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Evaluation of potential health risk of arsenic-affected groundwater using indicator kriging and dose response model

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Abstract

This study analyzed the potential health risk associated with the ingestion of arsenic-affected groundwater in the arseniasis-endemic Lanyang plain of northeastern Taiwan. Indicator kriging was used to estimate arsenic concentrations in groundwater. Target cancer risk (TR) and dose response functions were adopted to evaluate the potential health risk based on the estimated arsenic concentration distributions. The estimated arsenic concentrations in groundwater reveal that arsenic concentrations (>50 μg/L) in well water are high in six townships — JiaoSi, YiLan, JhungWei, WuJie, DonShan and LouDon. Highest arsenic concentrations (70.32 μg/L) are in the YiLan and the JhungWei townships. The estimated TR values at the arsenic-affected townships are ten times more than an acceptable standard (10^{-6}). The largest TR values are 145.5 and 91.2 times higher than an acceptable standard for males and females, respectively. The estimated annual mortalities by arsenic-induced internal cancers occur in the YiLan township (ten cases), LouDon (five cases), WuJie (three cases), JhungWei (two cases) and DonShan (one case). The highest number of mortalities per year in the study area is 24. Residents of the six townships with high arsenic-affected groundwater should use tap water as drinking water and use groundwater only for other purpose. The well water in other townships in the Lanyang plain has no adverse effects on human health.

Keywords: Arsenic; Indicator kriging (IK); Dose response; Target cancer risk (TR)

1. Introduction

Arsenic is widely distributed in the Earth's crust and concentrated in pyrite, hydrous Fe oxides and sulfide compounds. Arsenic may dissolve in water from these minerals, depending on pH, redox conditions and temperature (Smedley and Kinniburgh, 2002) and thus be transported in the environment in the water. The main source of arsenic exposure for the general population is the ingestion of drinking water with high levels of arsenic (WHO, 1981; ATSDR, 1993). In a rural area on the southwestern coast of Taiwan, blackfoot disease (BFD) is known as an endemic peripheral vascular disease. Arsenic has been identified as a major risk factor for BFD (Shen and Chin, 1964; Tseng, 1977). Ingestion of arsenic compounds in well water has also been associated with age-adjusted mortality from diabetes (Lai et al., 1994), hypertension and cerebrovascular disease (Brown and Chen, 1995), and cancers of the lung, liver, bladder and kidney, prostate and nasal cavity (Wu et al., 1989; Chen and Wang, 1990).

Chiou et al. (1997) investigated that the arsenic contents of groundwater in the Lanyang plain that

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exceeded the current Taiwan EPA limit of 10 μg/L for drinking water, and those of some wells are up to 600 μg/L or higher. Chen et al. (1995) indicated that arsenite and arsenate represented 87% and 5.8%, respectively, of the total arsenic content in the well water in the Lanyang plain. Since groundwater is abundant, the residents of the Lanyang plain have used shallow wells (depths <40 m) to obtain drinking water since 1940s (Chiou et al., 2000). A tap water system has been established in the early 1990s, and over 90% of households have tap water served. However, groundwater is still commonly used as a source of drinking water (Chiou et al., 2000). The residents have used high-arsenic artesian well water over 50 years (Chiou et al., 1997). Significant dose-dependent relationships were established between the arsenic concentration in well water and an increased risks of cerebrovascular disease, urinary cancer and other cancers (Chiou et al., 1997, 2000, 2001), moreover, adverse pregnancy outcomes (Yang et al., 2003) was found and warrants further attention.

The estimation of spatial distribution of contaminant groundwater quality is very important in the health risk assessment. The accuracy of the direct analysis of in-situ data is often dubious because the field investigation is limited by time and cost and the observations contain considerable uncertainty. Geostatistics, therefore, is widely used for the spatial estimation with the consideration of spatial variability. Specifically, indicator kriging (IK) (Goovaerts, 1997) and Bayesian Maximum Entropy method (BME) (Christakos, 2000) are both more advanced due to their ability to take the data uncertainty into account. IK has been widely applied on the analysis of the soil contamination (Smith et al., 1993; Oyedele et al., 1996; Juang and Lee, 1998; Castrignanò et al., 2000; van Meirvenne and Goovaerts, 2001; Lin et al., 2002), and the estimation of its relation to spatial distribution of health risk (Istok and Pautman, 1996; Saisana et al., 2004; Liu et al., 2004; Juang et al., 2004; Jang et al., 2006). BME has also been applied on spatial health risk assessment on many topics, such as the arsenic study (Serre et al., 2003; Lee et al., 2005), and influenza mapping in California (Choi et al., 2003). Among them, IK is a frequently adopted as a non-parametric geostatistical method. IK makes no assumption regarding the distributions of variables, and a 0–1 indicator transformation of data is adopted to ensure that the predictor is robust to outliers (Cressie, 1985). In an unsampled location, the values estimated by IK represent the probability that does not exceed a particular threshold. Therefore, the expected value derived from indicator data is equivalent to the cumulative distribution function of the variable (Smith et al., 1993). The incorporation of epidemiological framework with IK has been discussed in the studies of the estimation of lung cancer risk (Vieira et al., 2002), and the impact on human health and potential remedies for arsenic-containing drinking groundwater in Bangladesh (Yu et al., 2003).

To evaluate the risk of long-period exposure to arsenic, this study adopted indicator kriging to estimate arsenic exposure distributions in well water in the Lanyang plain of northeastern Taiwan. The target cancer risk and cancer dose response function of ingested arsenic in well water were mapped to evaluate the potential risk to human health and population mortality, respectively. The results of the probabilistic risk assessment provide suitable utility modes of groundwater in the arseniasis-endemic Lanyang plain.

2. Study area

The Lanyang plain, located in YiLan County in northeastern Taiwan, is the alluvial fan of the Lanyang river. The area is triangular, with the Pacific Ocean next to the east, the Snow mountains to the northwest and the Central mountains to the southwest. The main river, the Lanyang river, flows through the middle of the area from west to east (Fig. 1). The area is approximately 400 km^2, with sides of about 30 km each. The study area consists of ten townships, which contain 97% of the populations (about 451,000) of the YiLan County. The groundwater flows from west to east. The western parts of the plain near by the Snow and Central mountains form the main recharging area of groundwater, and rain water is the main source of groundwater.

Although a high percentage of households have been served by tap water, groundwater is still used as a popular source of drinking water of residents in the study area. The arsenic levels in the well water in different regions are markedly varied. The main source of exposure to inorganic arsenic among residents is the ingestion of groundwater from wells (Chiou et al., 2001). Arsenic in groundwater mainly results by geogenic release from sedimentary formation of the marine deposit formed in Quaternary period (Chen et al., 1995; Chiou et al., 2001; Shen, 2006).

3. Materials and methods

3.1. Well water samples

This study used data surveyed by the Environmental Protection Bureau (EPB) of the YiLan County Government