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Spatial analysis of the risk to human health from exposure to arsenic contaminated groundwater: A kriging approach

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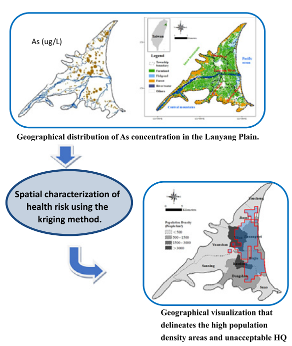
HIGHLIGHTS

- Spatial analysis of health risk for arsenic exposure from drinking groundwater
- Application of two kriging approaches: OK and IK
- HQ map using OK approach shows an excellent agreement with HQ sampled results.

GRAPHICAL ABSTRACT



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ABSTRACT

A long-term groundwater quality survey in northeastern Taiwan's Lanyang Plain has revealed obvious contamination of the groundwater in some areas, with measured As concentrations in excess of the acceptable level of 10 μg/L. Efforts for assessing the health risk associated with the intake of As through the drinking of contaminated groundwater are a necessary part of the important work of health risk management. However, the standard approach to assessing risks to human health does not adequately account for spatial heterogeneity in the measured As concentrations. Thus, this study applies two different kriging approaches to carry out a spatial analysis of the health risk associated with ingesting As through the drinking of groundwater in the Lanyang Plain. It is found that the indicator kriging (IK) approach, with occurrence probability threshold values of 0.4, 0.5 and 0.6 yields correct classification percentages of 75%, 68% and 61%, respectively, of unacceptable HQ zones. An HQ map prepared with the ordinary kriging (OK) approach shows a correct classification of unacceptable HQ zones of 80%. Considering that the OK approach does not require subjective selection of an occurrence probability threshold value as is the case with the IK approach and can yield a higher percentage of correct classification for unacceptable HQ zones, it is recommended as a more direct and reliable method for spatial analysis of human health risk due to arsenic exposure through the drinking of groundwater. The results show that the geographical distribution of unacceptable HQ zones is concentrated in the eastern part of the study area, which includes the high-population density townships. In other words, 34% of the people had access to groundwater where the HQ was >1. The results of this type of spatial health risk assessment can provide a basis for improving the decision-making process for health risk management.

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1. Introduction

Arsenic (As) is widely recognized as among the most toxic chemical elements and is also generally considered to be the primary naturally occurring carcinogen found in the environment whether in the groundwater, soil, sediment or surface water (Nriagu, 2002; Bundschuh et al., 2013; Smedley and Kinnniburgh, 2002; Gallego et al., 2015; Rieuwerts et al., 2014; Venkatramanan et al., 2016; González-Fernández et al., 2018). Groundwater is one of the most important sources of water resources in Taiwan's northeastern Lanyang Plain and is widely used for drinking, irrigation, and aquaculture because of its abundant supply. However, long-term groundwater quality monitoring data clearly show that the As content in the groundwater in many locations exceeds the acceptable level of 10 μg/L recommended by the World Health Organization (WHO) (EPB, 1997, 1998, 1999). Elevated As levels in the groundwater have been identified as a serious and widespread problem all over the world with a large number of studies confirming that exposure to As can cause various types of acute and chronic health hazards (Engel and Smith, 1994; Halder et al., 2013). Thus, the elevated As concentrations in the groundwater in some areas of the Lanyang Plain can be expected to have an adverse impact on the health of the resident, making this an issue of critical environmental and public health concern. The massive quantities of groundwater still being used by the residents of the Lanyang Plain to satisfy household demands, makes assessment of the risk to human health due to As intake from the drinking of the groundwater an important step in protecting their health.

Measurement data from monitoring wells clearly indicate considerable spatial variability in As concentrations in the Langyang Plain meaning that the associated risk to human health will also vary from region to region corresponding to variations in the arsenic concentration levels in the groundwater. Although it is important to understand these variations, however, in the standard approach to conducting health risk assessment, spatial variability of the groundwater quality has been neglected. Clearly, there is an urgent need to improve health risk assessment due to As exposure by taking into account the oftentimes substantial variability in contamination from region to region.

Efforts to effectively measure the spatial concentration of contamination in soil and water quality in the field are both expensive and time-consuming. Geostatistical kriging techniques, including the assessment of variograms, are increasingly being used for spatial characterization of soil and water quality parameters as well as assessment of the associated health risks (Goovaerts, 1997). There are many examples of kriging methods being used for the spatial evaluation of soil quality and groundwater in the literature (see Diodato and Ceccarelli, 2004; Antunes and Albuquerque, 2013; Boente et al., 2017; Dalla Libera et al., 2017). Lee et al. (2007) used an indicator kriging (IK) method for spatial evaluation of the potential carcinogenic health risks of drinking groundwater containing As for the residents of the Lanyang Plain. Jang et al. (2008) adopted a multivariate IK (MVIK) method for spatial determination of the safe zones for groundwater used for irrigation in the Choushui River alluvial plain based on the water quality criteria for irrigation in Taiwan. Lee et al. (2008) applied MVIK for spatial characterization of the groundwater quality and proposed a zonal management strategy for multi-purpose groundwater utilization in the Lanyang Plain in northern Taiwan. Recently, an MVIK approach has been used for determining zones safe for the utilization of groundwater for purposes of irrigation, aquaculture, and drinking (Lee et al., 2008; Jang et al., 2012a, 2012b, 2013, 2016).

Emery and Ortiz (2004) examined the drawbacks and limitations of the IK approach when applied to continuous variables, within the scope of the lognormal random function mode. They suggested the IK method may lead to strong biases in the evaluation of the resources and reserves in ore deposits. In contrast, Liang et al. (2016) adopted the ordinary kriging (OK) method to estimate the spatial distribution of the water quality parameters and proposed a zonal management strategy for multi-purpose groundwater utilization in the Pingtung Plain, southern Taiwan. Liang et al. (2017) also applied the OK method for spatial assessment of the health risk arising from exposure due to As ingested through the drinking of groundwater in the Pingtung Plain. Marinoni (2003) pointed out that the OK results frequently show much less model variability of the variables than is the case in reality because the OK method sometimes overestimates low values or underestimates high values. This phenomenon is called the “smoothing” effect. The ‘smoothing’ effect is not as strong when the variable shows low variability, but the greater the variability of the variable, the stronger the ‘smoothing’ effect will be.

The HQ is one of the most straightforward approaches used for the screening of health risk by comparison of the total daily dose to a threshold reference standard. The IK approach is an alternative to the OK approach for performing spatial interpolation for variables with threshold values. However, both the IK and OK have their own limitations and advantages. To determine which is more appropriate for this type of study, we compare the results of spatial analysis for threshold-based health risk assessment obtained using both approaches. Spatial analysis of the non-carcinogenic health risk associated with As exposure through the drinking of groundwater in the Langyang Plain is first carried out using both the IK and OK approaches. Comparison is then made between the hazard quotient maps obtained using these two kriging methods as well as the computed HQ results obtained from monitoring well data to validate the spatial interpolations. The results are expected to indicate specific regions where the health risk is higher which would help the authorities to develop more effective health management plans.

2. Materials and methods

This approach to conducting health risk assessment is based on the non-carcinogenic HQ model recommended by the US Environmental Protection Agency (USEPA). Both IK and OK approaches are used for spatial analysis of the health risk associated with arsenic intake from the drinking of groundwater in the Lanyang Plain.

2.1. Noncarcinogenic health risk assessment

Health risk assessment is aimed at characterizing the adverse effects on human health of exposure to environmental hazards. The health risk from non-carcinogenic exposure caused by the intake of As is considered in this study. For this purpose, we adopt the standard recommended by the USEPA for evaluation of the HQ, where HQ is defined as the ratio of the daily dose (*DI*) of the suspected hazardous substance, in this case, arsenic, to the oral reference dose (*RfD*) below which no adverse effects are expected and is calculated by

$$HQ = \frac{DI}{RfD} \tag{1}$$

where *DI* is the daily dose of As (mg/kg bw/day); *RfD* is the oral reference dose, as defined by the US EPA (USEPA, 2012). The value of *RfD* for As is 3.2 μg/day (USEPA, 2012).

When the calculated *HQ* value is <1, no adverse non-carcinogenic effects are expected; otherwise an adverse non-carcinogenic risk is regarded as possible.

The daily dose of As, *DI* in Eq. (1) is calculated by multiplying the As concentration in the groundwater by the rate of daily water intake, normalized to 1 kg of body weight (divided by body weight) as follows (IRIS, 1998):

$$DI = \frac{C_W \cdot IR}{BW} \tag{2}$$

where C_W is the As concentration in the groundwater (mg/L); *IR* is the daily water intake rate (L/day); and *BW* is the body weight (kg). The daily water intake rate and body weight data required for calculation