Enhancing the Roles of Groundwater in the Context of the Sustainable Development Goals via Aquifer Vulnerability Assessment

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Abstract*—Groundwater resources in Thailand have become central to socio-economic development over the course of decades, including providing water for domestic use, enabling food production, and sustaining critical ecosystems function. In some parts of the country, groundwater is often preferred over surface water because of its relative stability in terms of both quality and quantity. Sustainable and equitable groundwater use plays a critical role in the context of SDGs as follows: groundwater is most explicitly linked to ensuring availability and sustainable management of water and sanitation for all (SDG 6); and groundwater can also directly contribute to poverty eradication (SDG 1), food security (SDG 2), gender equality (SDG 5), sustainability of cities and human settlement (SDG 11), combating climate change (SDG 13), as well as protecting terrestrial ecosystems (SDG 15). Overall sustainable groundwater use can only be achieved through policy recommendation and implementation related to proper monitoring, management and governance that uses integrated and precautionary approaches while giving appropriate attention to the potential boundary nature of groundwater. For such implementation of the SDGs at the strategic policy making-level, assessing groundwater quality at the larger scale is particularly important for designing efficient monitoring strategies in sustainable water resources management plans. For our nation's groundwater resource, there is also evidence to suggest that the quality of groundwater is also under threats as a result of high concentrations of human/economic activities (e.g., industrial, agricultural and household). Numerous groundwater contaminated sites have been reported from both natural and anthropogenic activities with extent of plume migration, leading to a degrading quality of groundwater which is unacceptable for safe human consumption. Therefore, this paper attempts to assess vulnerability and pollution risk of groundwater by compilation of the most recent local- to regional-scale information on all major soil, land use, geology, hydrogeology, surface pollution sources, and climate conditions in Geographical Information System (GIS)-based environment in the Central and Northern parts of Thailand where groundwater resources are overexploited and an unknown number are experiencing pollution problems and/or degradation of groundwater dependent ecosystems. Groundwater vulnerability maps are constructed by means of DRASTIC method involving overlaying the DRASTIC vulnerability map with land use and potential pollution sources. Linear regression statistical analysis between rainfall-groundwater depth and adjusted hydraulic conductivity (K) are applied to modify some parameters in the original DRASTIC model. Some area in the central Chao Phraya region is dominated by high pollution risk classes and this is very strongly related to shallow groundwater systems and the development of agricultural activities. DRASTIC mapping models are validated using observed nitrate data in groundwater as a proxy of pollution risk. The original DRASTIC model provides a conservative estimate of low risk while the advanced DRASTIC model shows better regression coefficient between the vulnerability index and nitrate concentration.

Keywords—SDG; groundwater vulnerability; GIS; remote sensing; DRASTIC; risk map

I. INTRODUCTION

Groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity [**1-3**]. It has been recognized as the major and sometimes the preferred source of drinking water in rural as well as urban areas due to its relative stability in terms of both quality and quantity as it caters up to 80% and 50% of the total drinking water and agricultural water requirement in many parts of Thailand, respectively. The occurrence of drought and heavy rainfall are the most important climatic extremes having both short- and long-term impacts on the groundwater availability. Besides the natural forces creating pressure on water resources, ever-increasing human water demand have become the primary drivers of the pressure affecting our water systems.

Sustainable and equitable groundwater use plays a critical role in the context of SDGs as follows: groundwater is most explicitly linked to ensuring availability and sustainable management of water and sanitation for all (SDG 6); and groundwater can also directly contribute to poverty eradication (SDG 1), food security (SDG 2), gender equality (SDG 5), sustainability of cities and human settlement (SDG 11), combating climate change (SDG 13), as well as protecting terrestrial ecosystems (SDG 15). Overall sustainable groundwater use can be achieved through policy recommendation and implementation related to proper monitoring, management and governance that uses integrated and precautionary approaches while giving appropriate attention to the potential boundary nature of groundwater. For such implementation of SDGs at the strategic policy making-level and defining sustainable water resources management plans at the national scale, assessments of groundwater resources quantitatively and qualitatively as well as other associated pressures are strongly needed [**4**] for designing efficient monitoring strategies in sustainable water resources management plans.

Several efforts have been undertaken by academic researcher along with Department of Groundwater Resources Thailand (DGR) to improve the knowledge of groundwater systems in Thailand both at local- and national-scales. Studies have confirmed that groundwater in Thailand is abundant and subjected to different pollution pressure exerted by several sources as a results of high concentrations of human/economic activities from industrial, agricultural, and household, such as leaking sewage systems, solid waste dumpsites, household waste pits, surface water infiltration spots, agricultural activities, petrol service stations (i.e., underground storage tanks), and abandoned wells. Numerous groundwater contaminated sites have been reported from both natural and anthropogenic activities with extent of plume migration, leading to a degrading quality of groundwater which is unacceptable for safe human consumption. According to our evaluation, the major issues of surface water/groundwater quality in Thailand may be listed as follows: i) nitrate pollution; ii) heavy metal pollution; iii) pathogenic agents; iv) organic pollution (e.g., hydrocarbons and volatile organic compounds; v) salinization; and vi) acid mine drainage. At the national- and regional-scales, studies include the development of Thai National groundwater maps, the assessment of groundwater potential, the assessment of basin yield, storage capacity, flow types and saturated thickness, drought vulnerability, and groundwater quality baseline mapping. Assessing groundwater vulnerability and pollution risk at the large scale is necessary and particularly important for monitoring progress in sustainable development and the implementation of the UN SDGs for water.

In this context, assessing the groundwater vulnerability for pollution is important for designing efficient regional scale groundwater management and protection strategies. When dealing with groundwater vulnerability, a difference can be made between ***specific vulnerability*** and ***intrinsic vulnerability*** [**5**]. Intrinsic vulnerability of an aquifer can be defined as the capacity with which a contaminant introduced at the ground surface can reach and diffuse in groundwater [**6**]. Specific vulnerability, on the other hand, is used to define the vulnerability of groundwater to a particular contaminant or a group of contaminants. For specific vulnerability, specific physic-chemical properties from contaminants should be considered [**7**]. Groundwater pollution risk can be defined as the process of estimating the possibility that a particular event may occur under a given set of circumstances [**8**] and the assessment is achieved by overlaying hazard and vulnerability [**7, 9]**. Several approaches exist for assessing groundwater vulnerability as they can be grouped into methods based on the use of i) process-based simulation models; ii) statistical models; and iii) overlay and index methods [**7, 10, 11, 12**]. Alternatively, they can be classified according to the degree of integration of monitoring data in the vulnerability assessment **[13]**. Hence, distinction can be made between vulnerability assessment methods based on generic data, based on groundwater monitoring data, or hybrid methods based both on monitoring and generic data.

Within the class of generic data based methods, the most established method worldwide is the DRASTIC method [**14, 15]**. The method has been widely used for regional vulnerability assessments in many parts of the world, including USA **[16, 17]**, China **[18]**, Canada **[19**], India **[20]**, Turkey [**21**], Tunisia [**22, 23**], and South Africa [**24**]. The DRASTIC method, as like similar index models, has many advantages: i) the method has a low cost of application and can be applied at the regional scale, because it is based on often easily available generic data [**14]**); and ii) the use of a high number of input data layers is believed to limit the support of errors or uncertainties of the individual data layer in the final output [**25; 26]**. Despite its popularity, the DRASTIC method has as well some disadvantages [**27]**. First, many variables are factored into the vulnerability index. All these factors are not necessarily sensitive for groundwater vulnerability for a particular setting [**6]**. Hence, in many cases vulnerability can be explained with a subset of DRASTIC factors. Second, studies based on DRASTIC method tend to overestimate the vulnerability of porous media aquifers compared to aquifers of fractured media [**26**]. Third, only a few studies have been performed to validate the DRASTIC vulnerability method at the regional scale. Despite these disadvantages, the DRASTIC method can easily be deployed to make continental scale assessment of groundwater vulnerability.

The major attempts in this study are therefore to assess the groundwater vulnerability using the DRASTIC indicator methodology by compilation of the most recent local- to regional-scale information on all major soil, land use, geology, hydrogeology, surface pollution sources, and climate conditions in Geographical Information System (GIS)-based environment in the Central and Northern parts of Thailand where groundwater resources are overexploited and an unknown numbers are experiencing pollution problems and/or degradation of groundwater dependent ecosystems. As some area in the central Chao Phraya region is dominated by high pollution risk classes and this is believed to be strongly related to shallow groundwater systems and the development of agricultural activities. Linear regression statistical analysis between rainfall-groundwater depth and adjusted hydraulic conductivity (***K***) are applied to modify some parameters in the original DRASTIC model. The final original and modified DRASTIC mapping models are validated using observed nitrate data in groundwater as a proxy of vulnerability and pollution risk.

II. MATERIALS AND METHODS

A. *Study Area*

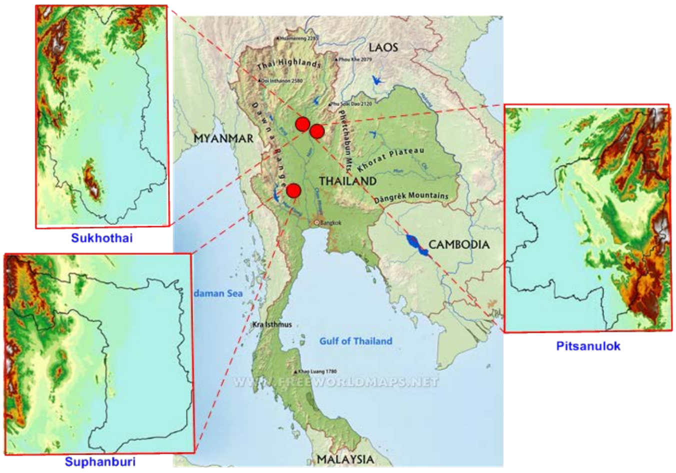


Fig.1 Study Area.

Pitsanulok, Sukhothai, Suphanburi, and Chanchoengsao are the focusing areas selected for this study as illustrated in **Fig. 1**. Sukhothai and Pitsanulok provinces are located in the upper central plain of Thailand covering approximately 18,000 km^2. The main landuse is 63% agricultural, out of which 21% is irrigated and 24% forest. The basin is surrounded in the East and West by volcanic rocks. The average elevation of the basin is 40-60 m above mean sea level. The basin drains into the lower basin in the South where some free discharge is partially obstructed by crystalline rocks. The 900-1,450 mm annual rainfall within the study region is apportioned to 81% in the wet season (April-September) and 19% in the dry season (October-March).

Suphanburi province is approximately 100 km west of Bangkok, the Capital city of Thailand. Topography is mainly flood plain in the east and mountainous areas in the west. Agricultural land covered much of the flood plain in the eastern and southeastern parts of the study area. Approximately 42% of the study area is occupied by forest, 35% by agricultural land, and 23% by others (such as urban areas and water bodies). The major field crops are rice and sugarcane (cover more than 50% of the total agricultural area). Average annual rainfall of 976 mm was reported for the entire province based on 30 years period of data (between 1989-2008) with the peak rainfall in September. **Ramnarong (1993)** [**28**] described that the study area has been hydrologically divided into highland and lowland areas, in which groundwater occurs in several consolidated and unconsolidated aquifers, underlying most of the agricultural lowland. These aquifers consisted of gravel, sand, and clay of deltaic plains, recent alluvial plains, and rolling terraces. Yields of all aquifers in the study area range from 1-50 m^3/yr.

B. *DRASTIC Model*

In the present study, DRASTIC method is employed for evaluating groundwater vulnerability for pollution. The acronym DRASTIC corresponds to the initials of the seven variables that drives vulnerability as defined according to **Aller et al. (1987)** [**14**] and shown in **Table 1**.

The DRASTIC vulnerability index was carried out by the addition of the different products (rating × weight of the corresponding parameter), using the following equation:

$$D_i = D_w D_{r,i} + R_w R_{r,i} + A_w A_{r,i} + S_w S_{r,i} + T_w T_{r,i} + I_w I_{r,i} + C_w C_{r,i} \qquad \textbf{(1)}$$

Table 1 Weight setting for DRASTIC parameters [**14**]

Symbol	Parameter	Weight
$\boldsymbol{D_w}$	Depth to Water	5
$\boldsymbol{R_w}$	Net Recharge	4
$\boldsymbol{A_w}$	Aquifer Media	3
$\boldsymbol{S_w}$	Soil Type	2
$\boldsymbol{T_w}$	Topography	1
$\boldsymbol{I_w}$	Impact of Vadose Zone	5
$\boldsymbol{C_w}$	Hydraulic Conductivity	3

Table 2 Five Classes/Degrees of DRASTIC Vulnerability **[29]**

DRASTIC Index	Vulnerability Class
> 176	Very High
146-175	High
115-145	Moderate
84-114	Low
< 84	Very Low

where $\boldsymbol{D_i}$, is the DRASTIC index; ***D***, ***R***, ***A***, ***S***, ***T***, ***I***, and ***C*** are the seven parameters as defined in **Table 1**; and the subscripts ***r***, ***i*** are ***w*** are the corresponding rating for grid cell ***i*** and weights.

Table 3 Data Sources for DRASTIC 7-Layer Generation

Raw Data	Sources	Format	Resolution/Scale	Date	Output
Groundwater Depths	DGR	Shapefile	1 km	2008	Depth of Water (***D***)
Recharge Data	DGR	Point Measurement	-	2008	Recharge (***R***)
	University of Frankfurt	Shapefile	0.5° × 0.5°		
GLiM	Hamburg University	Geodatabase	1: 3,750,000	2012	Aquifer Media (***A***) and Impact of Vadose Zone (***I***)
Aquifer Media	DGR	Shapefile	1 km × 1 km	2009	
Soil Data	LDD	Shapefile	1 km × 1 km	2009	Soil Type (***S***)
	ISRIC, World Soil Information	Raster	1 km × 1 km	2014	
SRTM90	UCL/Elle-Geometrucs (Belgium) and CGIAR/CSI	Raster	90 m × 90 m	2000	Topography (***T***) or Slope (%)

The weights indicate the relative importance of each DRASTIC parameter with respect to the other parameters. These weights are constant [**30**]. Also, for each DRASTIC parameter, the designated rating varies from 1 o 10. The rating ranges were determined depending on the properties at the specific area of interest. A good knowledge of geology and hydrogeology of the research area is a pre-requisite to determine the ratings assigned in this study were similar to the typical ratings suggested in the original DRASTIC study [**14**]. Finally, for purposes of interpretation, we subdivided the possible values of the DRASTIC index calculated into 5 classes/degrees of vulnerability as shown in **Table 2**.

C. Data Acquisition and Database Compilation

We constructed a GIS database for hydrogeology, geology, soil, groundwater recharge, and topography of the study area. **Table 3** shows the data of the constructed GIS database. We processed all data with ArcGIS 10.2^{TM}, QGIS ^{TM}, and Matlab ^{TM}.

Data came in various spatial resolutions. We re-sampled data layers to be suitable with the proposed resolution of the GIS model. We proposed a 1 km × 1 km (for area with local data) and 15 km × 15 km (for area with global meta data only) resolutions for this study, based on the fact that this resolution was reasonable compromising between different resolutions of the datasets, computing constraints, and regional extent. We obtained the vulnerability maps, after classifying and assigning relative ratings and weights, then overlaying the individual maps in a GIS environment. **Fig. 2** gives an overview of the methodology used to develop the intrinsic groundwater vulnerability map. Each parameter processes in the GIS described below.

D. Development of the DRASTIC Parameters

Depth to Groundwater (D)

The 'Depth to Water Table' (***D***), is the vertical distance from the land surface to the top of the saturated zone in the aquifer. It represents the distance that a potential contaminant must travel before reaching the aquifer. Consequently, ***D*** will have an impact on the degree of interaction between the percolating contaminant and the subsurface materials (air, minerals, water) and, therefore on the degree and extent of the physical and chemical attenuation and the degradation process [**31**]. In general, the vulnerability for pollution should decrease with ***D***. For our study, ***D*** was calculated from the data as presented by 1:50,000 groundwater maps provided by DGR (2008). Some extra groundwater depth data was not continuous and originally obtained from other local studies in a categorical data format.

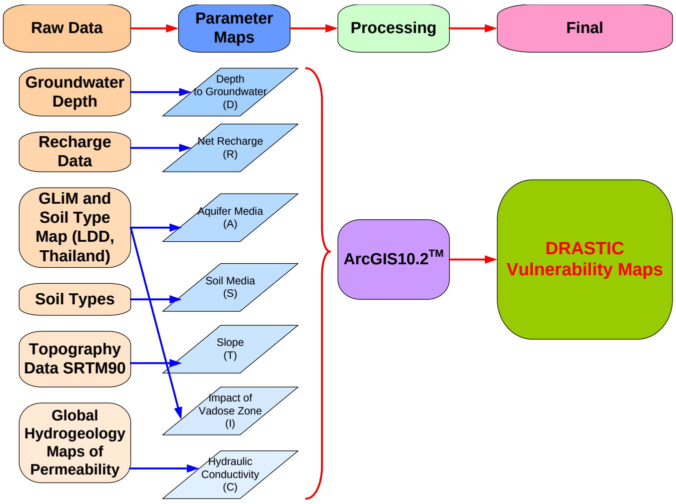


Fig.2 Methodology Flowchart to Develop Groundwater Vulnerability Map with DRASTIC Index Model in GIS Environment.

Table 4 Rate and Weight of 7 DRASTIC Parameters (Modified from **Aller et al. 1987 [14]**)

Depth to Groundwater (m)		Net Recharge (mm)		Topography (%)		Hydraulic Conductivity (m/d)		Soil Media	
Interval	Rating	Interval	Rating	Interval	Rating	Interval	Rating	Soil Classes	Rating
0-7	10	0-45	1	0-2	10	0.0 - 5.00	1	Clay	1
7-25	8	45-123	3	2-4	9	5.01 – 15.00	2	Clay Loam	3
25-50	5	123-224	6	4-8	8	15.01 – 35.00	3	Loam	5
50-100	3	224-355	8	8-12	5	35.01 – 75.00	4	Loamy Sand	7
100-250	2	>355	9	12-18	3	75.01 – 155.00	6	Sandy Clay	2
> 250	1			> 18	1	155.01 – 315.00	8	Sandy Clay Loam	4
								Sandy Loam	6
						> 315.01	10	Silty Clay Loam	3
								Sand	9
Weight = 5		Weight = 4		Weight = 1		Weight = 3		Weight = 2	

Table 5 Rate and Weights (***A***=3 and ***I***=5) of Aquifer Media (***A***) and Impact of Vadose Zone (***I***) (Modified from **Aller et al. 1987 [14]**)

Lithology Classes[32]	Hydrolithology Classes[33]	Bedrock Materials	***A*** and ***I*** Ratings
Unconsolidated Sediments	Unconsolidated		8
	c.g. unconsolidate	Alluvial Deposits, Dune Sands	
	f.g. unconsolidate	Loess (Aeolian Sediment), Organic Sediment	
Siliciclastic Sediments	Siliciclastic Sedimentary	Limestone, Sandstone	6
	c.g. siliciclastic sedimentary	Dolomite, Siltstone, Salt	
	f.g. sedimentary	Conglomerate, Shale	
Mixed Sedimentary Rocks	Carbonate	Karst Limestone	10
Carbonate Sedimentary Rocks			
Evaporites			
Acid Volcanic Rocks	Volcanic	Permeable Basalt	9
Intermediate Volcanic Rocks			
Acid Plutonic Rocks	Crystalline	Igneous/Metamorphic Rocks	A(3) and I(4)
Intermediate Plutonic Rocks			
Basic Plutonic Rocks			
Metamorphic Rocks			
Water Bodies	*Other Rock*	-	8

*Net Recharge (**R**)*

The 'Net Recharge' (***R***) represents the amount of water per unit area of land penetrating the ground surface and reaching the water table. It is thus influenced by the amount of surface cover, the slope of the land surface, the permeability of the soil and the amount of water that recharge the aquifer. The dispersion and dilution of contaminants are known to greatly depend on the volume of water available in the vadose zone as well as in the saturated zone and thus on the net recharge. High recharge areas are definitely more vulnerable than low recharge areas. Net recharge values were mainly derived from the global-scale modeling of groundwater recharge (**34**) assimilated with some local observation data from Department of Groundwater Resources Thailand (DGR).

*Aquifer Media (**A**)*

The 'Aquifer media' (***A***), refers to a type of consolidated or unconsolidated material which hosts the aquifer [**21**]. ***A*** was referred from three main data sources: (1) the high resolution global lithological database (GLiM) [**32**]; (2) the global permeability estimates of **Gleeson et al. (2011) [33]**; and (3) DGR. The analysis of the global permeability has permitted to identify parent material for each hydrolithologic unit. The GLiM databases encompass 16 lithological classes, which we then assumed to represent geology. Aquifer media were determined of each hydrolithology with similar hydrological characteristics **[33]**, e.g., unconsolidated sediments, siliciclastic sediments, carbonate rocks, crystalline rocks, and volcanic rocks. The vulnerability of the aquifer will increase of the grain size and the fractures or openings within the aquifer will increase **[35**].

*Impact of the Vadose Zone (**I**)*

The role of the unsaturated zone above the water table is integrated in the ***I*** parameter. It is an important parameter in the estimation of vulnerability, because it influences the residence time of pollutants in the unsaturated zone, and hence the attenuation probability. Similar to the ***A*** parameter, the method used to identify the vadose zone material depend on GLiM data and the DGR hydrogeological map. The weights and ratings for ***I*** are tabulated in **Table 5**.

*Topography (**T**)*

The 'Topography' (***T***), determines the runoff and infiltration capacity of the surface water into the soil, and hence the capacity to introduce pollutants into the soil. If the slope is important, more runoff will be generated and hence groundwater contamination risk will be low. However, flat areas tend to retain water for a longer period, therefore increasing the potential for migration of contaminants. The ***T*** was inferred from the 90 m Shuttle Radar Topography Mission (SRTM90) database. The slope values were generated with the SRTM 90 by using the Spatial Analyst software of ArcGIS10.2^{TM}. The slope layers were re-sampled and re-classified with the ratings into 6 classes.

Soil Media (S)

Soil is the first media the contaminant passes through when it percolates into the ground, and thus has a significant impact on the amount of recharge that can infiltrate and the ability of a contaminant to vertically penetrate into the vadose zone [**36]**. For this study, the soil map of Thailand was inferred from the data officially collected by Land Development Department in 2009

*Hydraulic Conductivity (**C**)*

The 'Hydraulic Conductivity' (***C***), is a measure of the ability of the aquifer to transmit water when submitted to a hydraulic gradient. It determines the migration velocity of pollutants, and hence the residence time and attenuation potential. High conductivity values usually are associated to higher contamination risks **[31]**). We inferred the hydraulic conductivity map generated from the global hydrogeolgical map of permeability and porosity [**33]** and 1:50,000 hydrogeological map of parts of Thailand (DGR). The global permeability map is generally given in log values of permeability (***k***). The hydraulic conductivity (***K***) can be calculated from the **Equation 2** below.

$$K = \frac{k\rho g}{\mu} \qquad \textbf{(2)}$$

where ***K*** (m/s) is hydraulic conductivity which depends on fluid viscosity and density; $\boldsymbol{\rho}$ (kg/m^3) is the fluid density (= 999.97 kg/m3 for water), ***g*** (m/s^2) is the acceleration due to gravity (= 9.8 m/s^2); and $\boldsymbol{\mu}$ (kg/m-s or Pa-s) is the viscosity of the fluid.

E. Validation using Local Spatially Distribution Patterns of Observed Nitrate

DRASTIC indicator model proposed above is an indirect way for evaluating vulnerability and pollution potential of groundwater systems at a regional scale. This method heavily relies on accessible generic data and should therefore be validated. Indeed, the use of methods that are not validated can result in erroneous conclusions and subjective vulnerability assessment [**37]**. However, since intrinsic and vulnerabilities only measure the likelihood that groundwater systems may be degraded, or become degraded in the future, it cannot be measured directly ***in-situ***. This challenges the empirical validation of vulnerability mapping (**38**).

In this study, we compare the vulnerability patterns with proxies of vulnerability that can be measured ***in-situ*** using the degradation of groundwater quality by nitrates from agriculture activities and urban development. Also, main groundwater monitoring programs in Thailand always include nitrate as a monitoring parameter, and therefore nitrate contamination are commonly available at the regional scale. The spatial distribution patterns of nitrate in groundwater are therefore presumably closely related to the spatial patterns of anthropogenic activities and are thus reasonable proxies for the spatial patterns of overall vulnerability. Existing groundwater nitrate contamination data in Suphanburi province were collected from more than 160 groundwater samples, most of which surrounding heavily fertilization crop lands. The validation of the groundwater vulnerability map was accomplished through the nitrate distribution analysis and the vulnerability classes. ArcGIS10.2^{TM} was employed to distribute spatially and compared with the various degrees of DRASTIC vulnerability maps.

III. RESULTS AND DISCUSSIONS

A. Rating of DRASTIC Parameters and Aquifer Vulnerability

Ratings and weights of each parameter of DRASTIC are illustrated in **Tables 4 and 5**, with scales varying from 1 to 10. The higher the number, the greater the pollution we should expect.

The ***D*** map is show in **Fig.3** generated with values ranged from 0 to shallow groundwater depth and deeper groundwater depth. The shallow groundwater depth areas are more susceptible to contamination according to DRASTIC assumptions. The high values of ***D*** are located in large sedimentary aquifer which contains a considerable proportion of Thailand's groundwater. The assigned ***D*** ratings vary between 1 and 10, according to the classification of **Aller et al. (1987) [14]**. The highest scores of 9 and 10 are assigned where the depths are in the class 0-7 m and 7-25 m, respectively. The lowest depths are assigned with a rating of 1.

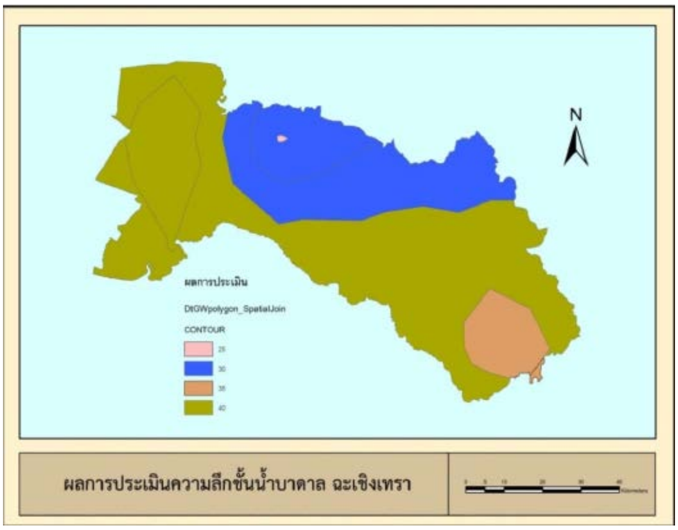


Fig. 3 DRASTIC Rating of the Depth to Groundwater (***D***) in Chachoengsao Province of Thauiland

The ***R*** map is illustrated in **Fig. 4** which was generated and later layered up to construct the final DRASTIC map. Pitsanulok, Sukhothai, and Suphanburi have areas with low net recharge rate (< 50 mm/year) for which a rating of 1 is assigned, and other areas with high recharge ranges (> 225 mm/year), for which a rating of 9 is assigned,

The ***A*** map is also shown in **Fig. 5**. The ratings in **Table 5** are assigned as commonly found in previous studies. A rating of 10 is assigned to high permeable rock/porous media. The major aquifer media in the study area is unconsolidated sediments (i.e., clay, sand, and gravel), which is assigned a rating of 8 (**39**). A low rating of 3 is assigned to crystalline rocks, fractured igneous and other metamorphic rocks in the area.

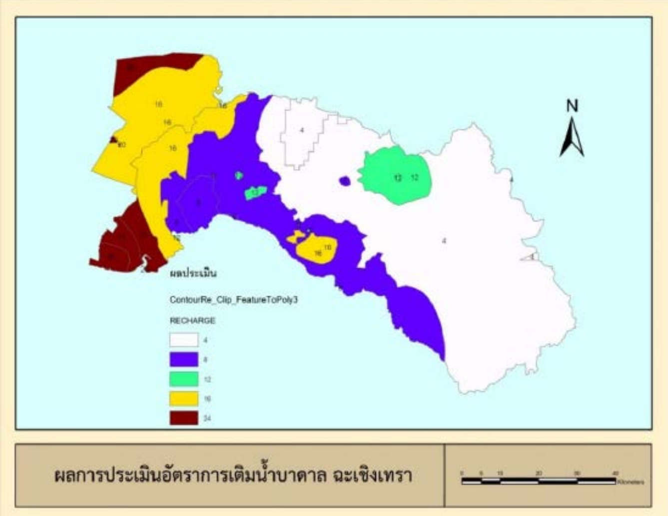


Fig. 4 DRASTIC Rating of the Recharge (***R***) in Chachoengsao Province of Thailand

Fig. 5 DRASTIC Rating of the Aquifer Media (***A***) in Chachoengsao Province of Thailand

The texture based ***S*** map is represented in **Fig. 6**. Soils are mapped in 7 different classes. The dominant textures at the representative sites are sandy clay, loam and clay loam. The silty clay and sandy soil types appear in a lower proportion. The highest rating of 9 is assigned to the sandy soil and the lowest rating of 1 to the clayey soil. There is no information available on soils in some parts of the study areas, thus these parts were left 0.

The ***T*** map representing the surface slope is shown in **Fig. 7**. A gentle slope of 0-4% is dominating the largest portion of Pitsanulok and Sukhothai, and therefore a rating score of 9 and 10 is assigned to this class, indicating that there is a large susceptibility of pollution infiltration. The highest slopes are located in the mountainous proximity in Suphanburi area where larger slopes of 18% can be found, leading to the minimal potential effects on the groundwater vulnerability.

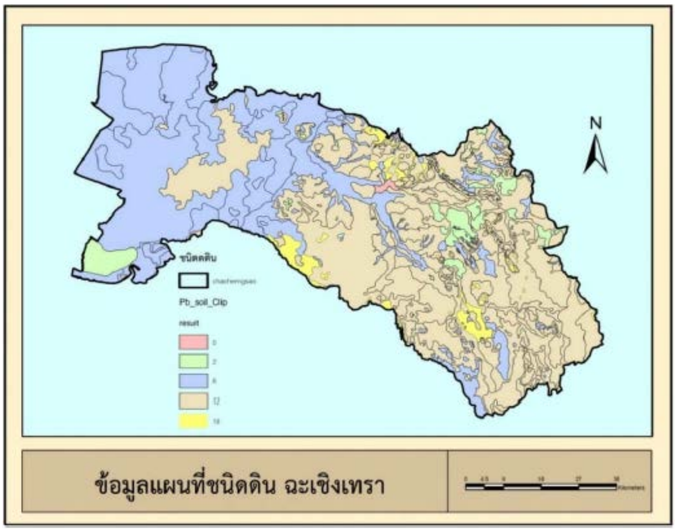


Fig. 6 DRASTIC Rating of the Soil Type (***S***) in Chachoengsao Province of Thailand

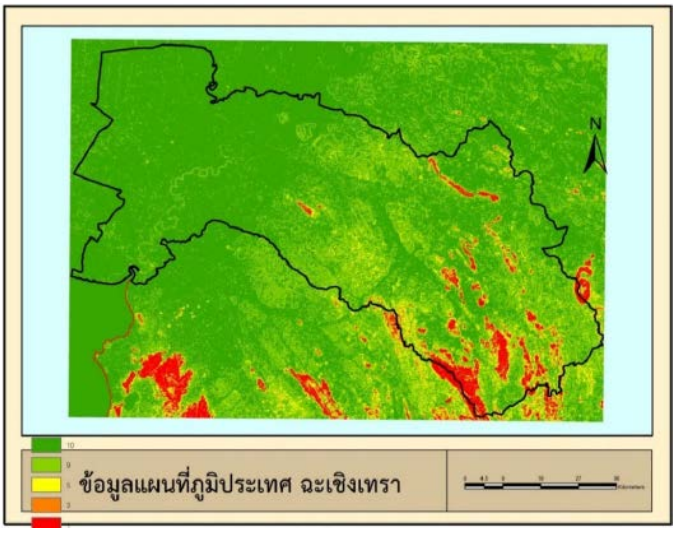


Fig. 7 DRASTIC Rating of the Topography/Slope (***S***) in Chachoengsao Province of Thailand

The ***I*** map is presented in **Fig. 8**. The data used for this purpose is basically the same set of data for generating the ***A*** map. Although the same hydrolithology is employed for both ***A*** and ***I*** parameters, the final maps turned out differently because the crystalline rocks (igneous/metamorphic rocks) of the vadose zone are assigned a rating of 4 for ***I*** **[14]**. Weights and ratings for ***I*** are shown in **Table 4**.

The ***C*** map is shown in **Fig. 9**. The hydraulic conductivity calculated is inferred both from global permeability database and local permeability measurements and has been classified into 6 classes. In general, the variability of C parameter is not high. Lowe hydraulic conductivity values, as low as 0.01 m/d, can be commonly found in the study area. The averaged hydraulic conductivity range is between 0.04 to 0.13 m/d.

The resultant DRASTIC map is shown now in **Fig. 10**. DRASTIC classes have been grouped into very low, low, moderate, high, and very high vulnerability intervals. We observed a very low and low vulnerability in the Western part of the province where large sedimentary basins are found with high recharge rates. Indeed, the absence of important anthropogenic activities should be in combination with very low and low contamination risks. In general, high vulnerability areas are lower-land where intensive agricultural activities and urban development are concentrated. On the other hands, a region with low vulnerability degree does not really mean that it is free from groundwater contamination, but it rather represents relatively less susceptible to contamination compared with other regions.

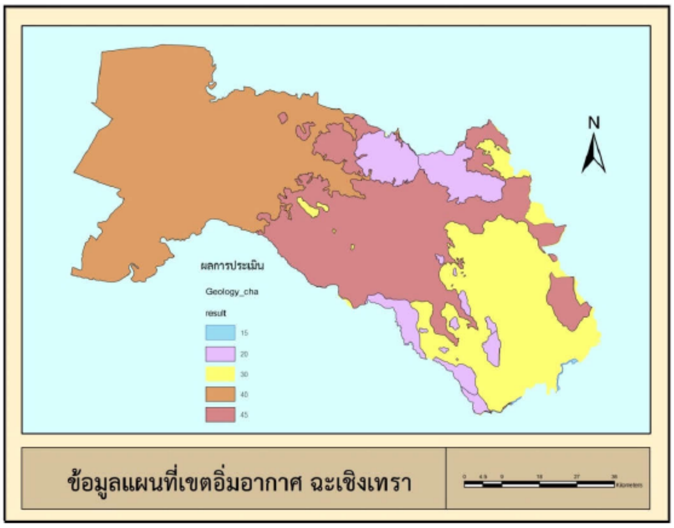


Fig. 8 DRASTIC Rating of the Impact of Vadose Zone (***I***) in Chachoengsao Province of Thailand

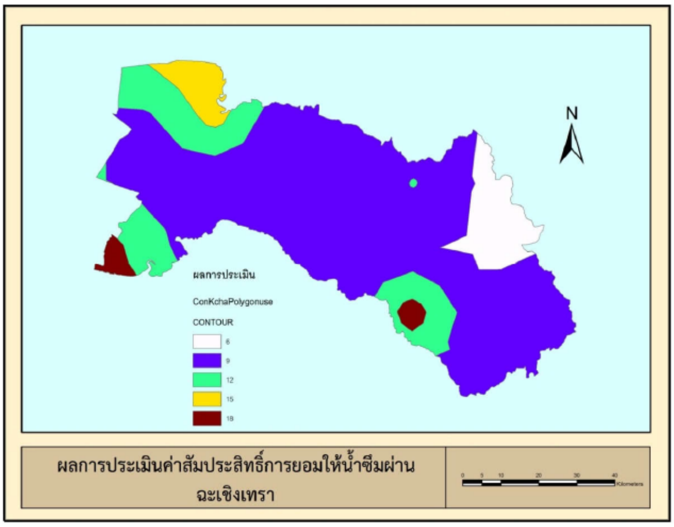


Fig. 9 DRASTIC Rating of the Hydraulic Conductivity (***C***) in Chachoengsao Province of Thailand

The intrinsic vulnerability map in **Fig. 10** indicated that the representative study areas are dominated by very high and high intrinsic vulnerabilities. The shallow groundwater depths in these regions along with high recharge rate explain this high intrinsic vulnerability. In the northeastern part of Chachoengsao has been characterized as low intrinsic vulnerability due to its deeper groundwater depth and very low recharge rates. The topography parameter had the highest impact for assessing the intrinsic vulnerability of our study area. The impact of vadose zone, the aquifer media, and depth to groundwater had a moderate mean rating value. The soil media, net recharge, and hydraulic conductivity play the least important roles in quantifying vulnerability based on DRASTIC indexing method.

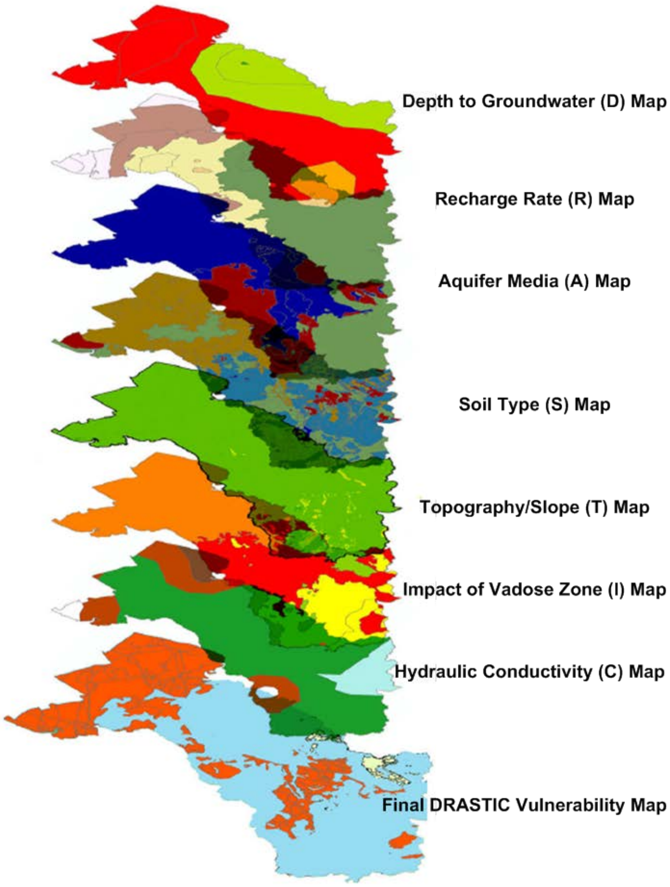


Fig. 10 Final DRASTIC Vulnerability Map in Chachoengsao Province of Thailand

B. Validation of the Groundwater Vulnerability Map

Spatial Concentrations of Nitrate

The spatial distribution of nitrate in groundwater in Suphanburi province is illustrated in **Fig. 11**. More than 160 long-term groundwater samples were collected from domestic and monitoring wells at various depths (100 samples from < 30 m deep, and 60 samples from > 30 m deep) and analyzed. Samples were carefully preserved and transported back for further chemical parameter analyses at a certified analytical laboratory in Bangkok. The environmental parameters include: total hardness as $CaCO_3$, non-carbonated hardness as $CaCO_3$, total dissolved solid, BOD, alkalinity, Fe, Mn, Cu, Zn, SO_4, Cl, F, nitrate (NO_3^-), As, CN^-, Pb, Hg, Cd, Se, Hexavalent Cr, and Ni. Nitrate spatial distribution patterns were processes in ArcGIS environment.

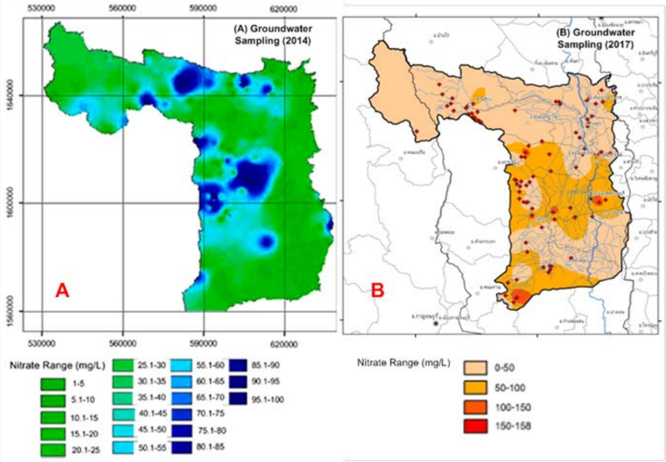


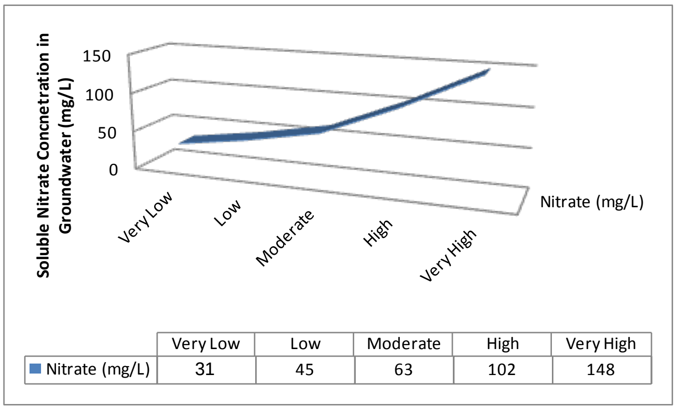
Fig. 11 Extent of the Spatial Soluble Nitrate Contamination in Groundwater in Suphanburi Province: (A) Data from Groundwater Sampling in 2014; and (B) Data from Recent Groundwater Sampling in 2017.

The distribution of nitrate in groundwater in Suphanburi province indicated that there were abundant of soluble nitrate detected in aquifer systems underneath Suphanburi. Areas that were subjected to the most severe contamination are U-Thong (central part of Suphanburi) and Song-Pee-Nong (southern part of Suphanburi). Also in this work, groundwater samples were taken to evaluate the extent of nitrate contamination in Suphanburi (from the same municipal wells and monitoring wells previously sampled). The current spatial distribution of nitrate in groundwater is compared with the results previously examined as shown in **Fig. 11**.

Since naturally occurring concentration of nitrate are generally less than 2 mg/L nitrate N, nitrate concentration detected in the environment greater than 2 mg/L should ne consider anthropogenic-origin. Using the nitrate MCL at 45 mg/L, the results in **Fig. 11** indicate that the extent of nitrate contamination in groundwater has actually been expanding in 3 years time span from 2014 to 2017. Some nitrate hotspots, particularly in Song-Pee-Nong (southern part of Suphanburi), Nong-Ya-Sai (north part of Suphanburi), and Dan-Chang (north western of Suphanburi), are disappeared and nitrate concentration detected in groundwater is below 45 mg/L. However, the majority of nitrate former hot spots still noticeably exist with nitrate concentrations as high as 100 mg/L, i.e., in Derm-Baang-Nang-Buad and U-Thong. To make the story worse, the new nitrate hot spots with extremely high concentrations up to 158 mg/L are observed based on the investigation in this work as can be seen in Muang and Southern Song-Pee-Nong districts shown in **Fig. 11**.

Regression of Aggregated Nitrate Concentration Data with Intrinsic Vulnerability of Groundwater in Suphanburi

The authors also further aggregated the observed maximum nitrate concentration for each vulnerability class and compared it with vulnerability degree. In this approach, DRASTIC index has been used as surrogate of the vulnerability map and regressed against the extracted nitrate concentration. **Fig. 12** illustrates that the aggregated maximum nitrate concentration data are positively correlated to the intrinsic vulnerability (R^2 = 0.89), suggesting that the generic model for mapping vulnerability in groundwater is consistent with observed nitrate inferred from the literature. We chose the maximum nitrate concentrations as aggregate values in order to show the performance of groundwater vulnerability model because the sample size may not be large enough for single measurement validation. The aforementioned results suggest that further validation using more extensive data set is recommended.



	Very Low	Low	Moderate	High	Very High
■ Nitrate (mg/L)	31	45	63	102	148

Fig. 12 Correlation between Maximum Nitrate Concentration and DRASTIC Vulnerability Level with R^2 = 0.89.

IV. CONCLUSIONS

We assessed the intrinsic vulnerability of Thailand's groundwater vulnerability to pollutions. The empirical index model DRASTIC was employed in GIS environment to provide an effective analysis environment and a strong capacity for handling large amounts of spatial data. We identified 7 environmental DRSTIC parameters: Depth to Groundwater (***D***), net recharge (***R***), aquifer media (***A***), soil media (***S***), topography (***T***), impact of vadose zone (***I***), and hydraulic conductivity (***C***) from available generic global data assimilated with sparse local observations. We classified and coded these main geo database to create an intrinsic groundwater vulnerability map, resulting in DRASTIC index varies between 66 and 213. DRASTIC index were further classified into 5 classes/degrees, ranging from very low; low; moderate, high, and very high.

Despite the lack or very limited groundwater contamination data in Thailand, we attempted to validate our intrinsic vulnerability assessment using soluble nitrate concentration data as proxies for groundwater vulnerability. Potential effects of nitrate on the quality of surface water and groundwater as well as the implications of such effects on human health (especially to children), pose issues of international concern that require science-based assessment and response. Suphanburi is selected as our tested area due to the previous reports on surface and subsurface nitrate contamination. Recent evidence from this study indicates that nitrate levels exceed the maximum contaminant level (MCL) of 45 mg/L in aquifer systems that underlie agriculture-dominated area with the maximum soluble nitrate concentration up to 158 mg/L near Muang and Southern Song-Pee-Nong districts. Nitrate hotspots have been re-identified based on the more recent discovery. 30% of shallow groundwater samples (< 30 m) are detected with higher nitrate concentration than MCL whereas only 23% of groundwater samples taken from > 30 m deep are found contaminated, suggesting the direct association major nitrate contamination in groundwater aquifer with potential source on the ground surface. High nitrate concentrations detected from our investigations coincide with high intrinsic vulnerability based on the vulnerability map of Suphanburi generated from empirical DRASTIC index method, illustrating the consistency between the calculated vulnerability using generic data and real observation. DRASTIC vulnerability assessment procedures and vulnerability maps generated as outputs from this work can improve effectiveness and efficiency of potential national groundwater management and monitoring programs. The vulnerability map at the national-scale is necessary to achieve SDGs in the context of SDG 6, SDG 1, SDG 2, SDG 5, SDG 11, SDG 13, and SDG 15 as it can serve as a general guideline for sustainable groundwater use through policy recommendation and implementation related to proper monitoring, management and governance that employs integrated and precautionary approaches while giving appropriate attention to the potential boundary nature of groundwater.

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