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Comprehensive assessment and visualized monitoring of urban drinking water quality

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ABSTRACT

It is important to comprehensively assess and monitor drinking water quality to ensure a safe and clean drinking water supply. A real-time comprehensive assessment based on modeling and visualized monitoring of urban drinking water quality is discussed in this paper. A weighted aggregative index, a method for evaluating problems with multiple indexes, is used to evaluate the drinking water quality in Shanghai city. Considering the disadvantages of the subjective and objective weighted methods, a combined weighted index method called the geometric mean weighted method is proposed to assign weights to the indexes of drinking water in order to make the weight distribution more scientific, reasonable and robust. Then, the drinking water quality is displayed visually by a distribution map of drinking water quality based on a geographic information system (GIS). This real application shows that the proposed methods are effective and promising for the assessment and monitoring of water quality.

1. Introduction

Seventy percent of the Earth's surface is covered by water. Of all the water on Earth, 97.5% is salt water, leaving only 2.5% as fresh water. Only approximately 1% of the world's fresh water is accessible for direct human use. However, water pollution is one of the top environmental issues and has introduced serious problems in the world, as a growing number of water sources have been contaminated by biological, organic and inorganic pollutants. Especially in developing countries, such as Nepal, India, Bangladesh and China, the pollution of rivers is severe and critical near urban stretches due to huge amounts of pollution caused by urban activities [1]. The water quality deterioration in the eastern part of the Malaysian peninsular, especially in Gebeng, is also serious due to the impact of anthropogenic activities, such as rapid urbanization and industrialization [2]. In a recent national report on water quality in the United States, 45% of assessed stream miles, 47% of assessed lake acres and 32% of assessed bays and estuarine square miles were classified as polluted [3]. With the rapid economic growth in China, urban drinking water quality is now facing serious challenges. Approximately 90% of the water in the cities of China is polluted to varying degrees [4]. According to the 2009 statistics from the Ministry of Environmental Protection (MEP) of China, there were 80 water pollution accidents that year. In China's key cities, 27% of the centralized drinking water sources did not meet official standards, and half a billion Chinese had no access to safe drinking water [5]. Water pollution is the leading cause of deaths and diseases worldwide. Across the globe, 6000 children die of diseases and 30 million people die of cancers caused by drinking polluted water each year. In developing countries, 80% of human diseases is associated with polluted drinking water. An estimated 580 people in India die of water pollution related illnesses every day [6]. Therefore, the quality of drinking water is a powerful environmental determinant of health. The assurance of drinking water safety is a foundation for the prevention and control of waterborne diseases. Safe and clean drinking water is a vital resource for everyone.

The WHO (World Health Organization) has produced international norms on water quality in the form of guidelines, which are used as the basic regulations and standards in developing and developed countries. Drinking water quality standards give the required limitation for different characteristics of drinking water. The WHO guidelines for drinking water quality have 144 indexes according to the hygienic standards for drinking water, 102 indexes in USA and 106 indexes in China. Those indexes are set at levels necessary to assess and protect the public from health risks associated with consuming contaminants in drinking water supplies. Some indexes are considered of primary importance to the quality of drinking water, while others are of secondary importance. Researchers have made a series of studies on the choice of indexes and the methods of water assessment [7]. Single index analysis is a typical approach for assessing and monitoring drinking water quality [8]. However, any single water quality index describes the water quality form single perspective and cannot reflect the overall drinking water

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quality conditions. Multiple indexes methods provide a way to comprehensively evaluate drinking water quality by combining chemical, physical and biological monitoring methods to achieve the best picture of the water quality conditions.

The weighted aggregative index is a statistic for a collection of items weighted to reflect the relative importance of the items with regard to the overall phenomenon. Then, water quality is expressed and assessed by a single comprehensive index based on multiple indexes. The key to the weighted aggregative index method is to distribute reasonable weight to each index. Generally, the weight distribution method can be categorized into the subjectivity and objectivity methods. The most common subjective weighting methods include the AHP (analytic hierarchy process) [9–11] and expert evaluation method [12]. The objective weighting methods include the entropy weight method [13], variation coefficient method [14,15] and PCA (principal component analysis) [16]. Subjective weighting methods are often affected largely by human factors, while objective weighting methods completely rely on sample data, which are often contaminated by noise. To make the weight distribution of each index more scientific and reasonable, a robust approach is to combine the weight information from the different weighting methods according to some combinational principles. The purpose of the combinational weighted index methods is to combine the weights obtained from the subjective and objective weighting methods to determine a new and reasonable weight distribution. The linear weighted method is a straightforward combinational weighted method that obtains the combination weights through a weighted average of the subjective and objective weights. This process of distributing weights does have arbitrariness [17]. The Spearman coefficient of rank correlation is a relatively complicated method to obtain the combination weights [18]. The multiplication normalization method is another approach that determines the combination weights through multiplication of the subjective and objective weights. However, the method usually yields an unreasonable weight distribution due to the phenomenon of a multiplier effect from multiplication. A new method, called the geometric mean weighted method (GMWM), is discussed in this paper to obtain a more reasonable weight distribution.

The current situation and drinking water quality problems are analyzed briefly below:

1. Traditional water quality monitoring is defined as the sampling and analysis of water constituents and conditions. The drinking water quality is evaluated by a score of a single factor index; the scores from the different single factor indexes could conflict with each other when one index score rises and another one declines.
2. Drinking water quality is characterized by geography, which depends on the location, and the conditions of the water source from which it is treated and transferred. The geographic data and information, which are strongly correlated with drinking water quality, should be included in the assessment and monitoring of drinking water quality.
3. With the development of infrastructure, drinking water data are abundant, but the value of the information is poor. The comprehensive assessment and monitoring based on a water quality model will play an important role in ensuring safe and clean drinking water in the future.
4. The openness and transparency of water quality information to the public is beneficial to the improvement of water quality. The United States has one of the safest water supplies in the world. However, the national statistics do not specifically inform citizens on the quality and safety of the water coming out of the tap.
5. Information technology, such as visualization technology and the internet, will make the assessment and monitoring of water quality more intuitive and convenient. The comprehensive assessment and monitoring of drinking water quality provides a powerful tool for government and health supervision agencies that need to make informed decisions.

In this paper, we discuss the visualized and real-time comprehensive assessment and monitoring of urban drinking water quality based on modeling, GIS, information technology and field studies. A combinational weighted index method, called the geometric mean weighted method (GMWM), is proposed to assign weights to the indexes of drinking water in order to make the comprehensive assessment more scientific, reasonable and robust. Distribution maps of drinking water quality based on GIS technology enable the monitoring agencies, government and public to have an overall intuitive assessment and to make better informed decisions. The proposed methods are applied to the comprehensive assessment and visualized monitoring methods of drinking water quality in Shanghai city in China.

2. Research objective

Located on the southeast coastal areas of China, Shanghai is the largest Chinese city by population. It borders Jiangsu Province and Zhejiang Province and is surrounded by the Yangtze River, East China Sea and Hangzhou Bay. Shanghai is often regarded as one of the fastest growing cities over the past 20 years. The rapid industrialization and urbanization introduce significant pressure to the drinking water system. Many of the pipes that supply the water to citizens are quite old. Although located near the East China Sea, Shanghai is plagued with a chronic lack of clean drinking water. Meanwhile, the city has experienced a salt tide over more than 20 years, affecting the drinking water of approximately 2 million residents. Therefore, monitoring and assessing the drinking water quality is important and necessary in order for government and health supervision agencies to make informed decisions and ensure clean and safe drinking water for the public.

The water supply system of Shanghai is composed of the raw water collection, water abstraction and raw water transfer, water purification and treatment, water distribution network and secondary water supply system to customers. The water distribution network is composed of large networks of storage tanks, valves, pumps and pipes that transport drinking water to consumers. The water distribution network plays a key role in supplying customers with safe and clean drinking water. This paper aims to build the comprehensive assessment model for the drinking water quality of Shanghai. Then, the drinking water quality is shown and monitored visually by a GIS based distribution map.

Fig. 1 is a simplified map of Shanghai, which mainly shows the monitoring sites of drinking water. The top right corner shows the Chongming islands on a smaller scale. One blue circle on the map represents the geographical location of a monitoring site. The comprehensive assessment and monitoring of the drinking water quality is conducted based on the indexes of 215 monitoring sites.

3. Assessment model of drinking water quality

An assessment model of drinking water quality is based on combinational weighted aggregative index methods, which include two processes – the weight distribution of drinking water indexes and comprehensive scores of drinking water quality. The distribution of proper weights is a crucial procedure that greatly affects the comprehensive evaluation results. A small change of weight may cause a significant variation of the evaluation results. Subjective and objective weighting methods are employed to obtain a new and robust weight distribution. The AHP method is employed to determine the weights as a subjective weighting method, and the entropy weighting method and variation coefficient method to determine the weights are employed as the objective weighting methods. Then, a geometric mean method is proposed to compute the comprehensive weights of the drinking water indexes.

3.1. Subjective weighting method

A subjective weighting method is based on the experience of experts in the related field. The analytic hierarchy process (AHP) is a