วิศวกรรมสารฉบับวิจัยและพัฒนา
Engineering Journal of Research and Development
วิศวกรรมสถานแห่งประเทศไทย ในพระบรมราชูปถัมภ์
The Engineering Institute of Thailand under H.M. The King's Patronage

ปีที่ 30 ฉบับที่ 4 ตุลาคม-ธันวาคม 2562
Volume 30 Issue 4 October-December 2019
Received 28 January 2019
Revised 21 March 2019
Accepted 31 March 2019 Physical Sciences

PRELIMINARY ASSESSMENT OF SEAWATER INTRUSION ON PHUKET ISLAND USING GROUNDWATER DATA ANALYSIS AND GEOGRAPHIC INFORMATION SYSTEM (GIS) TECHNIQUES

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บทคัดย่อ

การรุกล้ำของน้ำทะเลสู่แหล่งน้ำใต้ดินเป็นปัญหาสำคัญที่จะนำมาซึ่งการขาดแคลนน้ำจืดในอนาคต วัตถุประสงค์หลักสำหรับงานวิจัยนี้เพื่อประเมินปัญหาการรุกล้ำของน้ำทะเลสู่แหล่งน้ำใต้ดินในพื้นที่ชายฝั่งของเกาะภูเก็ต แผนที่แสดงการรุกล้ำของน้ำทะเลสำหรับเกาะภูเก็ตจะถูกสร้างขึ้นจากการวิเคราะห์ข้อมูลทางเคมีของน้ำใต้ดินที่ได้จากการบ่อน้ำใต้ดินที่ขุดขึ้นเพื่อผลิตน้ำใต้ดินสำหรับอุปโภคและบริโภค ความเข้มข้นของสารคลอไรด์และปริมาณของของแข็งที่แขวนลอยหรือละลายอยู่ในน้ำใต้ดินจะถูกใช้นำมาวิเคราะห์เป็นตัวแปรสำคัญสำหรับการประเมินการรุกล้ำของน้ำทะเล ความสัมพันธ์ระหว่างค่าเฉลี่ยของสารคลอไรด์และปริมาณของของแข็งที่แขวนลอยหรือละลายอยู่ในน้ำใต้ดินใน 8 ตำบลพื้นที่ศึกษาชายฝั่งของเกาะภูเก็ต (ตำบลฉลอง ตำบลราไวย์ ตำบลกะรน ตำบลกมลา ตำบลไม้ขาว ตำบลเชิงทะเล ตำบลศรีสุนทร และตำบลเทพกษัตรี) จะถูกวิเคราะห์เพื่อประเมินปัญหาการรุกล้ำของน้ำทะเลสู่แหล่งน้ำใต้ดิน แผนที่แสดงการรุกล้ำของน้ำทะเลที่ถูกสร้างขึ้นจะสามารถระบุพื้นที่ความเสี่ยงต่อปัญหาการรุกล้ำของน้ำทะเล (พื้นที่ที่มีสารคลอไรด์มากกว่า 600 มิลลิกรัมต่อลิตรและปริมาณของของแข็งที่แขวนลอยหรือละลายอยู่ในน้ำใต้ดินมากกว่า 1,500 มิลลิกรัมต่อลิตร) แผนที่การรุกล้ำของน้ำทะเลของเกาะภูเก็ตถูกสร้างด้วยวิธีการทางระบบสารสนเทศภูมิศาสตร์โดยมีข้อมูลการใช้น้ำใต้ดินและค่าสัมประสิทธิ์ของการไหลเป็นตัวแปรเสริม แผนที่แสดงให้เห็นว่าพื้นที่ชายฝั่งของตำบลไม้ขาวเป็นพื้นที่ที่มีความเสี่ยงสูงสำหรับการเผชิญปัญหาการรุกล้ำของน้ำทะเล ขณะที่ชายฝั่งพื้นที่ตำบลกมลา ตำบลราไวย์ และตำบลฉลองเป็นพื้นที่เสี่ยงปานกลาง ส่วนพื้นที่ศึกษาที่เหลือเป็นพื้นที่มีความเสี่ยงต่ำหรือยังไม่พบปัญหาการรุกล้ำของน้ำทะเลของเกาะภูเก็ต

คำสำคัญ: การรุกล้ำของน้ำทะเล; การวิเคราะห์ข้อมูลน้ำใต้ดิน; ความเข้มขนสารคลอไรด์; ปริมาณของของแข็งที่แขวนลอยหรือละลายอยู่ในน้ำใต้ดิน; ระบบสารสนเทศภูมิศาสตร์

ABSTRACT

Seawater intrusion can gradually cause a severe problem by contaminating freshwater aquifers and causing a lack of fresh water. The main purpose of this study was to assess the seawater intrusion problem in the coastal area of Phuket. To map the seawater intrusion, an analysis of existing groundwater chemistry data (2003-2016), obtained from groundwater producing wells and monitoring wells, was carried out. Chloride (Cl) concentration and Total Dissolved Solids (TDS) were the two main indicators of seawater intrusion. The average Cl concentration and TDS are highly correlated in a cross-plot in 8 sub-districts (Chalong, Rawai, Karon, Kamala, Mai Khao, Choeng Thale, Sisunthon and Thep Krasattri) of Phuket, and the risk areas with seawater intrusion problem were identified by these levels exceeding threshold (600 and 1,500 mg.L^{-1} for Cl concentration and TDS, respectively). A map of Phuket seawater intrusion was created by GIS techniques, by overlaying the based maps for Cl, TDS, groundwater extraction, and transmissivity. The map indicates that the coastal area in the northern part (Mai-Khao) have serious seawater intrusion, while the coastal areas of Kamala, Rawai, and Chalong, close to the middle and the southern part have only moderate seawater intrusion.

KEYWORDS: Seawater intrusion, Groundwater data analysis, Chloride (Cl) concentration, Total dissolved solids (TDS), GIS

1. Introduction

Phuket Island is a well-known tourist attraction in Thailand, with around 9 million visitors in 2013 and growth rate of approximately 100,000 visitors/year (unpublished tourist data from the Department of Tourism, Thailand) [1]. The rapid increases in population, tourism, and economic growth have severely increased water demands in the Phuket area. In Phuket, the water supply source is 68% groundwater and 32% surface water. Overuse of groundwater near the coast contributes to intrusion by seawater. Consequently, the groundwater close to the coast shows a relatively high salinity. Seawater intrusion is globally a common problem in the coastal areas by the sea. It is normally caused by prolonged changes in coastal groundwater levels, and seawater intrusion is the main cause of high groundwater salinity, bringing with it also high TDS. In addition, the reduction in fresh groundwater of a coastal aquifer results in the freshwater-seawater interface moving inland, to previously freshwater areas [2-4]. The balance between freshwater and seawater on Phuket, with intrusion from the Andaman Sea, has been disturbed by excessive pumping to meet the water demands rapidly increased by tourism. This study mainly utilized unpublished groundwater data (2003 - 2016) from the Department of Groundwater Resources (DGR) of Thailand, and the analyzed water chemistry data, i.e. TDS and chloride concentrations, for 67 groundwater producing wells and 11 monitoring wells on Phuket. The main purpose of this study was to assess the groundwater quality and to identify seawater intrusion into the groundwater of Phuket. GIS techniques were applied to the water chemistry data for mapping the areas characterized by a high level of groundwater salinization, where the presence of seawater had strongly increased both TDS and chloride concentration.

1.1. Phuket Geological Setting and Hydrogeology

Phuket shown in figure 1a is a largely sized island with approximately 70% of its area covered by mountains stretching from North to South, and 30% of flat plain areas, mainly in the middle and eastern parts of the island. It is located in the Andaman Sea, on the West side of peninsular Thailand. Geographically, there are no main rivers, but there are nine brooks and creeks. The western coast has stretches of mountain and white sandy beaches, and the highest point is at Mai-Sip-Song, 529 m above the mean sea level (MSL). The eastern part is dominated by muddy soil and mangrove forests. The total forest area is around 307.90 km^2, contributed by 9 forests and 7 mangrove forests (192,437 Rai, 2007 – 2009). Phuket is located at 7°53′24″N and 98°23′54″E and the total area is 576 km^2 (including the province's other islands). Basically, Phuket is geologically composed of igneous rock (granite and granodiorite) in the western part, and of sedimentary rock (mudstone and conglomerate) in the central part [5-6]. The geological setting of Phuket is naturally formed through a tectonic setting in the southern part of Thailand and has a major fold with intrusive granite in the North-South direction. Phuket has both a fold produced by granite intrusion in the Cretaceous age and a fault caused by the convergent boundary of a tectonic plate, creating a subduction zone in the Andaman region. Quaternary sediments in this area have accumulated unexpected geomorphology variations in the recent neo-tectonic age [7].

Rainfall is the main source of fresh water supply, with high rainfall intensity. The mountains covering 70% of the island cause rains all years around, with both southwest and northeast monsoons. The distribution of monthly average rainfall in Phuket province was assessed for the five years 2007-2011. Rainfall is the highest during the rainy season from April to November, while the summer lasts from December to March [8]. The total annual amount of rainfall in all river basins (25 river basins) in Thailand is estimated to be 800,000 million m^3. The groundwater is stored in several consolidated rock aquifers (47%), unconsolidated rock aquifers (24%), and intercalations between consolidated and unconsolidated rock aquifers (29%). Based on unpublished borehole data, Phuket's subsurface has been categorized into 3 main layers as shown in figure 1: (1) topsoil, (2) weathered and fractured granite and (3) granite as bedrock. Phuket's aquifer is considered as an unconfined aquifer which the main water table is possible to increase and decrease through the saturated zone. The main aquifer layer of Phuket is the weathered or fractured granite. Fractured granite, moreover, is solid rock layer where groundwater is found in fractures, joints or cracks in the rock. The fractured aquifer can be found in many different types of rocks including granite and basalt. Aquifer may contain fresh, brackish or salty water in volumes ranging from minor to large [9]. The highest groundwater potential is located in Tepkrasattri district, Thalang city, and this potential aquifer is divided into haft of sedimentary and metamorphic rock in the range of 240 – 720 m^3/day at depths from 20 to 40 m, sand beach sediment 120 – 240 m^3/day at depths from 2 to 4 m, alluvial sediment with the range of 48 – 240 m^3/day at depths 10 – 25 m, and gravel (mountain fragment) sediment with 120 – 360 m^3/day at depths 20 – 30 m, as shown in figure 1b and 1c. Sea level rise caused by global warming might become a root cause for seawater trying to enter the freshwater aquifers. The rise of sea level could also lift the entire aquifer and this lifting would help alleviate the overall long-term impacts of seawater intrusion. There has been a gradual rise of Andaman mean sea level from 1992 to 2016 at the rate of around 4.2 mm/year [10].

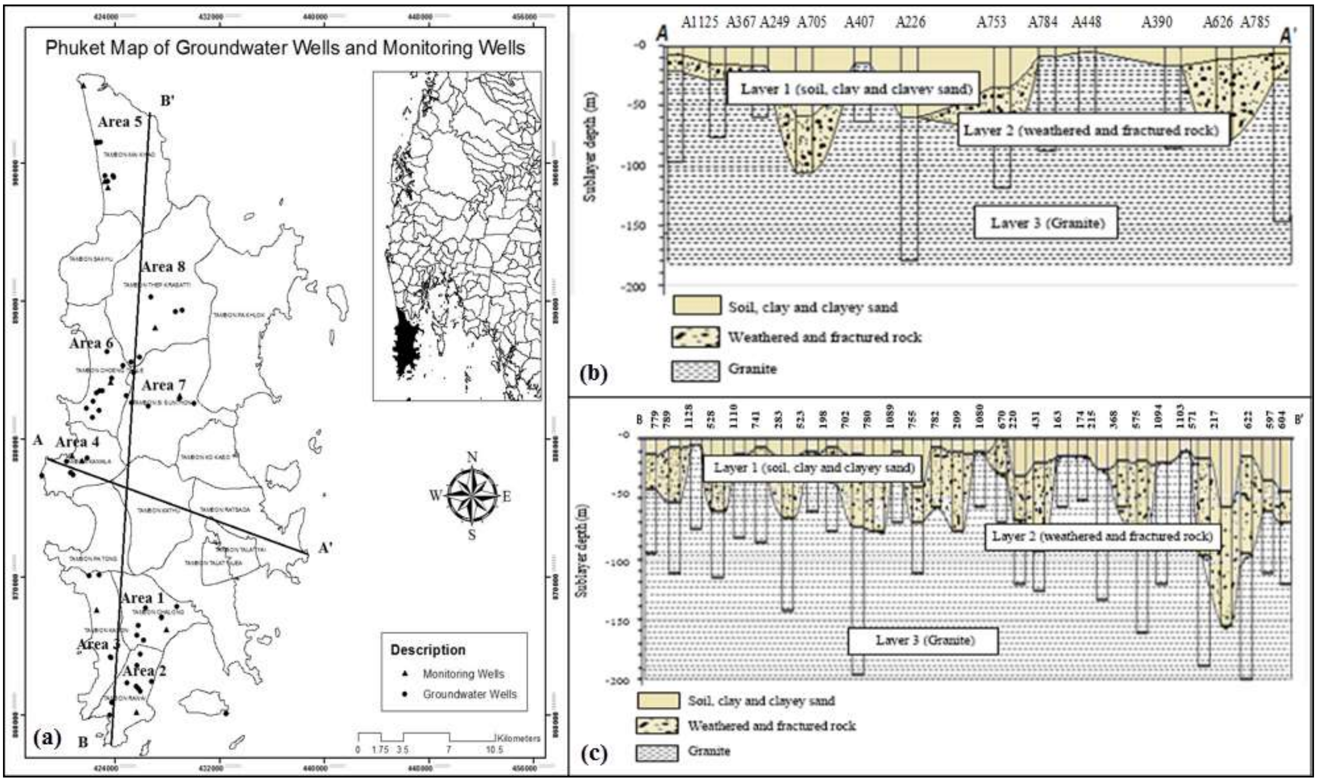

Figure 1 Phuket map (a) monitoring wells and groundwater wells); (b) the cross-sections AA' (east-west); (c) BB' (north-south) along which thickness of aquifer has been surveyed

1.2. Phuket Groundwater Situation

Groundwater pumping rate in Phuket remained steady at just over 1,000 m^3/day from 2006 to 2012, followed by a significant rise to approximately 55,000 m^3/day in 2016, and the increasing trend is expected to continue. It is evident that the average groundwater consumption on Phuket increased continuously from 2006 to 2016. On the other hand, the level of groundwater in Phuket gradually decreased during 2006-2009, then remained constant from 2009 to 2011 before steeply increasing up to now. That the Phuket groundwater level increased despite its high extraction rate likely implies seawater intrusion [11].

2. Assessment of Phuket Seawater Intrusion

This study utilized mainly existing groundwater data acquired by the Department of Groundwater Resources of Thailand in Phuket province, Thailand. Groundwater samples were taken from the field and were analyzed for anions and cations in the laboratory, including Cl, TDS, and groundwater level in groundwater producing wells and monitoring wells. Transmissivity data were obtained only for the groundwater producing wells, while groundwater extraction data were obtained from the monitoring wells for 3 years (2014-2016). The other information, i.e. the distance from monitoring wells to the sea and hydraulic conductivity, are used to support the assessment result to be discussed in section 3.2. Areas of assessment fall into 8 sub-districts, namely Chalong (No.1), Rawai (No.2), Karon (No.3), Kamala (No.4), Mai-Khao (No.5), Choeng-Thale (No.6), Sisunthorn (No.7), and Thep-Krasatti (No.8), as shown in figure 1a. Chloride concentration and TDS are the two main chemical indicators of seawater intrusion problem on Phuket. The mapping of seawater intrusion was done using GIS technique, in order to show the high-risk areas for seawater intrusion on Phuket. Details of the methods in this research are discussed next.

2.1. Data Collection

The groundwater data for analyzing seawater intrusion was obtained from the Department of Groundwater Resource (DGR). It is categorized into two main types of yearly datasets covering 3 districts (Kathu, Thalang, and Mueang) on Phuket. The first dataset is for groundwater producing wells (wells No. A1-67) and another dataset represents the monitoring wells (wells No. B1-11). The Cl and TDS concentration data come from 67 groundwater producing wells (from 2003 to 2010) and from 11 network monitoring wells (from 2012 to 2016). The groundwater extraction data in those eight areas were also gathered from monitoring well data during 2014-2016, while the transmissivity data were taken from both producing and monitoring wells from 2003 to 2016. They are used as considering factors causing seawater intrusion. In addition, the transmissivity parameter from pumping test data was considered as a supplement factor for analyzing seawater intrusion problem in Phuket. The transmissivity and groundwater extraction data are shown in Table 1.

2.2. Groundwater Data Analysis

2.2.1. Historical TDS and Chloride Concentration

Cl and TDS concentration data of the entire Phuket were averaged to plot the time series during 2003 – 2016. Cl concentration and TDS were assessed for yearly data on each district in Phuket. Seawater intrusion problem is here defined by thresholds: TDS of the groundwater exceeds 1,500 $mg.L^{-1}$, and drinking water should have Cl concentration less than 600 $mg.L^{-1}$ [12].

2.2.2. Correlation between TDS and Cl Concentration

Waters with TDS in the ranges 1-1,000 $mg.L^{-1}$, 1,000-10,000 $mg.L^{-1}$, 10,000 -100,000 $mg.L^{-1}$ and lastly above 100,000 $mg.L^{-1}$, are generally labelled as fresh, brackish, saline, and brine water, respectively [13]. In addition, according to Drinking Water Quality Standard in Thailand (DWQST), the maximum allowable concentration of Cl and TDS for freshwater should be smaller than 600 $mg.L^{-1}$ and 1,500 $mg.L^{-1}$, respectively [14]. However, TDS is just a measurement of the combined contents of both inorganic and organic substances, contained in a liquid in molecular, ionized or micro-granular suspended form. High concentration of Cl contributes to high TDS. Cross-correlation of these quantities was analyzed to better distinguish between seawater and groundwater. The high correlation of TDS and Cl concentration indicates the area is strongly affected by seawater intrusion. Cross-plots of average

Table 1 Monitoring well data

Study Areas	ID	UTM-XY	Groundwater Extraction (m^3/day)	Groundwater level (m)	Cl ($mg.L^{-1}$)	TDS ($mg.L^{-1}$)	Hydraulic Conductivity (m/h)	Distance from sea (m)	Year
Area 1 (Chalong)	B10	427899 86612	379.50	2.09	1750	3480	0.0063	943	2014
			427.08	2.43	1710	3325			2015
			367.17	2.60	1720	3380			2016
Area 2 (Rawai)	B11	425630 860102	524.33	3.10	3200	5955	0.0030	726	2014
			581.25	3.45	3200	6085			2015
			594.42	4.41	3200	6035			2016
Area 3 (Karon)	B9	422544 867537	1613.50	5.45	28	151	0.0065	508	2014
			1855.25	6.07	35	179.5			2015
			2143.42	9.28	23.5	177.5			2016
Area 4 (Kamala)	B3	420666 878738	452.75 (2014) 444.50 (2015) 480.75 (2016)	2.23	5720	10790	0.0059	185	2014
				2.39	5670	10850			2015
				2.65	5665	10675			2016
	B8	421464 878738		1.36	19	177.5		946	2014
				5.11	19.5	288			2015
				1.80	24	285			2016
Area 5 (Mai Khao)	B4	423191 898623	2039.92 (2014) 1915.92 (2015) 2115.83 (2016)	1.61	305	858	0.0049	458	2014
				2.24	320	892			2015
				2.47	305	852			2016
	B5	423426 898623		0.60	1800	3790		300	2014
				1.26	650	1510			2015
				1.34	540	1250			2016
	B6	421559 905609		1.96	17000	29750		180	2014
				1.86	10200	18650			2015
				2.15	10800	20000			2016
Area 6 (Choeng Thale)	B1	423630 884067	920.00	1.88	11.5	127.5	0.0048	1640	2014
			1096.83	1.74	10.5	123.5			2015
			1071.25	2.40	11	129			2016
Area 7 (Sisunthon)	B2	428895 883097	470.00	7.75	8	72.5	0.0027	4000	2014
			559.50	8.99	6	76			2015
			573.33	9.51	6.2	74			2016
Area 8 (Thep Krasitti)	B7	427056 888021	1201.75	2.67	19	152	0.0043	5350	2014
			1204.67	3.17	26.5	174.5			2015
			1186.83	3.67	17.5	154.5			2016

TDS and Cl concentration were created for 8 districts covering the Phuket Island. Finally, the assessment map of Phuket seawater intrusion was created using TDS and Cl concentration as the two main parameters. The map indicates those areas identified from cross-plots of TDS and Cl concentration.

2.2.3. Trend Curve Comparison of Groundwater Extraction, Groundwater Level and Ground Water Salinities (TDS and Cl Concentration)

The trends between water salinities (TDS and Cl concentration) and groundwater level in time series (2003-2016) and groundwater extraction rate during (2014-2016) indicate that when the groundwater level drops during over-pumping of groundwater, the seawater can intrude into the aquifer replacing fresh water as the natural recharge of the coastal zones. Plots of time trends in groundwater salinity (TDS and Cl concentration), groundwater level, and groundwater extraction confirm that reduction of the fresh groundwater causes seawater to move into inland, intruding into the aquifer previously containing fresh water, so the groundwater salinity has the same trend with the groundwater level. Therefore, the increment of the groundwater level during high rate of groundwater extraction is caused by seawater intrusion in areas of coastal zones as the natural recharge.

2.3. GIS Analysis

Mapping seawater intrusion on Phuket Island was done using GIS analysis with overlays. The overlays in GIS provide map layers with different attributes merged into a single output map [15]. The single output maps of Cl concentration, TDS, transmissivity, and groundwater extraction from spatial GIS analysis were the base maps for overlaying. In fact, high transmissivity can cause seawater intrusion problems along coastal areas [13, 15 and 16]. Groundwater extraction and transmissivity are parameters enhancing the overlay map of seawater intrusion in Phuket. Groundwater extraction was used to assess seawater intrusion in this study because the exploitation of groundwater causes seawater intrusion in coastal areas: areas with high rate of groundwater extraction tend to have an elevated risk of seawater intrusion. A weighting technique was employed to overlay these maps. During the weighted overlay analysis, the ranking was given for each individual parameter of each thematic map and the weighted were assigned by the users according to the influence of the different parameters [17]. The two main parameters Cl and TDS were given 70% weight, while the two supporting parameters were given 30% weight. This approach integrated Cl, TDS, transmissivity, and groundwater extraction as indicators for areas with high tendency of seawater intrusion. The seawater intrusion rates (high, moderate, and low) are assigned: 1) Map label: Low/ No seawater intrusion, TDS: 1-1,000 $mg.L^{-1}$, Cl: 1-600 $mg.L^{-1}$, Water status: Freshwater, 2) Map label: Medium/ Moderate, TDS: 1,000-10,000 $mg.L^{-1}$, Cl: 600-5,000 $mg.L^{-1}$, Water status: Brackish water, 3) Map label: High/Serious, TDS >10,000 $mg.L^{-1}$, Cl >5,000 $mg.L^{-1}$, Water status: Saline water.

3. Results and Discussion

The historical groundwater salinity (Cl and TDS) on Phuket shows increasing overall trends during 2003 -2016, as seen in figure 2a and 2b. The increasing groundwater salinity may imply seawater intrusion problems present in the coastal areas. The areas with rapidly increasing salinity are Mai-Khao, Kamala, Chalong, and Rawai districts. These areas also have TDS and Cl concentration above the respective thresholds: the TDS exceeds 1,500 mg.L-1 and the Cl concentration is above 600 mg.L-1.

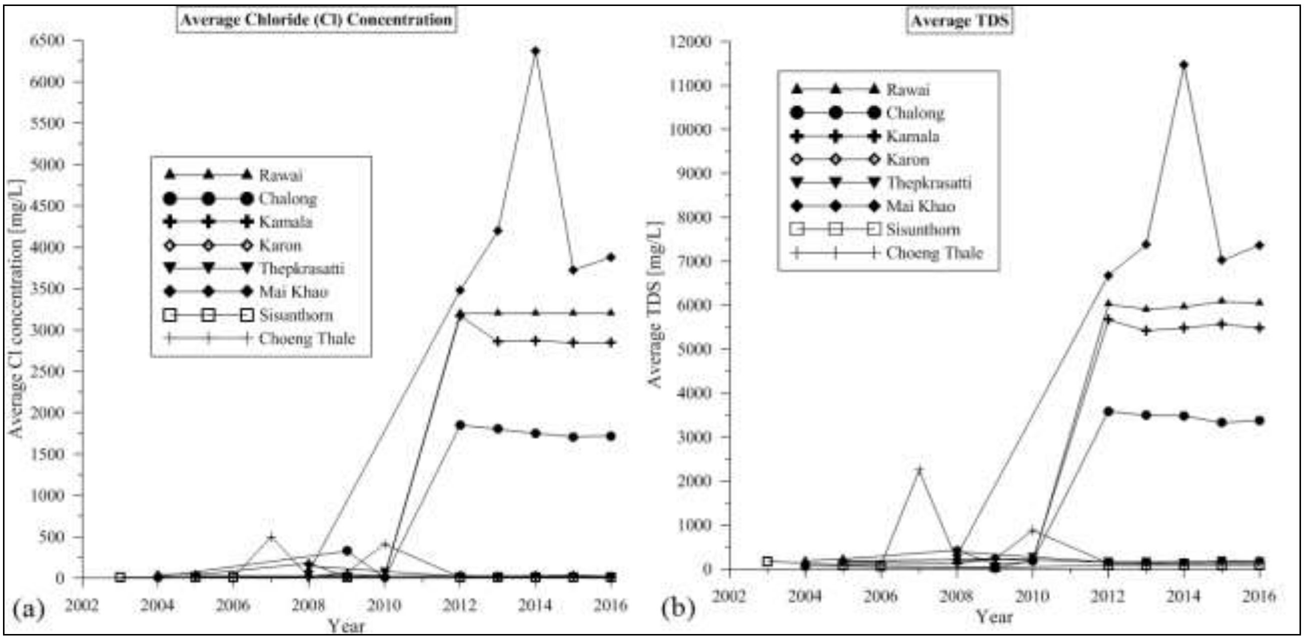

Figure 2 Trends of average TDS and Cl concentration from 2002 to 2016 in 8 sub- districts (a) average TDS; (b) average Cl

3.1. Cross-plot of Chloride Concentration and TDS

The increase of the Cl concentration along with the increase of the TDS indicates the mixing of groundwater with a volume of seawater because the salinization depends on the increase of both TDS and Cl concentrations. Both TDS and Cl are indicators of seawater intrusion, thus the concentration of both TDS and Cl in the groundwater is the main parameters exploring seawater intrusion problem in the study areas. In particular, Cl has a significant effect on TDS, electrical conductivity, and the salinity of the water because Cl is a conservative ion which is usually not affected by ion exchange processes [18]. The cross-plots of these two indicators (average Cl concentration and TDS) indicate very high correlations in all other sub-districts except for the Karon and Sisunthorn districts, as shown in figure 3d and 3h. The districts with seawater intrusion problem have a high correlation between average Cl concentration and TDS, and also the average Cl concentration and TDS are above the thresholds 600 and 1,500 mg.L^{-1}, respectively. However, some districts, specifically Choeng-Thale (Area 6) and Thep-Krasatti (Area 8), have a high correlation of average TDS and Cl concentration, but the Cl concentration is not above the threshold level (figure 3g and 3i). Consequently, Choeng-Thale and Thep-Krasatti sub-district are not considered to have seawater intrusion problem. In terms of Mai Khao, the maximum average Cl concentration and TDS are approximately 7,000 mg.L^{-1} and 12,000 mg.L^{-1}, which are above the respective thresholds. Therefore, it can be concluded that the area at highest risk to be affected by seawater intrusion is the Mai-Khao district (Area 5). On the other hand, Karon (Area 3) and Sisunthorn (Area 7) districts are unlikely to encounter seawater intrusion, since the average TDS and Cl concentration are very low and no correlation compared to the other districts (figure 3d and 3h). These two areas (Area 3 and 7) show no correlation between Cl and TDS because the groundwater in the aquifer of these two areas is still fresh which is not contaminated by seawater. The maximum value of TDS and Cl in these area account for just under 250 mg.L^{-1} and 40 mg.L^{-1}, respectively, which do not exceed the threshold values indicating the seawater intrusion.

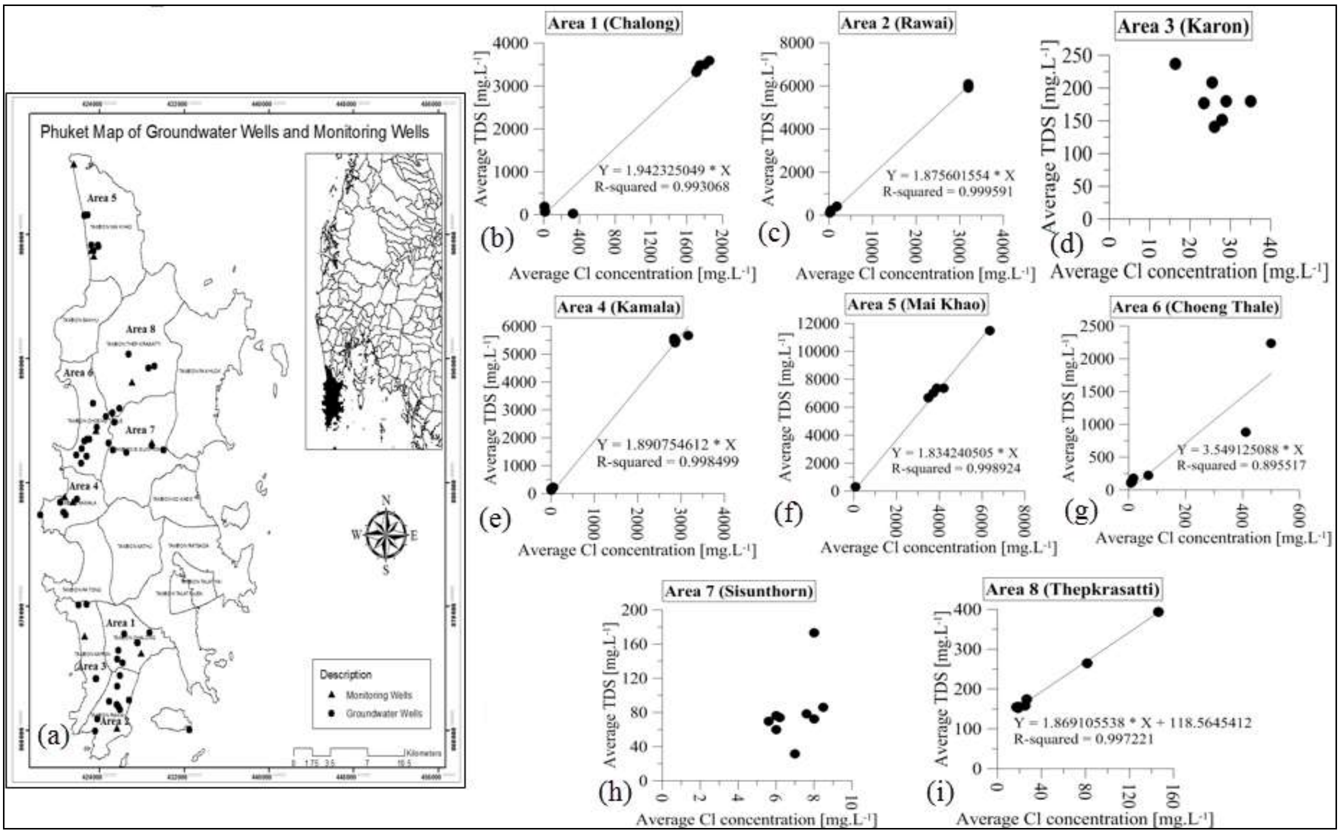

Figure 3 Cross-plots of average TDS and Cl (a) Phuket map of groundwater wells and network monitoring wells; (b) Chalong; (c) Rawai; (d) Karon; (e) Kamala; (f) Mai-Khao; (g) Choeng-Thale; (h) Sisunthon; (i) Thep-Krasatti

3.2. Groundwater Level and Groundwater Extraction Trends Versus Groundwater Salinity Trends

It is commonly known that the trends of groundwater salinities (Cl concentration and TDS) are opposite to those of the groundwater level, i.e. when groundwater level drops the seawater intrudes into the fresh water increasing the salinities. However, the seawater intrusion can act as natural recharge in the coastal area, the groundwater level in coastal zones might be increased due to the groundwater recharge of the seawater intrusion. The relationship among groundwater extraction, groundwater salinities (Cl and TDS), and groundwater level in those 8 study areas are analyzed as shown in figure 4. The rate of groundwater extraction in 2016 was much more than that in 2014 in most areas, except Area 1, 6 and 8. The groundwater level tends to increase with increasing groundwater salinities, as seen in the cross-plots in figure 4. The Areas 1, 2, 4, and 5 (Chalong, Rawai, Kamala, and Mai-Khao districts) are here identified as seawater intrusion areas from the cross-plots. In contrast, Areas 3, 6, 7, and 8 (Karon, Choeng-Thale, Sisunthorn, and Thep-Krasatti districts) were unaffected by seawater intrusion, and do not show the negative correlations of groundwater level with groundwater salinities. figure 4 is analyzed in order to show that the seawater intrusion problem in Phuket coastal areas (Area 1, 2, 4,

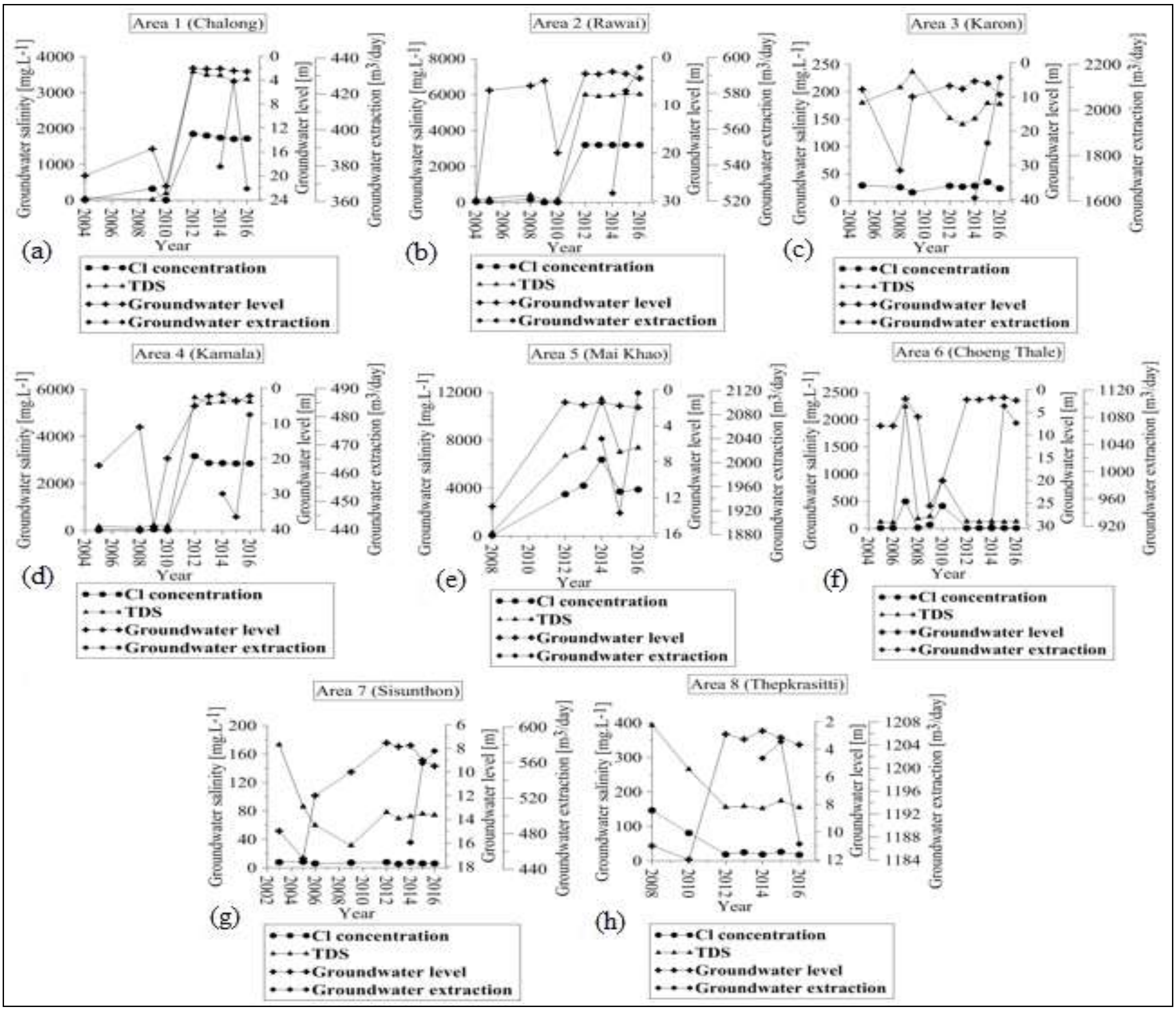

Figure 4 Groundwater level and groundwater extraction trends versus groundwater salinity trends (a) Chalong; (b)Rawai; (c) Karon; (d) Kamala; (e) Mai-Khao; (f) Choeng-Thale; (g) Sisunthon; (h) Thep-Krasatti

and 5) is caused by the over-use of the groundwater extraction influencing the groundwater level increases due to seawater intrusion as the natural recharge in the coastal areas. However, the groundwater extraction rate and the groundwater level of the Area 1 decrease in the following year (2014-2016), while the groundwater salinities (Cl concentration and TDS) are still higher than the threshold numbers (figure 4a), this is due to the high hydraulic conductivity and shallow depth of the aquifer in this area.

In cases of Areas 3 (Karon) and 7 (Sisunthon), although Area 3 had a high rate of the groundwater extractions during 2014 -2016, but the groundwater level since 2008 increased and still maintained up to 2016. Hence, the low concentrations of Cl and TDS might be implied that the freshwater water was recharged into the aquifer in order to balance the state of equilibrium between the recharge of fresh water and seawater intrusion, while the Area 7 shows that the depth and the distance of the aquifer are quite deep and far from the sea (see on Table 1). Therefore, this area (Area 7) has no problem with the seawater intrusion. Moreover, the main reason in which the Area 6 and 8 have no problem on seawater intrusion is the distance between the monitoring wells and the sea (Table 1), even though there is the high rate of the groundwater extractions in these areas. In general, the monitoring wells far from the sea will obtain the salinity data (Cl and TDS) below the standard or threshold numbers (600 $mg.L^{-1}$ and 1500 $mg.L^{-1}$ for Cl and TDS, respectively). However, the distance of the wells from the sea is not only a factor for investigating the seawater intrusion problem in the coastal areas. For instance, Well B9 (Area 3) and Well B5 (Area 5) are quite the same distance from the sea, but Well B5 has encountered the seawater intrusion whereas Well B9 does not have the seawater intrusion problem. In addition, the history data of Cl and TDS (figure 2) show that all areas did not have the problem of the seawater intrusion up to 2010. Then Areas 1, 2, 3, and 5 encountered the seawater intrusion problem due to the effects of absent rainfalls in 2009 - 2011 (based on unpublished data) causing the starting point of non-equilibrium in 2010 and increasing groundwater extractions in 2012 [11]. These examples demonstrate that the main reason to influence the seawater intrusion problem is likely to be due to an over-exploitation of the groundwater and an amount of rainfall.

3.3. Mapping of Seawater Intrusion on Phuket Island

Mapping of average TDS and Cl concentration, transmissivity, and groundwater extraction in single maps used GIS techniques. All the single output maps were used for overlaying to get the Phuket seawater intrusion map shown in figure 5. The map shows the coastal areas of Mai-Khao district in the top part of Phuket Island that has an attractive beach, as the highest risk areas for seawater intrusion problem, it means that Mai-Khao district is encountering with the seawater intrusion problem because this area has mainly high concentrations of TDS and Cl in the groundwater (TDS and Cl are higher than 10,000 $mg.L^{-1}$ and 5,000 $mg.L^{-1}$ respectively) with supporting information of a transmissivity of the aquifer property and a rate of the groundwater extraction. In addition, three coastal areas of Kamala, Rawai and Chalong districts in the Southern part of Phuket are likely to have moderate seawater problems because the areas have the TDS and Cl concentrations, as main parameters, reaching the limitation standard of groundwater for TDS and Cl (the range of TDS and Cl concentration are 1,000 - 10,000 $mg.L^{-1}$ and 600-5,000 $mg.L^{-1}$ respectively) and the transmissivity of the aquifer property and the groundwater extraction as supporting parameters are in moderate range for seawater intrusion. While the rest of the areas shows in the map that they are no seawater intrusion for years of 2003 – 2016.

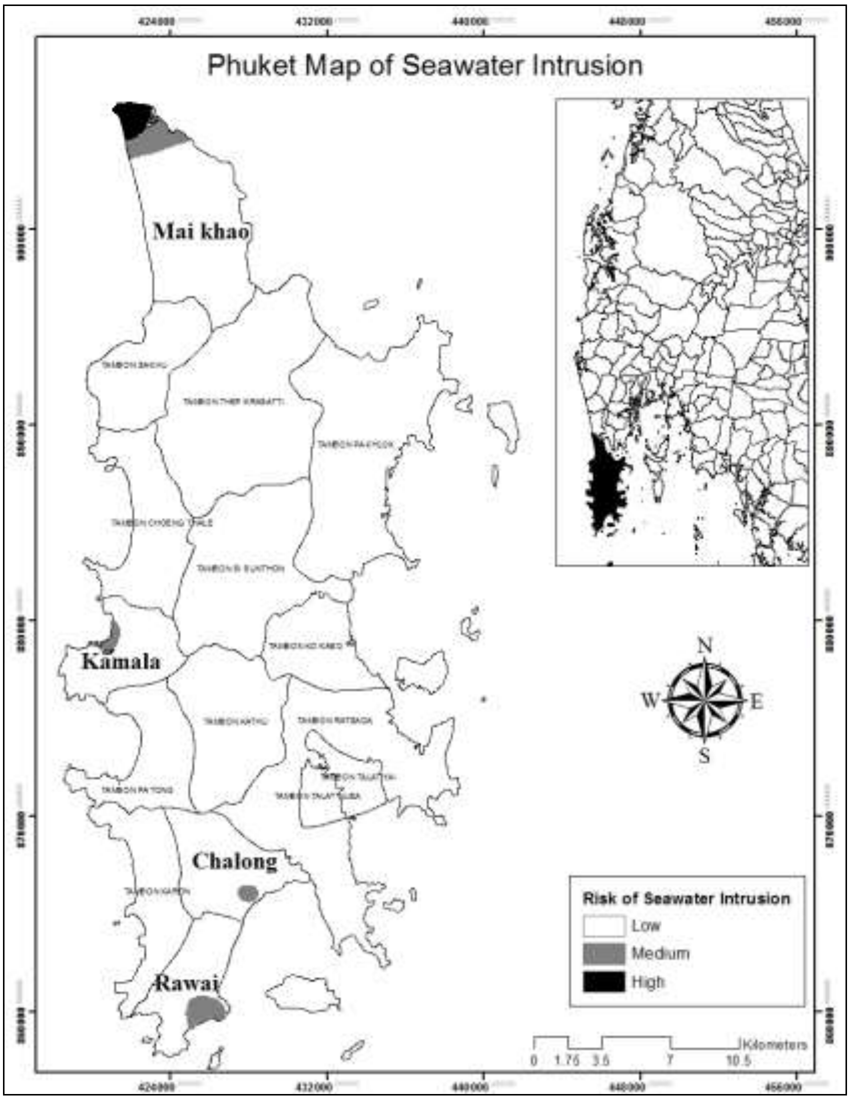

Figure 5 Map of seawater intrusion risk in Phuket

4. Conclusion

Phuket Island has a high risk of seawater intrusion due to the surrounding Andaman Sea with saline water, the increased groundwater exploitation and the high mobility of hydrogeological properties of the fractured aquifer. The current study sought to assess the seawater intrusion situation in that potentially high-risk area. TDS and Cl concentrations can be used as the two main indicators in an analysis of seawater intrusion risks. When these indicators are concordant with high correlation and exceed some threshold levels (600 and 1,500 $mg.L^{-1}$ for Cl concentration and TDS, respectively), the groundwater has been intruded. In addition, the groundwater level trend was used to confirm the seawater intrusion, by its level decreasing while TDS and Cl concentration increased. An assessment map of seawater intrusion on Phuket Island was created by GIS techniques (figure 5). The areas with the highest risk of seawater intrusion on Phuket are the coastal areas of Mai-Khao, while in the middle and southern part of the island the Kamala, Rawai and Chalong sub-districts have coastal areas subject to moderate risk. The rest of the study areas (Karon, Choeng-Thale, Sisunthon, and Thep-Krasatti) found that they have on the problem in the seawater intrusion. Finally, this study does not take the seasoning effect into account for analyzing the seawater intrusion in Phuket, thus the period of the obtained data is supposed to play an important role for taking seasoning effect into account in term of seawater intrusion assessment.

Acknowledgment

This research utilized groundwater data gracefully provided by the Department of Groundwater Resource (DGR), Thailand. We also express our sincere thanks to the Interdisciplinary Graduate School of Earth System Science and Andaman Natural Disaster Management (ESSAND) for many suggestions and helpful support. Finally, we would like to thank PSU English Clinic, Assoc. Prof. Seppo Karrila, for English editing.

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