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Detecting and predicting the impact of land use changes on groundwater quality, a case study in Northern Kelantan, Malaysia

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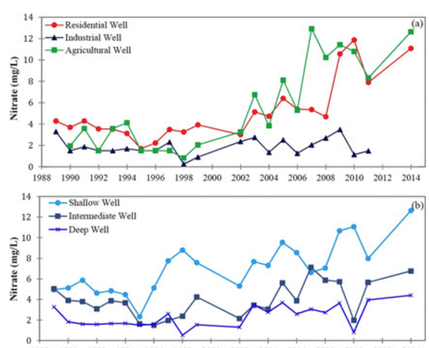
HIGHLIGHTS

- This study aims to quantify impact of deforestation on groundwater quality.
- Groundwater quality variations detected in Kelantan from 1989 to 2014
- Nitrate increased 8.1% annually in agricultural wells.
- The significant increase in nitrate was only observed in a shallow aquifer.
- ARIMA model predict nitrate will rise 2.64% annually until 2030.

GRAPHICAL ABSTRACT



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ABSTRACT

The conversions of forests and grass land to urban and farmland has exerted significant changes on terrestrial ecosystems. However, quantifying how these changes can affect the quality of water resources is still a challenge for hydrologists. Nitrate concentrations can be applied as an indicator to trace the link between land use changes and groundwater quality due to their solubility and easy transport from their source to the groundwater. In this study, 25 year records (from 1989 to 2014) of nitrate concentrations are applied to show the impact of land use changes on the quality of groundwater in Northern Kelantan, Malaysia, where large scale deforestation in recent decades has occurred. The results from the integration of time series analysis and geospatial modelling revealed that nitrate (NO_3-N) concentrations significantly increased with approximately 8.1% and 3.89% annually in agricultural and residential wells, respectively, over 25 years. In 1989 only 1% of the total area had a nitrate value greater than 10 mg/L; and this value increased sharply to 48% by 2014. The significant increase in nitrate was only observed in a shallow aquifer with a 3.74% annual nitrate increase. Based on the result of the Autoregressive Integrated Moving Average (ARIMA) model the nitrate contamination is expected to continue to rise by about 2.64% and 3.9% annually until 2030 in agricultural and residential areas. The present study develops techniques for detecting and predicting the impact of land use changes on environmental parameters as an essential step in land and water resource management strategy development.

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1. Introduction

Massive urbanization and industrialization, development of agricultural lands, deforestation, mining and road building as examples of human activities have resulted in global climate change, regional ecological deterioration, and landscape degradation (Deng and Shangguan, 2016; Pérez-Fernández et al., 2016). Land degradation may have a direct impact on soil degradation, which destroys ecosystem functions and effects the hydrological, biological and geochemical cycles (Keesstra et al., 2012; Pérez-Fernández et al., 2016). Land use and land cover patterns are the cumulative results of numerous natural and socio-economic factors in relation to human activities in time and space. Generally, the world's natural resources are utilized in an unsustainable manner due to unprecedented population growth, and industrial and agricultural development (Keeler and Polasky, 2014).

According to the United Nations Food and Agricultural Organization (FAO), an estimated 5.2 million hectares of forests were lost from 2000 to 2010 (FAO, 2010), with shows the highest rate of deforestation in Asia (FAO, 2012). Around 15% of tropical rainforests are in Southeast Asia, which play a significant role in environmental biodiversity, as well as stabilizing the world's climate and protecting the environment against soil erosion, floods, and droughts. The FAO (2010) reported a yearly tropical rainforest loss in Southeast Asia of 2.4 Mha in the 1990s, 0.4 Mha from 2000 to 2005, and 1.0 Mha for the period 2005–2010. The consequences of land use changes not only affect climate change, wildlife habitats, soil carbon storage and soil erosion, but also have a negative effect on water quality by increasing sediments, nutrients, and agricultural chemicals (Zhang et al., 2015).

In 2016, the United Nations adopted the Sustainable Development Goals (SDGs) in which the protection of water resources is an important topic. To be able to do this it is of importance to understand the complex interactions between land use, the soil system and ecosystem services (Keesstra et al., 2016). A good understanding of linkages between surface and sub-surface processes in the nutrient and hydrological cycle will be essential to be able to develop sustainable land and water management strategies.

The conversion of natural forests and grassland to urban and farmland, together with population growth and intensive agricultural activities, is producing a potential source of contaminants from fertilizers, sewage disposal, and landfill, which often influence the hydrological system and change the runoff and water quality (Fletcher et al., 2013). Valle et al. (2014) mentioned that human association to some land uses as a source of groundwater quality changes, directly or in directly. In recent decades, increasing nitrogen and nitrate concentrations in surface and groundwater have been of great concern due to the drastic agricultural and urban development (Gardner and Vogel, 2005), which revealed a certain relation between the nitrate concentration in the water resources and agricultural activities (Yu et al., 2014).

Previous studies mostly characterized the status of nitrate concentration in the groundwater (García-Díaz, 2011; Kurunc et al., 2016), influence on public health (Manassaram et al., 2007; Powlson et al., 2008), source of nitrate (Wakida and Lerner, 2005; Lawniczak et al., 2016), and transport and vulnerability in aquifers based on the short-term fluctuations (Kurunc et al., 2011; Sheikhy Narany et al., 2013). However, it is difficult to quantify and detect the link between land use changes and human activities, and groundwater quality due to the variability of nitrate concentrations across the landscape (Zhang et al., 2013). Chen et al. (2010) revealed that nitrate concentration in groundwater in areas used for rotating irrigated cultures was higher than areas occupied by forests in Huantai County in the North China Plain. In other research by Schilling and Jacobson (2010) in Neal Smith National Wildlife Refuge, Iowa, USA, nitrate concentration in groundwater decreased by converting cropland to perennial land cover (prairie) within a decade. In similar research by Valle et al. (2014) the impact of land use conflicts on quality of groundwater in the Sordo River basin (northern Portugal), which represented high concentration of nitrate in moderate and major conflict areas, as result of the nitrification of N-fertilizers. Therefore, the application of historical groundwater nitrate data can be applied to detect the impact of urbanization and agricultural development on water quality (Gardner and Vogel, 2005).

Malaysia, where rapid deforestation and urbanization (around 7%) have been reported from the 1970s to 1990s (Hassan, 2004), were used to reveal the impact of land use changes on groundwater quality. According to the current literature it would be expected that the extensive and rapid land use changes to crops, paddy, palm oil and rubber cultivation, would significantly increase the nitrate concentration of the shallow aquifers (Gardner and Vogel, 2005; Keeler and Polasky, 2014).

Historical environmental observations play an important role for detecting environmental changes over time. Time series analysis is another type of quantitative prediction, which is the record of consecutive observations (Temme et al., 2004) to develop the models describing the underlying relationships (Zhang, 2003). Therefore, the pattern of recorded data should be identified to characterize the nature of the phenomena and to predict future values. The underlying relationships between the past observations of the same variable could be applied to develop a model to extrapolate the time series in the future. Although hydrological systems have highly stochastic nature, suitable models have been developed to describe the complex phenomena. Accurate prediction of the concentration of contamination in ground water is a vital tool to assess the success of land and water resource management. The autoregressive integrated moving average (ARIMA) model is one of the most popular time series prediction models, and is helpful in predicting the future values based on past observations (Zhang et al., 2013).

The main aim of the present study was to detect, predict, and visualize the temporal and spatial variation of nitrate in groundwater due to long term land use changes in Northern Kelantan by integrating time series analyses and geospatial modelling, which give a clear view of the influence of human activities on the environment.

2. Materials and methods

2.1. Study area

The study was carried out in Northern Kelantan in the north-eastern side of Kelantan State, the largest state in Peninsular Malaysia, which lies between latitudes 5° 53 N and 6° 14 N and longitudes 102° 7 E and 102° 28 E (Fig. 1a). The study area covers an area of around 880 km^2; mostly consisting of alluvial deltas and coastal plains (Sefie et al., 2015). Since Malaysia is in an equatorial zone, the climate is controlled by the northeast (NE) and southwest (SW) monsoon's regimes. The annual rainfall changes from 1750 mm in the monsoon season from November to January and 0 mm in the dry season from March to May. The average temperature is around 26 °C throughout the year in the study area.

Northern Kelantan is covered by Quaternary alluvium of marine and fluviatile origin, which has a large potential for groundwater sources. Mesozoic granitic and sedimentary or metasedimentary bedrock underlay the alluvium layer, which mainly consists of shale, sandstone, phyllite and slate. The thickness of the quaternary alluvium varies from a few meters near the mountains to >150 m near the coast (Nur-Hayati, 2011) (Fig. 1e).

Based on lithological studies, the study area consists of three aquifer layers; shallow aquifer, intermediate aquifer, and deep aquifer. The shallow aquifer is mostly unconfined and semi-confined with varying from 2 to 3 m up to 17.5 m. The intermediate and deep aquifers lie at a depth of around 20 m to 50 m, and >50 m, respectively (Nur-Hayati, 2011). Generally, the shallow aquifers fed by precipitation, feeding rivers. Based on the study of Noor (1979), the shallow and intermediate aquifers are hydraulically interconnected due to the existence of the silty layer between them.