the limit of the cap-and-trade system, as shown in constraint (7). Meanwhile, environmental limits are also set for different kinds of participants, as shown in constraints (8)–(9).

$$\sum_{i=1}^{I}\sum_{j=1}^{J}X_{ij}^{A}\overline{\alpha}_{ij}+\sum_{s=1}^{S}X_{s}^{M}\overline{\gamma}_{s}(1-\lambda)\leq TP, \tag{7}$$

$$\sum_{i=1}^{I}AA_{i}\leq T^{A}, \tag{8}$$

$$\sum_{s=1}^{S}AM_{s}\leq T^{M}. \tag{9}$$

(4) Technical constraints.

Constraints (10)–(12) promise the decision variables are non-negative, and the direction of effluent trading is buying or selling at one time.

$$X_{ij}^{A},X_{s}^{M},y_{li}^{A'A},y_{il}^{AA'},y_{si}^{MA},y_{is}^{AM},y_{ns}^{M'M},y_{sn}^{MM'}\geq 0, \tag{10}$$

$$\left(y_{il}^{AA'}+y_{is}^{AM}\right)\times\left(y_{li}^{A'A}+y_{si}^{MA}\right)=0, \tag{11}$$

$$\left(y_{sn}^{MM'}+y_{si}^{MA}\right)\times\left(y_{ist}^{AM}+y_{ns}^{M'M}\right)=0. \tag{12}$$

### 2.4. Global model and solution procedure

Based on the above problem description and modeling, the proposed global model is presented, followed by the solution procedure to gain a robust solution.

#### 2.4.1. Global model

The global model for optimizing production level of each sector and trading amounts among them is presented as model (13).

$$\max f^{A}+f^{M}$$

$$s.t.\begin{cases}
f^{A}=\sum_{i=1}^{I}\left(\sum_{j=1}^{J}X_{ij}^{A}b_{j}^{A}-\left(\sum_{l=1}^{I}y_{il}^{A'A}+\sum_{s=1}^{S}y_{si}^{MA}-\sum_{s=1}^{S}y_{is}^{AM}-\sum_{l=1}^{I}y_{il}^{AA'}\right)c^{A}\right)\\
f^{M}=\sum_{s=1}^{S}\left(X_{s}^{M}b^{M}-\left(\sum_{n=1}^{S}y_{sn}^{M'M}+\sum_{i=1}^{I}y_{is}^{AM}-\sum_{i=1}^{I}y_{si}^{MA}-\sum_{n=1}^{S}y_{sn}^{MM'}\right)c^{M}\right)\\
\sum_{j=1}^{J}A_{ij}-\sum_{j=1}^{J}X_{ij}^{A}\overline{\alpha}_{ij}\geq\sum_{s=1}^{S}y_{is}^{AM}+\sum_{l=1}^{I}y_{il}^{AA'},\text{if}\sum_{j=1}^{J}A_{ij}\geq\sum_{j=1}^{J}X_{ij}^{A}\overline{\alpha}_{ij}\\
M_{s}-X_{s}^{M}\overline{\gamma}_{s}(1-\lambda)\geq\sum_{i=1}^{I}y_{si}^{MA}+\sum_{n=1}^{S}y_{sn}^{MM'},\text{if}M_{s}\geq X_{s}^{M}\overline{\gamma}_{s}(1-\lambda)\\
\sum_{s=1}^{S}y_{is}^{AM}+\sum_{l=1}^{I}y_{il}^{AA'}+\sum_{i=1}^{I}y_{si}^{MA}+\sum_{n=1}^{S}y_{sn}^{MM'}=\sum_{i=1}^{I}y_{li}^{A'A}+\sum_{s=1}^{S}y_{si}^{MA}+\sum_{i=1}^{I}y_{is}^{AM}+\sum_{n=1}^{S}y_{sn}^{M'M}\\
\sum_{j=1}^{J}X_{ij}^{A}\overline{\alpha}_{ij}\leq\sum_{j=1}^{J}A_{ij}+\sum_{l=1}^{I}y_{li}^{A'A}+\sum_{s=1}^{S}y_{si}^{MA}-\sum_{s=1}^{S}y_{is}^{AM}-\sum_{l=1}^{I}y_{il}^{AA'}\\
X_{s^{M}}\overline{\gamma}_{s}(1-\lambda)\leq M_{s}+\sum_{n=1}^{S}y_{ns}^{M'M}+\sum_{i=1}^{I}y_{ist}^{AM}-\sum_{i=1}^{I}y_{si}^{MA}-\sum_{n=1}^{S}y_{sn}^{MM'}\\
\sum_{i=1}^{I}\sum_{j=1}^{J}X_{ij}^{A}\overline{\alpha}_{ij}+\sum_{s=1}^{S}X_{s}^{M}\overline{\gamma}_{s}(1-\lambda)\leq TP\\
\sum_{i=1}^{I}AA_{i}\leq T^{A}\\
\sum_{s=1}^{S}AM_{s}\leq T^{M}\\
X_{ij}^{A},X_{s}^{M},y_{li}^{A'A},y_{il}^{AA'},y_{si}^{MA},y_{is}^{AM},y_{ns}^{M'M},y_{sn}^{MM'}\geq 0\\
\left(y_{il}^{AA'}+y_{is}^{AM}\right)\times\left(y_{li}^{A'A}+y_{si}^{MA}\right)=0\\
\left(y_{sn}^{MM'}+y_{si}^{MA}\right)\times\left(y_{ist}^{AM}+y_{ns}^{M'M}\right)=0
\end{cases} \tag{13}$$

### 2.4.2. Solution procedure

The idea of Bertsimas and Sim (2004)'s robust counterpart transformation is applied, which helps to withstand random parameter (i.e. $\overline{\alpha}_{ij}, \overline{\gamma}_s$) in model (13). Different from the Soyster (1973)'s robust formulation, given the necessary protection of the constraints by maintaining a gap between the left-hand side and the right-hand side of the equation, a robust parameter $\Gamma$ is added to adjust the robustness of the proposed model against the level of the solution's conservatism.

Consider the $i$th constraint (5): $\sum_{j=1}^{J} X_{ij}^{A}\overline{\alpha}_{ij} \le \sum_{j=1}^{J} A_{ij} + \sum_{l=1}^{I} y_{li}^{A'A} + \sum_{s=1}^{S} y_{si}^{MA} - \sum_{s=1}^{S} y_{is}^{AM} - \sum_{l=1}^{I} y_{il}^{AA'}, i = 1,2,\cdots, I$ for example. It is easy to change the sets of constraints as follows, $\sum_{j=1}^{J} X_{ij}^{A}\alpha_{ij} + \max\{\sum_{j=1}^{J} \xi_{ij}X_{ij}^{A}\widehat{\alpha}_{ij}\} \le \sum_{j=1}^{J} A_{ij} + \sum_{l=1}^{I} y_{li}^{A'A} + \sum_{s=1}^{S} y_{si}^{MA} - \sum_{s=1}^{S} y_{is}^{AM} - \sum_{l=1}^{I} y_{il}^{AA'}, i = 1,2,\cdots,I$. It is hard to solve the model directly because of its non-linear character.

Let $\beta_i = \max\{\sum_{j=1}^{J} \xi_{ij}X_{ij}^{A}\widehat{\alpha}_{ij}\}$, which equals the objective function of the following linear optimization model (14):

$$\max \sum_{j=1}^{J} X_{ij}^{A}\widehat{\alpha}_{ij}z_{ij}$$
$$s.t.\left\{\begin{array}{c} \sum_{j=1}^{J} z_{ij} \le \Gamma_i \\ 0 \le z_{ij} \le 1 \end{array}\right\} \tag{14}$$

Firstly, model (14) is reformulated as a linear optimization model, namely model (15). Secondly, an equivalent linear formulation of constraint (5) is written as model (16). In the same way, equivalent linear formulation models (17) and (18) for constraints (6) and (7) can be obtained, respectively. Finally, an equivalent model (19) of global model (13) is gained, which solves the uncertain sets. By strong duality, since model (14) is feasible and bounded for all the robust parameters, the dual model (15) is also feasible and bounded and their objective values coincide (Bertsimas and Sim, 2004). Hence, the objective values of models (13) and (19) are the same after the conversion

$$\min \sum_{j=1}^{J} q_{ij}^{A} + \Gamma_i p_i^{A}$$
$$s.t.\left\{\begin{array}{c} q_{ij}^{A} + p_i^{A} \le X_{ij}^{A}\widehat{\alpha}_{ij} \\ q_{ij}^{A} \ge 0 \\ p_i^{A} \ge 0 \end{array}\right\} \tag{15}$$

$$\left\{\begin{array}{c} \sum_{j=1}^{J} X_{ij}^{A}\alpha + \sum_{j=1}^{J} q_{ij}^{A} + \Gamma_i p_i^{A} \le \sum_{j=1}^{J} A_{ij} + \sum_{l=1}^{I} y_{li}^{A'A} + \sum_{s=1}^{S} y_{si}^{MA} - \sum_{s=1}^{S} y_{is}^{AM} - \sum_{l=1}^{I} y_{il}^{AA'} \\ q_{ij}^{A} + p_i^{A} \le X_{ij}^{A}\widehat{\alpha}_{ij} \\ q_{ij}^{A} \ge 0 \\ p_i^{A} \ge 0 \end{array}\right\} \tag{16}$$

$$\left\{\begin{array}{c} X_s^{M}\gamma(1-\lambda) + q_s^{M} + \Gamma_s p_s^{M} \le M_s + \sum_{n=1}^{S} y_{ns}^{M'M} + \sum_{i=1}^{I} y_{ist}^{AM} - \sum_{i=1}^{I} y_{si}^{MA} - \sum_{n=1}^{S} y_{sn}^{MM'} \\ p_s^{M} + q_s^{M} \ge X_s^{M}\widehat{\gamma}_s(1-\lambda) \\ q_s^{M} \ge 0 \\ p_s^{M} \ge 0 \end{array}\right\} \tag{17}$$

$$\left\{\begin{array}{c} \sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij}^{A}\alpha_{ij} + \sum_{s=1}^{S} X_s^{M}\gamma_s(1-\lambda) + \sum_{i=1}^{I}\left(\sum_{j=1}^{J} q_{ij}^{A} + \Gamma_i p_i^{A}\right) + \sum_{s=1}^{S}\left(q_s^{M} + \Gamma_s p_s^{M}\right) \le TP \\ q_{ij}^{A} + p_i^{A} \le X_{ij}^{A}\widehat{\alpha}_{ij} \\ p_s^{M} + q_s^{M} \ge X_s^{M}\widehat{\gamma}_s(1-\lambda) \\ q_{ij}^{A} \ge 0, q_s^{M} \ge 0 \\ p_i^{A} \ge 0, p_s^{M} \ge 0 \end{array}\right\} \tag{18}$$

$$
\begin{aligned}
&\max f^A + f^M \\
&s.t.\begin{cases}
f^A = \sum_{i=1}^{I}\left[\left(\sum_{j=1}^{J} X_{ij}^A b_j^A - \left(\sum_{l=1}^{I} y_{il}^{A'A} + \sum_{s=1}^{S} y_{si}^{MA} - \sum_{s=1}^{S} y_{is}^{AM} - \sum_{l=1}^{I} y_{il}^{AA'}\right) c^A\right)\right] \\
f^M = \sum_{s=1}^{S}\left[\left(X_s^M b^M - \left(\sum_{n=1}^{S} y_{sn}^{M'M} + \sum_{i=1}^{I} y_{is}^{AM} - \sum_{i=1}^{I} y_{si}^{MA} - \sum_{n=1}^{S} y_{sn}^{MM'}\right) c^M\right)\right] \\
\sum_{j=1}^{J} X_{ij}^A \alpha + \sum_{j=1}^{J} q_{ij}^A + \Gamma_i p_i^A \le \sum_{j=1}^{J} A_{ij} + \sum_{l=1}^{I} y_{li}^{A'A} + \sum_{s=1}^{S} y_{si}^{MA} - \sum_{s=1}^{S} y_{is}^{AM} - \sum_{l=1}^{I} y_{il}^{AA'} \\
X_s^M \gamma(1-\lambda) + q_s^M + \Gamma_s p_s^M \le M_s + \sum_{n=1}^{S} y_{ns}^{M'M} + \sum_{i=1}^{I} y_{ist}^{AM} - \sum_{i=1}^{I} y_{si}^{MA} - \sum_{n=1}^{S} y_{sn}^{MM'} \\
\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij}^A \alpha_{ij} + \sum_{s=1}^{S} X_s^M \gamma_s(1-\lambda) + \sum_{i=1}^{I}\left(\sum_{j=1}^{J} q_{ij}^A + \Gamma_i p_i^A\right) + \sum_{s=1}^{S}\left(q_s^M + \Gamma_s p_s^M\right) \le TP \\
p_i^A + q_{ij}^A \ge X_{ij}^A \widehat{\alpha}_{ij} \\
p_s^M + q_s^M \ge X_s^M \widehat{\gamma}_s(1-\lambda) \\
q_{ij}^A \ge 0; p_i^A \ge 0; q_s^M \ge 0; p_s^M \ge 0 \\
\sum_{s=1}^{S} y_{is}^{AM} + \sum_{l=1}^{I} y_{il}^{AA'} + \sum_{i=1}^{I} y_{si}^{MA} + \sum_{n=1}^{S} y_{sn}^{MM'} = \sum_{l=1}^{I} y_{il}^{A'A} + \sum_{s=1}^{S} y_{si}^{MA} + \sum_{i=1}^{I} y_{is}^{AM} + \sum_{n=1}^{S} y_{sn}^{M'M} \\
\sum_{i=1}^{I} AA_i \le T^A \\
\sum_{s=1}^{S} AM_s \le T^M \\
X_{ij}^A, X_s^M, y_{li}^{A'A}, y_{il}^{AA'}, y_{si}^{MA}, y_{is}^{AM}, y_{ns}^{M'M}, y_{sn}^{MM'} \ge 0 \\
\left(y_{il}^{AA'} + y_{is}^{AM}\right) \times \left(y_{li}^{A'A} + y_{si}^{MA}\right) = 0 \\
\left(y_{sn}^{MM'} + y_{si}^{MA}\right) \times \left(y_{ist}^{AM} + y_{ns}^{M'M}\right) = 0
\end{cases}
\end{aligned}
\tag{19}
$$

## 3. Case study

In order to demonstrate the feasibility of the proposed model for production level plan and effluent trading management, a real-world case study is conducted in the Citarum river, Indonesia, as shown in Fig. 1. The planning horizon of this study is 2030.

### 3.1. Problem description

The Citarum river is located at 5° 21′-6° 21′ South and 105° 7′-106° 22′ East and covers an area of 221.1 $km^2$. As Indonesia's most strategic river, it is the water source for the Saguling, Cirata, and Jatiluhur reservoirs (a source of water for three hydroelectric power stations serving two cities). The annual flow in the Citarum river is 210 $m^3/s$ (D'Arrigo et al., 2011). Under the current efforts of the government, there are three key wastewater sources that authorities have focused on: domestic waste, textile industrial waste, and agricultural waste.

By 2030, the river will support around 28 million people who rely on it for daily activities such as cooking, bathing, and laundry (Vatvani, 0000). These reservoirs not only supply fresh water for 80% of Bandung and Jakarta's domestic demand, but also irrigate 22,260 ha of rice and non-rice fields. NPS pollutants from farmlands flow directly into the river under the impact of topographic inequality and concentrated rainfall (Bank, 0000; Leimona et al., 2010). In addition, it is able to supply for up to 40% of Indonesia's textile industry water demands. After water use and industrial production, 280 t of toxic waste per day are pouring into Citarum river. Even worse, only 10% of factories along the river put their waste through a wastewater management plant. Which is called a vicious circle that, with the destruction of water environment, the report stated that "There is an agricultural area nearby, which under normal circumstances would yield nine tons of crops in 1 ha of land. But after being contaminated by toxic waste from these

**Table 2**
Equivalent of various water pollutants (kg).

| Pollutant | Pollutant equivalent |
|---|---|
| COD | 10.00 |
| TN | 3.00 |

**Table 3**
Average effluent data.

| Type | COD in Textile products | TN in Paddy land | TN in Palauija land |
|---|---|---|---|
| Value | 36 kg/kg | 50 kg/(ha • a) | 25 kg/(ha • a) |

industries, the harvest only yields 4 tons of crops."

Hence, a reasonable plan for production level and farm land use is urgent surrounded the Citarum river.

### *3.2. Pollution equivalent and total permitted effluent determination*

Effluents include nine main types of water pollutants: chemical oxygen demand (COD), petroleum, cyanide, total arsenic, total mercury, lead, tin, hexavalent chromium, and ammonia nitrogen. Phosphorus and nitrogen are related to the eutrophication of water, and COD is widely used to reflect the industrial pollution. In the real-world practice, different pollutants are traded among each other in a same watershed; hence, an index–pollution equivalent-is applied to present the transformation of the different types of pollutants. Pollution equivalent is a relative quantity related to relevant pollutants or pollution discharge activities, stipulated according to the degree of harm from various pollutants or pollution discharge activities to the environment, the toxicity to organisms, and the technical economy of treatment (Khairiah et al., 2016a, b). The pollution equivalent of some pollutants are listed in Table 2. For simplicity, this study chooses COD to evaluate the water quality and transfers the other types of pollutants into COD.

According to the water quality standards of Government Regulation No. 82 (2001) on water quality management and water pollution control, the pollutant concentration of COD will be limited to 20 mg/L by 2030. Also, a equation ($H = \Delta Co \times Fl \times Time \times 10^{-6}$) is used to calculate the water environmental capacity (denoted by H), where Co is the pollutant concentration (mg/L), Fl is the flow rate ($m^3$) and Time is the time period (d/a). Thus, the water environmental tolerance in 2030 is calculated as 126,144 t/a. The GDP in 2030 is predicted to be 15,825,361.30 billion Rp, with 1.30% (205,729.69 billion Rp) being contributed by textile factories. In this study, two processes of textile factories are analyzed: bleaching and dyeing. The retained profits of textile products are 1.95 million Rp/t (http://www.sjfzxm.com/hangye/201801-11-522535.html). The other data is listed in Tables 3–4 (Han et al., 2011; Syakur et al., 2017). Pollutants in domestic sector in 2030 is 4380 g/(person• a)). Based on the collected data, a managerial tool is gained to decide the optimal planting plan and the production level of factories, with the objectives of reducing the effluent emission while allocating the effluent emission rights among different users by 2030.

**Table 4**
Related data simulated in 2030.

| Year | Paddy yield | Price | Cost |
|---|---|---|---|
| 2030 | 6.47 $\times$ $10^3$kg/ha | 2126 Rp/kg | 5.51 million Rp/ha |
| Year | Palauija yield | Price | Cost |
| 2030 | 2.94 $\times$ $10^3$kg/ha | 2975 Rp/kg | 3.83 million Rp/ha |

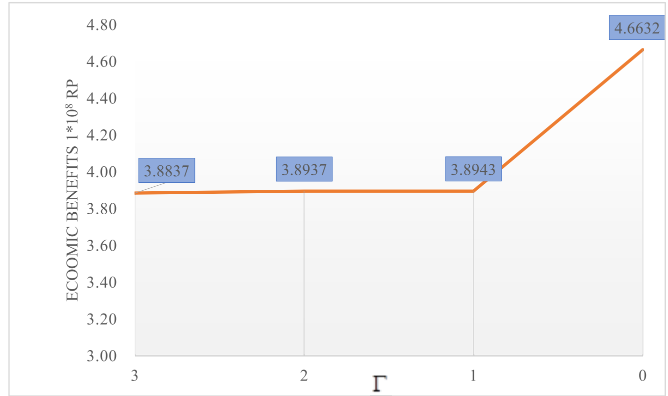



**Fig. 4.** Economic benefits.

### *3.3. Net benefit and emission quantity*

Fig. 4 shows the total economic benefits within the watershed under four scenarios. The results indicate that the economic benefits vary from $3.88 \times 10^{12}$ RP to $4.66 \times 10^{12}$ RP. The highest economic benefit occurs when the largest constraint-violation is permitted ($\Gamma = 0$), whereas the lowest economic benefit occurs under the scenario where no constraint-violation is allowed. The economic benefit will decrease with the rise of Γ. By changing the budget level of Γ, decision makers need to make a trade-off between economic benefit maximization and system constraints to violation risks. To be specific, if less attention is paid to environmental constraint violation risks, the production level will increase, and on the contrary, the total benefits will also increase.

Table 5 demonstrates that the total emission quantity is $8.63 \times 10^7$ under the four scenarios, which suggests a vigorous economic development in developing countries with the precondition that the actual pollutant discharge should not be more than the upper limit. In other words, economic development should not happen at the cost of the environment. Besides, higher robust parameter values and lower environmental capacity values are defined in the proposed model for decision makers who want to give more attention to environment protection and emission quantity reduction in the future.

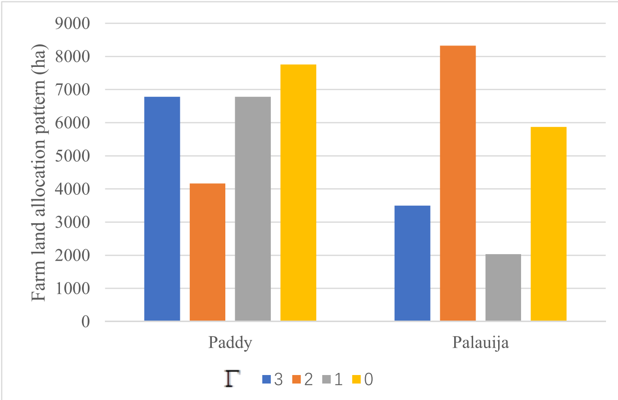
### *3.4. Land use and industrial production level patten*

Fig. 5 depicts the optimal production results under different scenarios. Results show that uncertainty has different effects on farmland use and textile production levels. Table 6 show that, from $\Gamma = 0$ to $\Gamma = 4$, production level increases from 1958562 to 2348203 t/a. The fluctuation of farmland use between paddy and Palauija reveals the necessary modification when it comes to different future situations. For example, for a decision maker who allows no violations of the constraints, they would allocate more farmland for paddy growth instead of Palauija growth.

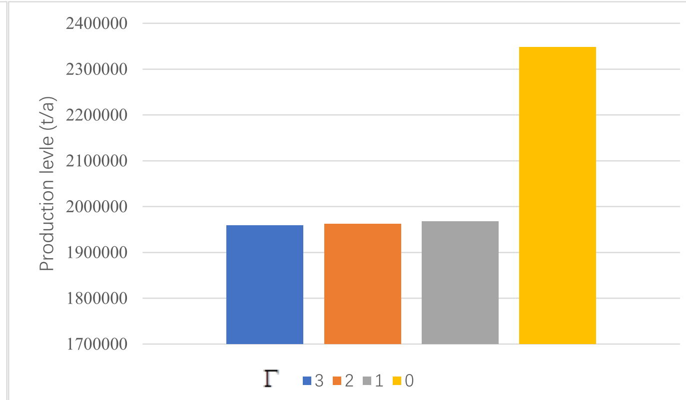
The potential total permitted effluent increases with the decrease in the robust parameter, so industry managers would decide to produce more high-revenue goods. Agricultural sector

**Table 5**
Values of objective function and total emission quantity in 2030.

| Variables | $\Gamma = 3$ | $\Gamma = 2$ | $\Gamma = 1$ | $\Gamma = 0$ |
|---|---|---|---|---|
| Objective function (Rp) | $3.88 \times 10^{12}$ | $3.89 \times 10^{12}$ | $3.89 \times 10^{12}$ | $4.66 \times 10^{12}$ |
| Total emission quantity (t/a) | | $8.63 \times 10^7$ | | |




(a) Optimal allocation pattern in agricultural sector




(b) Optimal allocation pattern in non-agricultural sector

**Fig. 5.** Optimal production pattern in terms of agricultural and non-agricultural sectors.

**Table 6**
Optimal solution of land use, production level in 2030.

| Variables | $\Gamma = 3$ | $\Gamma = 2$ | $\Gamma = 1$ | $\Gamma = 0$ |
|---|---|---|---|---|
| $X_1^A$ (ha) | 6786 | 4164 | 6786 | 7757 |
| $X_2^A$ (ha) | 3500 | 8328 | 2035 | 5876 |
| $X^M$ (t/a) | 1958562 | 1962696 | 1967880 | 2348203 |

managers would balance a trade-off between paddy and Palauija plant and sell excess effluent quotas to industries. In this way, the economic benefits within the watershed would increase.

### 3.5. Effluent trading pattern

Table 7 shows the trading results, which varies from the constraint-violation parameters. The 2nd-4th columns are effluent trading quotas among the three participants: the paddy land planting manager, the Palauija land planting manager, and the textile industry manager. Fig. 6 depicts the trading directions and amounts. Blue rectangle presents the farm land 1, namely paddy land; orange rectangle presents the farm land 2, namely palauiga land; and green rectangle presents the textile industry. The trading direct is from the left side to the right side, respectively, and the data means the amounts of trading rights. The results reflect that uncertainty and robust parameter defined by decision makers would affects farmland use and the production level of the textile industry within the watershed.

Hence, for future planning, more information can be offered to decision makers with different attitudes toward environment protection and economic development, by changing the values of robust parameters. Thus, a suitable risk level caused by constraint violations, farmland use, and industrial production level patterns should be optimized based on the attitudes of decision makers associated with the preference between economic development and environmental protection.

**Table 7**
Effluent trading in 2030.

| Variables | $\Gamma = 3$ | $\Gamma = 2$ | $\Gamma = 1$ | $\Gamma = 0$ |
|---|---|---|---|---|
| $y^{A1M}$ (t/a) | 10309870 | 10488470 | 10712420 | 10235330 |
| $y^{A1A2}$ (t/a) | 8956372 | 9612940 | 9180310 | 9020095 |
| $y^{A2M}$ (t/a) | 1353500 | 875528 | 1532106 | 1215230 |
| $y^{AM}$ [a] (t/a) | 11663370 | 11363998 | 12244526 | 11450560 |
| $y^{A1}$ [b] (t/a) | 19266242 | 20101410 | 19892730 | 19255425 |

[a] Means the total bought effluent quotas of textile factory by adding $y^{A1M}$ and.$y^{A2M}$
[b] Means the total sold effluent quotas of paddy plant by adding $y^{A1M}$ and.$y^{A1A2}$

### 3.6. Comparison with deterministic optimization model

To further demonstrate the superiority of the proposed model for agricultural crop area planning and industrial production level using effluent trading, a traditional deterministic optimization model was formulated for the same case study. A deterministic model is equal to a situation with robustness parameter of 0. This means that all the uncertain parameters in Constraint, *i*, are forced to use the mean values, so there is no protection in the equation against uncertainty. On the contrary, if $\Gamma = 3$, an optimal solution can be obtained while guaranteeing that every constraint is satisfied for any possible value. In general, when the robustness parameter is equal to 0, a totally open attitude is given for water resource allocation despite water supply and demand uncertainty. On the contrary, when the robustness parameter is equal to 3, the most conservative solution is obtained. With the incorporation of polyhedral uncertainty sets, decision makers' attitudes towards uncertainty can be considered correspondingly. Next, we analyze the difference when considering different attitudes.

Tables 5–7 compares the changes when considering decision makers' attitudes from conservative to liberal views. Robust optimization has the ability to handle the uncertainty with more flexibility. From this aspect, the main advantage of the proposed model is that it can ease the decision makers burden, avoid information losses or distortions, and guide them in adjusting farmland planning, production levels, and effluent trading results under uncertainty.

## 4. Conclusion and managerial implications

This paper has developed a robust optimization method to balance a trade-off between sectoral production and effluent trading processes together under future uncertain conditions. Some specific conclusions and managerial implications can be summarized as follows.

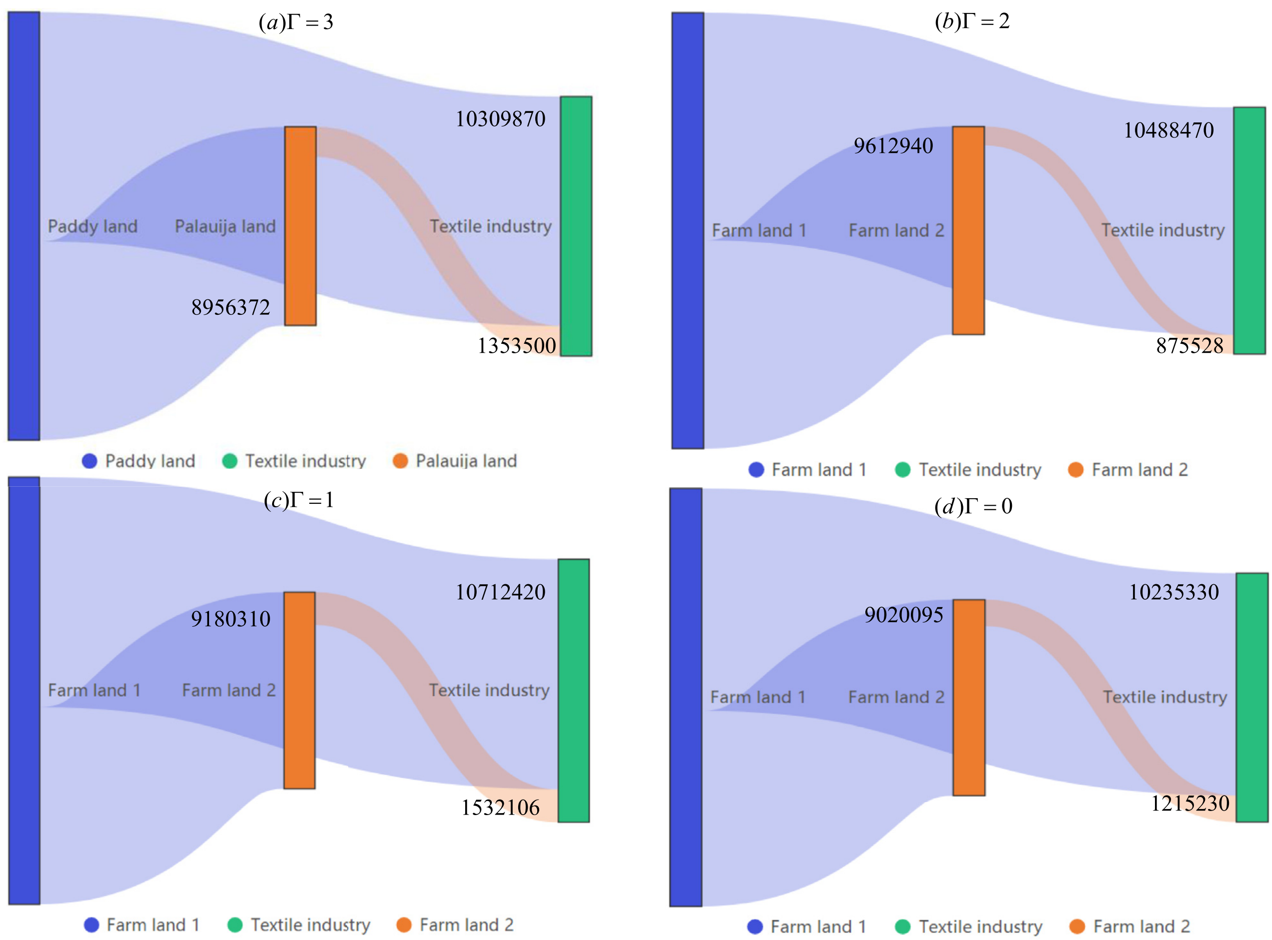



**Fig. 6.** Optimal effluent trading pattern in terms of agricultural and non-agricultural sectors.

### 4.1. Conclusion

Effluent trading is commonly used and has achieved significant success in reducing emission control costs in the US, Europe, Canada, Singapore, and other countries (Tietenberg, 2010). Based on the experience of international emission trading markets, there are still other potential issues that need to be addressed, beyond the issues discussed in this paper, such as the uncertain decision making environment, agricultural planting plans, and non-agricultural production level patterns, etc. This paper, therefore, proposed a robust optimization method to balance a trade-off between sectoral production and effluent trading processes together under uncertain future environments. The sectoral production process includes agricultural and non-agricultural sectors, and their specific planning consists of farmland use modification and industrial production level patterns. The effluent trading process, proven to be an economic means of improving water resource usage efficiency, is incorporated in this study to reallocate effluent emission rights. In this way, flexible decision-making results can be offered based on decision makers' attitudes. Overall, the proposed model will (1) identify an optimal effluent trading scheme that balances various production plans from multiple water users; (2) balance the trade-off between total emission reduction and total benefit maximization by changing budget levels; and (3) ease the decision makers burden, avoid information losses or distortions, and guide them in adjusting farmland planning, production levels, and effluent trading results under uncertainty.

This study is the first attempt to plan point-nonpoint effluent trading under uncertainty, while optimizing the sectoral production level in the Citarum River. The Citarum River, is a large polluted watershed in Indonesia, and was chosen as case study to prove the application of the proposed model. The following conclusions can be drawn from the results: (1) The total relative production level within the watershed increases with increases in budget levels, especially for the textile industry; (2) The agricultural sector conducted an effluent trading process from paddy land use to Palauija land use and other industries; and (3) Strategies for optimal land use, industrial production levels, and effluent trading amounts vary for decision makers with different attitudes (optimistic, neutral, passive) toward constraints-violation risks.

### 4.2. Managerial implications

First, the proposed robust optimization model, wherein uncertainty characterization and robust counterparts are incorporated, is able to offer flexible solutions to agricultural crops area planning and industrial production level planning under changing environment. Further, we undertook a series of analyses based on the changes in uncertainty budget levels. It is known that the probability of constraints violation is directly affected by budget levels, which is defined by decision makers based on their attitude towards risk. Correspondingly, the series of analyses find that risk-averse has a negative relation to economic development, but a positive relation to environmental protection and effluent control.

Hence, different options can be provided for decision makers with varying attitudes from risk-appetite to risk-averse. Specifically, for a risk-appetite decision maker, economic development is paid more attention meanwhile environmental problem may be ignored to some extent, hence, more environmental treatment technology should be invested to promise a sustainable development. On the contrary, for a risk-averse decision maker, it is suggested to appropriately use the economic tool—effluent trading—that is, adjusting the production level in agricultural or non-agricultural sectors to control and reduce total effluent emission amounts.

Second, this study introduces effluent trading into sectoral production process, because effluent emissions are highly related to production levels. Thus, the management paradigm enables decision makers to have comprehensive optimization abilities on effluent emissions and trading. Therefore, this research can assist organizational managers, regulating authorities, and policy & decision makers in understanding the trade-off between production levels and effluent control using effluent trading from both economic and environmental perspectives. In accordance with climate change and human invention, farmland use and production levels in non-agricultural sectors should be adjusted in the future, one of the suggestions is that importing more products, which may bring to more pollution during growth or production when the environmental capacity is lower than the mean value, on the contrary, expand the production level when the future environmental capacity is higher than the expected value. In general, in order to facilitate implementation of sustainable development, the agricultural and industrial characteristics and production levels should be optimized combined with effluent trading in the changing future conditions.

Third, implementing two-stage system paradigm helps to balance a trade-off between the effluent emission and trading processes. Effluent trading is known as an economic policy option for sustainable development. Effluent trading enabled emissions transferred from one place to another, effluent equivalent is defined in this paper to illustrate how many units of pollutant reduction a source must purchase from the other source in order to receive discharge permit for one-unit increase in its load. Here, two indexes: net benefit and emission quantity are used to explore the necessity of effluent trading. The solution to farmland use and production level of textile industry planning in Indonesia Citarum River show that the economic benefits increase, total effluent emission quantity decrease after the introduction of effluent trading. We analyze that extra consumption on effluent treatment and effluent trading make participants considering the trade-off between production and emission.

Overall, this study provides government planners and entrepreneurs with a two-stage framework to analyze sectoral production and effluent trading processes together, and conducts numerical case in Indonesia Citarum River to illustrate the feasibility of the proposed model. The results solved by the proposed model offer deeper insights on agricultural crops area planning and textile production level in the presence of effluent trading. In the future, the proposed model is suitable to cope with a real-world problem, which is easily influenced by changing environment, such as water allocation problem, elective surgery problem, etc.

### 4.3. Limitations

This study is the first attempt to plan point-nonpoint effluent trading under uncertain future environments while also optimizing the sectoral production levels. There are still other potential issues that need to be addressed, beyond the issues discussed in this paper, such as considering total costs associated with trading and costs associated with treatment.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**Zhongwen Xu:** Conceptualization, Methodology, Software. **Liming Yao:** Writing - review & editing. **Xudong Chen:** Data curation, Writing - original draft.

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## References

Bank, A.D.. Indonesia: integrated citarum water resources management investment program. https://www.adb.org/projects/37049-023/main. (Accessed 14 September 2018).

Bertsimas, D., Sim, M., 2004. The price of robustness. Oper. Res. 52, 35–53.

Birge, J.R., Louveaux, F., 2011. Introduction to Stochastic Programming. Springer Science & Business Media.

Cai, Y., Rong, Q., Yang, Z., Yue, W., Tan, Q., 2018. An export coefficient based inexact fuzzy bi-level multi-objective programming model for the management of agricultural nonpoint source pollution under uncertainty. J. Hydrol. 557, 713–725.

D'Arrigo, R., Abram, N., Ummenhofer, C., Palmer, J., Mudelsee, M., 2011. Reconstructed streamflow for citarum river, java, Indonesia: linkages to tropical climate dynamics. Clim. Dyn. 36, 451–462.

De Lange, W.J., Botha, A., Oberholster, P.J., 2016. Towards tradable permits for filamentous green algae pollution. J. Environ. Manag. 179, 21–30.

Dong, F., Liu, Y., Wu, Z., Chen, Y., Guo, H., 2018. Identification of watershed priority management areas under water quality constraints: a simulation-optimization approach with ideal load reduction. J. Hydrol. 562, 577–588.

Gunawardena, A., White, B., Hailu, A., Wijeratne, E., Pandit, R., 2018. Policy choice and riverine water quality in developing countries: an integrated hydro-economic modelling approach. J. Environ. Manag. 227, 44–54.

Gunawardena, A., Wijeratne, E., White, B., Hailu, A., Pandit, R., 2017. Industrial pollution and the management of river water quality: a model of kelani river, Sri Lanka. Environ. Monit. Assess. 189, 457.

Han, L.x., Huo, F., Sun, J., 2011. Method for calculating non-point source pollution distribution in plain rivers. Water Science and Engineering 4, 83–91.

Heitsch, H., Römisch, W., 2003. Scenario reduction algorithms in stochastic programming. Comput. Optim. Appl. 24, 187–206.

Khairiah, R.N., Prasetyo, L.B., Setiawan, Y., Kosmaryandi, N., 2016a. Monitoring model of payment for environmental service (pes) implementation in cidanau watershed with stands density approach. Procedia Environmental Sciences 33, 269–278.

Khairiah, R.N., Prasetyo, L.B., Setiawan, Y., Kosmaryandi, N., 2016b. Monitoring model of payment for environmental service (pes) implementation in cidanau watershed with stands density approach. Procedia Environmental Sciences 33, 269–278.

Leal Filho, W., 2012. Climate Change and the Sustainable Use of Water Resources. Springer.

Leimona, B., Pasha, R., Rahadian, N.P., et al., 2010. The livelihood impacts of incentive payments for watershed management in cidanau watershed, west java, Indonesia. Payments for environmental services, forest conservation and climate change 106–129 livelihoods in the REDD?

Li, Y., Huang, G., Li, H., Liu, J., 2014. A recourse-based interval fuzzy programming model for point-nonpoint source effluent trading under uncertainty. JAWRA Journal of the American Water Resources Association 50, 1191–1207.

Marzullo, R.D.C.M., Morita, D.M., 2018. New method to calculate water ecotoxicity footprint of products: a contribution to the decision-making process toward sustainability. J. Clean. Prod. 188, 888–899.

Mulvey, J.M., Vanderbei, R.J., Zenios, S.A., 1995. Robust optimization of large-scale systems. Oper. Res. 43, 264–281.
Narassimhan, E., Gallagher, K.S., Koester, S., Alejo, J.R., 2018. Carbon pricing in practice: a review of existing emissions trading systems. Clim. Policy 18, 967–991.
Nguyen, N., Shortle, J., Reed, P., Nguyen, T., 2013. Water quality trading with asymmetric information, uncertainty and transaction costs: a stochastic agent-based simulation. Resour. Energy Econ. 35, 60–90.
Rong, Q., Cai, Y., Chen, B., Yue, W., Yin, X., Tan, Q., 2017. An enhanced export coefficient based optimization model for supporting agricultural nonpoint source pollution mitigation under uncertainty. Sci. Total Environ. 580, 1351–1362.
Santoso, T., Ahmed, S., Goetschalckx, M., Shapiro, A., 2005. A stochastic programming approach for supply chain network design under uncertainty. Eur. J. Oper. Res. 167, 96–115.
Skurray, J.H., Pandit, R., Pannell, D.J., 2013. Institutional impediments to groundwater trading: the case of the gnangara groundwater system of western Australia. J. Environ. Plan. Manag. 56, 1046–1072.
Soltani, M., Kerachian, R., 2018. Developing a methodology for real-time trading of water withdrawal and waste load discharge permits in rivers. J. Environ. Manag. 212, 311–322.
Soyster, A.L., 1973. Technical note-convex programming with set-inclusive constraints and applications to inexact linear programming. Oper. Res. 21, 1154–1157.
Steinman, A.D., Ogdahl, M.E., Weinert, M., Thompson, K., Cooper, M.J., Uzarski, D.G., 2012. Water level fluctuation and sediment-water nutrient exchange in great lakes coastal wetlands. J. Gt. Lakes Res. 38, 766–775.
Syakur, A., Zaman, B., Affif, F., Nurjannah, S., Nurmaliakasih, D.Y., 2017. Application of Dielectric Barrier Discharge Plasma for Reducing Chemical Oxygen Demand (Cod) on Industrial Rubber Wastewater.
Tietenberg, T.H., 2010. Emissions Trading: Principles and Practice. Routledge.
Vatvani, C.. The toxic waste that enters Indonesia's citarum river, one of the world's most polluted. https://www.channelnewsasia.com/news/asia/indonesia-citarum-river-worlds-most-polluted-toxic-waste-10124436. (Accessed 14 April 2018).
Weidner, T., Yang, A., Hamm, M.W., 2019. Consolidating the current knowledge on urban agriculture in productive urban food systems: Learnings, gaps and outlook. J. Clean. Prod. 209, 1637–1655.
Wurzel, R.K.W., 2006. Environmental Policy-Making in Britain, Germany and the European Union. Manchester University Press.
Xiong, Z., Li, H., 2019. Ecological deficit tax: a tax design and simulation of compensation for ecosystem service value based on ecological footprint in China. J. Clean. Prod. 230, 1128–1137.
Yamout, G.M., Hatfield, K., Romeijn, H.E., 2007. Comparison of new conditional value-at-risk-based management models for optimal allocation of uncertain water supplies. Water Resour. Res. 43.
Zhang, J., Li, Y., Huang, G., 2014. A robust simulation–optimization modeling system for effluent trading–a case study of nonpoint source pollution control. Environ. Sci. Pollut. Control Ser. 21, 5036–5053.
Zhang, J., Li, Y., Huang, G., Baetz, B., Liu, J., 2017. Uncertainty analysis for effluent trading planning using a bayesian estimation-based simulation-optimization modeling approach. Water Res. 116, 159–181.
Zhang, J., Li, Y., Wang, C., Huang, G., 2015. An inexact simulation-based stochastic optimization method for identifying effluent trading strategies of agricultural nonpoint sources. Agric. Water Manag. 152, 72–90.