Science of the Total Environment 624 (2018) 283–293

Contents lists available at ScienceDirect

Science of the Total Environment

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

A cost-effective and efficient framework to determine water quality monitoring network locations

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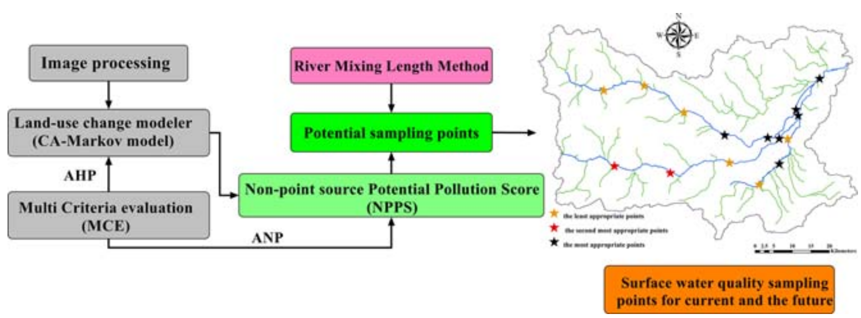
HIGHLIGHTS

- Integrated framework for cost-effective siting of water quality sampling points.
- Identified sampling locations based on current and future condition.
- Simulated spatial distribution of non-point sources from 1995 to 2036.
- Identified potential pollution to prioritize sampling points.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 October 2017
Received in revised form 10 December 2017
Accepted 11 December 2017
Available online xxxx

Editor: G. Ashantha Goonetilleke

Keywords:
Water quality monitoring network
River mixing length
ANP
Land-use change modeling
Cost-effective siting sampling locations

ABSTRACT

A crucial part in designing a robust water quality monitoring network is the selection of appropriate water quality sampling locations. Due to cost and time constraints, it is essential to identify and select these locations in an accurate and efficient manner. The main contribution of the present article is the development of a practical methodology for allocating critical sampling points in present and future conditions of the non-point sources under a case study of the Khoy watershed in northwest Iran, where financial resources and water quality data are limited. To achieve this purpose, the river mixing length method (RML) was applied to propose potential sampling points. A new non-point source potential pollution score (NPPS) was then proposed by the analytic network process (ANP) to classify the importance of each sampling point prior to selecting the most appropriate locations for a river system. In addition, an integrated cellular automata–Markov chain model (CA–Markov) was applied to simulate future change in non-point sources during the period 2026–2036. Finally, by considering anthropogenic activities through land-use mapping, the hierarchy value, the non-point source potential pollution score values and budget deficiency in the study area, the seven sampling points were identified for the present and the future. It is not expected, however, that the present location of the proposed sampling points will change in the future due to the forthcoming changes in non-point sources. The current study provides important insights into the design of a reliable water quality monitoring network with a high level of assurance under certain changes in non-point sources. Furthermore, the results of this study should be valuable for water quality monitoring agencies looking for a cost-effective approach for selecting sampling locations.

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https://doi.org/10.1016/j.scitotenv.2017.12.121
0048-9697/

1. Introduction

A water quality monitoring network (WQMN) is used to interpret current situations and trends in a surface water system and to support decision-makers in realizing and managing stakeholders' health risks (Baltacı et al., 2008; Telci et al., 2009; Xiaomin et al., 2016). One of the most important keys to monitoring water quality is to design suitable locations for sampling points (Sanders, 1983). The frequency of sampling and the mode of data presentation and interpretation become unimportant if gathered samples are not representative of the water body (Do et al., 2012). By selecting the best locations for sampling points, time and cost, which have major effects on the process of the WQM program, can be managed more effectively (Kovacs et al., 2016; Behmel et al., 2016).

Behmel et al. (2016) reviewed and summarized prolific literature on the WQMN program. Moreover, they remarked that there is not an eminently suitable and accepted approach to designing a WQMN program. It is widely acknowledged that most recent relevant studies have chiefly concentrated on mathematical aspects for the selection of water quality sampling locations (Do et al., 2012). To select representative sampling points, entropy and fuzzy approaches (Mahjouri and Kerachian, 2011; Memarzadeh et al., 2013; Chang and Lin, 2014a, 2014b) have been employed. In addition, the genetic algorithm method has been applied to select representative sampling points (Telci et al., 2009; Liyanage et al., 2016). Furthermore, a combination of numerical models, experiments, and matter-element analysis has been applied to assess WQMNs (Chen et al., 2012; Keum and Kaluarachchi, 2015). Some researchers have applied geostatistical methods (Beveridge et al., 2012), multivariate statistical techniques (Ouyang, 2005; Noori et al., 2010; Wang et al., 2014), and multi-objective analysis (Ning and Chang, 2002; Khalil et al., 2011; Aboutalebi et al., 2016) to optimize and propose sampling points. Furthermore, the combination of a fuzzy logic method and the geographical information system (GIS) (Strobl et al., 2006a) was applied to establish exact location of sampling points. However, in most of the above-mentioned studies, neither human activities nor natural processes were comprehensively considered (Do et al., 2012).

In contrast to the methods described above, some researchers have introduced alternative methods for locating sampling points and properly designing WQMN (Sharp, 1971; Sanders, 1983; Park et al., 2006; Do et al., 2011; Varekar et al., 2015, 2016). However, there are some limitations in employing these approaches for rivers without tributaries as well as short or long rivers. Moreover, there should be reliable and regular long-term data collection on the water quality parameters, which is not particularly applicable to developing countries (e.g., Iran) where there are limited financial resources and incomplete hydrological data sets (Choubin et al., 2018). In turn, Do et al. (2012) pioneered in using the Sanders (1983) modification of Sharp's approach and the river mixing length introduced by Day (1977) to solve the aforementioned issues in proposing sampling sites. The advantages of this method can be summarized in the following points: (i) it is mainly suitable for rivers with inaccurate or unreliable on hydraulic and flow characteristics data; (ii) it is appropriate for rivers of different lengths and without branches; (iii) it uses available watershed data to select sampling points; and (iv) it takes scale and frequency into account when there is a budget deficiency. However, in the aforementioned study, few non-point sources and water quality variables were used; furthermore, inter-relationship between criteria and sub-criteria has never been considered. In order to enhance, improve, and compensate for the shortcomings of previous studies, the analytic network process (ANP) procedure (Saaty and Takizawa, 1986) is needed. Other limitation of their study was to consider linear ground surface for buffer zone among candidate points (Varekar et al., 2015). It is also worth mentioning that none of the literature on representing sampling points is able to predict the effect of future land-use change (non-point sources) on the location of WQMNs.

It is necessary to carefully consider land-use activities, especially, future land-use changes in order to discern and manage non-point pollution sources, particularly in modeling water quality (Sivertun and Prange, 2003; Wilson and Weng, 2011). The novelty and advantages of predicting land-use change are as follows: (i) people will adapt to future changes in environment and will have sustainable management (PETIT et al., 2001; Rounsevell et al., 2006); (ii) it is needed in making comprehensive strategies at a given watershed in order to deal with short and long term environmental problems (Wilson and Weng, 2011); (iii) the potential impacts of land-use change on water resources will be recognized. A couple of computer models have been used to simulate future land-use change (Theobald and Hobbs, 1998). However, among these scientific endeavors to forecast spatio-temporal land-use change in the future, Cellular automata-Markov chain (CA–Markov) model has played a main role (Mitsova et al., 2011; Behera et al., 2012; Subedi et al., 2013; Rimal et al., 2017). Although there are many studies in assessing and predicting future land-use change, many studies have concentrated on urban land-use change (López et al., 2001; Sun et al., 2007; Yang et al., 2008; Sang et al., 2011; Mosammam et al., 2017; Aburas et al., 2017). Also, there is no literature directly identifying the impact of future land-use change on locating and relocating sampling points for WQMN in the future.

The objective of the current study is to propose and select sampling points for WQM under present and future conditions of non-point sources using an Iranian watershed as a case study. Firstly, the modified approach (Do et al., 2012) was employed to select potential sampling points based on existing data and budget limitations of the regional water authority. Secondly, land-use maps (1995, 2006, and 2016) were used to simulate the spatial distribution of land-use categories from 2016 to 2036 using the CA–Markov model. Thirdly, using the ANP method, relative pollution weight for each land-use category was calculated according to the review literature and professional questionnaire. Finally, non-point source potential pollution scores (NPPS) were identified for each candidate sampling point in order to prioritize and select sampling points for the years 2016, 2026, and 2036.

2. Material and methods

2.1. Study area

The Khoy watershed is located in West Azerbaijan province, northwest of Iran (Fig. 1). It has a drainage area of about 3166 km^2 and; its elevation varies significantly from about 938 m to 3670 m above sea level, with an average slope of 23.16%. Köppen-Geiger climate classification system classifies its climate as cold semi-arid with the mean annual precipitation of 281.92 mm, which decreases from approximately 400 mm in the west with high elevation to about 190 mm in the north east. The study area is a mountainous area comprising three main rivers: (1) Qutor Chai (110.13 km long); (2) Gazan Chai (around 40 km long); and (3) Qudox Bogan (98 km long). During the last decade, mismanagement, heavy use of the land (e.g., overgrazing), industrialization, urbanization around these rivers, and currently irregular data collection and inappropriate location of existing hydrometric stations (Fig. 1) have created an urgent need for a robust WQMN in the study area based on current and future conditions.

2.2. Designation of representative sampling points

To determine representative sampling point locations, the RML method introduced by Do et al. (2012) was applied. In this approach, rivers and branches are divided into small segments, which are equal to the mixing lengths of rivers. River mixing length describes a distance over which an upstream water parcel will hold its original properties before it is mixed with the surrounding downstream water (Day, 1977). They proposed that the middle of each segment can be considered as sampling points. We first determined the mixing lengths for