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ORIGINAL ARTICLE

A quantitative water resource planning and management model for an industrial park level

Yong Geng · Raymond Côté · Fujita Tsuyoshi

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Abstract This paper introduces an integrated water management model at the industrial park level. It suggests four approaches to water management: first, direct water reuse among users; second, water reuse among users by blending with freshwater; third, water reuse between users and a wastewater treatment plant; and fourth, groundwater recharge by reclaimed wastewater or other feasible applications in order to optimize the overall water efficiency. The model results in a comprehensive management methodology for optimizing water resources within an industrial park, seeking potential water reuse among industries, and incorporating the size and cost of reclaimed wastewater delivery systems. A case study is employed to test the model's feasibility. An economic analysis of the optimized water use network is also carried out, showing the potential water and cost savings.

Y. Geng
Institute for Eco-planning and Development,
Dalian University of Technology, Dalian,
People's Republic of China

R. Côté
School for Resource and Environmental Studies,
Dalhousie University, Halifax, NS, Canada
e-mail: rcote@mgmt.dal.ca

F. Tsuyoshi
National Institute for Environmental Studies, Tsukuba,
Ibaraki, Japan
e-mail: fujita77@nies.go.jp

Y. Geng (✉)
School of Management Building,
Dalian University of Technology,
Dalian 116024, People's Republic of China
e-mail: ecoplan@dlut.edu.cn

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Introduction

Reuse of treated wastewater has received more attention over the last decade. Treated wastewater can be used in agricultural irrigation, cooling of industrial plants, fire control facilities, recreation facilities, direct industrial reuse, groundwater recharge, etc. (Asano and Mills 1990; Bouwer 1991; Shelef 1991; Asano et al. 1992). However, challenges to its use include transportation and treatment costs, hazards related to environmental pollution and associated health risks. Managing and optimizing reclaimed water is a complicated interdisciplinary problem, which requires integrative planning (Asano 1991). A systems approach, based on a model, could assist in satisfying many constraints and decision-making criteria (Oron 1996). Although models can only approximate real life conditions, they provide a means of evaluating influences and options. Such models can support decision-makers in project evaluation and implementation (Oron 1996). In addition, modeling allows for the testing of hypothetical alternative plans of water use.

A potentially valuable application field for water management modeling is the industrial park, where there is shared infrastructure and a concentration of industries. According to UNIDO (1997), an industrial park can be defined as a tract of land developed and subdivided into plots according to a comprehensive plan with provision for roads, transport and public utilities for the use of a group of industries. Through industrial estates, firms benefit from economies of scale in terms of land development, construction, and common facilities (Côté et al. 1994).

Some parks are large consumers of water as a result of the nature of the industries and their density. Due to lack of information, cooperation and integration, many water reuse and recycling opportunities have not been identified although many parks have established wastewater treatment facilities and many tenant companies have their own water conservation programs. However, in some countries where water shortages are becoming increasingly severe, local governments have to manage the total freshwater supply to industries in order to satisfy the competing needs of households, local institutions, and agriculture. In addition, different industries within an industrial park have different needs. As such they may compete for the effluent from either wastewater treatment plant or from other companies, when quality is not a problem (Geng and Wu 2000). The cost of water may also become a factor and such effluent or process water would be expected to be cheaper than freshwater, thus, reducing the total production expense. With the increased interest in sustainable development, the implementation of a sustainable industrial ecosystem requires that wastes should be viewed as resources rather than as wastes to be discarded. Therefore, it is critical for industrial park managers to seek an integrated approach to reduce the total water use and optimize utilization of this resource.

Some efforts have been undertaken to model water allocation within an industrial park. For instance, Keckler and Allen (1999) used a linear programming model to evaluate water reuse scenarios at a large industrial park in Houston, Texas. Through the model, facilities could be added or deleted, water separated or blended, and types of treatment differentiated. However, their model did not integrate the relevant capital costs associated with pipelines and other infrastructure and construction costs involved with the installation of the infrastructure. Nobel and Allen (2000) presented a linear programming model that identified cost-optimal reuse scenarios applied to water reuse planning scenarios. In their model, they utilized a geographical information system (GIS) to provide the capability to compute distances based either on latitude and longitude or on addresses, which was useful in analyzing existing systems. However, this second model also did not incorporate capital costs. A universal integrated water resource management model at the industrial park level, particularly, considering those parks where water shortages are becoming pressing, is becoming increasingly important.

This paper discusses the overall management model for optimizing water resources within an industrial park. The model seeks to identify the potential water reuse opportunities among the industries and to incorporate the size and cost of reclaimed wastewater delivery systems. A case study of the Tianjin economic development area (TEDA) is employed to assess the model's feasibility. An economic analysis of the optimized water use network is carried out, showing the potential water and cost saving.

Description of a water system within an industrial park

Within an industrial park, the potential water resources include surface water, rainwater, groundwater and reclaimed wastewater, each with a maximum water yield, a quality profile as defined by the pollutant concentrations, and a maximum acceptable mass discharge of pollutants. Industrial parks also have extensive water infrastructure that must be planned and constructed, all with a maximum flow capacity, efficiency of removal and possible water losses. For instance, in China, water and wastewater treatment plants exist in every industrial park as required by the national environmental regulations (Yang et al. 2001). The tenant firms have their respective water demand, quality profiles, defining the maximum pollutant concentrations for the water to be accepted, quality degradation upon water consumption and use, and a possible ''in situ'' treatment facility with removal efficiency. Both the quality and quantity of flow to and from each of these facilities are important in water reuse planning.

This study seeks to maximize the total water efficiency within an industrial park. Whenever quality is sufficient, arguably the wastewater from one water user should be reused directly. However, if the quality is low, it could be blended with freshwater or treated in the wastewater treatment plant so that it may be reused by other water users or by park managers for irrigation and landscaping. The unwanted reclaimed water from wastewater treatment plants should be regarded as a future water resource rather than something to be discarded.

In order to develop a model for integrated water resource planning and management within an industrial park, several aspects should be considered. These include:

- economies of scale in treatment and transportation costs;
- water quality and quantity requirements for each user, allowing each user with low quality requirements to satisfy its demand from low quality sources (untreated or partially treated or blended with freshwater);
- interactions among the users and among treatment plants and users.
- potential reuse of reclaimed wastewater from wastewater treatment plant.

Water elements within an industrial park include water sources, water treatment plant, wastewater treatment plant (for industrial wastewater) and water users. The following introduces these elements in detail.

1. Water inputs: The possible water inputs in an industrial park include surface and ground sources. Each input is defined by (1) its location in the park, (2) water availability, expressed as the maximum water yield, (3) quality profile, defined in terms of the concentration of each pollutant occurring to enforce the water quality constraints during the planning process. In this study, we assume that water will be sent to the water treatment plant from water sources in order to improve its quality according to the local potable water standard, or to water users that don't require potable water without previous treatment.
2. Water treatment plant (WTP): The water treatment plant is defined by: (1) its location in the park, (2) production capacity, (3) water losses, (4) treatment performance, as given by the concentration that the plant achieves for each pollutant. This study presumes that the water treatment plant produces water according to the local potable water standard and assumes that freshwater from water treatment plant is sent to the users in the park. Figure 1 is a schematic presentation of interactions between water sources, water treatment plants and users.
3. Wastewater treatment plant (WWTP): The wastewater treatment plant is defined by: (1) its location in the park, (2) its maximum flow capacity, (3) water loss, (4) influent quality requirements, (5) treatment performance, as given by the concentration achieved for each pollutant. This study assumes that the wastewater treatment plant receives influent from the users in the park and sends some back to the users if the quality is not a problem. After this, the surplus effluent from the plant can be sent to recharge the local ground when the quality can meet with the standard of groundwater recharge. Or it can be used for landscaping or for any other feasible applications by considering the local demands if quality is not a problem. Figure 2 describes the interaction of the WWTP with other system elements.
4. Water users: A user here is the element in the system, which demands water. Tenant companies, management units, domestic users, and landscape sites are major users. A user is defined by: (1) its location, (2) water demand, (3) water losses, (4) water quality requirements, which represent the maximum acceptable concentration for each pollutant. This study allows a user to recycle water by itself or send the water directly to another user if its quality can meet with that user's requirements. A user can receive water from a surface or groundwater source, or a water treatment plant. It also can receive reclaimed wastewater from the wastewater treatment plant or from another user if the quality of such effluents meets its requirements. If the effluent cannot be recycled or reused by another user, such effluent should be sent to the wastewater treatment plant. The quality of such effluent before entering the wastewater treatment plant should at least meet with the input requirement of the wastewater treatment plant, therefore, previous treatment is indispensable for some users. Figure 3 describes the interactions among the various system elements.

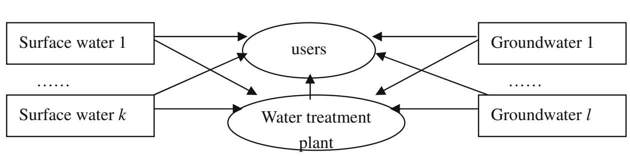

Fig. 1 Schematic presentation of water sources interactions with other system elements

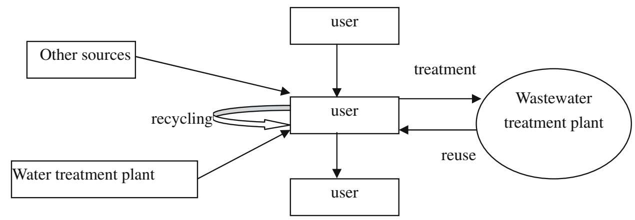

Fig. 2 Schematic presentation of a user interaction with other system elements

Objective function

An integrative approach is used in an attempt to encompass all relevant aspects of the considered water and wastewater management and reuse system in one model. The first step in such a model is to define an objective function, which is determined by a series of technological, legal and environmental constraints. In terms of an industrial park, we can define our objective as finding the most cost efficient solution for optimizing the supply and reuse of water. The cost includes that of water and wastewater treatment, the distribution cost including piping and pumping, and the amortized installation costs for new pipes.

The piping costs can be expressed in the form of αQ^{β}, where Q is the flow transported through pipes (USA EPA

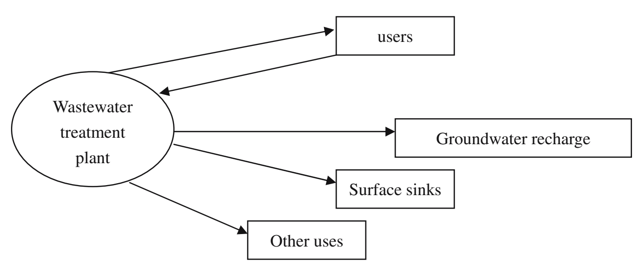

Fig. 3 Schematic presentation of the wastewater treatment plant interactions with other system elements

1978a; Wang et al. 1987; Oron 1996; Cao and Gu 1997; Tian et al. 2001). The α and β are coefficients, with β expressing the economies of scale, where usually $0 < \beta < 1$. This is because economies of scale were among the main factors influencing researchers to consider water system costs, where the locations of sources and their waste flows were fixed in advance, as are the regional treatment plant locations and the allowable pipeline routes. These economies of scale imply concavity when the functions are continuous. Similarly, the construction costs for pipes and pumps are expressed as $\alpha_1 Q^{\beta 1}$ (USA EPA 1978b; Wang et al. 1987; Oron 1996; Cao and Gu 1997; Tian et al. 2001) and the pumping costs are expressed as $\alpha_2 Q^{\beta 2}$ (USA Army Corps of Engineers 1973; USA EPA 1978a; Wang et al. 1987; Oron 1996; Cao and Gu 1997; Tian et al. 2001). The water and wastewater plant treatment costs also have a form similar to the pumping and piping costs (USA EPA 1979; Wang et al. 1987; Oron 1996; Cao and Gu 1997; Tian et al. 2001). Therefore, for the purposes of this study, the objective function will be set up to minimize the sum of daily piping costs, daily pumping costs, daily water and wastewater treatment costs for the whole system, and amortized daily construction costs for new pipes and pumps if water reuse is necessary. It can be expressed by the following equation:

$$Z_{\min} = \sum_{w \in W} \alpha_w Q_w^{\beta_w} + \sum_{y \in Y} \alpha_y Q_y^{\beta_y} + \sum_{p \in P} \alpha_p Q_p^{\beta_p} + \sum_{k \in K} \alpha_k (XF_k)^{\beta_k} + \sum_{i \in I} \alpha_i (XTT_i)^{\beta_i} \tag{1}$$

where Z = total daily cost of the whole water system; $\sum \alpha_w Q_w^{\beta w}$ = the whole daily piping costs, $\forall w$; W is the set of possible pipes connecting sources, users, treatment plants, and disposal sites (sinks), Q represents daily water flow, and α and β are coefficients, with β expressing the economies of scale. Similarly, $\sum \alpha_{\,y} Q_y^{\beta y}$ = the whole daily pumping costs, $\forall y$; Y is the subset of pipes requiring pumping. $\sum \alpha_p Q_p^{\beta p}$ = the daily amortized construction costs of new pipes and pumps, $\forall p$; P is the subset of new pipes and pumps considering water reuse. $\sum \alpha_k (XF_k)^{\beta k}$ = the whole daily water treatment plant cost, $\forall k$; XF_k represents the daily amount of fresh water from surface and ground source k to water treatment plant; $\sum \alpha_i (XTT_i)^{\beta i}$ = the whole daily wastewater treatment plant cost, $\forall i$; XTT_i represents the daily amount of wastewater from user i to the wastewater treatment plant.

Model constraints

The constraints define a feasible domain in the decision space. Subject to the kind of planning and management problem, the constraints can express restrictions placed on the wastewater quality for reuse, environmental regulations on wastewater, water demands, health risks, user's quality requirements, water balance, capacity constraints, non-negative constraints, groundwater recharge request, landscaping request, and requests for other uses.

Demand constraints

These sets of linear constraints force the water demand for each user i to be satisfied.

$$XF_i + \sum_l XS_{li} + XT_i + \sum_j XTU_{ji} \geq D_i \quad \forall i \tag{2}$$

where XF_i = the amount of freshwater sent from water treatment plant to user i, $\forall i$; XS_{li} = the amount of water from surface and ground water source l to user i without treatment, $\forall i$; XT_i = the amount of reclaimed water from wastewater treatment plant to user i, $\forall i$; XTU_{ji} = the amount of wastewater from user j to user i without treatment, $\forall i$.

Water balance constraints

These sets of linear constraints prevent violation of any mass balances throughout the system for each user, water treatment plant, and wastewater treatment plant. For users, the water balance equation can be expressed as following:

$$XF_i + XT_i + \sum_j XTU_{ji} + \sum_l XS_{li} - XTT_i - \sum_j XTU_{ij} = L_i \quad \forall i \tag{3}$$

where XF_i = the amount of freshwater sent from water treatment plant to user i, $\forall i$; XT_i = the amount of reclaimed water from wastewater treatment plant to user i, $\forall i$; $\sum XTU_{ji}$ = the amount of wastewater from user j to user i without treatment, $\forall i$; $\sum XS_{li}$ = the amount of water from surface and ground water source l to user i without treatment, $\forall i$; XTT_i = the amount of wastewater from user i to the wastewater treatment plant, $\forall i$; $\sum XTU_{ij}$ = the amount of wastewater from user i to user j without treatment, $\forall i$.

The water losses, including consumption, are considered constant for each user and are assumed known. In the real world, such data should be able to be collected from the users.

For water treatment plants, the water balance equation can be expressed as following

$$\sum_k XFk - XF_i = LT \quad \forall i, \tag{4}$$

where ΣXF_k = the amount of fresh water from surface and ground source k to water treatment plant, $\forall k$; XF_i = the amount of freshwater sent from water treatment plant to user i, $\forall i$.

Similarly, for wastewater treatment plant, the water balance equation should be:

$$\sum_i XTTi - \sum_i XTi - XRR - XLS - XOA = LTT \quad \forall i, \tag{5}$$

where XTT_i = the amount of wastewater from user i to the wastewater treatment plant, $\forall i$; XT_i = the amount of reclaimed water from wastewater treatment plant to user i, $\forall i$; XRR = the amount of reclaimed water from wastewater treatment plant to ground source for recharging groundwater; XLS = the amount of reclaimed water from wastewater treatment plant for landscaping; XOA = the amount of any other feasible applications of reclaimed wastewater; LTT = water losses at wastewater treatment plant.

Capacity constraints

These linear constraints limit the water entering a treatment plant according to its capacity.

For water treatment plant, this constraint should be expressed as following:

$$\sum_k XF_k \leq TC \quad \forall k, \tag{6}$$

where XF_k = the amount of fresh water from surface and ground source k to water treatment plant, $\forall k$; TC means treatment capacity at water treatment plant;

For wastewater treatment plant, this constraint should be expressed as:

$$\sum_i XTT_i \leq TTC \quad \forall i, \tag{7}$$

where XTT_i = the amount of wastewater from user i to the wastewater treatment plant, $\forall i$; TTC means treatment capacity at wastewater treatment plant.

Water quality constraints

This set of constraints forces the water flow distribution in the system to satisfy the quality requirements of each user.

For direct wastewater reuse from company j to company i, it may be possible only when:

$$c(P_n)_j \leq s(P_n)_i \quad \forall i,j, \tag{8}$$

where P_n represents pollutant n, n = 1,2,..., N (such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Organic Carbon (TOC), etc.); $C(P_n)_i$ means pollutant n concentration leaving user j, $\forall j$; $S(P_n)_i$ represents pollutant n standard required by user i, $\forall i$.

For reclaimed wastewater reuse from wastewater treatment plant to company i, it may be possible only when:

$$CT(P_n) \leq s(P_n)_i \quad \forall i, \tag{9}$$

where $CT(P_n)$ represents pollutant n concentration of reclaimed water from wastewater treatment plant.

For wastewater reuse from company j to company i by blending with freshwater, the ratio of wastewater to freshwater can be calculated by the following equation:

$$\gamma = \frac{C(P_n)_j - S(P_n)_i}{S(P_n)_i - CF(P_n)} \quad \forall i,j, \tag{10}$$

where $CF(P_n)$ means pollutant n concentration of freshwater from water treatment plant.

And then the relation between XF_i and $XTBU_{ji}$ should be:

$$XF_i = \gamma \times XTBU_{ji} \quad \forall i,j, \tag{11}$$

where $XTBU_{ji}$ means amount of wastewater from user j to user i blending with freshwater, $\forall i$, j.

Environmental regulation constraints

This set of constraints forces the quality of freshwater to satisfy the local freshwater quality requirements, and the quality of reclaimed water from wastewater treatment plant to satisfy the local groundwater recharge standard, the local landscaping standard, and standards for other uses.

For water treatment plant, it can be expressed as:

$$CF(P_n) \leq LS(P_n), \tag{12}$$

where $LS(P_n)$ means local pollutant n standard for freshwater;

for wastewater treatment plant, it can be expressed as:

$$CT(P_n) \leq LT(P_n), \tag{13}$$

where $LT(P_n)$ represents local pollutant n standard for wastewater discharge.

For groundwater recharge, it can be expressed as:

$$CT(P_n) \leq LRG(P_n), \tag{14}$$

where $LRG(P_n)$ means local pollutant n standard for groundwater recharge by reclaimed water.

For landscaping, it can be expressed as:

$$CT(P_n) \leq DLS(P_n), \tag{15}$$

where $DLS(P_n)$ means local pollutant n standard for landscaping by reclaimed water.

Non-negative constraints

This set of constraints requires that all the inputs and variables should be at least nonnegative.

Groundwater recharge constraint

This constraint requires that the amount of recharging groundwater by reclaimed wastewater should be no more than the groundwater recharge request. It can be expressed as:

$$XRR \leq GC, \quad (16)$$

where XRR means amount of reclaimed water from wastewater treatment plant to ground source for recharging groundwater; and GC means groundwater recharge request.

Landscaping constraint

This constraint requires that the amount of landscaping by reclaimed wastewater should be no more than the landscaping request. It can be expressed as:

$$XLS \leq DLS, \quad (17)$$

where XLS means amount of reclaimed water from wastewater treatment plant for landscaping; and DLS means landscaping request;

for any other uses, such as fire control and recharge of lakes and ponds, the quality and quantity of reclaimed wastewater also should meet the relevant standards.

Case study

Description of the case study site

In order to illustrate the model's feasibility and applicability for optimizing water resources within an industrial park, a case study is presented here. The selected case study site is the TEDA, the largest industrial park in China. This industrial park is located in the east portion of Tianjin Municipality, approximately 160 km from the city of Beijing. The key criteria for selecting participating companies revolved around the quantity and quality of their water demand and wastewater discharge. Specifically, the criteria were:

- The selected company must be a main water user and wastewater producer.
- The selected company has the incentives to improve their water management and would like to join this study.
- Documentation and relevant data for this organization must exist and be accessible.
- Individuals in the selected organization must be accessible and open to discuss through interviews and informal discussions.

On the basis of these criteria, the Environmental Protection Bureau (EPB) at TEDA provided a list of the company names, contact information and information of the water consumption and wastewater discharge of these companies to the principal researcher. A workshop was hosted in September 2002 with the help of TEDA EPB. The top twelve water users at TEDA were invited and the objectives and significance of this research were introduced. Of these, six companies finally decided to participate in the study. These are a power plant, a landscaping company, a chemical company, a textile company, a pharmaceutical company, and an electrical products company. In terms of water use quantity in TEDA, they rank no. 1, no. 2, no. 3, no. 4, no. 6 and no. 7, respectively. Besides these six companies, due to their important roles on water supply and wastewater treatment, the local water treatment plant (WTP) and wastewater treatment plant (WWTP) were also invited to participate. Therefore, in total, eight entities were identified as research participants. However, these represent a small percentage of the companies in TEDA as there are over 3,000 tenants in TEDA. Most of these are small water users and in many cases it is impossible to get accurate water related data from all the companies. Consequently, all other water users are regarded as one user and are not separated. Because four of these companies did not want their names released, all the companies were assigned codes. These companies were given the option of declining to participate at any time in the study. Within each company, the senior manager in charge of water management was identified as the primary contact. A seminar was then hosted in order to let those managers further understand the relevance of this research and what information and assistance they would be asked to provide.

Survey results

A detailed survey was carried out among those participating companies in order to collect necessary information and data on their water use and wastewater discharge. Questionnaires were administered during formal workshops and interviews, so the interviewer could probe respondents for greater clarity in answers and consistency in relation to the objectives of the questions (Fowler 1993). In this questionnaire, two water parameters are considered, including suspended solids (SS) and chemical oxygen demand (COD). More parameters can be added for model optimization, but these will make the solution more complex. SS and COD are widely used by water reuse planners (Ocanas and Mays 1981; Keckler and Allen 1999) and can be used as determinants for non-potable water reuse.

Table 1 shows water quantity and quality data for selected companies through surveys. All the data in this table are daily averages.

Table 2 lists the distances among selected tenants and these data have been collected because they influence the costs of piping and pumping, as well as construction costs for building the new connections. The distances reflect the actual lengths of pipe between companies. All the distances among tenants are provided by the TEDA Environmental Protection Bureau.

Table 3 lists the cost functions for this study, which were taken from a recent study done by Tian's group at Tianjin University (Tian et al. 2001). According to cost formulas provided by them, piping costs were integrated with pumping costs together because Tianjin is located on the North China plain and the land in TEDA is very flat (Tian et al. 2001). The construction costs formulae are based on non-corrodable PVC pipes. Daily operation and maintenance costs for the water treatment plant and wastewater treatment plant include those related to energy costs, salaries, amortized depreciation expenses, materials expenses (disinfectants and other chemicals, etc.), overhead, and other miscellaneous expenses (Tian et al. 2001).

Another survey finding is that the maximum treatment capacity of the water treatment plant is 50,000 m^3/day and the water loss rate is 13%, while the maximum treatment capacity of the wastewater treatment plant is 20,000 m^3/day and the water loss rate is 15%. The loss rate is an important factor in determining actual water inputs.

Table 1 Water quantity and quality data

Company	Water demand (10^3 m^3/day)	Effluent (10^3 m^3/day)	Input quality (mg/l)		Output quality (mg/l)	
			COD	SS	COD	SS
1[a]	6.21	0	300	200	N/a	N/a
2[b]	6.38	1.12	50	30	70	200
3[b]	3.22	2.33	0	5	400	52
4[a]	2.65	0.55	0	5	120	73
5[b]	1.16	0.70	40	50	130	131
6[a]	1.10	0.70	20	10	150	200
Others	11.21	6.45	0	0	n/a	n/a
WTP[b]	36.84	31.93	n/a	n/a	0	1
WWTP[b]	11.85	10.07	400	200	40	11

N/a not applicable, *n/a* not available, *others* all other users in TEDA

[a] Based on estimated data

[b] Based on actual measured data

Table 2 Distances among companies

Distances (km)	1	2	3	4	5	6	7	8
1	0	4.1	3.9	2.7	1.9	0.8	5.8	4.7
2	4.1	0	0.4	1.4	1.2	2.5	2.2	2.9
3	3.9	0.4	0	1.7	0.3	2.0	3.2	4.1
4	2.7	1.4	1.7	0	2.2	1.1	3.5	4.7
5	1.9	1.2	0.3	2.2	0	2.7	4.2	1.9
6	0.8	2.5	2.0	1.1	2.7	0	5.5	4.6
7	5.8	2.2	3.2	3.5	4.2	5.5	0	N/a
8	4.7	2.9	4.1	4.7	1.9	4.6	N/a	0

N/a not applicable

On the basis of these data, the next step is to seek potential water reuse opportunities among these participating companies based upon water quality. A matrix is employed in order to find potential water reuse opportunities, which can be found in Fig. 4. In this matrix, number 1 means that the quality of the effluent from user j can meet the quality demand of user i, and 0 means that user i cannot use the effluent from user j directly.

Model results

With these data, the next step is to run the quantitative model in order to seek the optimal water allocation scenario. Therefore, the objective function and constraints should be set up on the basis of the actual TEDA conditions. As previously stated, the objective in this case is to determine the minimum daily water system cost in TEDA considering water reuse. The costs include daily water and wastewater treatment costs and daily transporting costs consisting of piping and pumping costs, as well as those daily amortized construction costs for new pipes and pumps. Therefore, the objective function is the minimization of the sum of daily piping and pumping costs, daily water and wastewater treatment costs, and daily amortized

Table 3 Cost functions

Description	Cost function for application[a] (RMB)
1. Water treatment plant	$4211Q^{0.83^{b}}$
Operation and maintenance	
2. Wastewater treatment plant	$10281Q^{0.86}$
operation and maintenance	
3. Piping and pumping	$458 \times$ distance (km)$Q^{0.78}$
a. Operation and maintenance	$1.2513 \times 10^6 \times$ distance (km)$Q^{0.76}$
b. Construction	

[a] In this case, daily amortized construction cost for new pipes and pumps will be amortized by 15 years (365 days per year), with an annual interest rate of 5%

[b] The unit for Q is 10^3 m^3

	1	2	3	4	5	6	7	8
1	0	1	1	1	1	1	1	1
2	0	0	0	1	0	0	1	1
3	0	0	0	0	0	0	1	0
4	0	0	0	0	0	0	1	0
5	0	1	0	1	0	1	1	1
6	0	0	0	0	0	0	1	1

Fig. 4 Water reuse opportunities matrix among tenants

construction costs for new pipes and pumps, which is the same as Eq. (1):

$$Z_{\min} = \sum_{w \in W} \alpha_w Q_w^{\beta_w} + \sum_{y \in Y} \alpha_y Q_y^{\beta_y} + \sum_{p \in P} \alpha_p Q_p^{\beta_p} + \sum_{k \in K} \alpha_k (XF_k)^{\beta_k} + \sum_{i \in I} \alpha_l (XTT_i)^{\beta_l}. \quad (1)$$

In this case, based on the water reuse matrix, there are 29 variables, which can be found in Table 4. Constraints in this case include water demand for each user, water balance for each node and the requirements for water blending, capacity constraints, quality constraints, and environmental regulation constraints, as well as non-negative constraints.

Water demand for each user

$$Q_{2-1} + Q_{3-1} + Q_{4-1} + Q_{5-1} + Q_{6-1} + Q_{7-1} + Q_{8-1} = 6.21$$
$$Q_{7-2} + Q_{4-2} + Q_{8-1} = 8.38$$
$$Q_{7-3} = 3.22$$
$$Q_{7-4} = 2.65$$
$$Q_{2-5} + Q_{4-5} + Q_{6-5} + Q_{7-5} + Q_{8-5} = 1.16$$
$$Q_{7-6} + Q_{8-6} = 1.10$$
$$Q_{7-9} = 11.21$$

Water balance

$$Q_{7-1} + Q_{7-2} + Q_{7-3} + Q_{7-3} + Q_{7-4} + Q_{7-5} + Q_{7-6} + Q_{7-9} = 31.93$$
$$Q_{1-8} + Q_{2-8} + Q_{3-8} + Q_{4-8} + Q_{5-8} + Q_{6-8} + Q_{9-8} = 11.21$$
$$Q_{10-7} = \Sigma Q_{7-i}/0.867 \qquad (i = 1,2,3,4,5,6,9)$$
$$\Sigma Q_{8-j} + Q_{8-11} = \Sigma Q_{j-8} * 0.85 \qquad (j = 1,2,3,4,5,6,9)$$

Table 4 29 Variables for TEDA case

Q_{7-1}	Water flow from water treatment plant to company 1
Q_{7-2}	Water flow from water treatment plant to company 2
Q_{7-3}	Water flow from water treatment plant to company 3
Q_{7-4}	Water flow from water treatment plant to company 4
Q_{7-5}	Water flow from water treatment plant to company 5
Q_{7-6}	Water flow from water treatment plant to company 6
Q_{7-9}	Water flow from water treatment plant to other users
Q_{1-8}	Water flow from company 1 to wastewater treatment plant
Q_{2-8}	Water flow from company 1 to wastewater treatment plant
Q_{3-8}	Water flow from company 1 to wastewater treatment plant
Q_{4-8}	Water flow from company 1 to wastewater treatment plant
Q_{5-8}	Water flow from company 1 to wastewater treatment plant
Q_{6-8}	Water flow from company 1 to wastewater treatment plant
Q_{9-8}	Water flow from other users to wastewater treatment plant
Q_{2-1}	Water flow from company 2 to company 1
Q_{3-1}	Water flow from company 3 to company 1
Q_{4-1}	Water flow from company 4 to company 1
Q_{5-1}	Water flow from company 5 to company 1
Q_{6-1}	Water flow from company 6 to company 1
Q_{8-1}	Water flow from wastewater treatment plant to company 1
Q_{4-2}	Water flow from company 4 to company 2
Q_{8-2}	Water flow from wastewater treatment plant to company 2
Q_{2-5}	Water flow from company 2 to company 5
Q_{4-5}	Water flow from company 4 to company 5
Q_{6-5}	Water flow from company 6 to company 5
Q_{8-5}	Water flow from wastewater treatment plant to company 5
Q_{8-6}	Water flow from wastewater treatment plant to company 6
Q_{10-7}	Water flow from reservoir to water treatment plant
Q_{8-11}	Water flow from wastewater treatment plant to Bohai Sea
Q_{i-j}	Water flow from node i can be reused by node j. Its unit is 10^3 m^3/day

Requirements for water blending

In this case, effluent from node 3 can be sent to node 1 by blending with fresh water. The ratio $r_1 = (400 - 300)/(300 - 0) = 0.33$, and thus the resulting constraint is $0.33\ Q_{3-1} \leq Q_{7-1}$.

Effluent from node 4 can be sent to node 2 by blending with fresh water. The ratio $r_2 = (73 - 30)/(30 - 0) = 1.44$ and thus the resulting constraint is $1.4\ Q_{4-2} \leq Q_{7-2}$.

Effluent from node 8 can be sent to node 6 by blending with fresh water. The ratio $r_3 = (40 - 20)/(20 - 0) = 1$ and thus the resulting constraint is $Q_{8-6} \leq Q_{7-6}$.

Effluent from node 2 can be sent to node 5 by blending with fresh water. The ratio $r_4 = (200 - 50)/(50 - 1) = 3.06$ and thus the resulting constraint is $3.06\ Q_{2-5} \leq Q_{7-5}$.

Effluent from node 4 can be sent to node 5 by blending with fresh water. The ratio $r_5 = (120 - 40)/(40 - 0) = 2$ and thus the resulting constraint is $2\ Q_{4\text{–}5} \leq Q_{7\text{–}5}$.

Capacity constraints

These linear constraints limit the water entering a treatment plant according to its capacity.

For the water treatment plant, this constraint is expressed as: $Q_{10\text{–}7} \leq 50$.

For the wastewater treatment plant, this constraint is expressed as: $Q_{1\text{–}8} + Q_{2\text{–}8} + Q_{3\text{–}8} + Q_{4\text{–}8} + Q_{5\text{–}8} + Q_{6\text{–}8} + Q_{9\text{–}8} \leq 20$

Nonnegative constraints

This set of constraints requires that all the inputs and variables should be at least nonnegative.

$Q_{i\text{–}j} \geq 0$

Environmental regulation constraints

This set of constraints forces the quality of freshwater to satisfy local potable water quality requirements, and the quality of reclaimed water from wastewater treatment plant to satisfy local discharge standards. By reviewing relevant national standards, all the environmental regulations can be satisfied.

The model has a non-linear objective function and linear constraints. This non-linear program was solved by using CHJM, a Chinese solver specifically designed for modeling linear, non-linear and mixed integer optimization problems (Tang and Qin 1994). This solver was used because it has relatively friendly interface and can handle global optimization issues, while other solvers were not easily available or too expensive. Figure 5 shows the optimal flows for this run (Scenario 1), and Table 5 lists the summary figures for this case, including savings on total costs and total freshwater used, as well as the total reduction of wastewater discharge.

The results noted in Fig. 5 indicate that reclaimed wastewater will not be reused by any user, which means that TEDA still has potential to reduce total freshwater consumption. The greatest potential for reducing total freshwater consumption will be found in the ''zero emission'' scenario, where all the reclaimed wastewater from the wastewater treatment plant will be fully reused by the users. By changing $Q_{8\text{–}11}$ to zero in the constraint (11) and running the model again, the optimal results for a zero emission scenario are identified. Figure 6 shows the optimal flows for this run (Scenario 2), and Table 6 lists the summary figures for this scenario, including savings on total costs, total freshwater supply, and wastewater discharge reduction.

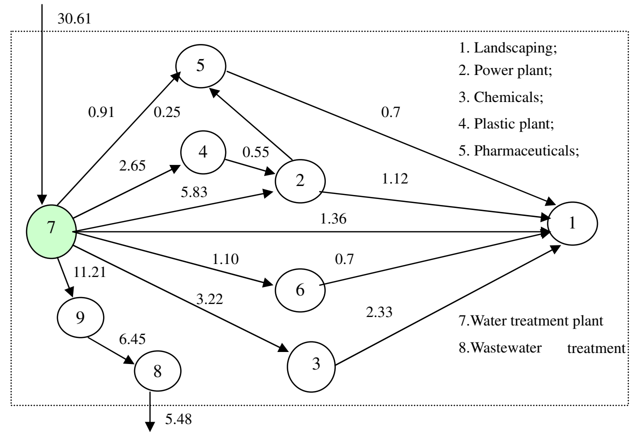

Fig. 5 Optimal flow with minimal cost (Scenario 1)

From the results noted in Table 6, it can be determined that total costs will be increased by 23.26%, total freshwater use is decreased by 34%, while the total discharge is zero. Consequently, this scenario is optimal as it realizes both the best freshwater conservation and zero emission benefits, when cost is not a factor. However, from a manager's perspective, due to budget and technology limits, this scenario is not the preferable choice because of the need to dispose of solid and semi-solid residue, which can add substantial costs.

Between the first scenario and the zero emission scenario, many different water distribution scenarios can be described. These can provide decision-makers with the complete economic and environmental surface so that they can understand the full set of alternatives and the trade-offs among them in terms of the desired objectives. In order to quantify these scenarios, the value of $Q_{8\text{–}11}$ (5.48×10^3 m^3/day) in the water balance constraint equation (Eq. 11) which relates to the reclaimed wastewater from wastewater plant to Bohai Sea in the Scenario 1 is constantly decreased by 0.01, i.e. 10 m^3/day, until this value becomes zero. This decrease results in 546 possible scenarios. By running the optimization solver again, these 546 new scenarios were created. Each scenario shows decision-makers the total

Table 5 Summary figures for Scenario 1 (minimal cost)

	Total costs (RMB/day)	Freshwater (10^3 m^3/day)	Wastewater (10^3 m^3/day)
Without reuse	2.005×10^6	36.84	10.07
With reuse	1.797×10^6	30.61	5.48
Saving (%)	10.37	16.9	45.6

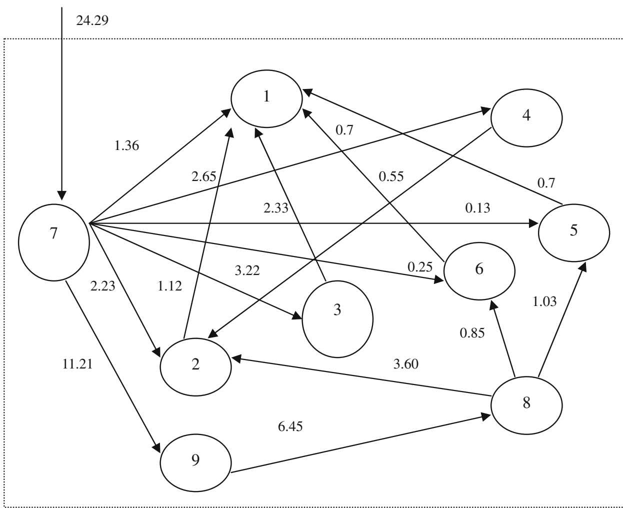

Fig. 6 Optimal flow for zero emission (Scenario 2)

water system cost, as well as the total freshwater saving and the reduction of wastewater discharge. This approach allows decision-makers to choose the relative weights for environmental and economic impacts by considering their own local conditions. They can choose the best scenario on the basis of their budget, their water conservation goals, and technological feasibility.

On the basis of these runs, two figures are presented in order to show the trade-offs between the total cost, total freshwater reduction and total wastewater reduction. Figure 7 shows the changing trend between the percentage of the reduction of total freshwater use and the percentage of total cost savings. This figure indicates that with water reuse, the total cost is first reduced by 10.3% (Scenario 1), while the total freshwater use is reduced by 16.9% and then the total cost will be linearly increased when total freshwater savings is increased. Figure 8 shows the changing trend between the percentage of reduction of total freshwater use and the percentage of reduction of total wastewater discharge. This figure indicates that the total wastewater discharge will be linearly reduced when more freshwater is saved, which means that a natural resource conservation benefit (freshwater saving) can be gained together with an environmental benefit (wastewater discharge reduction). Therefore, these figures can help an analyst to explicitly identify the trade-off between the total cost, total freshwater reduction and total wastewater reduction.

Table 6 Summary figures for zero emission scenario

	Total costs (RMB/day)	Freshwater (10^3 m^3/day)	Wastewater (10^3 m^3/day)
Without reuse	2.005×10^6	36.84	10.07
With reuse	2.256×10^6	24.29	0
Saving (%)	–12.52	34.1	100

In the case of TEDA, the surplus reclaimed wastewater from the wastewater treatment plant should be further used for some non-potable purposes, like fire control, groundwater recharge, construction purposes, or irrigation in neighboring communities, rather than being discharged into the local Bohai Sea. Compared with other alternatives, groundwater recharge will be a better option because TEDA is located in the world's largest land subsidence area (TEDA 2002). Recharging groundwater using surplus reclaimed wastewater can certainly alleviate land subsidence and seawater intrusion problems and help restore the local ecosystem. However the current model doesn't include the cost for groundwater recharge not does it include the costs for other possible uses.

Model applicability

The case of TEDA shows us that the application of this quantitative model has merit in allowing managers to assess real situations, providing an integrated approach for maximizing water resource efficiencies within an industrial park. The model has been designed to allow flexibility in its application. Different park planners or managers could therefore apply this model to their own conditions since water resources needs, conditions, and priorities differ from region to region and park to park. Some parks may only have one water source linked with the local water piping system, while other parks may have diversified sources. Also, industrial park managers do not need to identify the quality and quantity requirements of all the water users in order to apply the optimization model. Some parks may have hundreds of water users, which will make the calculation process more difficult. However, most users consume relatively little water and may not be in a position to utilize any reclaimed wastewater. According to Chi, often the top ten water users in an industrial park or zone consume over 75% of all the water resources (Chi 2002). Therefore, managers may only need to consider those large water users and avoid incorporating other small water users into the model. In this regard, they will need to calculate the exact influent amount to the wastewater treatment plant and the exact effluent amount from the water treatment plant and regard all small users as one user.

The model assumes that system parameters are constant during the planning period. Thus the problem can be simplified since many uncertainties may make it very complicated. For instance, if the input value of SS is always changing, then the model cannot be run at all. In this

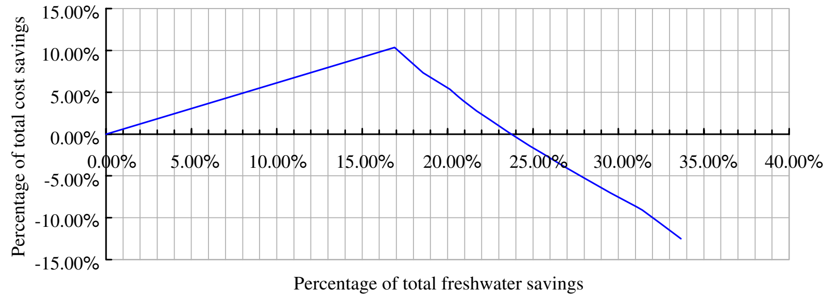

Fig. 7 Percentage of total freshwater savings related to the percentage of total cost savings

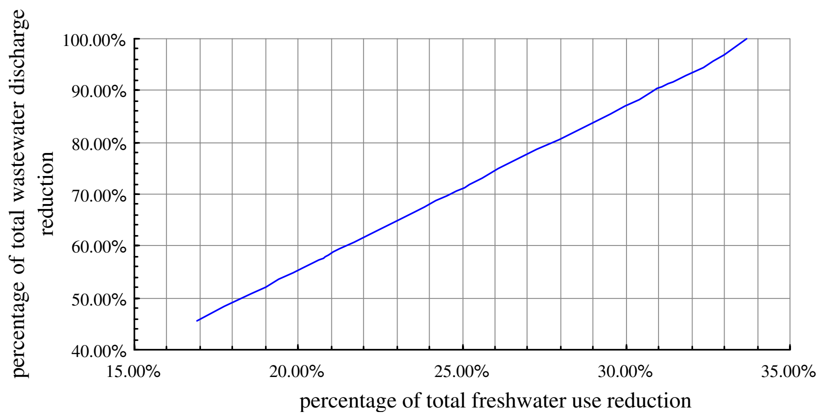

Fig. 8 Percentage of total freshwater use reduction vs. percentage of total wastewater discharge reduction

case, the model user has to input an average value of SS as a constant. Also, when applying this model within an industrial park, industrial park managers should not ask those participating companies that can reuse reclaimed wastewater to uninstall their current water connections with the freshwater treatment plant. These users still require some potable water for sanitation purposes. Therefore, a dual piping system is needed. This measure helps avoid potential water supply crises, especially when the water quality from some users changes and doesn't meet with the input demand of receiving users.

The model is designed to handle a large number of common water/wastewater parameters, such as BOD, COD, TSS, TOC, TDS and metals. This number can be increased if necessary. There may be upwards of 20 water characteristics that must be tracked and monitored to assure reliable operation (Byers 1995). Therefore, simplification will very likely be necessary if industrial park managers want to systematically implement an integrated water resource management scheme. Developing categories of water streams and water requirements can greatly simplify this task. To accomplish this may require some trial and error, but can be beneficial. In many cases, two or three common constituents, like COD, BOD and TSS, may be adequate (Byers 1995; Keckler and Allen 1999; Nobel and Allen 2000). The initial survey can gather information from the users that will suggest an appropriate simplification. However, if a single parameter makes the water unusable for many or most applications (such as Hg or Cu), then the managers would assume that wastewater from this user could not be reused by any other users. A typical example is that most electro-plating industries are small, but produce significant heavy metal pollution. Consequently, the effluent from such industries is usually not allowed to be reused by any users.

This model considers capital cost, including those related to energy costs, salaries, amortized depreciation expenses, materials expenses, overhead, and other miscellaneous expenses. Such a consideration can better reflect the real total costs related with water system. For example, once a pipe must be installed between two water users for water reuse, the construction cost for such a connection should be included in the total costs. In many instances, such a cost may be much higher than the operation and maintenance costs, therefore, it should be included in the objective function. In this regard, the TEDA case study demonstrates this very well. Figure 7 shows that the total costs will be increased when attempts are made to reduce the total water use. This is because new pipes must be constructed for water reuse among different water users. Consequently, the managers have to consider this factor in making their decisions.

This model doesn't consider water reuse or recycling inside the users' facilities. In order to further optimize water resource utilization, all the users should first initiate their own water reuse or recycling program for processes.

Technologies e.g., water pinch technology, and management methods e.g., cleaner production, can help to reduce total water consumption at the individual company level.

Basically, the model will have more flexibility by setting up the potential water users as variables rather than constants. If an additional company moves in, managers can simply incorporate information by adding the new information concerning water requirements, and then run the solver again in order to obtain a new water reuse scenario. Similarly, when a company leaves the park, the variables and constraints can be changed so as to identify a new water reuse scenario to reflect the changing circumstances.

Generally, the quantitative model presented in this paper can contribute to an understanding of the bigger picture. This can be achieved by incorporating broader environmental, social, and economic effects in the objective function to be optimized. However, this will be complicated because it is difficult to simultaneously optimize for multiple objective functions, at least some of which are not quantifiable. Therefore, the focus is on minimizing the cost of industrial park's water network since cost is generally the managers and users' most important concern. Even by doing so, some environmental, social, and economic effects can still be addressed. These include reduction of freshwater use and wastewater discharge, improved public image, reduced total costs, increased revenue, and competitive ability.

Conclusions

The increasing water shortage issue, especially in industrial parks in some regions and countries, requires practitioners to optimize the use of current water resources that are available. In the planning and implementation of wastewater reclamation and reuse, the reuse application will govern the wastewater treatment needed and degree of reliability required for the treatment processes and operations. Because wastewater reclamation entails the provision of a continuous supply of water with almost consistent water quality, it should be regarded as a common practice, especially in the industrial parks, where water consumption can be substantial.

This paper introduces a generalized model for integrated water resource planning and management within an industrial park. It considers the economies of scale in water treatment and distribution and by doing so, can assist managers of industrial parks to determine the minimum costs for water allocation. As such, the model can be a valuable decision tool for smart planning of water resources. Within the context of each park's parameters and management, this model allows for a great degree of flexibility and potential improvement in current use patterns.

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Appendix: Notation

The model notation can be expressed as follows: (the units for flows are in tons per day, and the units for pollutant concentration are mg/l)

XF_k amount of fresh water from surface and ground source k to water treatment plant,
XS_{li} amount of water from surface and ground water source l to user i without treatment,
XF_i amount of freshwater sent from water treatment plant to user i,
XT_i amount of reclaimed water from wastewater treatment plant to user i,
XTT_i amount of wastewater from user i to the wastewater treatment plant,
XTU_{ji} amount of wastewater from user j to user i without treatment,
$XTBU_{ji}$ amount of wastewater from user j to user i blending with freshwater,
XRR amount of reclaimed water from wastewater treatment plant to ground source for recharging groundwater,
XLS amount of reclaimed water from wastewater treatment plant for landscaping,
XOA amount of any other feasible applications of reclaimed wastewater,
$C(P_n)_i$ pollutant n concentration leaving user i,
The required inputs include:
N number of users within an industrial park,
D_i water required by user i,
L_i water losses by user i,
LT water losses at water treatment plant,
LTT water losses at wastewater treatment plant,
TC treatment capacity at water treatment plant,
TTC treatment capacity at wastewater treatment plant,
GC groundwater recharge request,
DLS landscaping request,
$LS(P_n)$ local pollutant n standard for freshwater,
$LT(P_n)$ local pollutant n standard for wastewater discharge,
$LRG(P_n)$ local pollutant n standard for groundwater recharge by reclaimed water,
$DLS(P_n)$ local pollutant n standard for landscaping by reclaimed water,
$CF(P_n)$ pollutant n concentration of freshwater from water treatment plant,

$CT(P_n)$ pollutant n concentration of reclaimed water from wastewater treatment plant,
$S(P_n)_i$ pollutant n standard required by user i,
P_n pollutant n, $n = 1,2,..., N$; (such as BOD, COD, TSS, and TOC, etc.),
N number of pollutants.

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