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Zonal management of multi-purpose use of water from arsenic-affected aquifers by using a multi-variable indicator kriging approach

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Summary This work presented a probability map of groundwater resources for multi-purpose uses (irrigation, aquaculture and drinking water) of arsenic (As)-affected aquifers in the Lanyang Plain, northeastern Taiwan. The assessment was based on As and other several compounds and factors that adversely affect water-quality. Multiple-variable indicator kriging (MVIK) was adopted to evaluate numerous hydrochemical parameters for the three water-quality standards in Taiwan. Hydrochemical parameters of groundwater were classified into four main hazard categories — saline hazard, nitrogen hazard, As hazard and Fe—Mn hazard. Safe and potentially hazardous groundwater regions for multi-purpose use were delineated according to estimated probabilities by using MVIK. Analytical results for MVIK critical probability of >0.5 demonstrate that the proximal-fan, partial central distal-fan and mid-fan, and northern distal-fan aquifers complying with most water-quality standards are optimal zones for extracting safe groundwater. Notably, the deep aquifer has a high hazard rating and is less safe than the shallow aquifer. The Fe—Mn hazard in Lanyang Plain groundwater presents in most aquifers, and is partially combined with other hazards, such as the nitrogen hazard and the As hazard. A zonal management plan based on safe groundwater use is formulated to help local governments develop groundwater resources in the Lanyang Plain.

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Introduction

Management and effective use of groundwater typically face great challenges, due to the spatial variability of groundwater quality, and the difficulties in satisfying different water-quality standards for various water use sectors demand. Thus, a comprehensive management index of groundwater for multi-purpose use (irrigation, aquaculture and public water supply) is needed. Groundwater naturally contains many ions and can adversely impact on irrigation, aquaculture and drinking water uses. Water-quality is one of the most critical factors in multi-purpose uses for groundwater. For instance, excessive ions in irrigation water may adversely impact the environment. The most common ions presented in groundwater are chloride (Cl^-) and sodium (Na^+), particularly in coastal regions. Generally, high concentrations of Cl^- and Na^+ in water retard the plants growth (Karaivazoglou et al. 2005; Grieve et al. 2006). Arsenic (As) accounts for various health hazards (Chiou et al., 2001; Lee et al., 2007). When used for irrigation and aquaculture, groundwater with high As contents is toxic to crops and fish and also results in bioaccumulation of As in their organs, which then poses a potential threat to human health (Huq and Naidu, 2005; Liu et al., 2005; Jang et al., 2006). Growth of farm fish and crops is also influenced by high manganese (Mn) levels (van der Vorm and van Diest, 1979; Frías-Espericueta et al., 2003). Although nitrogen compounds in irrigation water facilitate plant growth, excessive nitrogen leaching into groundwater and surface water adversely affect human health (Yang et al., 1998; Màrquez et al., 1998; Lake et al., 2003).

Spatial distributions of groundwater quality are commonly heterogeneous, varying with depths and locations. However, only limit field data can be acquired due to time and cost constraints. Sparsely measured data contain considerable uncertainty. Geostatistics is widely used in modeling spatial variability and distributions of field data with uncertainty. Indicator kriging (IK), which is a frequently employed non-parametric geostatistical method, makes no assumption of variable distributions and a 0—1 indicator transformation of data is applied to make the predictor robust for outliers. At an unsampled location, the values estimated by IK are probabilities that do not exceed a specific threshold. Indicator kriging has been frequently applied for estimating the soil pollution by specific heavy metals. For example, Juang and Lee (1998), Castrignanò et al. (2000) and van Meirvenne and Goovaerts (2001) utilized IK to estimate the probabilities of heavy metal distributions in fields and to delineate hazardous areas. Liu et al. (2004) and Goovaerts et al. (2005) used IK to assess As pollution in groundwater and mapped the extents of As pollution in aquifers. Saisana et al. (2004) used IK to classify zones polluted with airborne nitrogen dioxide relative to regulatory standards.

Integrating multiple parameters is important for effective assessment and classification of soil and groundwater quality. Smith et al. (1993), Oyedele et al. (1996), Halvorson et al. (1996) and Diodato and Ceccarelli (2004) successfully applied a multiple-variable indicator kriging (MVIK) to determine soil quality in farmed fields. However, few studies have applied MVIK to identify the zonation of multi-purpose water uses in groundwater aquifers. Assessing groundwater quality is also required, using multiple parameters (Jurdi et al., 2002). In Taiwan, water-quality standards for irrigation, aquaculture and drinking water utilized different hydrochemical items and concentration standards. Thus, MVIK is applied to assess groundwater quality for multi-purpose use in this study (Xu et al., 2006).

The objective of this work is to evaluate groundwater quality in the aquifers in the Lanyang Plain for multi-purposes using MVIK. Numerous hydrochemical parameters of groundwater quality were partitioned into four main hazard categories — saline hazard, nitrogen hazard, Fe—Mn hazard and As hazard. The extent and safety of potential hazards were delineated according to various estimated probabilities using MVIK. Analytical results may help Taiwanese government administrators establish a sound plans for groundwater development and management in regions with limited water resources. Moreover, this study can be adopted by other countries to manage effectively multi-purpose groundwater use worldwide.

Study area

Study area and hydrogeology

The Lanyang Plain, which is located in YiLan County in northeastern Taiwan (Fig. 1), is the alluvial fan of the Lanyang River. The area is triangular, bordered by the Pacific Ocean next to the east, Snow Mountains located to the northwest, and Central Mountains located to the southwest. The main river, the Lanyang River, flows through the middle of the area and flows west to east. The area is approximately 400 km^2 with each side of triangular region about 30 km long (Fig. 1). The groundwater flows from west to east. The western sections of the plain near the mountains comprise the main area for groundwater recharge. Natural recharge is the groundwater resource (Peng, 1995). Unconsolidated sediments underlying the alluvial fan contain abundant groundwater and are of the Quaternary age. The plain is partitioned into proximal-fan, mid-fan, and distal-fan areas Chen (2000). According to the core compositions at different depths at the 22 drilling stations in the Lanyang Plain (Taiwan Central Geological Survey, available on <http://www.hydro.meacgs.gov.tw/Rock13.htm>), the hydrogeological setting of the Lanyang Plain is roughly divided into three aquifers (Fig. 2). The Water Resource Agency (WRA) has set up 40 wells with depths of 18.9—233 m for monitoring the levels and background quality of groundwater, which is sampled and analyzed annually (<http://www.gweb.wra.gov.tw/wrweb/>). Aquifer 1 is 26.1—56.7 m deep, aquifer 2 is 70.6—139 m deep, and aquifer 3 is 157.9—233 m deep (Fig. 2) (Lee et al., 2008).

Due to insufficient surface water, many residents in the Lanyang Plain extract massive amounts of groundwater for irrigation, aquaculture and household use. Many tourism and manufacturing industries recently developed rapidly in these regions, exacerbating problem of insufficient water resources. Reservoirs are typically difficult and costly to construct. Therefore, with limited water resources, groundwater is considered an alternative to surface water. Agriculture, such as paddy and upland fields, is a common land use