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Hydrogeologic characteristics and groundwater potentiality mapping using potential surface analysis in the Huay Sai area, Phetchaburi province, Thailand

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ABSTRACT: The Huay Sai Royal Development Study Centre, located in southern Thailand, one of the agricultural areas still faces a lack of water, especially in the drought season. The aims of this study were to explain the hydrogeological characteristics of aquifers and evaluate the groundwater potentiality. The results revealed three types of aquifer: unconsolidated floodplain deposits aquifer (Qfd) and the consolidated Permo-Carboniferus metasedimentary (PCms) aquifer and granitic (Gr) aquifer. The main groundwater direction of the Qfd and PCms aquifers flow from the south-western to the north-eastern area. The groundwater potential, as assessed by potential surface analysis (PSA), using the rainfall, recharge, lithology, lineament density, slope, drainage density, depth to groundwater and water quality as thematic layers in a GIS system. Groundwater potentiality classes ranged from very high (in the Rai Mai Pattana area) to very low (in the Sam Praya area). The output groundwater potential map was congruent with the maximum yield data carried out by the Department of Groundwater Resources (DGR). The map declared that the Huay Sai area is commonly of moderate groundwater potentiality, where this category covers an area of 116.6 km^2 (56.74% of the study area).

Key words: hydrogeological characteristics, groundwater potentiality map, Huay Sai, Thailand

1. INTRODUCTION

Huay Sai is one of the coastal aquifers in southern Thailand that has developed water shortage problems in the past few decades, particularly in summer seasons, because most of the area is used for intensive agriculture. In the past, Huay Sai had an abundant and plentiful water supply and was mainly covered forest areas with river reaches and water resources. Later, the area was intruded and forest areas were damaged and contaminated by intensively applied agro-chemicals. Consequently, the area rapidly deteriorated within a few years and the effects on the ecosystem, such as the loss of top soil, loss of protective cover and deteriorated soil, adversely affected plant growth. His Majesty King Bhumibol Adulyadej initiated the establishment of the Huay Sai Royal Development Study Centre to evaluate and remedy the deteriorated area. In addition to agriculture, the high growth rate of tourism and related industries has led to the development of resorts and hotels with an increased water demand on the area. In response to this increasing water demand, groundwater exploration and exploitation of the coastal sand's aquifer and a fractured granite aquifer have been carried out by both the government and private sectors.

Although the Huay Sai Royal Development Study Centre was established to solve the water shortage problems, some areas are still faced with a lack of water, especially in the dry (drought) season. The main problem of groundwater supplies is due to the over-extraction through intensified agricultural production, tourist development and domestic water demand that overburdens the underground supply and exceeds the sustainability of groundwater resources (Khan et al., 2008; Lachaal et al., 2011; Rahman, 2001; Voudouris, 2006). This problem could be better understood by evaluating the local geological and hydrogeological characteristics that account for the hydraulic properties of these aquifers. The occurrence of groundwater is widely spread out in space and time, where the spatial-temporal variations depend upon the surface and subsurface characteristics, such as fractures, land use, landforms and lithology, as a marker of groundwater existence (Bilal and Ammer, 2002; Edet et al., 1998; Ganapuram et al., 2008; Savane et al., 1996; Sener et al., 2005; Kumar et al., 2007; Saud, 2010). Previous studies have found that the factors that determined the groundwater potentiality map differ in their degree of influence on each study site. Moreover, many studies (Chenini and Ben Mammou, 2010; Ganapuram et al., 2008; Megesh et al., 2012) have not been supported by field verification to assure their reliability.

Therefore, in this study, mapping of the hydrogeological characteristics and groundwater potentiality of the Huay Sai region was conducted to assess the groundwater potential in terms of both the water quality and quantity as a guideline for the alleviation of water shortages and improved water resource management. The aims of this study were: (i) to understand the hydrogeological characteristics of aquifers using geophysics, geological, topographical and hydrogeological data to explain the hydrogeological conceptual model of the groundwater system, (ii) to delineate the groundwa-

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ter potential zone via applied potential surface analysis (PSA) using both groundwater quality and quantity aspects and (iii), the reliability of groundwater potential mapping was investigated in order to validate the correct application of this method.

2. MATERIALS AND METHODS

2.1. The Study Area

The study area was based upon the Huay Sai Royal Development Study Centre and adjacent areas and covers ~205 km^2 encompassing Tambon Sam Phraya, Tambon Huay Sai Nua and Tambon Rai Mai Phattana, Amphoe Cha-am and Changwat Phetchaburi (Fig. 1). The study area is located in the southern portion of Thailand and is bounded by longitudes 99°45′–99°55′E and latitudes 12°37′–12°45′N, and on the eastern side by the Gulf of Thailand. Formerly, the Huay Sai area was fertile but following deforestation and inappropriate agricultural practices, such as excessive tillage and agrochemical usage, a rapid onset of topsoil erosion and adverse effects on the remaining soil structure and biological communities and water content and course occurred. The topsoil erosion and lack of productivity have resulted in a rapid change in the local area conditions. At present, the government is focused on conducting studies and research on methods to restore the deteriorated forests and to develop integrated farming systems and agro-forestry in the area (Fig. 2).

2.2. Geological Setting

Geologically, Permo-Carboniferous metasedimentary rocks and some Permian dolomitic limestones are distributed as mountain ranges in the west of the study area extending from the north to the south. Cretaceous granite and volcanic intruded as mountain ranges and isolated hills are found in the eastern part of the study area. Moreover, Quaternary period sediments composed of fluvial deposits along streams and collovial sediments are mainly deposited around the hill foot. Groundwater in this area is stored in both unconsolidated rocks, as unconsolidated floodplain deposit aquifers (Qfd) and in cracks, fractures, faults, bedding planes and large cavity of consolidated rocks of

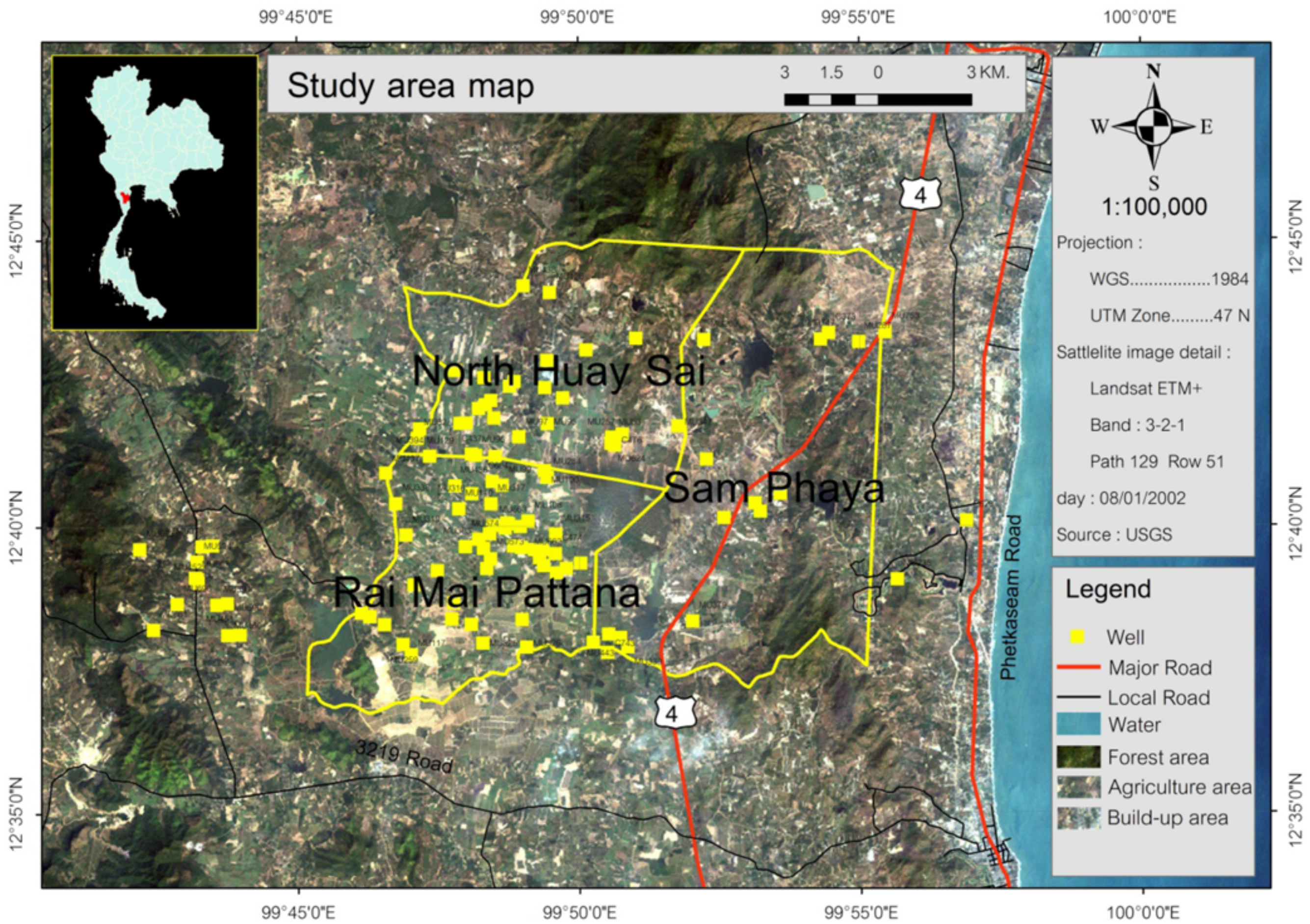

Fig. 1. Location of the study area, modified from DGR (2001).

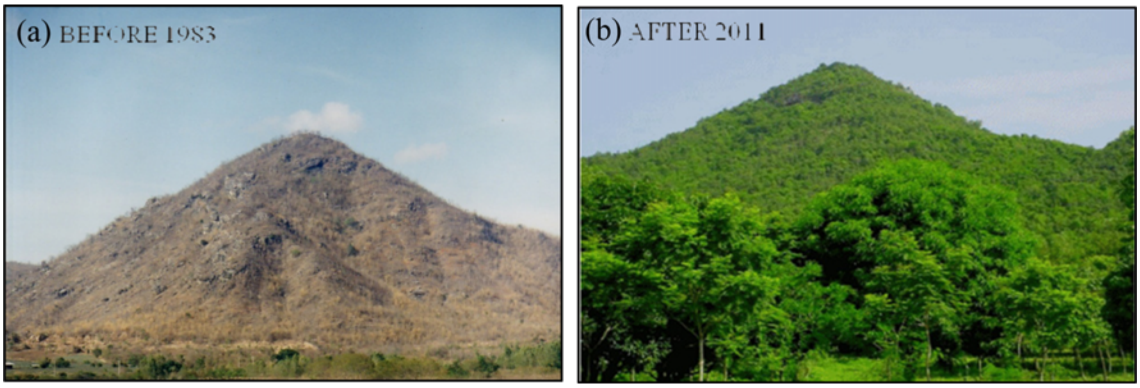

Fig. 2. Area under Huay Sai Royal Development Study Centre showing (a) before 1983 and (b) after 2011 (SOURCE: http://www.huaysaicenter.org/index.php).

Permo-Carboniferous metasediment (PCms) and granitic (Gr) aquifers.

2.3. Analytical Methods

All data were derived from the related literature and geological, topographical and land use maps. The lithologic well logs, pumping test data and hydrogeochemical data of water samples were obtained from the Department of Groundwater Resources (DGR, 2001). In addition, water levels were measured directly in fieldwork.

Hydrogeological cross-sections were constructed in several lines. Groundwater level data collected from fieldwork were analyzed and separated into the groundwater level in the Qfd and PCms aquifers. Insufficient data on the Gr aquifer was available for analysis. Then, the groundwater level contours were plotted and, after incorporation with several hydrostratigraphical sections, the hydrogeological schematic was finally completed.

From the pumping data, unconfined and confined aquifers were evaluated for their hydraulic properties in terms of their transmissivity (T) and hydraulic conductivity (K). Hydrogeochemical data were displayed in the tertiary piper diagrams. Major cations and anions found were Na^+, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, NO_3^-, HCO_3^- and CO_3^{2-}. The water type classification was based on the study of Galloway and Kaiser (1980).

Groundwater potentiality has been carried out to evaluate the spatial relationships among the different controlling parameters that contribute groundwater occurrence in the study area. Each factor influencing on groundwater occurrence, were classified from very high to very low contribution on groundwater potentiality. The weights and rates used were modified and optimized by the extracted factors from the successful and gave reliable results of experience or judgments of the hydrogeologists and the knowledge of hydrogeologists, based on their field surveys and in-situ investigations, on mapping groundwater potential zones, which were qualitative methods (Teeuw, 1995; Edet et al., 1998; Robinson et al., 1999; Das, 2000; Bilal and Ammar, 2002; Sener et al., 2005; Tesfaye, 2010) taken into account qualitative methods, such as geostatistical normalization and cross-validation (Isaaks and Srivastava, 1989). Therefore, the weights and rates were adopted based on magnitude of relation between each factor have been integrated in the GIS multilayer system; consequently, the output

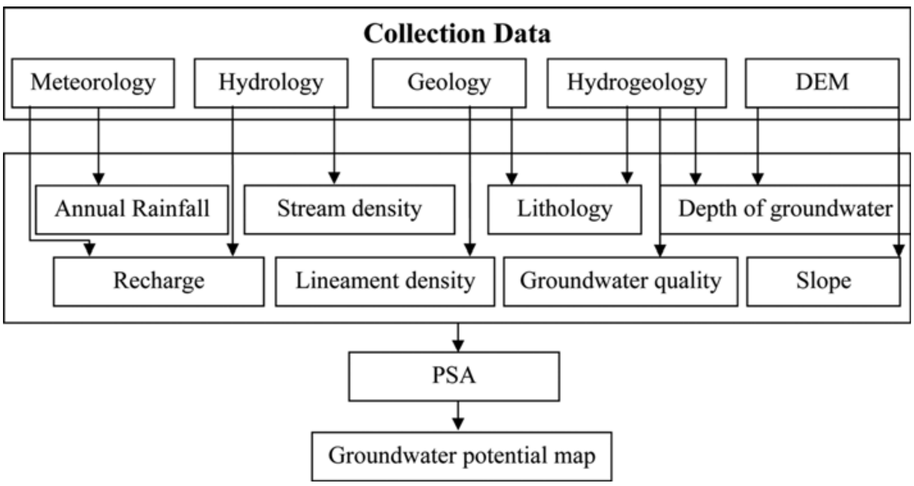

Fig. 3. Flow chart of the groundwater potential assessment used in this study, modified from Elewa and Qaddah (2011).

Table 1. Sources of data layer related to groundwater productivity of study area

Category	Format	Source of data
Annual rainfall data	Table	Thai Meteorological Department (TMD)
Potential recharge	Map	Thai Meteorological Department (TMD)
Geology data	Map	Department of Mineral Resources (DMR)
Structure data	Map	Department of Mineral Resources (DMR)
Groundwater level	Map	Field investigation
GW Quality (TDS)	Map	Field investigation
Drainage density	Map	Drainage density generated from DEM with resolution 30 m
Slope	Map	Ground slope obtained from DEM with resolution 30 m

results of groundwater potentialility revealed the contribution in terms of both the water quality and quantity as a guideline for the alleviation of water shortages and improved the water resource planning and management. The eight layers of rainfall, groundwater recharge, lithology, lineament density, depth to groundwater, water quality, drainage density and slope were built in a GIS and assigned appropriate weights and ranks according to their relative importance to the groundwater potentiality (Fig. 3). Their sources of these data were shown in Table 1. Ground truthing had been carried out on the depth of groundwater and groundwater quality during field survey in 2010. The groundwater potentiality map was then created using potential surface analysis (PSA) as shown in Equation (1):

$$E = \sum W_f R_f \quad (1)$$

where E is the degree of effectiveness for each factor, W_f is the weight factor and R_f is the rank factor.

3. RESULTS AND DISCUSSION

3.1. Conceptual Model of Hydrogeological Characteristics

From a hydrogeological point of view, with respect to the geophysics, geological, topographical and hydrogeological data, the underground water was classified into three types of aquifer, as Qfd, PCms and Gr. The Qfd aquifer, which occurred in Quaternary, was a consolidated unconfined phreatic aquifer, and was superimposed upon successive confined PCms and Gr aquifers. The PCms aquifer occurred in rocks from the Permian-Carboniferous period and the Gr aquifers occurred in rocks of various ages that are younger than Permian-Carboniferous period and mainly yielded a high amount of water located in the eastern part of the basin. The hydrogeological schematic of aquifer systems and groundewater flow is shown in Figure 4, where there are two recharge zones, the western sandstone zone and the eastern granitic zone.

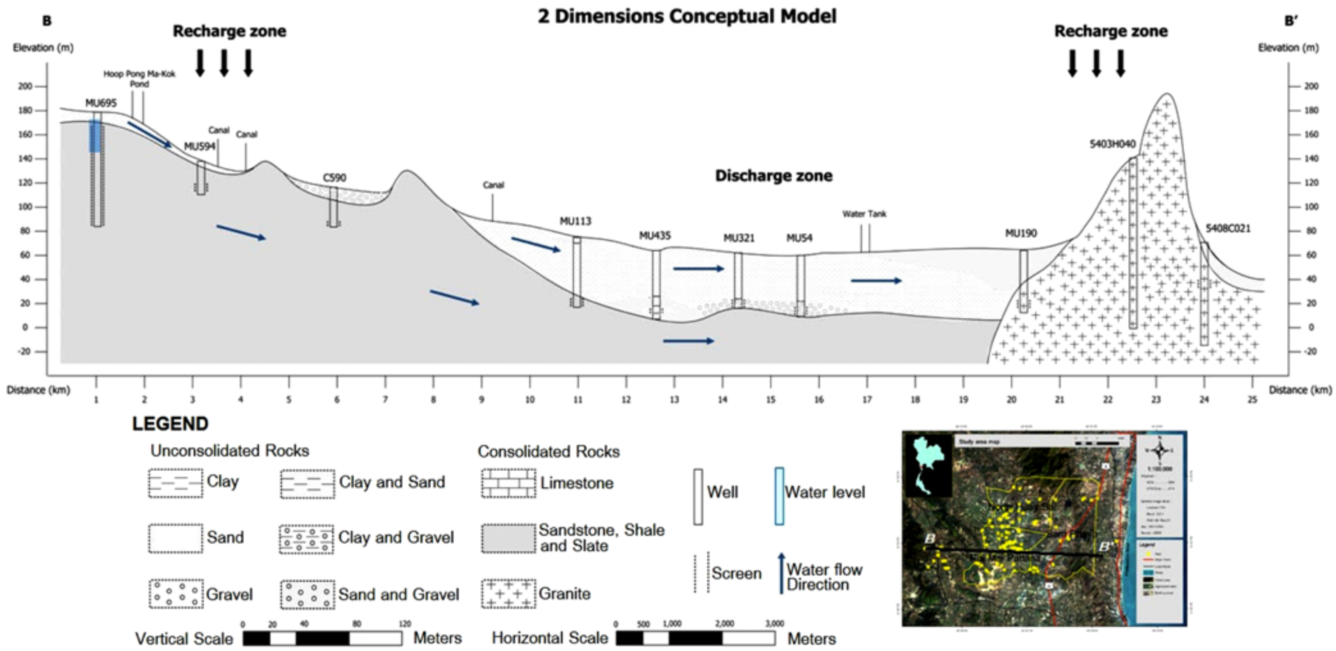

Fig. 4. Schematic of hydrogeological aspects.

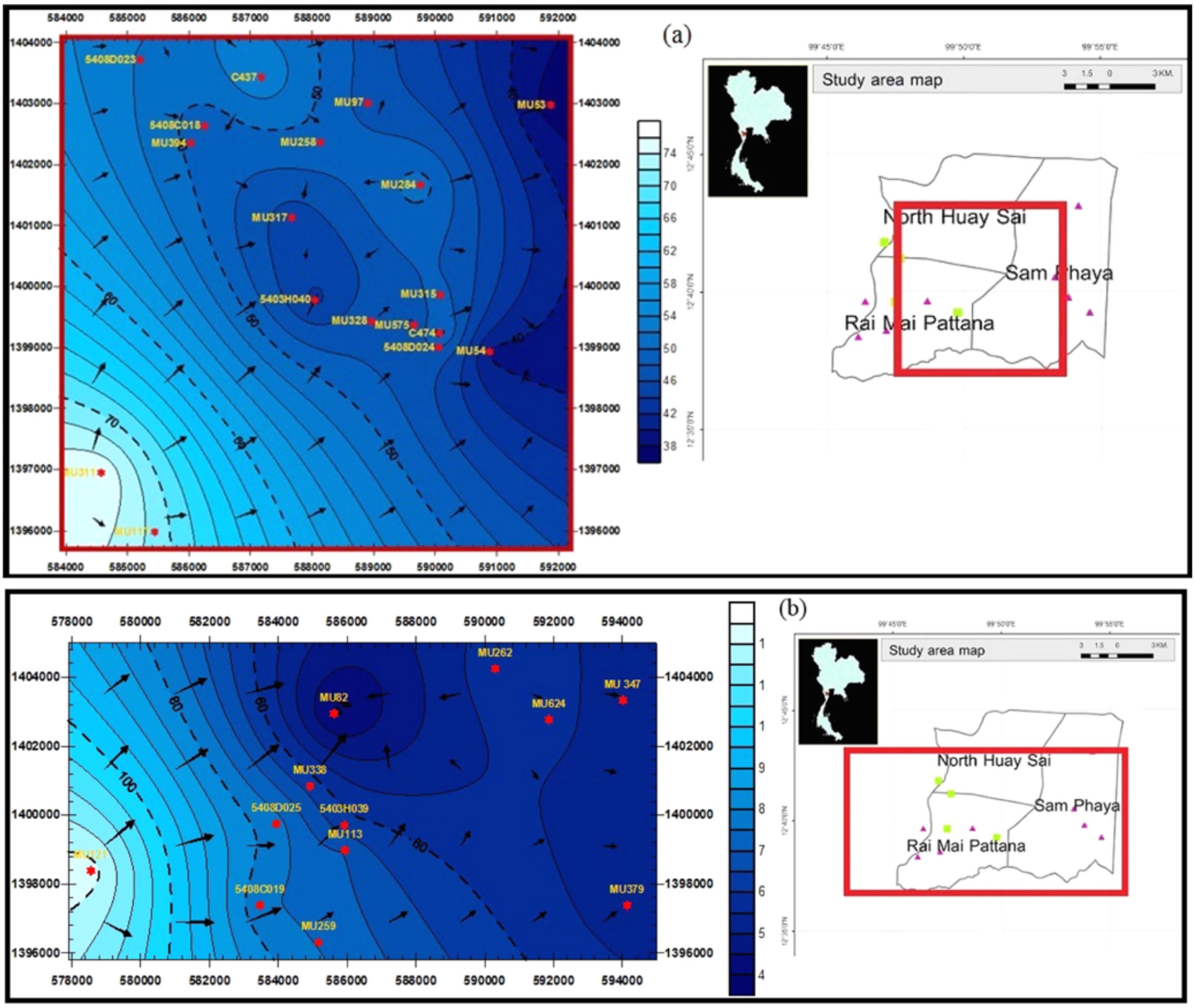

Fig. 5. Groundwater flow in the (a) floodplained (Qfd) and (b) metasedimentary (PCms) aquifers.

The Qfd aquifer, distributed over Tambon Huay Sai Nua, Tambon Rai Mai Phattana and Tambon Sam Phraya, is on the top with an average thickness of 30–40 m. The PCms aquifer is underneath the Qfd aquifer and is distributed in Tambon Huay Sai Nua, Tambon Rai Mai Phattana and Tambon Sam Phraya, with an average thickness of more than 100 m. The Gr aquifer intrudes through the Qfd and PCms aquifers in the eastern area at Tambon Sam Phraya, and has an average thickness of more than 80 m.

The groundwater level, ascertained from the fieldwork, was compared with the mean sea level (MSL). Generally, the groundwater direction of both the Qfd and PCms aquifers flow from the south-west to the north-east (Fig. 5) with a mean hydraulic gradient approximately 0.0018, as measured from the compiled piezometric maps. However, some areas showed characteristic cones of depression. As described above, the mountainous areas behave as recharge zones and the floodplain behaves as a discharge zone.

From the pumping test data derived from 12 wells, four wells for each of the PCms, Gr and Qfd aquifers (Fig. 6), the unconfined (Qfd) aquifer was analyzed by the Neuman method and the confined aquifers (PCms and Gr aquifers) were analyzed by the Theis, Cooper & Jacob and Hantush methods following Fetter (2002). The derived T and K values are summarized in Table 2 (PCms and Gr aquifers) and Table 3 (Qfd aquifer) with representative examples of the analysis shown in Figure 7. The average K value for the PCms and Gr aquifers ranged broadly similar from 0.063 to 0.080 and from 0.033 to 0.036 m/day, respectively, whilst overall the results obtained by the Hantush method were similar to those from the Theis and the Cooper & Jacob methods, indicating that there might be no leakage in the Gr and PCms aquifers. However, the T and K values of the Qfd aquifer, as analyzed by the Neuman method, were sig-

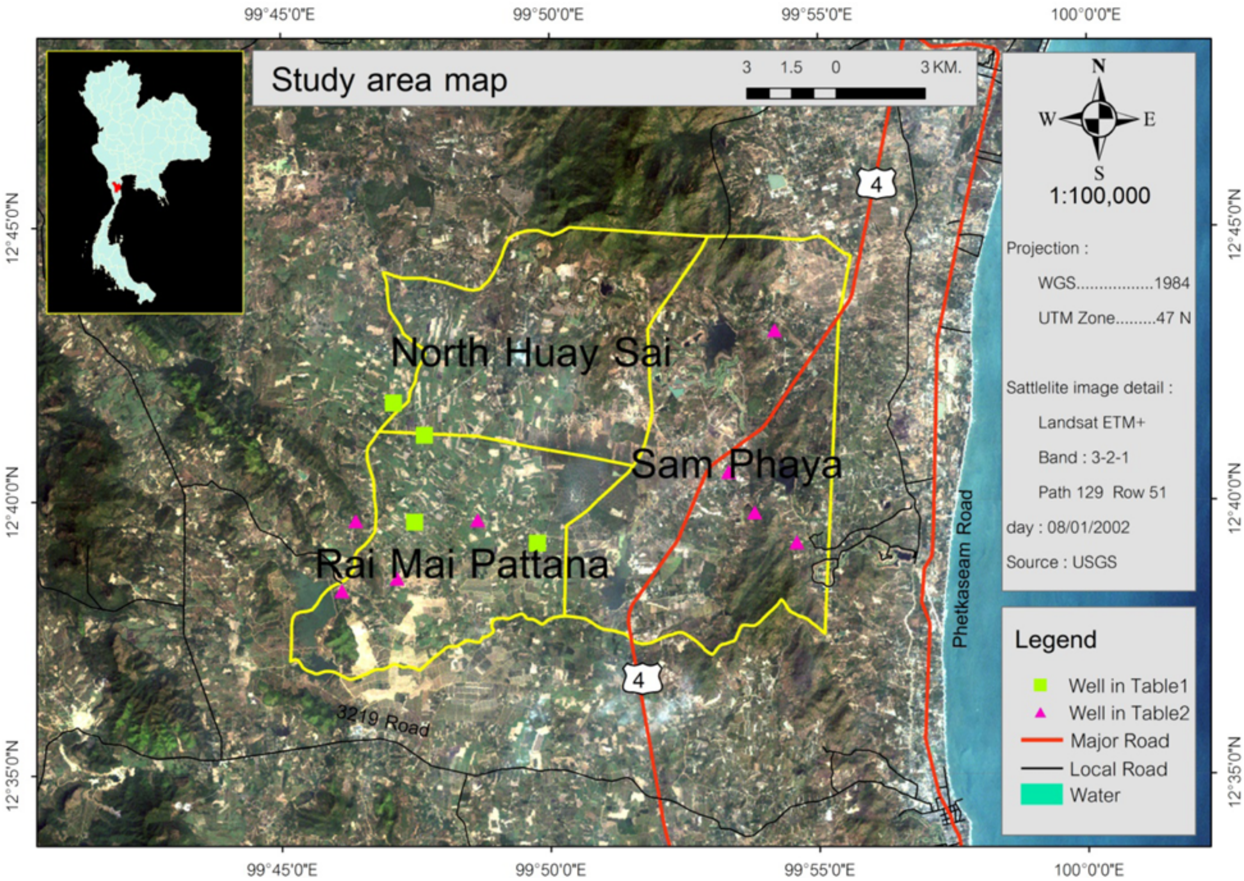

Fig. 6. Location of the 12 wells used in the aquifer pumping test.

Table 2. Transmissivity (T) and hydraulic conductivity (K) values in the metasedimentary aquifer (PCms) and the granitic aquifer (Gr) derived from the Theis, Cooper & Jacob and Hantush methods

Well no.	Aquifer type	Theis method		Cooper & Jacob method		Hantush method	
		T (m^2/day)	K (m/day)	T (m^2/day)	K (m/day)	T (m^2/day)	K (m/day)
5408C019 (Well 3)	PCms	9.520	0.099	8.630	0.089	9.520	0.099
5403H039 (Well 5)	PCms	3.110	0.082	4.540	0.119	2.770	0.073
5408D025 (Well 8)	PCms	1.840	0.023	2.570	0.032	1.460	0.018
Average ± SD	PCms	4.823 ± 4.117	0.068 ± 0.040	5.247 ± 3.091	0.080 ± 0.044	4.583 ± 4.325	0.063 ± 0.041
5408D026 (Well 4)	Gr	10.000	0.113	10.000	0.113	10.000	0.113
5403H042 (Well 9)	Gr	0.218	0.002	0.225	0.002	0.194	0.002
5408C021 (Well 10)	Gr	1.660	0.022	1.070	0.014	1.860	0.025
5403H043 (Well 12)	Gr	0.382	0.003	0.457	0.004	0.340	0.003
Average ± SD	Gr	3.065 ± 4.668	0.035 ± 0.053	2.938 ± 4.721	0.033 ± 0.053	3.099 ± 4.662	0.036 ± 0.053

Well 7 was not analyzed because screens have been opened in two aquifer.

nificantly greater than the corresponding values for the Gr and PCms aquifers, at ~90- and ~180- fold greater, respectively.

3.2. Hydrogeochemical Characteristics

The chemical constituents of the water from the Qfd, PCms and Gr aquifers are shown in Table 4. The hydrogeochemical characteristics of the water were analyzed based on the study of Galloway and Kaiser (1980). Pattern diagram was initially introduced by Hill (1940) and later improved by Piper (1944). Groundwater types of the Qfd and PCms aquifers were in zones 4, 7 and 9, which are calcium bicarbonate (Ca-HCO_3), calcium-sodium bicarbonate (Ca-Na-HCO_3) and sodium bicarbonate (Na-HCO_3), respectively, whilst that for the Gr aquifer was in zones 5,

Table 3. Transmissivity (T) and hydraulic conductivity (K) values in the unconsolidated (Qfd) aquifer

Well No.	Aquifer type	Neuman method	
		T (m^2/day)	K (m/day)
5408D023 (Well 1)	Qfd	91.400	6.090
5408C018 (Well 2)	Qfd	89.800	6.910
5403H040 (Well 6)	Qfd	61.300	7.670
5408D024 (Well 11)	Qfd	71.700	3.110
Average	Qfd	78.550 ± 14.562	5.945 ± 1.997

7 and 9, which are calcium-sodium bicarbonate chloride (Ca-Na-HCO_3-Cl), Ca-Na-HCO_3 and Na-HCO_3, respectively (Fig. 8). Increased chloride concentration in the water from the Gr aquifer may be due to the removal of other ions from the system by adsorption or by precipitation or due to the chemical reaction between groundwater and ions in the sediment or rock as the groundwater percolates through the aquifers.

3.3. Groundwater Potentiality

The eight layers integrated to perform the groundwater potentiality mapping in this study were assigned the weights according to their relative importance to the groundwater potentiality as follows: rainfall (30%), groundwater recharge (20%), lithology (20%), lineament density (10%), depth to groundwater (5%), water quality (5%), drainage density (5%) and slope (5%), and were then built in a GIS manipulation. These eight factors were evaluated as below and then inte-

Table 4. Geochemical data[a] in groundwater samples

Well No.[b]	Location	Aquifer[c]	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}	CO_3^{2-}	HCO_3^{-}	pH	EC	TDS
5408C018 (well 2)	Huay Sai Nua	Qfd	70	60	150	6.0	6	61	0	790	7.6	1250	812
5408D023 (well 1)	Huay Sai Nua	Qfd	68	65	110	5.6	8	68	0	717	7.6	1180	767
MC102	Huay Sai Nua	Qfd	48	17	280	10.0	3	240	0	592	7.8	1590	1030
MU258	Huay Sai Nua	Qfd	78	27	36	3.6	8	36	0	403	6.9	690	452
MU53	Huay Sai Nua	Qfd	110	46	140	15.0	42	120	0	699	7.9	1380	897
C475	Huay Sai Nua	Qfd	52	27	22	3.1	4	17	0	292	7.1	483	314
C693	Huay Sai Nua	Qfd	78	57	160	32.0	6	160	0	730	7.3	1500	975
5408D024 (well 11)	Rai Mai Pattana	Qfd	75	65	110	7.3	3	57	0	754	7.4	1170	760
5403H040 (well 6)	Rai Mai Pattana	Qfd	32	41	96	7.7	5	75	12	411	8.2	858	558
MU311	Rai Mai Pattana	Qfd	32	17	110	2.3	11	49	0	405	7.9	740	481
MU108	Rai Mai Pattana	Qfd	170	14	89	7.8	7	56	0	698	7.1	1120	728
C743	Rai Mai Pattana	Qfd	84	24	130	5.8	34	140	0	442	7.5	1100	715
MU106	Rai Mai Pattana	Qfd	88	18	33	8.5	23	22	0	403	7.7	675	439
MU112	Rai Mai Pattana	Qfd	62	70	310	2.4	2	190	0	1020	7.6	1890	1230
MU82	Huay Sai Nua	PCms	95	37	120	5.0	7	48	0	688	7.4	1100	715
MU438	Huay Sai Nua	PCms	130	43	81	11.0	2	150	0	586	7.3	1250	812
MU262	Huay Sai Nua	PCms	94	40	140	27.0	4	82	0	782	7.2	1300	845
5408C019 (well 3)	Rai Mai Pattana	PCms	48	58	66	0.4	10	16	7	570	8.6	851	553
5403H039 (well 5)	Rai Mai Pattana	PCms	92	61	100	6.0	9.0	61	0	790	7.8	1350	878
5408C020 (well 7)	Rai Mai Pattana	PCms	110	68	110	6.1	21	210	11	580	8.4	1430	930
5408D025(well 8)	Rai Mai Pattana	PCms	85	41	10	1.3	4	21	0	470	7.5	746	485
MU259	Rai Mai Pattana	PCms	37	31	240	1.5	5	14	0	862	7.9	1220	793
MU661	Rai Mai Pattana	PCms	190	78	110	1.5	79	210	0	785	7.2	1720	1120
MU127	Sam Phraya	PCms	59	11	47	4.0	23	52	0	259	7.2	577	376
5403H043 (well 12)	Sam Phraya	Gr	9.6	24	380	2.9	2	66	17	947	8.4	1540	1000
5408C021 (well 10)	Sam Phraya	Gr	88	40	170	0.5	48	240	0	433	7.7	1440	936
5408D026 (well 4)	Sam Phraya	Gr	64	28	180	1.6	17	81	0	682	7.6	1210	786
5403H042(well 9)	Sam Phraya	Gr	35	22	250	8.5	1.0	150	5	598	8.8	1320	858
MU135	Sam Phraya	Gr	110	17	140	5.2	7	91	0	620	7.3	1140	741
C373	Sam Phraya	Gr	120	26	230	9.0	2	230	0	687	7.2	1630	1060

[a]TDS = total dissolved solids (ppm); EC = Electrical conductivity (μS), and all ions are shown in mg/L.
[b]Well numbers in parentheses are from this study and are as shown in Tables 1 and 2.
[c]Aquifer types are designated as: Qfd = Quaternary period floodplain deposits; PCms = Permo-Carboniferus metasedimentary, and Gr = granite.

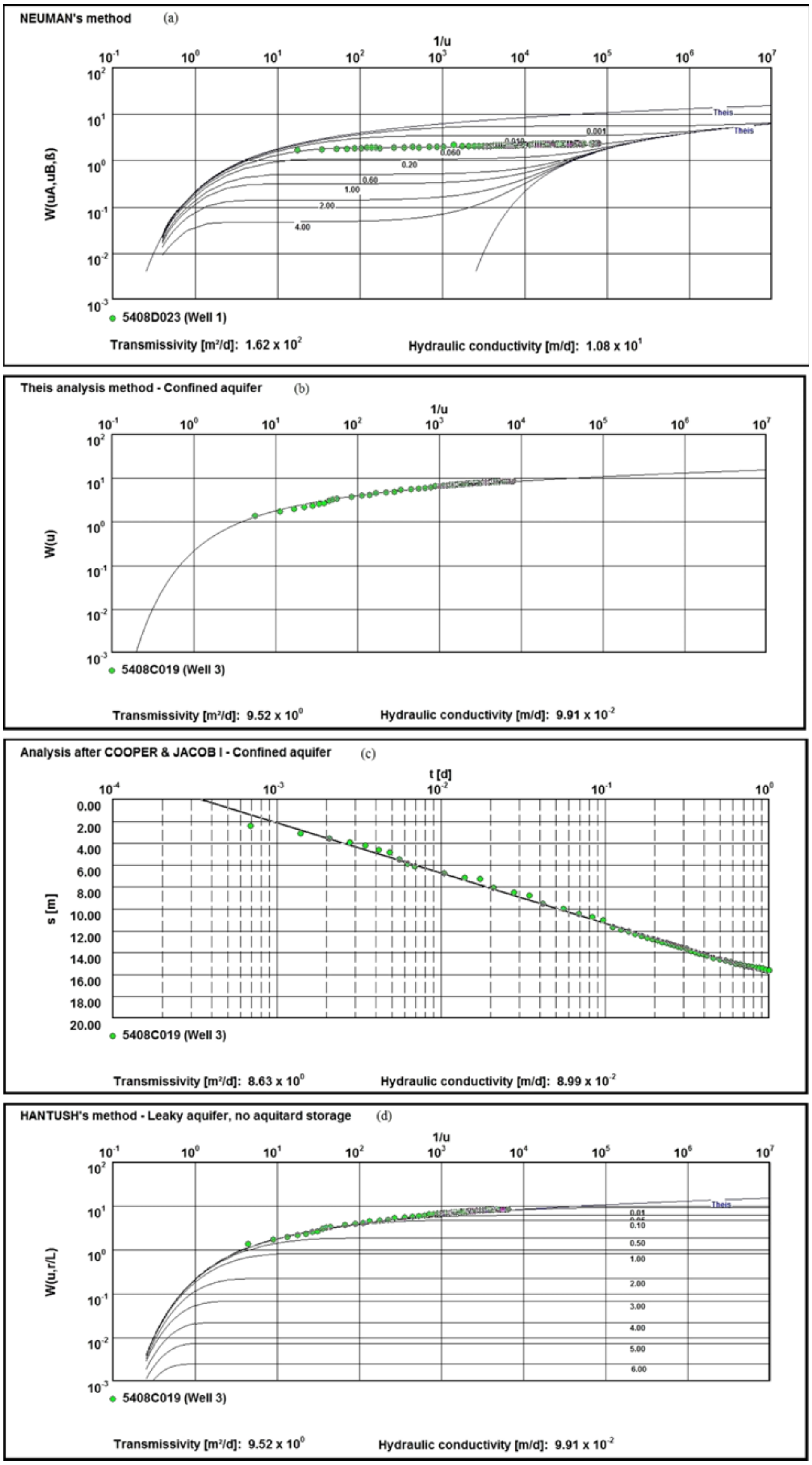

Fig. 7. The pumping test data analysis for (a) well 1 (Qfd aquifer) analyzed by the Neuman method, and well 3 (PCms) analyzed by the (b) Theis, (c) Cooper & Jacob, and (d) Hantush methods.

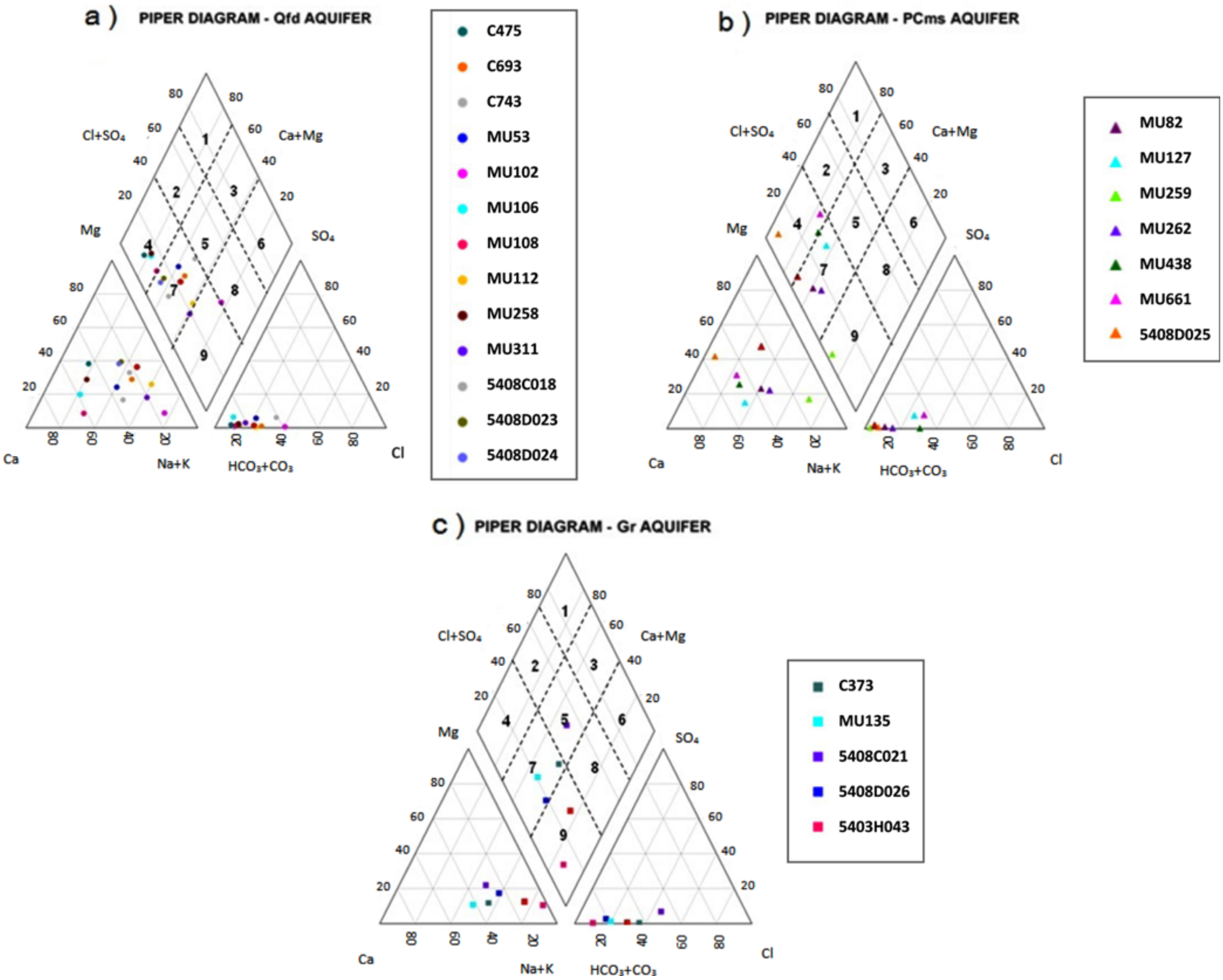

Fig. 8. Piper diagram of the (a) unconsolidated Qfd aquifer, and the consolidated (b) PCms and (c) Gr aquifers.

grated into the GIS multilayer system, with the groundwater potentiality map being classified into the five rates (ranks of groundwater potentiality within each weight) of very high, high, moderate, low and very low groundwater potentiality (Table 5). The rank classes were classes as 100–80, 80–60, 60–40, 40–20 and 20–0%. Hence, the average of ranking for each class was 90, 70, 50, 30 and 10% of very high, high, moderate, low and very low potential, respectively in terms of their influence with respect to groundwater occurrence. The degree of effectiveness (E) for each factor derived from data multiplication of the weight and the rank ($W_f \times R_f$). Through the integration of these factors in the GIS multilayer system, the groundwater potentiality map was generated with five classes, ranging from very low to very high potentiality. This is ascribed as: <20% (very low), 20–40% (low), 40–60% (moderate), 60–80% (high) and >80% (very high) for the potential of groundwater occurrence.

3.3.1. Rainfall factor

Rainfall is the water source but because the area is located in a rain shadow region with a low rainfall amount as compared to surrounding areas, direct recharge to the groundwater from rainfall is minimal. In this regard, the total annual rainfall data from 1981–2010, derived from the Thai Meteorological Department (TMD) was analyzed rainfall distribution over the entire area using the isohyetal method and discriminated into five classes as follows: <858, 858–898, 899–939, 980–940, >981 mm/year (Fig. 9a and Table 5). The output map revealed that the high areas receive much more rainwater than the flat areas. The total annual rainfall varies from a maximum of over 1000 mm in the south-west mountainous part of the Tambon Rai Mai Pattana to a minimum of less than 858 mm in lowlands of north-eastern part of the Tambon Sam Phraya. This layer was given a weight of 30 in the potential surface analysis.

Table 5. Ranks and weights for factors and their influencing classes used for groundwater potentiality mapping (adapted from Elewa and Qaddah (2011))

Data layer (factor)	Class	Average rank (R_f)	Weight (W_f)	Degree of effectiveness (E)
Rainfall	Very high	90		27
	High	70		21
	Moderate	50	30% (0.3)	15
	Low	30		9
	Very low	10		3
Potential recharge	Very high	90		18
	High	70		14
	Moderate	50	20% (0.2)	10
	Low	30		6
	Very low	10		2
Lithology	Very high	90		18
	High	70		14
	Moderate	50	20% (0.2)	10
	Low	30		6
	Very low	10		2
Lineament density	Very high	90		9
	High	70		7
	Moderate	50	10% (0.1)	5
	Low	30		3
	Very low	10		1
Depth of groundwater	Very high	90		4.5
	High	70		3.5
	Moderate	50	5% (0.05)	2.5
	Low	30		1.5
	Very low	10		0.5
Groundwater quality	Very high	90		4.5
	High	70		3.5
	Moderate	50	5% (0.05)	2.5
	Low	30		1.5
	Very low	10		0.5
Drainage density	Very high	90		4.5
	High	70		3.5
	Moderate	50	5% (0.05)	2.5
	Low	30		1.5
	Very low	10		0.5
Terrain slope	Very high	90		4.5
	High	70		3.5
	Moderate	50	5% (0.05)	2.5
	Low	30		1.5
	Very low	10		0.5

3.3.2. Potential recharge factor

In this study area located in semi-arid area and mostly showed a flat area, where flow is relatively slow and the retention time for evaporation will enhance; consequently, a portion of surface runoff will be lost and is insignificant for recharge estimation (Kinzelbach et al., 2002). Hence, the potential recharge was calculated from the total rainfall minus total evapotranspiration as shown in Equation (2). Furthermore, the study of Ateawung (2010) found that surface runoff in Africa were generally very low (less than 0–10 mm/yr). In other words, most of water from rainfall infiltrated to the shallow aquifers. This factor is one of the most

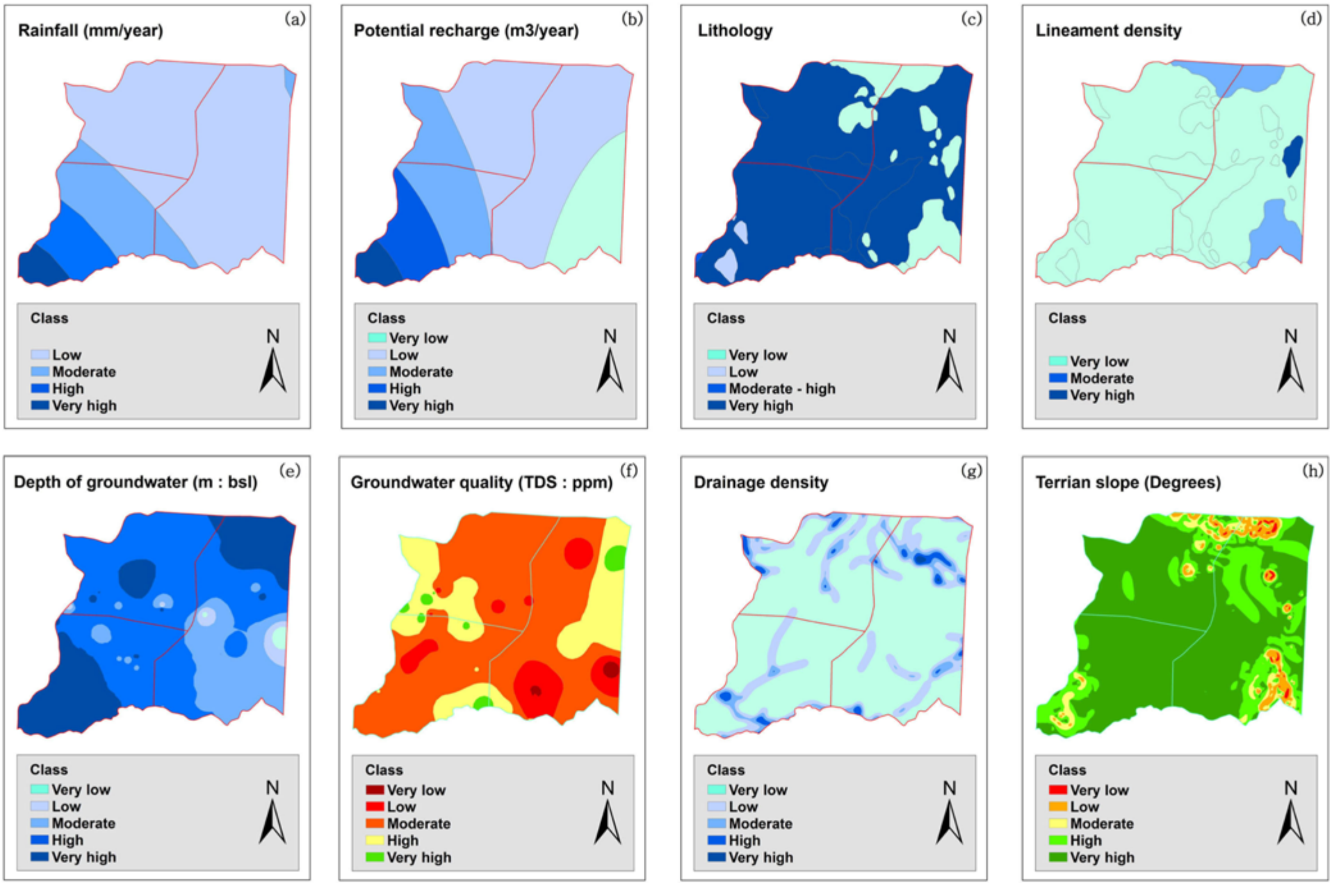

Fig. 9. Spatial data weights of the eight factors used in the overlay technique in GIS. The factors are shown in the five classes of very low, low, moderate, high and very high for: (a) rainfall (mm/year), (b) potential recharge (m^3/year), (c) lithology, (d) depth of groundwater (m below sea level), (e) total dissolved solids (ppm), (f) lineament density, (g) drainage density, and (h) terrain slope.

influencing parameters on mapping groundwater potential areas; therefore, it was assigned a weight of 20. For long-term averaged steady-state conditions, the potential recharge rate could be estimated using the water budget equation and overlay method in GIS as shown in Equation (2) and categorized into five classes as follows: <78.6, 78.6–80.6, 80.6–82.6, 82.6–84.6, >84.6 mm/month (Fig. 9b and Table 5). Rainfall and potential recharge factors may affect each other positively, where the higher the rainfall amount, the higher the groundwater recharge, and vice versa (Figs. 9a and b).

$$R = P - ET \tag{2}$$

where R is the potential recharge rate (mm), P is the precipitation amount (mm), ET is the actual evapotranspiration (mm).

3.3.3. Lithology factor

The relationship between rock types (lithology) and the hydrogeological characteristics, including their water infiltration capacity, varied directly. In other words, the rock type with various fracture systems, joints, and dykes, is the major water-controlling factor which influences the capacity and specific storage of groundwater. The rocks become aquifers through of weathering developed fractures by secondary porosity. This geologic map was derived from the available database of geological maps of scale 1:50000. The different lithologies have been marked out and digitized as polygons and then generated as a thematic map. According to the pumping test data from the 12 wells, the T and K of the Qfd aquifer are greater than those for the PCms and Gr aquifers. This area is dominantly covered by alluvial floodplain (83.20%) followed by granite (15.20%) and metasedimentary (1.60%). Alluvial floodplain consists of layers of sand, gravel, clay, silt and mixture. The thickness of alluvial floodplain ranges between 5 m to 60 m, which is the major aquifer of groundwater sources in this area. The most important factors is the clay content in different lithologic formations, particular in both bare soils and sedimentary rocks, because it controls water percolation and decreases the permeability among rocks. Furthermore, rock hardness was accounted in the classification because hard rocks are frequency brittle and results in fracturing systems, which in turn increase rock permeability and facilitate water infiltration. Hence, a classication of the lithologic factors according to their hydrogeological properties of different lithological formations was carried out; thereafter, a map with four classes was created to reveal rock formations of similar hydrologic characteristics (Fig. 9c and Table 5). The classified litholgic map with four classes was used as one of GIS thematic layer and assigned a weight of 20 in the potential surface analysis.

3.3.4. Lineament density factor

Because the joints and fractures in rocks (lineament) increase their secondary permeability and porosity, and so accelerate the rate of water percolation to recharge the aquifers (Haridas et al., 1998), the lineament density of a hard rock is of considerable importance in identifying groundwater potential areas. The lineament density was deduced from the secondary porosity. For this reason, lineament density factors were assigned as a major factor in considering groundwater potential areas. The structural lineation map was introduced to explore groundwater potential by El-Shazly et al. (1980). The geologic structure data, which was received from Department of Mineral Resources (DMR), were incorporated into the GIS. The resulting lineament density map was divided into five classes, with each class according to a range of lineament density, which showed the number of lineament per unit areas (1000 m^2). Most of the lineament in the area covered three categories as follows: very low (0 m per 1000 m^2), moderate (0.54–0.61 m per 1000 m^2) and very high (>0.61 m per 1000 m^2) (Fig. 9d and Table 5). The highest lineament density categories (>0.61 m per 1000 m^2) occurred within the Cretaceous granite and volcanic intruded as mountain ranges and isolated hills found in the eastern part of the study area. This layer was given a weight of 10 in the potential surface analysis

3.3.5. Depth of groundwater

The depth of water below ground level, which affects its accessibility, depends upon many factors, such as the topography and meteorological and hydrogeological conditions. Moreover, the groundwater table can also change due to natural phenomena and human activities especially in the shallow unconfined aquifers that are greatly affected by surface activities. The attributed data of the groundwater level from total number of 124 well points (drilled wells and hand-dug wells), which were derived from DGR and the field investigation, and were then compiled and interpolated by the isohyets method as a thematic layer for the GIS manipulation. The map revealed characteristic of cones of depression in the central part of the study area. The depth of groundwater was in the range from 2 to 27 m from the ground surface. The depth to groundwater level increases in Cretaceous granitic aquifer (depth to water table ranged 17 to 27 m.) located in the east southern part of the study area, whereas it decreases in central and west southern parts for the Quaternary alluviul aquifers (depth to water table ranged from 2 to 7 m.). The recharge groundwater mostly has been taken place through sandstone aquifer outcrop in western upland areas. The depth of the groundwater was categorized into the five class distributions as follows: 2–7 m, 7–12 m, 12–17 m, 17–22 m and >22 m, and the results are shown in Figure 9e and Table 5. This layer was assigned a weight of 5 in GIS manipulation.

3.3.6. Groundwater quality factor

The total dissolved solids (TDS) level is one of the groundwater quality aspects, and is the summation of the cations and anions in groundwater including those ions that adversely affect the environment and/ or human beings, such as NO_3^-, Pb^{2+} and As^{3+}. The TDS concentration in groundwater is a significant factor which should be considered in groundwater potentiality assessment and the Thai TDS standard has been announced by the DGR. The data for TDS concentration obtained from the field measurements at this study site, which were categorized by hydrogeologic units, revealed that the Gr aquifer in the area has the best groundwater quality (<500 ppm), whereas the Qfd had a moderate groundwater quality (500–1500 ppm). Most wells located in the Qfd were higher than 500 ppm. The worst category of groundwater quality (>1500 ppm) was not found in these regions. The groundwater quality data from the observation wells were interpolated and classied into the five classes as follows: 363–540, 540–721, 721–899, 899–1077, 1077–1256 ppm. The output map was shown in Figure 9f and Table 5. The groundwater quality layer was assigned of 5 in GIS manipulation.

3.3.7. Drainage density

At this study site the intermittent streams have a surface flow only during the wet periods of the year, when the water table rises above the streambed. After that, any water that had not evaporated infiltrates into the subsurface and replenishes the groundwater storage, where the rate of water recharge is governed by the drainage characteristics. In other words, the density of drainage is an important factor in the groundwater potential assessment. Hence, the drainage density has frequent been used as one of thematic layer for GIS manipulation to propose groundwater potential areas, which was studied by Edet et al. (1998) and Robinson et al. (1999). The drainage density, as the unit length of a stream channel per unit area, has been shown to vary between regions because of different climatic characteristics, natural landscape characteristics and land use impacts (Tucker and Bras, 1998), and was calculated using Kernel's method. A surface drainage map was generated from the DEM of 30 m resolution, toposheets at 1:50,000 scale. These classes were categorized into the five classes as follows: <1.37, 1.37–4.23, 4.23–8.03, 8.03–15.33, 15.33–

27.06 m/m^2 and then were generated as a thematic layer for the GIS manipulation with a weight of 5, shown in Figure 9g and Table 5.

3.3.8. Terrain slope

In hydrology studies, the slope is a factor that can significantly influence the pool or pond after raining. In addition, the slope is also a signicant factor in determining the infiltration rate because the relationship between slope and infiltration of water body varies inversely to the groundwater recharge rate. In other words, the water infiltration decreases as the slope steepness increases (Doll et al., 2002). This study area covered mountainous terrains in the north and south eastern portions with 15–30° and 30–60° about 7.91 km^2 (3.84%) and 0.92 km^2 (0.45%), respectively; hence, the slope was included to consider as one of GIS layer with a weight of 5 in the potential surface analysis. The slope map of Huay Sai was generated from the Digital Elevation Map (DEM) of 30 m resolution, and revealed the flat terrain in the central part of the area, which has a high possibility that the water will remain on the surface long enough to infiltrate. The slope classification was categorized into the five classes, where the maximum slope influencing terrain is 60%, according to SOTER (SOils and TERain) Model (Van Engelen and Wen, 1995; Elewa and Qaddah, 2011). The results are shown in Figure 9h and Table 5.

The results of the PSA analysis are shown in Table 6 and Figure 10. The output map with five major categories of groundwater potentiality was classified into 5 classes as follows: <20% (very low), 21–40% (low), 41–60% (moderate), 61–80% (high) and >80% (very high) for groundwater potentiality. The groundwater potentiality classes ranged from very high in the Rai Mai Pattana area to very low in

Table 6. Areas of groundwater potentiality classes (km^2)

Potentiality class	Very low	Low	Moderate	High	Very high	Total
Area (km^2)	7.77	33.6	116.6	44.8	2.64	205.4
Area (% of total area)	3.78	16.37	56.74	21.81	1.28	100

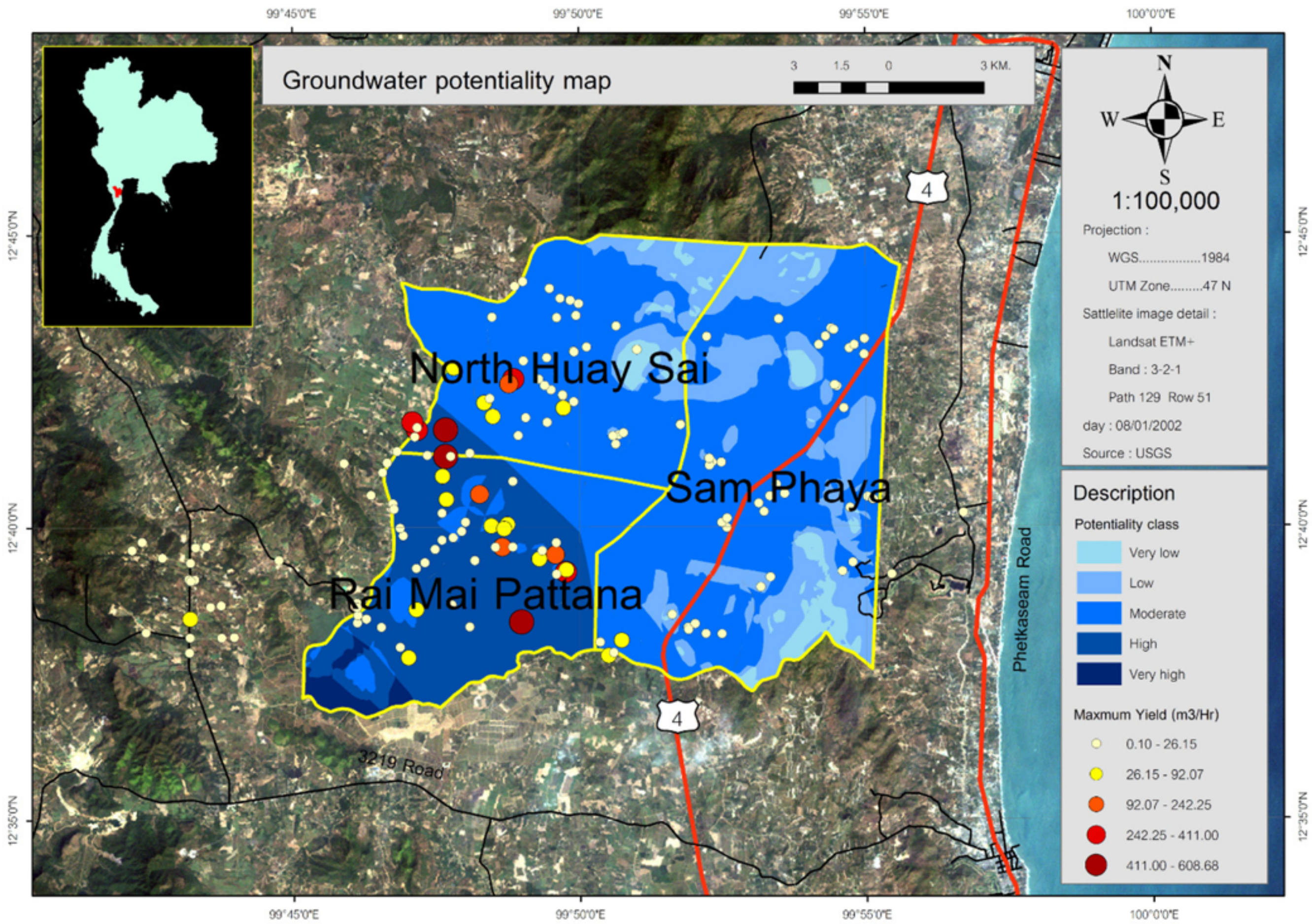

Fig. 10. Groundwater potentiality map of the study area.

Table 7. Model validation using maximum yield data

Potentiality class	Very low	low	Moderate	High	Very high	Total
Observed wells	1	6	73	44	–	124
Observed wells (% of total)	0.81	4.84	58.87	35.48	–	100
Highest maximum yield (m^3/hr)	1.58	5.54	310.1	608.9	–	
Lowest maximum yield (m^3/hr)	1.58	1.51	0.42	0.85	–	
Average maximum yield (m^3/hr)	1.58	3.45	12.40	77.00	–	
Median maximum yield (m^3/hr)	1.58	3.31	2.56	9.91	–	

the Sam Praya area, which is consistent with where rainfall and groundwater recharge are relatively high and rock fractures are dominant, which often are located in the elevated area in the southwestern part of the Huay Sai area. The low groundwater potential zones mainly comprise structural granite hills and escarpments which give high surface runoff and low recharge rate. The resulting map showed areas having very high groundwater potential revealed an area of 2.64 km^2 (1.28% of the study area), whereas the regions exhibited by very low groundwater potentiality is approximately 7.77 km^2 (3.78% of the study area). The map declared that the Huay Sai area is commonly of moderate groundwater potentiality, where this category covers an area of 116.6 km^2 (56.74% of the study area) (Table 6 and Fig. 10). However, hydrogeological characteristics, such as the T, K, specific capacity and yield values, were also significant factors in determining the groundwater potential. Hence, for verification of the validity of the groundwater potential map, the maximum yield was used to indicate the groundwater potentiality, for the maximum yield of a well is controlled by the available drawdown and the specific capacity when the drawdown in the well equals the available drawdown (Ralph, 2004).

Therefore, the validity of the groundwater potential map was checked against the published hydrogeological map carried out by DGR and the hydrogeological characteristics mentioned above. The validation of 124 DGR wells is shown in Table 7, where a concordant justification was reached. However, the areas with a very low or very high groundwater potential could not be validated because of insufficient data. A comparative analysis was applied between the classes of maximum yield in groundwater wells and the classes illustrating different groundwater potential zones in the output groundwater potential map and was found to be congruent (Fig. 10). Most groundwater wells (>94%) with average maximum yields of 12.40 and 77.00 m^3/hr locate in the categories of moderate and high, which showed that the groundwater potential zones obtained from this model have a good agreement with the actual well data. Therefore, the output map can be used as a preliminary reference of groundwater prospect zones and also to provide recommendations to solve the water scarcity and groundwater protection from deterioration and depletions.

4. CONCLUSIONS

In the Huay Sai Royal Development Study Centre and the adjacent areas of Amphoe Cha-am and Changwat Phetchaburi, there are three types of aquifers: the unconsolidated (i) floodplain deposited Qfd aquifer and the consolidated (ii) PCms and (iii) Gr aquifers. The Qfd and PCms aquifers were distributed over Tambon Sam Phraya, Tambon Huay Sai Nua and Tambon Rai Mai Phattana, whilst the Gr aquifer was found in Tambon Sam Phraya in the eastern part of the study area. The groundwater flows from the southwestern area to the north-eastern area. The yield potential of the groundwater in the different aquifers ranged in the following order (largest to smallest): Qfd > PCms > Gr. Cones of depression were found in the central areas and resulted from large scale water extraction from wells for agricultural purposes. Most of the groundwater types in the study area were of the $Ca\text{-}HCO_3$, $Na\text{-}HCO_3$, $Ca\text{-}Na\text{-}HCO_3$ and $Ca\text{-}Na\text{-}HCO_3\text{-}Cl$.

Groundwater potentiality classes, ascertained using an overlay technique in GIS, ranged from very high (in Rai Mai Pattana area) to very low (in Sam Praya area), where a concordant justification was reached with the maximum yield and the hydrogeological characteristics. Moreover, it can be concluded that PSA in GIS manipulation are very efficient and useful, time and cost effective tool for the identification of mapping groundwater potentiality. These form the fundamental basic data for groundwater exploration planning and sustainable management of future groundwater budgets.

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REFERENCES

Ateawung, J.N., 2010, A GIS based water balance study of Africa. Master thesis, Vrije Universiteit Brussel, Belgium, 55 p.

Bilal, A. and Ammar, O., 2002, Rainfall water management using satellite imagery: examples from Syria. International Journal of Remote Sensing, 23, 207–219.

Chenini, I. and Ben Mammou, A., 2010, Groundwater recharge study in arid region: an approach using GIS techniques and numerical modeling. Computer and Geosciences, 36, 801–817.

Das, D., 2000, GIS application in hydrogeological studies. Available via http://www.gisdevelopment.net/application/nrm/water/overview/wato0003.htm Cited March 2013.

Department of Groundwater Resources (DGR), 2001, Groundwater Guide Manual Book, Phetchaburi Province. Department of Groundwater Resources, p. 1–52.

Doll, P., Lehner, B., and Kasper, F., 2002, Global modeling of groundwater recharge. Proceedings of the 3rd International Conference on Water Resources and the Environmental Research, Vol. 1. Technical University of Dresden, Germany, July 22–25, p. 27–35.

Edet, A., Okereke, S., Teme, C., and Esu, O., 1998, Application of remote sensing data to groundwater exploration: a case study of the Cross River State, southeastern Nigeria. Hydrogeology Journal, 6, 394–404.

Elewa, H.H. and Qaddah, A.A., 2011, Groundwater potential mapping in the Sinai Peninsula, Egypt, using remote sensing and GIS-watershed-based modeling. Hydrogeology Journal, 19, 613–628.

El-Shazly, E.M., Abdel Haday, M.A., El Ghawaby, M.A., Salman A.B., El Rakaiby, M.M., and El Aasy, I.E., 1980, Structural lineation maps of Sinai, scale 1:250,000. Academy of Scienctific Research and Technology, Remote Sensing Center, Cairo.

Fetter, C.W., 2002, Applied hydrogeology, Fourth Edition. Prentice-Hall, New Jersey, 598 p.

Galloway, W.E. and Kaiser, W.R., 1980, Catahoula formation of the Texus coastal plain: origin, geochemical evolution, and characteristics of uramium deposits. University of Texus Bureau of Economic Geology Report of Investigation 100, 81 p.

Ganapuram, S., Kumar, G., Krishna, I., Kahya, E., and Demirel, M., 2008, Mapping of groundwater potential zones in the Musi basin using remote sensing and GIS. Advances in Engineering Software, 40, 506–518.

Haridas, V.R., Aravindan, S., and Girish, G., 1998, Remote sensing and its application for groundwater favourable area identification. Quarterly Journal of GARC, 6, 18–22.

Hill, R.A., 1940, Geochemical patterns in Coachella valley, California. Transactions-American Geophysical Union, 21, 46–53.

Isaaks, E.H. and Srivastava, R.M., 1989, An introduction to applied geostatistics. Oxford University Press, New York, 561 p.

Khan, S., Rana, T., and Gabriel, H.F., 2008, Hydrogeologic assessment of escalating groundwater exploitation in the Indus Basin, Pakistan. Hydrogeology Journal, 16, 1635–1654.

Kinzelbach, W., Aeschbach, W., Alberich, C., Goni, I.B., Beyerle, U., Brunner, P., Chiang, W.H., Rueedi, J., and Zoellmann, K., 2002, A Survey of Methods for Groundwater Recharge in Arid and Semi-arid Regions. Early Warning and Assessment Report Series, UNEP/DEWA/RS.02-2, United Nations Environment Programme, Nairobi, Kenya.

Kumar, P., Gopinath, G., and Seralathan, O., 2007, Application of remote sensing and GIS for the demarcation of groundwater potential areas of a river basin in Kerala, southwest coast of India. International Journal of Remote Sensing, 28, 5583–5601.

Lachaal, F., Bedir, M., Tarhouni, J., Gacha, A.B., and Leduc, C., 2011, Characterizing a complex aquifer system using geophysics, hydrodynamics and geochemistry: A new distribution of Miocene aquifers in the Zeramdine and Mahdia–Jebeniana blocks (east-central Tunisia). Journal of African Earth Sciences, 60, 222–236.

Megesh, N.S., Chandrasekar, N., and Soundranayagam, J.P., 2012, Delineation of groundwater potential zones in Theni district, Tamil Nada, using remote sensing, GIS and MIF techniques. Geoscience Frontiers, 3, 189–196.

Piper, A.M., 1944, A graphic procedure in the geochemical interpretation of water analysis. Transactions-American Geophysical Union, 25, 914–928.

Rahman, H.A., 2001, Evaluation of Groundwater Resources in Lower Cretaceous Aquifer System in Sinai. Water Resources Management, 15, 187–202.

Ralph, C.H., 2004, Basic ground-water hydrology, U.S. Geological Survey Water-Supply paper 2220, 86 p.

Robinson, C., El-Baz, F., and Singhory, V., 1999, Subsurface imaging by RADARSAT: comparison with Landsat TM data and implications for groundwater in the Selima area, northwestern Sudan. Canadian Journal of Remote Sensing, 25, 268–277.

Saud, M.A., 2010, Mapping potential areas for groundwater storage in Wadi Aurnah Basin, western Arabian Peninsula, using remote sensing and geographic information system techniques. Hydrogeology Journal, 18, 1481–1495.

Savane, I., Goze, B., and Gwyn, H., 1996, Cartographic and structural study using Landsat in the Ivory Coast. Proceedings of the 26th International Symposium on Remote Sensing of Environment, Vancouver, BC, 25–29 March, p. 92–97.

Sener, E., Davraz, A., and Ozcelik, M., 2005, An integration of GIS and remote sensing in groundwater investigations: a case study in Burdur, Turkey. Hydrogeology Journal, 13, 826–834.

Teeuw, R., 1995, Groundwater exploration using remote sensing and a low-cost geographic information system. Hydrogeology Journal, 3, 21–30.

Tesfaye, T.G., 2010, Groundwater potential evaluation based on integrated GIS and remote sensing techniques, in Bilate river catchment: South rift valley of Ethiopia. Master thesis, Addis Ababa University School of graduate studies department of earth sciences, Ethiopla, 96 p.

Tucker, G.E. and Bras, R.L., 1988, Hill slope processes, drainage density, and landscape morphology. Water Resources Research, 34, 2751–2764.

Van Engelen, V.W.P. and Wen, T.T., 1995, Global and national soils and terrain digital database (SOTER). Procedures manual (revised edition). International Soil Reference and Information Centre, Wageningen, The Netherlands, 125 p.

Voudouris, K.S., 2006, Groundwater Balance and Safe Yield of the coastal aquifer system in NEastern Korinthia, Greece. Applied Geography, 26, 219–311.

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