Environ Sci Pollut Res (2015) 22:11504–11512
DOI 10.1007/s11356-015-4347-4

RESEARCH ARTICLE

Contamination of nitrate in groundwater and its potential human health: a case study of lower Mae Klong river basin, Thailand

Jaturong Wongsanit[1] · **Piyakarn Teartisup**[2] · **Prapeut Kerdsueb**[2] · **Prapin Tharnpoophasiam**[3] · **Suwalee Worakhunpiset**[3,4]

Received: 7 November 2014 / Accepted: 9 March 2015 / Published online: 1 April 2015

Abstract Nitrate contamination in groundwater is a worldwide problem especially in agricultural countries. Environmental factors, such as land-use pattern, type of aquifer, and soil-drainage capacity, affect the level of contamination. Exposure to high levels of nitrate in groundwater may contribute to adverse health effects among residents who use groundwater for consumption. This study aimed to determine the relationship between nitrate levels in groundwater with land-use pattern, type of aquifer, and soil-drainage capacity, in Photharam District, Ratchaburi Province, lower Mae Klong basin, Thailand. Health risk maps were created based on hazard quotient to quantify the potential health risk of the residents using US Environmental Protection Agency (U.S. EPA) health risk assessment model. The results showed the influence of land-use patterns, type of aquifer, and soil-drainage capacity on nitrate contamination. It was found that most of the residents in the studied area were not at risk; however, a groundwater nitrate monitoring system should be implemented.

Responsible editor: Philippe Garrigues

✉ Suwalee Worakhunpiset
suwalee.wor@mahidol.ac.th

1 Faculty of Veterinary Medicine, Kasetsart University, Kampangsaen District, Nakhon Pathom 73140, Thailand

2 Faculty of Environment and Resources Studies, Mahidol University, 999 Phuttamonthon Road, Salaya, Nakhon Pathom 73170, Thailand

3 Faculty of Tropical Medicine, Mahidol University, 420/6 Ratchawithi Road, Bangkok 10400, Thailand

4 Department of Social and Environmental Medicine, Faculty of Tropical Medicine, Mahidol University, 420/6 Ratchawithi Road, Bangkok 10400, Thailand

Keywords Nitrate · Groundwater · Health risk assessment · Methemoglobinemia · Lower Mae Klong river basin · Ratchaburi Province · Thailand

Introduction

Nitrate contamination in groundwater is a worldwide problem (Spalding and Exner 1993; Dunn et al. 2005; Liu et al. 2005; U.S.EPA 1993; Kyllmar et al. 2004). Nitrate is soluble in water, easily leaches through soil, and accumulates in groundwater (Nolan 2001). The natural level of nitrate in groundwater is ≤2 mg/L NO_3-N (Mueller and Helsel 1996) or 10 mg/L NO_3^-. Nitrate levels exceeding the background level may indicate contamination from sewerage, septic systems, industrial wastewater, and fertilizer (U.S.EPA 1993; Kyllmar et al. 2004; Liu et al. 2005; Burkart and Kolpin 1993; Mohamed et al. 2003; Keeney 1986; Eckhardt and Stackelberg 1995). Factors associated with the level of nitrate contamination include geological background, land-use pattern, agricultural practice, soil-drainage capacity, and type of aquifer (Nolan 2001; Hatfield and Follett 2008; Gardner and Vogal 2005; Meinardi et al. 1995; Fewtrell 2004; Dubrovsky and Hamilton 2010).

Exposure to high levels of nitrate from the consumption of contaminated water contributes to methemoglobinemia. The severity of this syndrome depends on exposure dose and individual susceptibility such as age, gender, genetics, or other health conditions. Infants aged below 6 months are at the highest risk of this syndrome due to low levels of a key methemoglobin reduction enzyme in the red blood cells (Shearer et al. 1972; Fan and Steinberg 1996; Avery 1999; Knobeloch et al. 2000; Trivedi and Vediya 2012; U.S. EPA 2013). It has also been reported that older children exposed to >50 mg/L NO_3^- nitrate in drinking water had a higher prevalence of methemoglobinemia than those exposed to drinking water containing nitrate <50 mg/L NO_3^- (Sadeq et al. 2008). In addition, long-term exposure to nitrates might elevate the risk of non-Hodgkin's lymphoma (Weisenberg 1990; Payne 1993; Bruning-Fann and Kaneene 1993; van Maanen et al. 1994; Ward et al. 1996; Parslow et al. 1997; Barrett et al. 1998; Weyer et al. 2001; Wolfe and Patz 2002).

Nitrogen-based fertilizers are applied to enhance crop productivity. After nitrogen-based fertilizer treatment, soil microorganisms transform nitrogen into ammonium-nitrogen and nitrate-nitrogen, which plants use for growth (Frate 2007). Nitrogen in excess of plant uptake will leach through the soil, leading to groundwater contamination. Fertilizer consumption in Thailand has continued to increase since 2004 (Bureau of Agriculture Policy and Planning 2010). Some studies reported the level of nitrate contamination in groundwater to exceed the acceptable level of groundwater quality for drinking purpose (Kwanmeung et al. 2002; Rangsayatorn 2006; Tirado et al. 2008).

Photharam District, Ratchaburi Province, is located in the lower Mae Klong basin, in western Thailand. The area is primarily agricultural, and some residents still use groundwater for consumption. This study aimed to assess the relationship between land-use type, type of aquifer, and soil-drainage capacity with nitrate levels in groundwater. In addition, the potential health risks, in terms of the residents' hazard quotient (HQ) from exposure to nitrate in groundwater, were calculated using the health risk assessment model (U.S. EPA Region 6 2005); health risk maps were also created.

Materials and methods

Study area

Photharam District, Ratchaburi Province, is located in the lower Mae Klong basin in western Thailand. It covers an area of 417.009 km^2. The topography consists mainly of a flat plain, which is generally covered by agricultural land and communities, with a small area of forest in the west. It is divided into 19 subdistricts, 156 villages, 6 municipals, and 14 subdistrict administrative organizations. The total population in 2007 was 830,275; most worked in the agricultural sector. The most important water resource is the Mae Klong river (Amphoe 2008). Groundwater supplies in this area are obtained mainly from unconsolidated deposits of flood plain, delta, and terraces. The sediments are more than 400 m thick, with at least three aquifers from 200 m deep to land surface. An intermediate and deep aquifer is separated by a thin confining clay layer, leading to hydraulic interconnection between layers. The average annual recharge was estimated at 1.50 cm or approximately 10 % of annual rainfall. Groundwater discharge occurs by various means including plant transpiration, springs and diffusion, or discharge into streams. (Dutta et al. 1998).

Sources of data

Land-use data

Land-use data were extracted from the Land Development Department land-use map (2001). The data were classified into three groups: paddy field, sugarcane, and mixed orchard, according to the major characteristic of the area (http://photharam.ratchaburi.doae.go.th).

Aquifer data

Aquifer data was derived from the Department of Groundwater Resources hydrogeology map (2001). Aquifers were classified into three types: Permian Carboniferous metasediment aquifer (PCms), floodplain deposit aquifer (Qfd), and younger terrace deposit aquifer (Qyt). PCms are metasediment aquifers composed of clastic sedimentary rock including quartz, feldspar, phyllite, and slate. Tuff and agglomerates can be found in rock fractures. These aquifers yield 5–10 m^3/h. Qfd are alluvial floodplain aquifers composed of gravel, sand, and clay. These aquifers occur within the floodplain depths ranging between 20 and 60 m and yield from 20 to 50 m^3/h. Qyt are composed of gravel, sand, silt, and clay next to the alluvial floodplain aquifer. The average yield is 20 m^3/h with a depth range of 30 to 100 m.

Soil-drainage capacity data

Soil-drainage capacity was categorized into four groups—very well drained, well drained, moderately drained, and poorly drained, according to soil texture, as indicated in soil series data from the Land Development Department (2014).

Groundwater nitrate concentration data

Groundwater nitrate concentration data used in this study was derived from the study of Wongsanit (2009). The level of nitrate contamination in groundwater was classified into three categories—background level (<10 mg/L NO_3^-), acceptable level (range from 10 to 45 mg/L NO_3^-), and exceed the acceptable level (>45 mg/L NO_3^-).

Data analysis

Statistical analysis was performed using SPSS statistical software (version 18). The Kruskal-Wallis test was used to determine relationships between groundwater nitrate concentration and environmental factors (land-use pattern, type of aquifer, and soil-drainage capacity). Significance was set at 95 % (or $\alpha=0.05$).

Quantitative health risk assessment

According to the inadequate amount of evidence in humans for the carcinogenicity of nitrate in drinking water, only noncarcinogenic health effects posed by long-term exposure to nitrate in drinking water were quantified in terms of hazard quotient (HQ) using the US EPA health risk assessment model (U.S. EPA Region 6 2005) as shown in Eq. (1).

$$HQ = CDI/RfD \quad (1)$$

where *CDI* is the sum of nitrate intake via drinking water as shown in Eq. (2) (U.S. EPA 1989; U.S. EPA 1991), and RfD is a nitrate reference dose which is 1.6 mg/kg/day (IRIS 2012).

$$CDI = C \times IR \times EF \times ED/(BW \times AT) \quad (2)$$

where

C	Nitrate concentration (mg/L)
IR	Intake rate (1 L/day for children and 2 L/day for adults)
EF	Exposure frequency (365 day/year)
ED	Exposure duration (6 years for children and 30 years for adults)
BW	Body weight (15 kg for children and 60 kg for adults)
AT	Averaging time (365 days/year×6 years for children and 365 days/year×30 years for adults)

An HQ value >1 indicated a significant noncarcinogenic risk level (U.S. EPA Region 6 2005).

Health risk mapping

The HQ value of each sampling point was calculated and used to simulate the health risk level over the entire study area. ArcGIS Desktop version 9.1 (with Geostatistical Analyst extension) was used to generate a predictive risk area from HQs in the form of a risk map using ordinary kriging interpolation method, which provided the least error HQ prediction. The risk area was classified into four classes: class 1, HQ≤1; class 2, HQ≥1–2; class 3, HQ≥2–3; and class 4, HQ>3.

Results and discussion

Nitrate concentration in groundwater

Groundwater nitrate concentrations of 73 sampling wells (Fig. 1) derived from the study of Wongsanit (2009) were used in this study. Nitrate concentrations ranged from 1 to 110 mg/L NO_3^- with the mean of 8.17 mg/L NO_3^-, and the median of 1.1 mg/L NO_3^-. Four samples exceeded the acceptable level of groundwater quality for drinking purpose (Ministry of Natural Resources and Environment 2008). The results showed most of the samples (80.8 %) had nitrate contamination levels <10 mg/L NO_3^-, 13.7 % had nitrate levels between 10 and 45 mg/L NO_3^-, and four samples (5.5 %) had >45 mg/L NO_3^- (Fig. 2).

The distribution of nitrate contamination levels in different land-use patterns is shown in Fig. 3. Among four groundwater samples containing nitrate more than the acceptable level, three were in sugarcane planting areas and one sample was in a mixed orchard area. The median nitrate concentration in the mixed orchard, paddy field, and sugarcane planting areas was 1.1, 5.8, and 14.5 mg/L NO_3^-, respectively. The Kruskal-Wallis test showed nitrate contamination levels among land-use patterns were statistically significantly different ($p<0.05$) (Table 1).

The distributions of nitrate contamination levels in the three aquifer types are shown in Fig. 4. The median nitrate concentrations in PCms, Qfd, and Qyt were 10.15, 1.1, and 1.05 mg/L NO_3^-, respectively. The Kruskal-Wallis test showed nitrate contamination levels among aquifer types were statistically significantly different ($p<0.05$) (Table 1).

The distributions of nitrate contamination levels in the area with different soil-drainage capacities are shown in Fig. 5. The median nitrate concentration in very well drained, well drained, moderately drained, and poorly drained soils were 8.5, 1.1, 10.25, and 1.1 mg/L NO_3^-, respectively. The Kruskal-Wallis test showed that nitrate levels differed significantly by soil-drainage capacity ($p<0.05$) (Table 1).

Human health risk of nitrate in groundwater

Human health risk was calculated based on the US EPA model and the parameters previously described. The results showed that the HQ values ranged between 0.04 and 4.58 for children and 0.02 and 2.29 for adults. The mean±SD of HQ values for children was 0.34±0.72 and for adults, 0.17±0.36. The highest HQ values were 4.58 and 2.29 for children and adults, respectively. There were five wells with HQ values >1 for children and four wells with HQ values >1 for adults.

Health risk map

In this study, ordinary kriging, multiquadric, thin-plate spline, inverse distance weighting, inverse multiquadric, and simple kriging were performed to create the prediction models based on the HQ value of each well. The mean absolute percentage error (MAPE) was calculated to validate the models. The results showed ordinary kriging was the most appropriate model

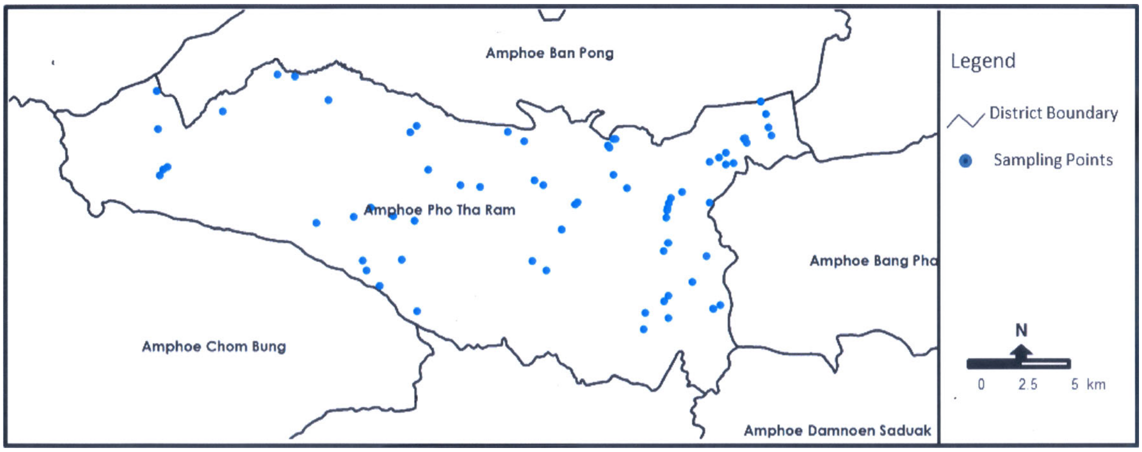

Fig. 1 Sampling locations

since it provided the smallest MAPE compared with the other models. Ordinary kriging was used to create a health risk map using spherical semivariogram parameters. The range, nugget, and partial sill were 13,825, 0.034, and 0.277 m, respectively. The predictive ability of the model was assessed by cross-validation. The MAPE of the final model was 5.63.

The health risk map of the children showed that 92.81 % of the study area was class 1; 5.99 %, class 2; 0.96 %, class 3; and 0.24 %, class 4 (Fig. 6). For the adults, most of the study area (98.80 %) was class 1, 1.16 % was class 2, and 0.04 % was class 3 (Fig. 7).

Discussion

Groundwater in some locations of Photharam District, Ratchaburi Province, had nitrate concentrations higher than the acceptable level of groundwater quality for drinking purpose, the highest concentration was 110 mg/L NO_3^-. This agreed with several studies that found high nitrate levels in groundwater, especially in intensive agricultural areas. The highest concentration of nitrate in groundwater in the study area was lower than that found in Nakhon Pathom and Kanchanaburi province, but higher than Chiang Mai and Suphan Buri Province (Phupaibul et al. 2004; Tirado 2007). Compared with other studies, the highest groundwater nitrate concentration in the study area was lower than those found in Spain and in northeastern Romania (Guimera 1998; Cãilean et al. 2009). However, it was higher than those found in Taiwan (96.06 mg/L NO_3^-), the Philippines (109.2 mg/L NO_3^-), northeast China (42.15 mg/L NO_3^-), and Malaysia (42.49 mg/L NO_3^-) (Lui et al. 2011; Tirado 2007; Su et al. 2013; Jamaludin et al. 2013). The presence of high levels of nitrate in groundwater worldwide indicates that groundwater quality is being deteriorated, and the population's health might be affected from exposure to nitrate in groundwater.

Our results also demonstrated the influence of land-use pattern, type of aquifer, and soil-drainage capacity on nitrate concentrations in groundwater. Sugarcane planting areas had the highest median nitrate concentration, followed by paddy field and mixed orchard; the Kruskal-Wallis test showed a significant difference in nitrate concentration by land-use pattern ($p<0.05$). The significant differences in groundwater nitrate levels between land-use patterns are likely to have resulted from different rates of fertilizer application in sugarcane

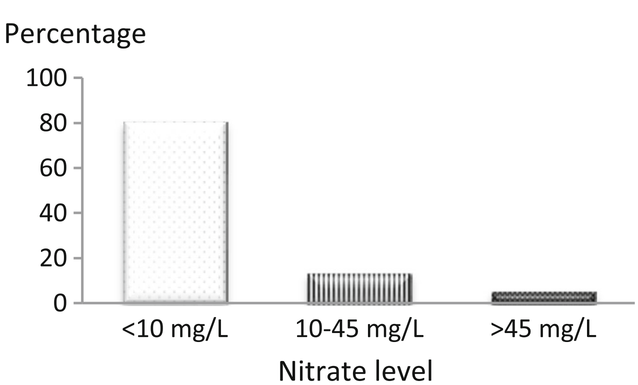

Fig. 2 Percentage of groundwater samples in the study area by nitrate contamination level

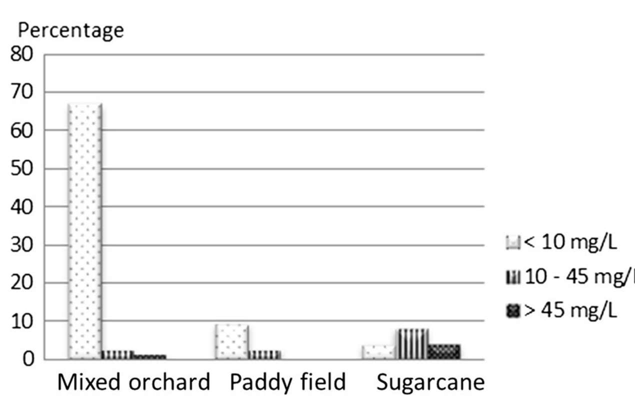

Fig. 3 Percentage of nitrate contamination levels for different land-use patterns

Table 1 Relationship of groundwater nitrate concentration and land-use pattern, type of aquifer, and soil-drainage capacity

	Number of samples	Mean NO_3 (mg/L NO_3^-)	Median NO_3 (mg/L NO_3^-)	Range NO_3 (mg/L NO_3^-)	*p* value
Land-use pattern					
Paddy field	9	6.59	5.80	1.10–17.00	.000
Mixed orchard	52	3.66	1.10	1.00–49.00	
Sugarcane	12	28.92	14.50	1.10–110.00	
Type of aquifer					
PCms	28	19.37	10.15	1.10–110.00	.000
Qfd	41	1.21	1.10	1.00–3.20	
Qyt	4	1.05	1.05	1.00–1.10	
Soil-drainage capacity					
Very well drained	4	9.08	8.50	5.30–14.00	.001
Well drained	41	4.82	1.10	1.00–49.00	
Moderately drained	8	17.71	10.25	4.20–51.00	
Poorly drained	20	11.03	1.10	1.00–110.00	

planting areas, mixed orchards, and paddy fields, which were 15, 7, and 6 kg N/Rai, respectively (Department of Agriculture 2014). Although fertilizer application in mixed orchard areas was greater than that in the paddy fields, the median groundwater nitrate concentrations did not correlate, which may be due to excessive fertilizer being applied to paddy fields (Witheetrirong et al. 2011). The result agrees with several studies that found the significant relationship between crop type/land-use and the level of groundwater nitrate (Zhang et al. 1996; Burow et al. 1998; Eckhardt and Stackelberg 1995; Nolan and Stoner 2000; Nolan 2001; Tong and Chen 2002; Jeyaruba and Thushyanthy 2009; Lockhart et al. 2013).

In terms of the type of aquifer, it was found that nitrate concentrations at sites located in a consolidated aquifer (PCms) were higher than those in an unconsolidated aquifer (Qfd and Qyt); the Kruskal-Wallis test showed a significant difference in nitrate concentrations in groundwater by aquifer type ($p<0.05$). This finding does not support the theory that unconsolidated aquifers facilitate water and contaminant leaching into the water table, leading to an increase in groundwater nitrate concentration (Nolan et al. 2002). This might be because unconsolidated aquifers are commonly adjacent to underlying rivers so that the groundwater nitrate level might be affected by recharge/discharge mechanism between groundwater and surface water (Nolan 2001; Hatfield and Follett 2008). In addition, the consolidated aquifers have fewer pores than unconsolidated aquifers, resulting in less water being available to dilute the contaminants that might contribute to the higher level of groundwater contamination (Morris et al. 2003).

In general, poorly drained soils can restrict the movement of nitrate into the water table (Gaines and Gaines 1994; Mueller et al. 1995) so that groundwater below that area should be at lower risk of nitrate contamination (Sophocleous et al. 1990; Townsend and Marks 1990). However, our study found that the median nitrate contamination levels at sites located in moderately drained soil were higher than those at sites located in very well-drained soil and well-drained soil; this might be due to the influence of other soil characteristics including soil depth and organic matter content on the possibility of nitrate percolation through the soil (Cook 1990; Gardner and Vogal 2005; Meinardi et al. 1995; Fewtrell 2004; Dubrovsky and Hamilton 2010). In

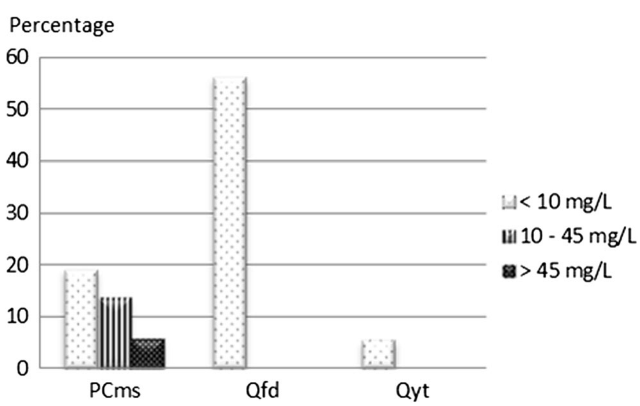

Fig. 4 Percentage nitrate contamination levels for different aquifer types

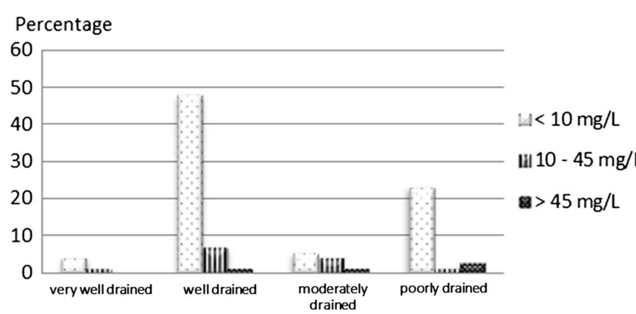

Fig. 5 Percentage nitrate contamination levels for different soil-drainage capacities

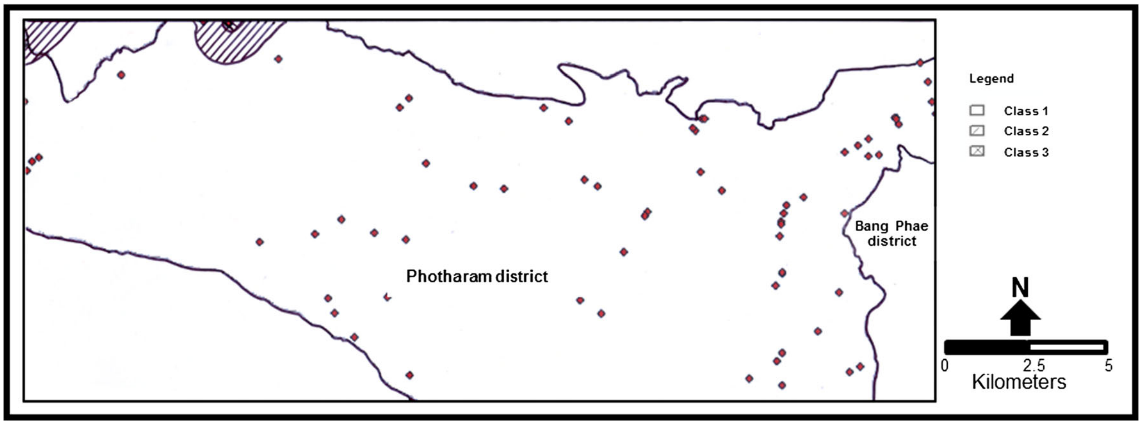

Fig. 6 Children's health risk areas in Photharam District, Ratchaburi Province, by class

addition, a higher level of groundwater nitrate in the area beneath moderately drained soil than well-drained soil might be affected by the higher nitrate leakage rate at medium depth in clay soil compared with sandy soil (Ehteshami et al. 2013) or a correlation of higher-risk land uses, such as sugarcane on moderately drained soil.

In this study, several interpolation methods were used to create predictive models based on the HQ value of each well. Ordinary kriging was the most appropriate model since it provided the smallest MAPE compared to the others. Several studies found ordinary kriging performed better than other methods (Reza et al. 2010; Baskan et al. 2009). However, its performance might be affected by several factors that characterize the datasets being interpolated, such as sampling density, sample distribution, and homogeneity/heterogeneity (Eldeiry and Garcia 2012). To determine the nugget effect caused by spatial heterogeneity, the ratio of nugget sill was calculated. The ratio of nugget sill in this study was 12.27 %, which indicated low heterogeneity or low nugget effect of the study area, leading to high predictive reliability.

The health risk maps created by ordinary kriging using spherical semivariogram parameters with the range of 13, 825 m, nugget of 0.034, and partial sill of 0.277 showed that some part of the study area had HQ >1, which indicated the residents in that area are prone to the adverse health effects of daily intake of groundwater contaminated by nitrate. In addition, the area with HQ >1 that mostly overlaps with sugarcane planting area also indicates the potential effect of land use on nitrate contamination in groundwater as previously mentioned.

Our study mainly focused on determining the effect of land-use pattern, type of aquifer, and soil-drainage capacity on groundwater nitrate contamination in the study area. However, several other factors are related to nitrate contamination level in groundwater, i.e., climate, precipitation, cropping system, agricultural practice, irrigation methods, well depth, and aquifer yield (Lichtenberg and Shapiro 1997; Nolan 2001; Debernardi et al. 2008; Jones and Olson-Rutz 2011; Letey and Vaughan 2013). Further research should be conducted that encompasses all potentially significant factors.

Conclusion

The study results indicate that fertilizer application contributes to groundwater contamination by nitrate. Regarding potential

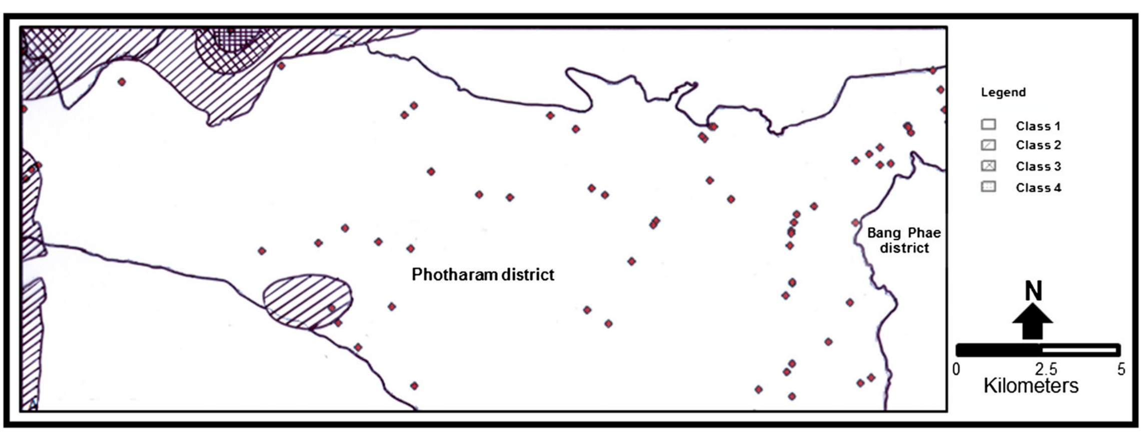

Fig. 7 Adults' health risk areas in Photharam District, Ratchaburi Province, by class

health risk from exposure to nitrate in groundwater, although the result from this study indicated that most residents in Photharam District were not at risk, some areas had HQ >1. Therefore, it is recommended that nitrogen management practices should be implemented, and groundwater nitrate should be monitored to prevent the adverse effect to human health.

Acknowledgments The authors would like to express sincere appreciation to the Groundwater Analysis Division, Department of Groundwater Resources, for support with groundwater sample analysis.

Compliance with ethical standards The authors declare that the manuscript is in compliance with ethical standards.

Conflict of interest The authors declare that they have no conflict of interest.

References

Amphoe Photharam (2008) http://203.157.146.10/population/pop_hcis.php Accessed 19 May 2008

Avery AA (1999) Infantile methemoglobinemia: reexamining the role of drinking water nitrates. Environ Health Perspect 107(7):583–586

Barrett JH, Parslow RC, McKinney PA, Law GR, Forman D (1998) Nitrate in drinking water and the incidence of gastric, esophageal, and brain cancer in Yorkshire, England. Cancer Causes Control 9: 153–159

Baskan O, Erpul G, Dengiz O (2009) Comparing the efficiency of ordinary kriging and cokriging to estimate the Atterberg limits spatially using some soil physical properties. Clay Miner 44(2):181–193

Bruning-Fann CS, Kaneene JB (1993) The effects of nitrate, nitrite, and N-nitroso compounds on human health: a review. Vet Hum Toxicol 35:521–538

Bureau of Agriculture Policy and Planning (2010), Thailand fertilizer consumption 2004–2011 http://www.fertilizer.org/…/2010_crossroads_laudee_slides.p Accessed 23 December 2013

Burkart MR, Kolpin DW (1993) Hydrologic and land-use factors associated with herbicides and nitrate in near-surface aquifers. J Environ Qual 22:646–656

Burow KR, Shelton JL, Dubrovsky NM (1998) Occurrence of nitrate and pesticides in groundwater beneath three agricultural land-use settings in the eastern San Joaquin Valley, California, 1993–1995. Water-Resource Investigation Report 97–4284. U.S. Geological Survey

Căilean D, Teodosiu C, Volf I, Ciobanu (2009) Occurrence and associated risk of nitrates/nitrites in the ground waters from the north-eastern part of Romania. In: Simeonov LI, Hassanien MA (eds) Exposure and risk assessment of chemical pollution – Contemporary methodology. Springer, The Netherlands, pp 383–397

Cook MG (1990) Good soil management helps protect groundwater. North Carolina Cooperative Extension Service AG-439-9

Debernardi L, De Luca DA, Lasaga M (2008) Correlation between nitrate concentration in groundwater and parameters affecting aquifer intrinsic vulnerability. Environ Geol 55:539–558

Department of Agriculture (2014) Vichakan. http://it.doa.go.th/vichakan/. Accessed: 7 January 2014 (in Thai)

Department of Groundwater Resources (2001) Hydrogeological map

Dubrovsky N, Hamilton P (2010) Nutrients in the nation's streams and groundwater: national findings and implications. U.S. Geological Survey, Reston, Virginia Fact Sheet 2010–3078. http://pubs.usgs.gov/fs/2010/3078/ Accessed: 25 February 2014

Dunn SM, Vinten AJA, Lilly A, DeGroote J, McGechan M (2005) Modelling nitrate losses from agricultural activities on a national scale. Water Sci Technol 51(3–4):319–327

Dutta D, Gupta D, Ramnarong V (1998) Design and optimization of a ground water monitoring system using GIS and multicriteria decision analysis. GWMR 18(1):139–147

Eckhardt DAV, Stackelberg PE (1995) Relation of ground-water quality to land use on Long Island, New York. Groundwater 33:1019–1033

Ehteshami M, Langeroudi AS, Tavassoli S (2013) Simulation of nitrate contamination in groundwater caused by livestock industry (Case Study: Rey). J Environ Prot. doi:10.4236/jep.2013.47A011

Eldeiry A, Garcia L (2012) Evaluating the performance of ordinary kriging in mapping soil salinity. J Irrig Drain Eng 138(12):1046–1059

Fan AM, Steinberg VE (1996) Health implications of nitrate and nitrite in drinking water an update on methemoglobinemia occurrence and reproductive and developmental toxicity. Regul Toxicol Pharmacol 23:35–43

Fewtrell L (2004) Drinking-water nitrate, methemoglobinemia, and global burden of disease: a discussion. Environ Health Persp 112(14): 1371–1374

Frate C (2007) Nitrogen transformation in soil University of California Cooperative Extension, Tulare County http://cdrf.org/wp-content/uploads/2012/01/11.7_Nitrogen_Transformations-final.pdf Accessed 15 September 2014)

Gaines TP, Gaines ST (1994) Soil texture effect on nitrate leaching in soil percolates. Common Soil Sci Plant Anal 25(13&14):2561–2570

Gardner KK, Vogal RM (2005) Predicting groundwater nitrate concentration from land use. Ground Water 43(3):343–352

Guimera J (1998) Anomalously high nitrate concentrations in groundwater. Groundwater 36(2):275–282

Hatfield JL, Follett RF (eds) (2008) Nitrogen in the environment: sources, problems and management, 2nd Edition. Academic, San Diego

IRIS-Integrated Risk Information System, U.S. EPA (2012) Nitrate (CASRN 14797-55-8) http://www.epa.gov/iris/subst/0076.htm Accessed 7 October 2013

Jamaludin N, Sham SM, Ismail SNS (2013) Health risk assessment of nitrate exposure in well water of residents in intensive agricultural area. Am J Appl Sci 10(5):442–448

Jeyaruba T, Thushyanthy M (2009) The effect of agriculture on quality of groundwater: a case study. Middel East J Sci Res 4(2):110–114

Jones C, Olson-Rutz K (2011) Crop and fertilizer management practices to minimize nitrate leaching. Montana State University Extension. MT201103AG New 1/11. http://msuextension.org/publications/AgandNaturalResources/MT201103AG.pdf. Accessed: 25 April 2014

Keeney D (1986) Sources of nitrate to groundwater CRC. Crit Rev Environ Control 16:257–304

Knobeloch L, Salna B, Hogan A, Postle J, Anderson H (2000) Blue babies and nitrate contaminated well water. Environ Health Perspect 108(7):675–678

Kwanmeung S, Navanugraha C, Pattanakiat S, Arunlertaree C (2002) Geographic information system for assessing land and subsurface water sensitivity to nitrate and phosphate contamination from swine farms in Muang District, Nakhon Pathom Province Dissertation, Mahidol University

Kyllmar K, Mårtensson K, Johnsson H (2004) Model-based coefficient method for calculation of N leaching from agricultural fields applied to small catchments and the effects of leaching reducing measures. J Hydrol 304:343–354

Land Development Department (2001) Land use map

Land Development Department (2014) Soil series. http://www.ldd.go.th. Accessed: 17 January 2014

Letey J, Vaughan P (2013) Soil type, crop and irrigation technique affect nitrogen leaching to groundwater. Calif Agric 67(4):231–241. doi: 10.3733/ca.E.v067n04p231

Lichtenberg E, Shapiro L (1997) Agriculture and nitrate concentrations in Maryland community water system wells. J Environ Qual 26(1): 145–153

Liu A, Ming J, Ankumah RO (2005) Nitrate contamination in private wells in rural Alabama, United States. Sci Total Environ 346:112–120

Lui CW, Lin CN, Jang CS, Ling MP, Tsai JW (2011) Assessing nitrate contamination and its potential health risk to Kinmen residents. Environ Geochem Health 33(5):503–14

Lockhart KM, King AM, Harter T (2013) Identifying sources of groundwater nitrate contamination in a large alluvial groundwater basin with highly diversified intensive agricultural production. J Contam Hydrol. doi:10.1016/J.Jconhyd.2013.05.008

Meinardi CR, Beusen AHW, Bollen MJS, Klepper O, Willems WJ (1995) Vulnerability to diffuse pollution and average nitrate contamination of European soils and groundwater. Wat Sci Tech 31:159–165

Ministry of Natural Resources and Environment (2008) Notification of the Ministry of Natural Resources and Environment: technical criterias and measures to prevent public health and environment hazard B.E. 2551 (in Thai)

Mohamed MA, Terao H, Suzuki R, Babiker IS, Ohta K, Kaori K et al (2003) Natural denitrification in the Kakamigahara groundwate basin, Gifu Prefecture, Central Japan. Sci Total Environ 307:191–201

Morris BL, Lawrence ARL, Chilton PJC, Adams B, Calow RC, Klinck BA (2003) Groundwater and its susceptibility to degradation: a global assessment of the problem and options for management. Early warning and assessment report series, RS, 03–3. United Nations Environment Programme, Nairobi

Mueller DK, Helsel DR (1996) Nutrients in the nation's waters too much of a good thing? U.S. Geological Survey Circular 1136

Mueller DK, Hamilton PA, Helsel DR, Hitt KJ, Ruddy BC (1995) Nutrients in ground water and surface water of the United States—an analysis of data through 1992: U.S. Geological Survey Water-Resources Investigations Report 95–4031, 74 p

Nolan BT (2001) Relating nitrogen sources and aquifer susceptibility to nitrate in shallow ground waters of the. United States: Ground Water 39(2):290–299

Nolan BT, Stoner JD (2000) Nutrients in ground waters of the conterminous United States, 1992–1995. Environ Sci Technol 34(7):1156–1165

Nolan BT, Hitt JK, Ruddy BC (2002) Probability of nitrate contamination of recently recharged groundwaters in the conterminous United States. Environ Sci Technol 36(10):2138–2145

Parslow RC, McKinney PA, Law GR, Staines A, Williams R, Bodansky HJ (1997) Incidence of childhood diabetes mellitus in Yorkshire, Northern England, is associated with nitrate in drinking water: an ecological analysis. Diabetologia 40(5):550–556

Payne MR (1993) Farm waste and nitrate pollution. In: Jones JG (ed) Agriculture and the environment. Ellis Hoewood Limited, New York, pp 63–73

Phupaibul P, Chitbuntanorm C, Chinoim N, Kangyawongha P, Matoh T (2004) Phosphorus accumulation in soil and nitrate contamination in underground water under export-oriented asparagus farming at Nong Ngu Lauem village, Nakhon Pathom province, Thailand. Soil Sci Plant Nutr 50(3):385–393. doi:10.1080/00380768.2004.10408492

Rangsayatorn N (2006) Shallow groundwater quality assessment in Muang District, Phayao. Naresuan Univ J 14(2):1–8

Reza SK, Sarkar D, Baruah U, Das TH (2010) Evaluation and comparison of ordinary kriging and inverse distance weighting methods for prediction of spatial variability of some chemical parameters of Dhalai district, Tripura. Agropedology 2(1):38–48

Sadeq M, Moeb CL, Attarassic B, Cherkaouid I, ElAouada R, Idrissia L (2008) Drinking water nitrate and prevalence of methemoglobinemia among infants and children aged 1–7 years in Moroccan areas. Int J Hyg Environ Health 211:546–554

Shearer LA, Goldsmith JR, Young C, Kearns OA, Tamplin BR (1972) Methemoglobin levels in infants in an area with high-nitrate water supply. AJPH 62(9):174–1180

Sophocleous M, Townsend MA, Whittemore DO (1990) Movement and fate of atrazine and bromide in central Kansas croplands. J Hydrol 115:115–137

Spalding RF, Exner ME (1993) Occurrence of nitrate in groundwater—a review. J Environ Qual 22:392–402

Su X, Wang H, Zhang Y (2013) Health risk assessment of nitrate contamination in groundwater: a case study of an agricultural area in Northeast China. Water Resour Manag 27:3025–3034

Tirado R (2007) Nitrate in drinking water in the Philippines and Thailand. Technical Note 10/2007. http://www.greenpeace.to/publications/nitrates_philippines_thailand.pdf Accessed: 22 December 2013

Tirado R, Englande AJ, Promakasikorn L, Novotny V (2008) Use of agrichemicals in Thailand and its consequences for the environment. Technical Note 03/2008. http://www.greenpeace.to/publications/GPSEA_agrochemical-use-in-thailand.pdf Accessed: 22 December 2013

Tong STY, Chen W (2002) Modeling the relationship between land use and surface water quality. J Environ Manag 66:377–393. doi:10.1006/jema.2002.0593

Townsend MA, Marks ET (1990) Occurrence of nitrate in soil and ground water in south-central Kansas; in, Proceedings Ground Water Management, 1990 Cluster of Conferences, Kansas City, Missouri, 20–21 February. National Water Well Association, Dublin, pp 145–158

Trivedi HB, Vediya SD (2012) Assessment of nitrate contamination of the groundwater samples in Bhiloda Taluka of Sabarkantha district, Gujarat. Int J of Pharm Life Sci 3(11):2103–2106

U.S. EPA (1989) Risk assessment guidance for superfund: Volume I. Human health evaluation manual (Part A). OERR. Washington, DC OERR. 9200 6-303-894 http://www.epa.gov/oswer/riskassessment/ragsa/pdf/rags_a.pdf Accessed 7 January 2012

U.S. EPA (1991) Risk assessment guidance for superfund: Volume I. Human health evaluation manual (Part B, Development of risk-based preliminary remediation goals) http://epa-prgs.ornl.gov/radionuclides/HHEMB.pdf Accessed 7 January 2012

U.S. EPA (1993) Wellhead protection: a guide for small communities (EPA/625/R-93/002). Office of Research and Development, Office of Water http://nepis.epa.gov/Adobe/PDF/30004L42.pdf Accessed 7 January 2012

U.S. EPA (2013) Basic information about nitrate in drinking water. http://water.epa.gov/drink/contaminants/basicinformation/nitrate.cfm Accessed 15 September 2014

U.S. EPA Region 6 (2005) Human Health Risk Assessment Protocol. http://www.epa.gov/osw/hazard/tsd/td/combust/finalmact/ssra/05hhrap7.pdf Accessed 19 January 2013

van Maanen JM, van Dijk A, Mulder K, de Baets MH, Menheere PC, van der Heide D et al (1994) Consumption of drinking water with high nitrate levels causes hypertrophy of the thyroid. Toxicol Lett 72(1–3):365–374

Ward MH, Mark SD, Cantor KP, Weisenburger DD, Correa-Villasenor A, Zahm SH (1996) Drinking water nitrate and risk of non-Hodgkin's lymphoma. Epidemiology 7:465–471

Weisenberg DD (1990) Environmental epidemiology of non-Hodgkin's lymphoma in Eastern Nebraska. Am J Ind Med 18(3):303–305

Weyer PJ, Cerhan JR, Kross BC, Hallberg GR, Kantamneni J, Breuer G et al (2001) Municipal drinking water nitrate level and cancer risk in older women; the Iowa women's health study. Epidemiology 11: 327–338

Witheetrirong Y, Tripathi NK, Tipdecho T, Pakpian P (2011) Estimation of the effect of soil texture on nitrate-nitrogen content in groundwater using optical remote sensing. Int J Environ Res Public Health 8: 3416–3436. doi:10.3390/ijerph8083416

Wolfe AH, Patz JA (2002) Reactive nitrogen and human health: acute and long-term implications. Ambio 31(2):120–125

Wongsanit J (2009) Risk assessment of nitrate contamination in groundwater using geoinformatics. Dissertation, Mahidol University

Zhang WL, Tian N, Zhang N, Xo L (1996) Nitrate pollution of groundwater in northern China. Short communication. Agric Ecosyst Environ 59:223–231