Ecological Indicators xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Stochastic optimization model for water allocation on a watershed scale considering wetland's ecological water requirement

Ye Xu[a,*], Yu Wang[b], Sha Li[a], Guohe Huang[c], Chao Dai[d]

[a] MOE Key Laboratory of Regional Energy and Environmental Systems Optimization, Resources and Environmental Research Academy, North China Electric Power University, Beijing 102206, China
[b] School of Geographical Science, Northeast Normal University, Changchun 130024, China
[c] Faculty of Engineering, University of Regina, Regina, Saskatchewan S4S 0A2, Canada
[d] School of Civil and Environmental Engineering, Nanyang Technological University, 639798, Singapore

ARTICLE INFO

Article history:
Received 15 October 2016
Received in revised form
15 December 2016
Accepted 13 February 2017
Available online xxx

Keywords:
Wetland restoration
Water allocation
Xiaoqing river watershed
Stochastic optimization

ABSTRACT

As the earth's kidney, the restoration and reconstruction of wetland ecosystem have aroused many concerns around the world. The way through supplying the water with sufficient quality and high quality to the wetland is an important restoration approach. However, the situation of water amount reduction and quality degradation leads to ecological water shortage and occupation. It is thus critical to meet the water demand of various users while ensuring ecological water requirement as much as possible. In this study, a stochastic-based water allocation optimization model on a watershed scale (i.e. LBNSCCP model) was proposed for supporting the water supply planning and wetland restoration activities of the Xiaoqing River watershed. The model objective was to minimize the total water supply cost; meanwhile, the water requirements of reed growth and other water users (i.e. industrial, agricultural and municipal sectors) were satisfied. Compared with the current operational scheme for water supply, the proposed method could lead to decreased water supply amount at a lower total cost. This is mainly because the design and implementation of existing water supply schemes are dependent on empirical experience and subjective judgment. The support of system analysis and optimization techniques could lead to more scientific and reasonable suggestions. Overall, the study demonstrated that the proposed water resources allocation model is an effective approach for achieving optimal water allocation and successful restoration of impaired wetland ecosystem.

1. Introduction

Wetland has the high primary productivity among all ecosystems and many ecological service functions, including environmental purification, adjustment in atmosphere and water cycle, wave dissipation and disaster reduction, respectively. Moreover, wetland owns abundant habitat type and high biodiversity, which is critical biological habitat and breeding site. However, a large part of wetlands are located in the transition zone of marine, river and terrestrial ecosystems, leading them to become the sensitive and fragile ecosystems. Recently, many wetlands were heavily influenced by dramatic human activities, such as agricultural reclamation and cultivation, industrial and municipal development, since they own superior location and rich resources (Lu, 2003). Therefore, it is imperative to restore impaired wetland system through effective engineering technologies and rational management approaches.

Referring to previous studies (Chatterjee et al., 2015; Peng et al., 2003; Zhang et al., 2011 Zhang and Wang, 2001), the actions through recovering the hydrological connection and improving the water quality are beneficial for accelerating wetland restoration process and restoring its ecological function. Currently, the provision in ecological water is the most urgent, since the precipitation amounts become decrease and ecological water requirement cannot be satisfied. As demonstrated in (Peng et al., 2003; Szemis et al., 2012), the ecological water requirement amount is defined as the water amount which maintains wetland ecosystem balance and ensures its basic functions. Currently, the common calculated approach of water required amounts in wetland ecosystem included two steps: (i) identify the ecological function division and determine the important species as protection target based on the

* Corresponding author.
E-mail addresses: xuye@ncepu.edu.cn, xuye0401@qq.com (Y. Xu), wangy577@nenu.edu.cn (Y. Wang), 2550934767@qq.com (S. Li), huangg@uregina.ca (G. Huang), daichao321@gmail.com (C. Dai).

http://dx.doi.org/10.1016/j.ecolind.2017.02.019
1470-160X/

Please cite this article in press as: Xu, Y., et al., Stochastic optimization model for water allocation on a watershed scale considering wetland's ecological water requirement. Ecol. Indicat. (2017), http://dx.doi.org/10.1016/j.ecolind.2017.02.019

investigation and analysis in local situation; (ii) calculate required water amounts of wetland system based on species' demand in water quantity and quality. Lian et al. (2008) selected the reed marsh and suaeda heteroptera as protected targets, since they provided suitable breeding habitats for some valuable birds (i.e. Red-crowned cranes and Saunders' Gull). The LEDESS model was used to determine the optimal range in supplied water amounts through predicting and evaluating ecological performance of the wetland under various water supply patterns. Powell et al. (2008) aims to restore floodplain wetlands of Australia Gwydir, where hydrological model was developed for determining the influence extent of flood duration, frequency and depth on the vegetation community. In fact, above research results only give the answer about what consequence is after the restoration activities? Under the context of water amounts shortage and quality degradation, we need to know how to design entire water supply network and allocate how much water amounts to impaired wetland ecosystem? The optimization model was capable of solving these problems.

Currently, many optimization models were extensively applied in regional water quantity and quality management (Cotter et al., 2014; Darradi et al., 2012; Fattahi and Fayyaz, 2010; Han et al., 2008; Huang and Loucks, 2000; Jenkins and Lund, 2000; Mewes, 2012; Qin and Xu, 2011; Slowinski, 1986; Wagner et al., 1994; Wilchfort and Lund, 1997; Yang, 2011; Zeng et al., 2016). For example, Qin and Xu (2011) proposed a regional water allocation optimization model, where designed water supply network includes two sources, four treatment plants, seven reservoirs and seven river reaches, respectively. The obtained water-provision schemes are useful in generating rational water management policies. Yang (2011) developed a multi-objective water allocation model for the Yellow River Delta in China, where Yellow River was considered as the water source and ecological water requirement of impaired wetland was satisfied. Above applied results demonstrated that, the optimization techniques for supporting regional water resources allocation were advanced. However, the lack of fresh water leads to the change in the structure and function of wetland. It is thus important to incorporate wetland user into traditional regional water supply system in order to avoid the occupation of wetland water and meet its water requirement. Referring to Wischmeier and Smith (1978), the rainfall records provided by 181 weather stations across the United States showed that the rainfall amounts follow the log-normal distribution rather than general normal distribution. The system variables associated with the rainfall volume should also follow the same distribution. For example, increased rainfall may result in an increase in runoff volume, reservoirs' inventory and the reduction in the vegetables' evaporation amounts, such that the ecological water requirement of the wetlands becomes less, and vice versa. Nevertheless, traditional stochastic chance-constrained programming (SCCP) model firstly proposed by Charnes and Cooper (1983) could only describe random variables as the normal distribution and was incapable of tackling other probabilistic distribution forms (Huang, 1996; Liu et al., 2008; Qin and Huang, 2009; Qin and Xu, 2011; Sethi et al., 2006). For example, Huang (1996) developed a stochastic water management model and applied it to solve a water quality management issue within an agricultural system. Qin and Huang (2009) developed an inexact stochastic chance-constrained quadratic programming model for supporting the stream water quality management. The obtained results are valuable for helping decision makers in seeking cost-effective water management strategies. It is thus desired that an effective SCCP model be advanced for tackling regional water allocation issue with the consideration of wetland's ecological water requirement.

Therefore, the major goal of this study is to establish a log-normal based stochastic chance-constrained programming model (LBNSCCP) for supporting water resource allocation issue of watershed, where the water supply network was composed of four types of users (i.e. industrial, agricultural, municipal and wetland), two types of water sources (i.e. surface water and groundwater) and two types of transfer facilities (i.e. treatment plants and reservoirs), respectively. The LBNSCCP model was applied to a water supply management system with the consideration of wetland' water demand of the Xiaoqing River watershed, China for demonstrating its feasibility and applicability. The paper will be organized as follows: (i) the introduction of water allocation system and the descriptions of formulation and solution procedures of the LBNSCCP model are included in the "Methodology" section; (ii) section "Case study" demonstrates general situation of studied region, especially the overview of impaired wetland; (iii) result analysis and potential improvement of the LBNSCCP model are provided in the "Result analysis" section; (iv) the "Conclusion" section provides a short summary.

2. Methodology

2.1. Formulation of regional water resources allocation model with consideration of wetland's water requirement

The establishment and operation of watershed's water supply management system, including the determination of system components, the design of system operation pattern and the generation of water allocation alternative, are directly related to the coordinated development of socio-economy and environment in entire watershed. In this study, the water allocation optimization model of the Xiaoqing River watershed is established, where the surface and underground water are determined as water sources; the treatment plants and reservoirs are designed as the transferred facilities due to seasonal variations in available water amounts and various users requirement in water quality. Moreover, the rapid socio-economical development leads to the increase in required water amounts of enterprises and residents, which may affect the ecological water usage and destroy local wetland ecosystem. Therefore, the wetland should be considered as potential user and is incorporated into entire water supply framework. The major task of local managers is to tackle water allocation issue of Xiaoqing River watershed through identifying system elements, estimating available water amounts and users' water demand, formulating water supply and allocation optimization model and generating water allocation pattern and restoration project of impaired wetland.

Objective function

$$Minimize\, f = \sum_{j=1}^{J}\sum_{t=1}^{T}\sum_{k=1}^{K} XJT_{jtk}(PR_{jk} + CJT_{jt}) + \sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{k=1}^{K} XTR_{trk}CTR_{tr} + \sum_{r=1}^{R}\sum_{z=1}^{Z}\sum_{k=1}^{K} XRZ_{rzk}CRZ_{rz} \tag{1a}$$

where f = the objective function representing total system cost ($); k (k = 1, 2, ..., K) = the index of time periods (i.e., months), where K is total number of time periods; j (j = 1, 2, ..., J) = the index of water sources, where J is total number of water sources; t (t = 1, 2, ..., T;) = the index of treatment plants, where T is total number of treatment plants; r (r = 1, 2, ..., R) is the index of reservoirs, where R is total number of reservoirs; z (z = 1, 2, ..., Z) is the index of river reaches, where Z are total number of river reaches and each reach contains one or two major water users; XJT_{jtk} = the decision variables representing water amounts transferred from water source to treatment plant, ($\times 10^3$ m^3); XTR_{trk} = the decision variables representing water amounts transferred from treatment to reservoir, ($\times 10^3$ m^3); XRZ_{rzk} = the decision variables representing