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An integrated approach for aquifer characterization and groundwater productivity evaluation in the Vientiane Basin, Lao PDR

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Abstract

The Vientiane Basin is at the center of the social-economic zone of Lao PDR so there is a high water demand which was estimated at householder consumption of about 100 liters/day/person. There are initiatives to enforce regulations for groundwater management but the data has insufficient. Hydrogeological characterization is one of the indicators and basic data to groundwater productivity evaluation. This study develops a pilot hydrogeological characterization in the Vientiane Basin followed by a Guide and a Standard Legend of the International Association of Hydrogeologists and methods of Thailand with integrated data on geology and hydrogeology from several sources by using the Geographic Information System tool for the creation of hydrogeological characterization maps and applies hydrogeology units of Thailand. The most significant features are discovered in the Xaysomboun formation (K2xb or K2sb) and some areas indicate brackish and saline groundwater. Similarly, the Thangon formation (K2tn) includes three-layers such as K2tn1, K2tn2, and K2tn3 of which K2tn1 is salty water. K2tn has some parts in the center of the Xaythany and Hadxayfong District where there is high groundwater salinity (TDS >1,500 mg/l) at shallow depths with low groundwater potential of about less than 2 m^3/hr. Chathaboury and Hadxayfong Districts are near the Mekong River and there is a higher groundwater potential of >20 m^3/hr and TDS <500 mg/l. Groundwater potential at the downstream of this basin or along the Mekong River or Transboundary aquifer between the Udon-Sakon Nakorn Basin (Thailand) and Vientiane Basin has a relatively high potential of 10 to >20 m^3/hr and is also one of the important freshwaters resources in the Vientiane Basin.

Keywords: Hydrogeological characterization, Groundwater, Groundwater potential, Groundwater management, Vientiane Basin

1. Introduction

The Lao People's Democratic Republic (Lao PDR) is a landlocked country in Southeast Asia but Laos is a water abundant country [1]. The FAO's country-level AQUASTAT database estimated the annual groundwater replenishment for Laos at around 37,900 MCM [2]. In Laos, the groundwater resource is one of the important sources of water for domestic use in rural areas [3], and small-town water utilization [4]. In 2005, groundwater use for household consumption in Laos was estimated at about 100 liters/day/person [5]. Groundwater is a main source that needs little or no treatment and does not pose any threat to human health when used for drinking.

The Vientiane Basin (VTB) is physically a part of the Khorat Plateau and Lower Mekong River 2 Aquifer [6]. This basin is also having the impact of subsurface saline water contamination due to the underlying sandstone, siltstone, shale and rock salt layers of Thangon formation similar to Mahasarakham Units in the Khorat Basin, Thailand [7].

Several organizations have tried to evaluate potential groundwater resources since 1993 [8-10], developing groundwater maps [11] and assessing recharge from hydrological analysis [12] numerical modeling [13] and groundwater potential evaluations [14]. Nevertheless, the technical information is essential in order to improve tools for groundwater management and evaluation of groundwater potential in Laos [15] and the VTB [16].

This study attempts to study and improve the hydrogeology map and groundwater potential by integrating information on groundwater productivity evaluation in data-scarce areas which focuses on the provision of groundwater productivity evaluation in the VTB. The information will be very important for groundwater use planning and support Laos's groundwater governance system development such as the Water and Water Resources Law [17] and the Regulation on groundwater management [18]. The hydrogeological characterization database in VTB can also be used for groundwater management under the internationally transboundary aquifers (TBAs) [19] in the Greater Mekong sub region (GMS).

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2. Materials and methods

2.1 Study area

The VTB is downstream of the Nam Ngum River Basin in central Laos of which the total area is 4,517 km^2. The elevation of this basin is between 155 to 900 Meters above Sea Level (MASL). The total population was around 800,000 people in 2020. In the hottest moths of March and April, average monthly temperature ranges from 30°C to 38°C, annual rainfall at Thangon Village station is 2,400 mm, annual runoff is 1,485 mm [20]. The VTB is an important area for social-economic development and has had high population growth in this area, consequently, there is a higher demand for water utilization. Surface water and groundwater resources are used for consumption, irrigation, and industries in urban and rural areas [1].

2.2 Methods

The methodology for hydrogeology maps, cross-section, groundwater expectation maps, and groundwater potential maps in VTB has followed the methodologies of Guideline and a Standard Legend International Association of Hydrogeologists from a provincial groundwater map guide book of the Department of Mineral Resources of Thailand [9].

The protocol of this research has been designed into four steps which is shown in Figure 1. The first process is data gathering and bore well investigation using multi-significant reports/literature, GIS, and groundwater investigation in Laos. The second process is synthesizing raw data and improving the hydrogeology map by interpretation of the geology and hydrogeology maps and cross-section. The third process is an integrated information and GIS from the second process; this process produced groundwater flow, groundwater expectations, and basic groundwater quality (salinity). The final process is data aggregation to develop a potential groundwater map.

2.2.1 Data base development and bore well database

There is reviewed data in Table 1 shows a summary of sources of data used from 1993-2020 from any sources used to improve the hydrogeology maps and draw cross-sections in this research.

This research used the Geological and Mineral Map of the Vientiane Area, 1985 (GMMVA1985) of the Laos Department of Geology (DoG) [8] as a base map for the hydrogeology map development integrated with the multi-data source. Additionally, the scale of the base map of hydrogeological characterization, 2020 is 1:100,000 and the coordinate system is WGS84 Zone 48N.

The hydrogeological cross-sections were drawn into six cross-sections from west to east and setup on a horizontal scale of 1cm/100 m and a vertical scale of 1cm/500 m. The sections were developed using multi sources data as illustrated in Table 1 and the GIS data set of the VTB. The main index well logs data are 18 potash investigation borehole logs in GMMVA1985 [8] and three potash investigation borehole logs in Thailand.

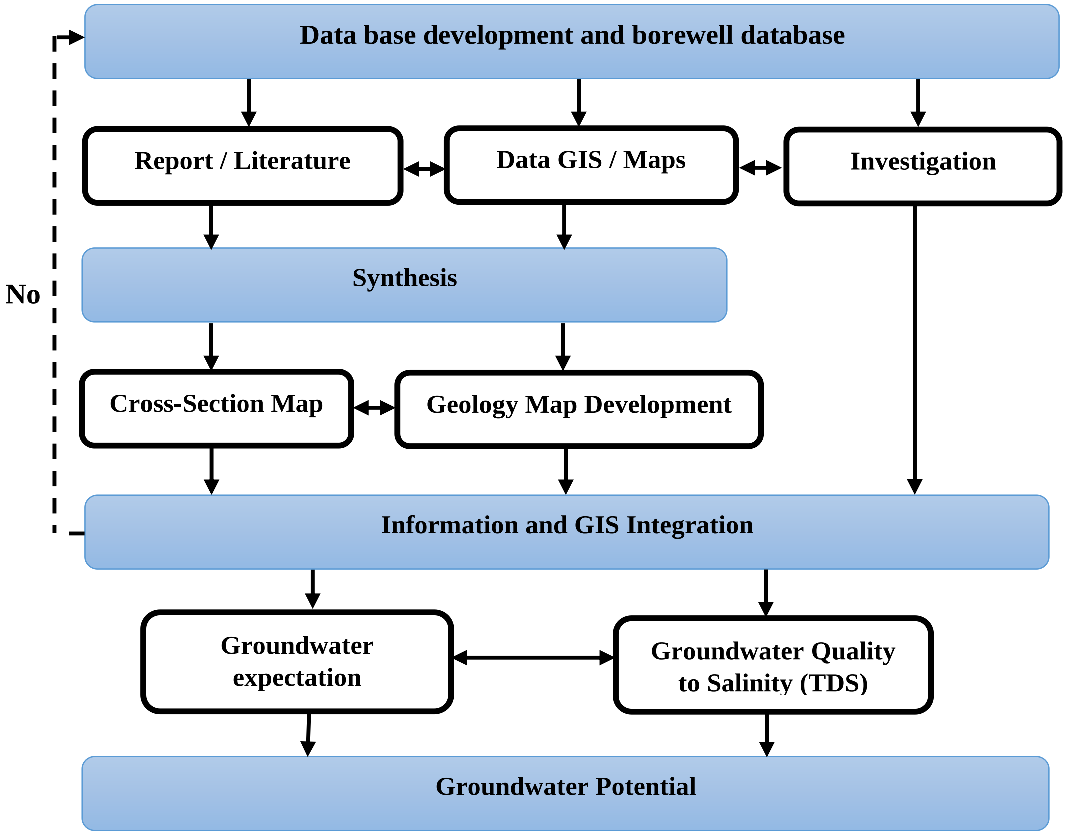

Figure 1 General workflow of the study

Table 1 Sources of the data used to develop the hydrogeological map cross-section

Sources Data	Document	Year	Areas	Interest
Department of Geology (DoG) [8]	Geological and Mineral Map of the Vientiane Area, 1985 (GMMVA1985)	1985	Vientiane Area	18 geologic logs of boreholes including LK1, LK3, LK5, LK4, LK6, LK 8, LK10, LK12, LK18, LK20, LK21, LK23, LK25, LK30, LK31, LK34, LK35 and LKII
Department of Mineral Resources (DMR) [9]	Geology Survey Report	1990	Nong Kai Province	Deep well geology logs including well no. K008, K044, K045, and K046
Japan International Cooperation Agency (JICA) [10]	Basic Design Study Report on The Project for Groundwater Development in Vientiane Province in Lao People's Democratic Republic	1993	Vientiane Province and the Vientiane Capital	105 geologies well logs
Srisuk et al. [11]	Groundwater Survey and Evaluation at Huaysone and Huay Sua, LAOS	1999	Naxaythong District /Vientiane Capital	Characteristics of rock units, and water quality
SinoHydro Mining (Lao) Co., Ltd [12]	Environment and Social Impact Assessment 50 kt/a Potassium Chloride Project.	2009	Vientiane Capital	Thongmang Village in the Xaythany District
SinoHydro Mining (Lao) Co., Ltd [13]	Environmental Impact Assessment of SinoHydro Mining)Lao (Co., Ltd 120kt/a KCL Project in Vientiane	2011	Vientiane Capital	Dongbong Village in the Xaythany District
Perttu et al. [14]	Characterization of aquifer in the Vientiane Basin, Laos, Using Magnetic Resonance Sounding and Vertical Electrical Sounding	2011	Vientiane Province	The result is identified in geological units
Department of irrigation of Laos (DOI) and International Water Management Instituted (IWMI) [15]	Report on the Well Drilling at Ban Akxang	2014	Phonehong District and Vientiane Province	There are 3 boreholes, which studied geology, pumping tests, and water quality
Department of Water Resources (DWR), Natural Resources and Environment Research Institute (NRERI) and International Water Management Instituted (IWMI) [16]	Groundwater Level Report	2015-2016	Vientiane Province and Vientiane Capital	Monitoring 30 boreholes of JICA 1990 in Vientiane Province and 14 new boreholes in the Vientiane Capital .
SSAFE Consult Sole Co., Ltd and Sichuan Above Advantage Lonmon Mining (Laos) Sole Co., Ltd [17]	Report Plan of Environment, Social and Natural Management and Monitoring of Potash Salt Mining and Processing Project in Pak Ngum District, Vientiane Capital	2015	Vientiane Capital	Phoav Village, the Pakngum District, the Vientiane Capital
Ministry of Natural Resources and Environment of Laos (MoNRE), International Water Management Instituted (IWMI), Khon Kean University (KKU) [18]	Draft Report Groundwater Model Development in Vientiane Plain	2017	Vientiane Plain	Groundwater assessment by using numerical model
Viossanges et al. [19]	Regional Mapping of Groundwater Resources in Data-Scare Regions :The Case of Laos	2017	Lao PDR	Develop map by using method on groundwater storage, aquifer productivity and aquifer recharge
Department of Public Health of Vientiane Capital [20]	Groundwater Use in Vientiane Capital, Lao PDR .Ministry of Pubic Heath of Laos (MPH) Final Report.	2017	Vientiane Capital	Groundwater Use
Department of Geology of Laos (DoG), Geoscience Programs in East and Southeast Asia (CCOP), and Department of Water Resources (DWR) [21]	Geology and Groundwater Level Report	2018-2019	Vientiane Capital	There are 2 sites at Dongmakkhai Village and Arkat Village .
Batelaan et al. [22]	Geophysics to enhance agricultural productivity and the livelihoods of smallholder farmers through improved groundwater management of the Vientiane Plain, Lao PDR	2018	Vientiane Province	Geophysical data in the Vientiane Basin
Xayavong et al. [23]	Seismic Refraction Exploration for Groundwater Potential Evaluation :A Case Study of Vientiane Province, Laos .	2020	Vientiane Capital	Groundwater Potential Evaluations in Vientiane Capital

2.2.2 Investigation

The investigation data include as coordinates of groundwater well, well depth of the borehole, the groundwater level, and the Total Dissolved Solids (TDS) which in this research consisted of a total of 173 wells and the data for 95% of the wells was collected at the temple, which displayed the symbol of the investigation area which were distributed throughout 170 villages. There is included three-times such as 1) in the wet season in November 2019; 2) in the dry season in March 2020 and, 3) in the wet season in July 2020. The locations had been distributed in 14 districts in the VTB area as shown in Figure 2.

2.2.3 Groundwater potential mapping

The development of a potential groundwater map applied groundwater expectation and groundwater quality. At the present time, Laos's governance has been established on the decree of environment standard 2017, but it does not consider the TDS of groundwater, nor classified groundwater quantity as well as Laos being data-scarce for groundwater quality for groundwater productivity evaluation. Therefore, the groundwater potential in VTB needed to use standards and methods on the provincial groundwater availability map of Thailand in 2001. The Thailand Department of Mineral Resource (DMR) guide lines [9] were modified from the World Health Organization (WHO) that classified the water quality on the basis of TDS as follows:

TDS <500 mg/L classified as good water quality
500< TDS < 1500 mg/L classified as moderate water quality
TDS > 1500 mg/L is classified as poor water quality
Groundwater availability index as shown in Figure 3.

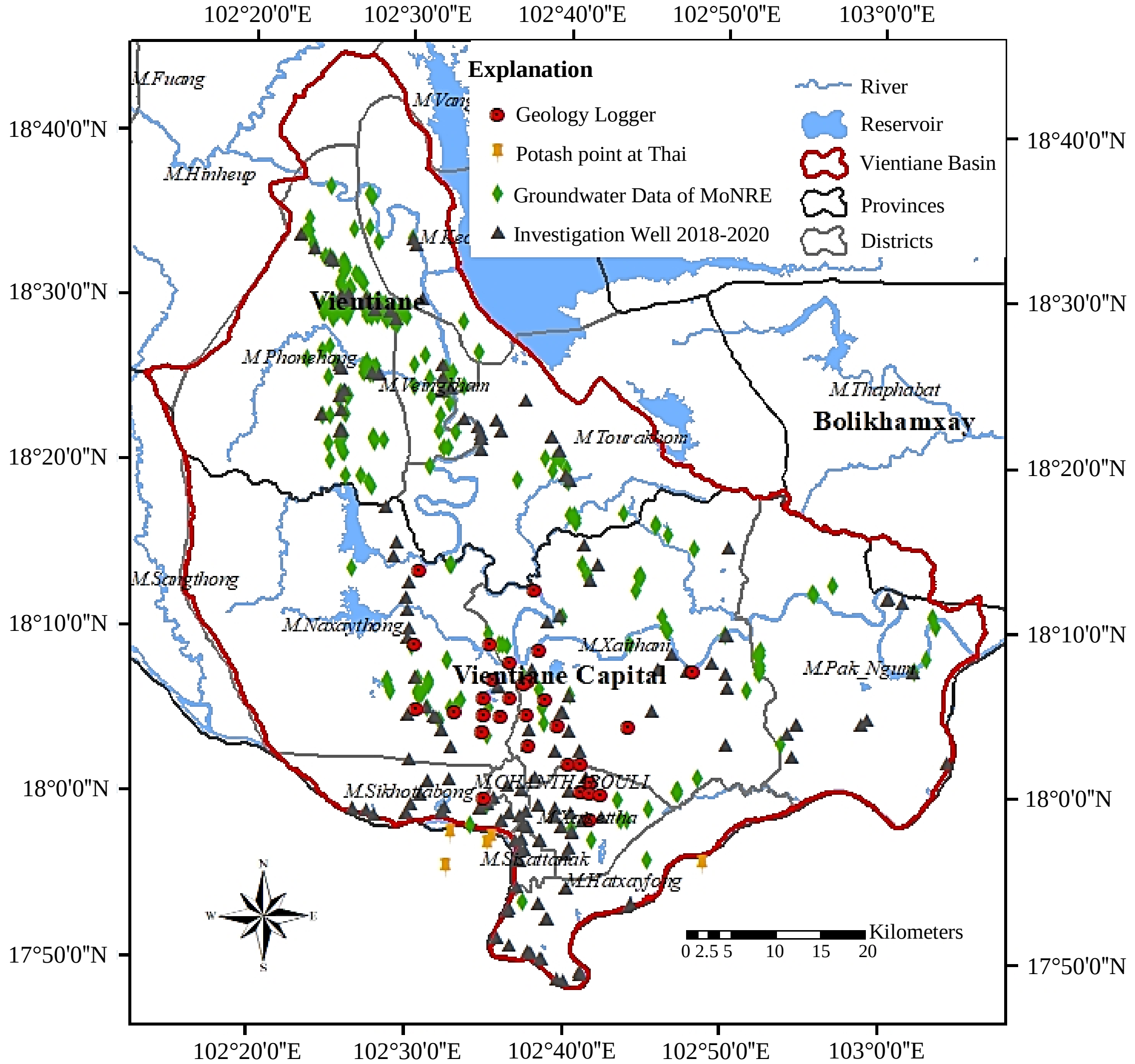

Figure 2 Investigation of groundwater wells, the water table and salinity in the Vientiane Basin

Ground water Quality (mg/L)	Expected Well Yield (m^3/hr) <2	2-10	10-20	>20
< 500	B1	B2	B3	B4
500-1,500	G1	G2	G3	G4
>1,500	O1	O2	O3	O4

Figure 3 Groundwater availability index

An improving GMMVA1985 [8] and developing hydrogeology map, 2020. First, integrate and collect multi-data sources on geology, hydrogeology, GIS data and etc. Then, secondly, the development on the groundwater flow map is also downhill and perpendicular to the water table contours. Therefore, the creation of the direction of groundwater flows maps by using contour datasets and groundwater levels from an investigation which predicts the direction(s) of groundwater flow. At Phou Pha Nag Mountai contours were drawn at 100 m intervals and downstream contours were drawn at 10 m intervals. Thirdly, development on the groundwater expectation map had considered and overlaid on the depth of each groundwater well, groundwater use of 173 wells and overlay a hydrogeology unit at Table 2 and there are arranged an expected well yield with four layers such as <2 m^3/hr, 2-20 m^3/hr, 10-20 m^3/hr and >20 m^3/hr. Fourth, the development of a groundwater quantity map which applied data on TDS from field investigations of 173 wells in VTB and used interpolation tools in ArcGIS and separated values of TDS into three layers such as <500 mg/l, 500-1,500 mg/l and >1,500 mg/l.

Finally, the development of the groundwater quantity map; data was overlayed on expected well yield and data on TDS from the investigation as well as applied groundwater flow to include for consideration. Therefore, the potential groundwater map is arranged with an expected well yield of four layers and TDS three layers which is shown in Figure 3.

3. Results

3.1 Hydrogeology units

Hydrogeological units were referred to Srisuk et al [11], data in Table 2, the GIS data set of VTB, Khorat Pleau of Thailand also equates hydrostratigraphic units as well as hydraulic parameters [14, 24, 25].

QIV, QIII, and N2-Q1vc are the Alluvium Units (Al) and the Terrace Unit (Te) of Thailand, of which Al is one of the major aquifers. It is composed of sand, clay, and gravel and is located along the flood plain of the Mekong River and Nam Ngum River, with a thickness of about 10-45 m. The equivalent characteristics of the rock are a group of Alluvial Deposits, which has an average yield of 5 to 20 m^3/hr. The Te is one of the sands and gravel aquifers that was found in the upland areas in the southern part of the studied area and in the central part of this basin, has a thickness of 10 to 50 m. The N2-Q1vc is the Khu Muang-Nam Mun Unit (Qkm) of Thailand, which has a thickness of about 30 to 50 m and has an average yield of 5 to 10 m^3/hr [26-28].

K2xb or K2sb is the Xaysomboun formation, which includes mica, sand, brownish clay, and white sand quartz, which has been sandwiched together. When compared with the geology of Thailand, it was found to be a Phutok unit (Tpt). The two classes of the Phutok are as follows: 1) the Upper Phutok unit (Upt), which has a thickness of 10 to 200 m, consists of fine-to-medium sandstone and siltstone; and 2) the Lower Phutok unit (Lpt), which consists of clay and clay stone and has an average thickness of about 10 to 300 m, is underlain by a layer of rock salt. The Phutok unit has an average yield of 6 to 10 m^3/hr, but in some areas the yield is more than 50 m^3/hr [26-28].

The Thangon formation (K2tn) is the Cretaceous Mahasarakham (Kms) of Thailand. The Kms unit has a very low-permeability and consists of rock salt, anhydrite, and gypsum, which is inter-bedded with mudstone deposited under Lpt at a thickness that varies from 50 to 600 m [26-28].

The Champa formation (K2cp) is the Cretaceous Khok Kruat (Kkk) of Thailand. The Kkk, which is found at the foot of the mountain, consists of siltstone and sandstone with a thickness of 50 to 400 m. The Khok Kruat has an average yield of less than 3m^3/hr [26-28].

The Phu Phanang formation (J-Kpn) is the Lower Khorat Group unit (Lkg) of Thailand, which consists of sandstone, siltstone, and clay stone, and it is a conglomerate of the Phu Phan, Sao Khua, Phra Wihan, and Phu Kradung formations. In addition, the Kkk has an average yield of less than 3 m^3/hr [26-28].

Table 2 The estimated ranges of the aquifer properties by hydrostratigraphic units

Hydrogeology Units	Kh (m/s)	Kv (m/s)	Ss (m^{-1})	S	Sy	Quantity of Groundwater (m^3/hr)
Alluvium (Al)	$1.1x10^{-7}$ to $1.1x10^{-5}$	$1.1x10^{-7}$ to $1.1x10^{-5}$	$1.0x10^{-2}$ to $1.0x10^{-5}$	-	0.01 -0.35	0.20 - 0.83
Terrace Deposit (Te)	$1.1x10^{-5}$ to $5.0x10^{-2}$	$1.1x10^{-6}$ to $5.0x10^{-3}$	$1.0x10^{-2}$ to $1.0x10^{-5}$	-	0.01- 0.35	
Upper phutok (Upt)	$3.7x10^{-7}$ to $1.8x10^{-6}$	$3.7x10^{-8}$ to $1.8x10^{-5}$	$1.0x10^{-3}$ to $1.0x10^{-5}$	0.01 - 0.20	-	0.25 - 0.42 or 2.083
Lower phutok (Lpt)	$1.1x10^{-7}$ to $2.7x10^{-4}$	$1.1x10^{-8}$ to $1.1x10^{-5}$	$1.0x10^{-3}$ to $1.0x10^{-5}$	0.01 - 0.20	-	
Rock salt (RS)	$1.1x10^{-14}$ to $2.7x10^{-15}$	$1.1x10^{-14}$ to $1.1x10^{-16}$	$1.0x10^{-5}$ to $1.0x10^{-8}$	0.01 -0.10	-	
Khok Kruat (Kk)	$7.5x10^{-8}$ to $5.8x10^{-5}$	$7.5x10^{-9}$ to $5.8x10^{-5}$	$1.0x10^{-3}$ to $1.0x10^{-5}$	0.01 -0.25	-	< 0.125
Lower Khorat Group (Lkg)	$7.5x10^{-9}$ to $5.8x10^{-7}$	$7.5x10^{-10}$ to $5.8x10^{-8}$	$1.0x10^{-3}$ to $1.0x10^{-5}$	0.01- 0.25	-	

Source: Department of Mineral Resources [9].

Note: Kh = Horizontal hydraulic conductivity; Kv = Vertical hydraulic conductivity; Ss = Specific storage; S = Storativity; Sy = Specific yield.

Table 3 Stratigraphic units and characteristics of groundwater parameters of the Vientiane Basin and Khorat Plateau

Vientiane Basin, Lao PDR			Khorat Plateau, Thailand				Groundwater yield (m^3/hr)
Geologic Units	**Geologic age**	**Thickness (m)**	**Geologic unit**	**Geoligc age**	**Thickness (m)**	**Depth of Aquifer (Meter)**	
QIV	Quatermary	0.5	Qa	Quaternary Alluvium	4-40	10-30	0.20 - 0.833
QII-III		20-25	Qt	Quaternary Terrace		10-40	
N2-Q1vc	Vientiane	70	Qkm	Terrace Deposits	30-50	70-100	0.20 - 0.42
K2xb	Xaysomboun	150	Tupt	Upper Phu Thok	50-785	10-50	0.25 - 0.42 or 2.083
			Tlpt	Lower Phu Thok		10-300	
K2tn3	Upper Thangon	>550	Kms	Cretaceous Mahasarakham	156-1,294	20-600	0.125 - 0.25
K2tn2	Middle Thangon						
K2tn1	Lower Thangon						
K2cp	Champa	400	Kkk	Khok Kruat	100-350	50-400	<0.125
			Kpp	Phu Phan	120-150	>1,500	<0.125
J-Kpn	Phu Phanang	350	JKpw	Phra Wihan	100-250		

Modified from Perttu et al. [14], Srisuk [28], Smith et al. [29] and Raksaskulwong et al. [30]

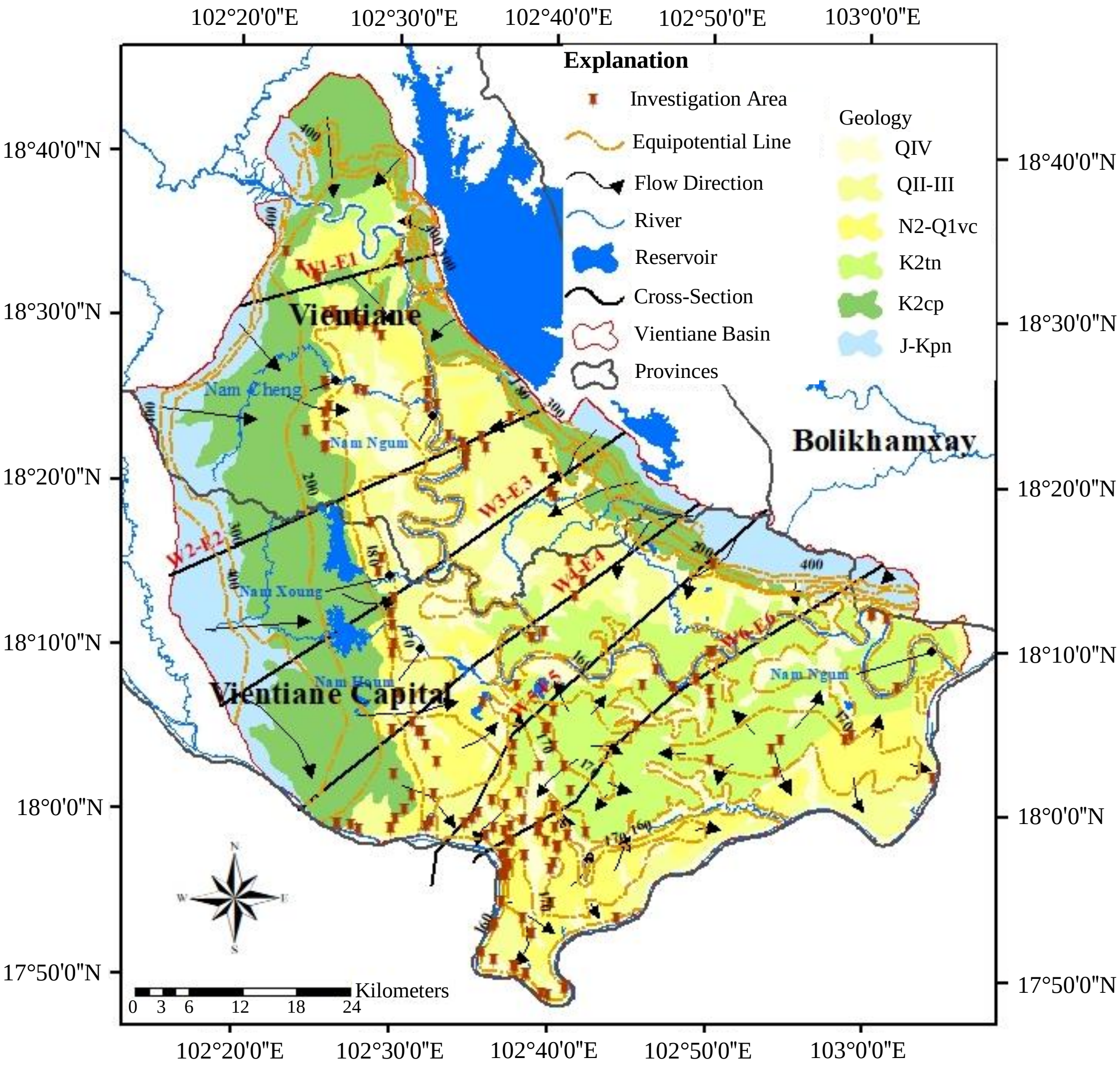

Figure 4 The hydrogeological map of the Vientiane Basin

3.2 Hydrogeological mapping

The GMMVA1985 mapped the geology of VTB and has compiled a groundwater probability map of Lao PDR of IWMI [8, 15, 19, 22]. The VTB was characterized by available geologic and hydro geologic information with existing geologic units and water well records as shown in Figure 4. Several hydrogeologic cross sections were made on the available geologic logs. Moreover, water levels in existing wells were measured and interpreted as hydraulic heads presenting equipotential lines that present general groundwater flow patterns in existing aquifers as depicted in the map in Figure 4. The hydrogeological map of the Vientiane Basin depicting hydro geologic cross sections in Figure 5 to Figure 10.

Also, 18 geologic logs of boreholes of Laos DoG showed the details of the geologic unit such as N2-Q1vc, K2xb, K2tn3, K2tn2, K2tn1, K2ns, K2tn3, and K2ns, in which the maximum depth geologic logs were at 628 m at LK21, and the minimum was 157 m at LK31. The analysis data between GMMVA1985 of Laos DoG and the geological logger's borehole did not match, which meant that the geology map focused on K_2tn but it did not show and did not explain the stratigraphic units on K2xb, K2ns, and K2tnr. Additionally, Logger bars LK1, LK3, LK4, LK5, LK10, and LK21 showed the detail of K2ns but K2ns is not explained in detail in the stratigraphic units of the GMMVA1985 [8]. This research had six cross-sections and the cross-sections showed information on geology layers, groundwater levels, equipotential lines, and the flow paths. Moreover, the cross-sections are one way to support updating the geology map, helping to discover the groundwater potential, and developing the groundwater use of the VTB.

First of all, the cross-section W1-E1 has only limited data on the geology log. The GMMVA1985 of Laos indicated neo-quaternary Q_{III}, cretaceous K2xb, K2tn, K2cp, and J-kpn [8]. However, this cross-section compared the data in the report Perttu et al. [14]; at site 37 (The geology unit at site 37 is K2xb). Therefore, the data has been updated on the cretaceous K2cp at the center of the cross-section to become K2xb. The area of the JICA [10] focused on the Phonhong, Thoulakom, and the Keo Oudom Districts in Vientiane Province. The area, which the JICA [10] focused on has many small undulating hills and consists of sand, gravel, clay, and silt layers of the Pliocene of Tertiary to the hills. The results of the geology of this project showed that there is minimal potential for groundwater development given that the sides of the cross-section W1-E1 are shown as K2cp and J-kpn. However, there is doubt about K2tn at this cross-section but we did not have more data to study and analyze, so it needs to keep to the information herewith.

Secondly, the hydrogeology at cross-section W2-E2 is difficult to interpretation due to the limited of data. The center of the area is covered by QIII and QVI, but it is just a thin layer, and K2cp is under the QIII and QVI, which means that this area has only limited groundwater potential. When drawing the K2tn cross-section, the stratigraphic units were not followed. This area is suspected of having showed K2tn units, but this research does not have any data to prove that, so it will be an area of interest for future studies. The near cross-section W2-E2 has research geophysics to boost agricultural productivity and enhance the livelihoods of smallholder farmers through improved groundwater management of the Vientiane Plan [19]. To accomplish this, the geophysical survey was used to investigate the groundwater at Ekxang Village, Thingnoung Village and Vienkham Village in the Phonehong District.

This investigation included a total of 6 sites, but the results from site 3 indicated that in this area, there is a small amount of groundwater salinity and that it is possibly K2tn. Moreover, cross-section W2-E2 perhaps has K2tn at the Nam Ngum River and under it, perhaps there is the N2-Q1vc unit.

Thirdly, cross-section W3-E3 has data log LK10 of the GMMVA1985 of Laos DoG [8] and data of Perttu et al. [14]; at site 5. The LK10 has a shallow depth of 134 m and the geology unit includes N2-Q1vc, K2tn2, K2tn1, and K2ns which N2-Q1vc has a shallow depth of 52 m whereas, most are deep geology units. Site 5 has a shallow depth of 30 m and is N2-Q1vc which the GMMVA1985 of Laos DoG [8] needs improved geology map 2D and shows detail in Figure 11. Moreover, this cross-section is related to cross-section W1-E1 and W2-E2 because there is a hold of K2cp and J-kpn and limited groundwater potential.

The cross-section W4-E4 starts at the Mekong River from the southwest to the northeast of the Vientiane Basin. The geology logger included LK4 and LK6 of the GMMVA1985 of Laos DoG [8] and data sites1 and site3 of Perttu et al. [14]; to be considered when drawing a cross-section. LK4 has a shallow depth of 138 m and LK6 has a shallow depth of 280 m. Site1 has a shallow depth of 60 m and site 3 has a shallow depth of 50m of which both sites are N2-Q1vc. The referred JICA [10] has information cross-section B-B' that is near cross-section W4-E4 of this paper. The cross-section B-B' displayed N2-Q1vc and K when compared to the GMMVA1985 of Laos DoG at around LK34 may be K2tn [8]. The W4-E4 cross-section reference at LK4 at the last layer is K2ns and LK4 near and connected K2cp as well as Table 3 comparing Lao Stratigraphy and the Thai equivalent of the Vientiane Basin which indicates that K2cp of Laos is Kkk of Thailand. The last layer of K045 is Kkk so possible to K2cp so possible K2ns is K2cp.

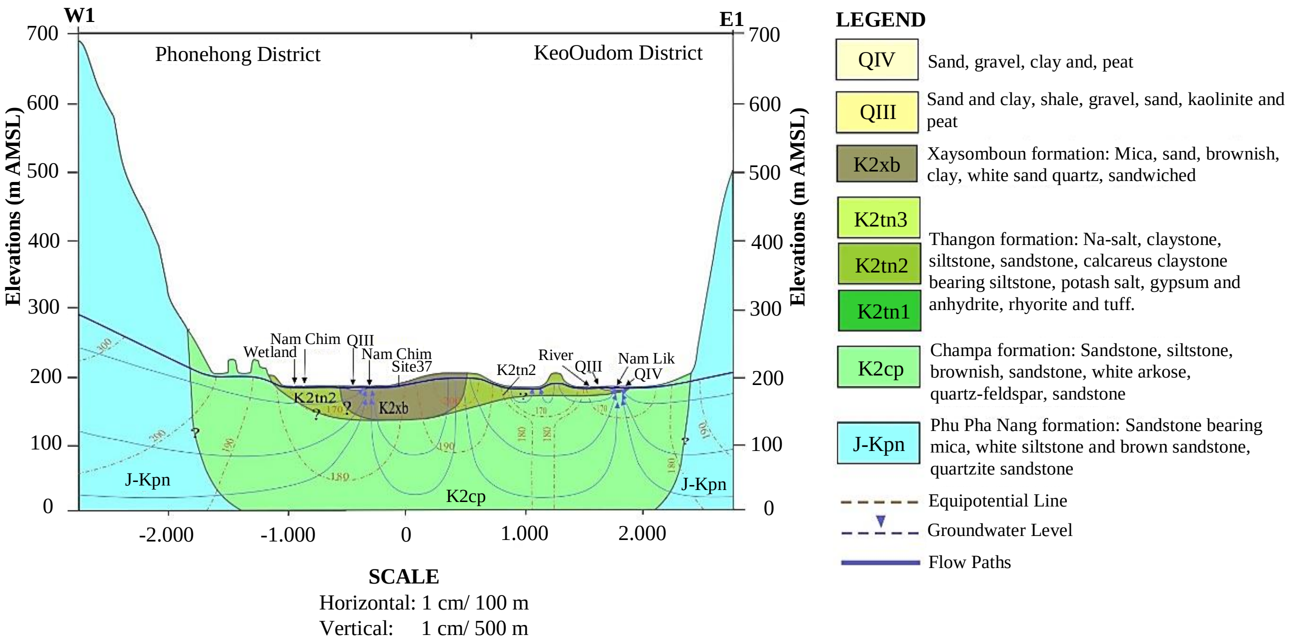

Figure 5 Cross-Section W1-E1

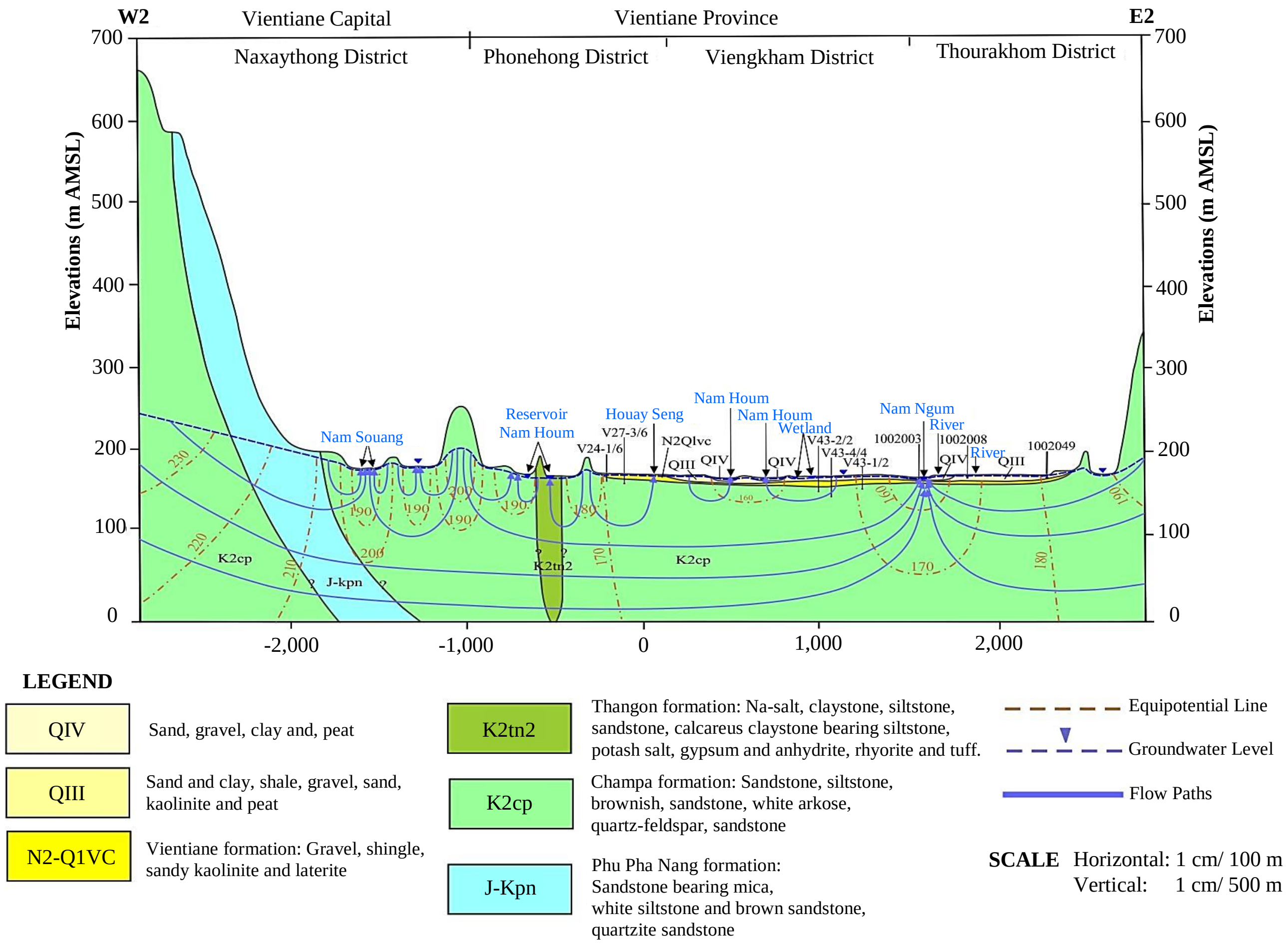

Figure 6 Cross-Section W2-E2

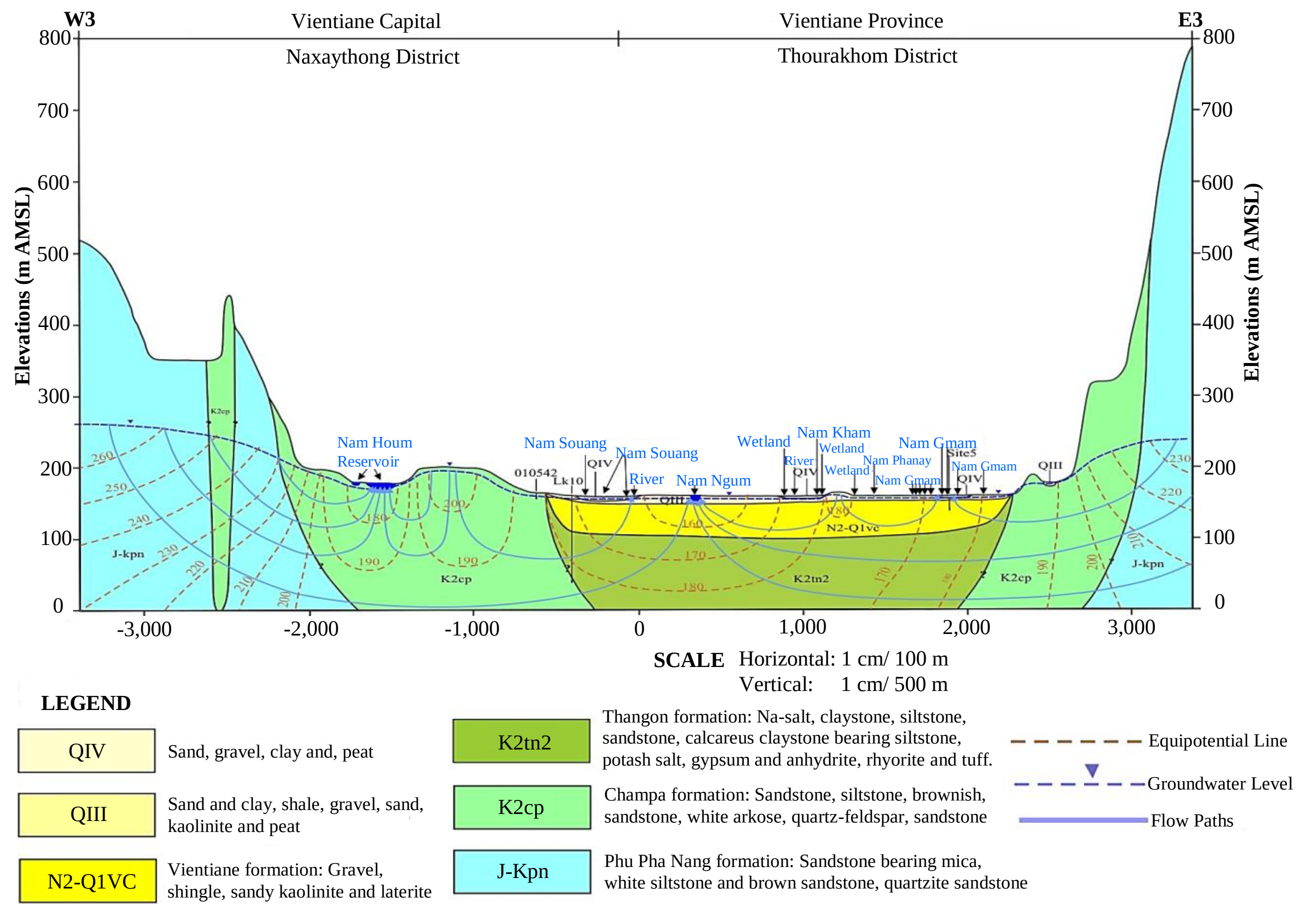

Figure 7 Cross-Section W3-E3

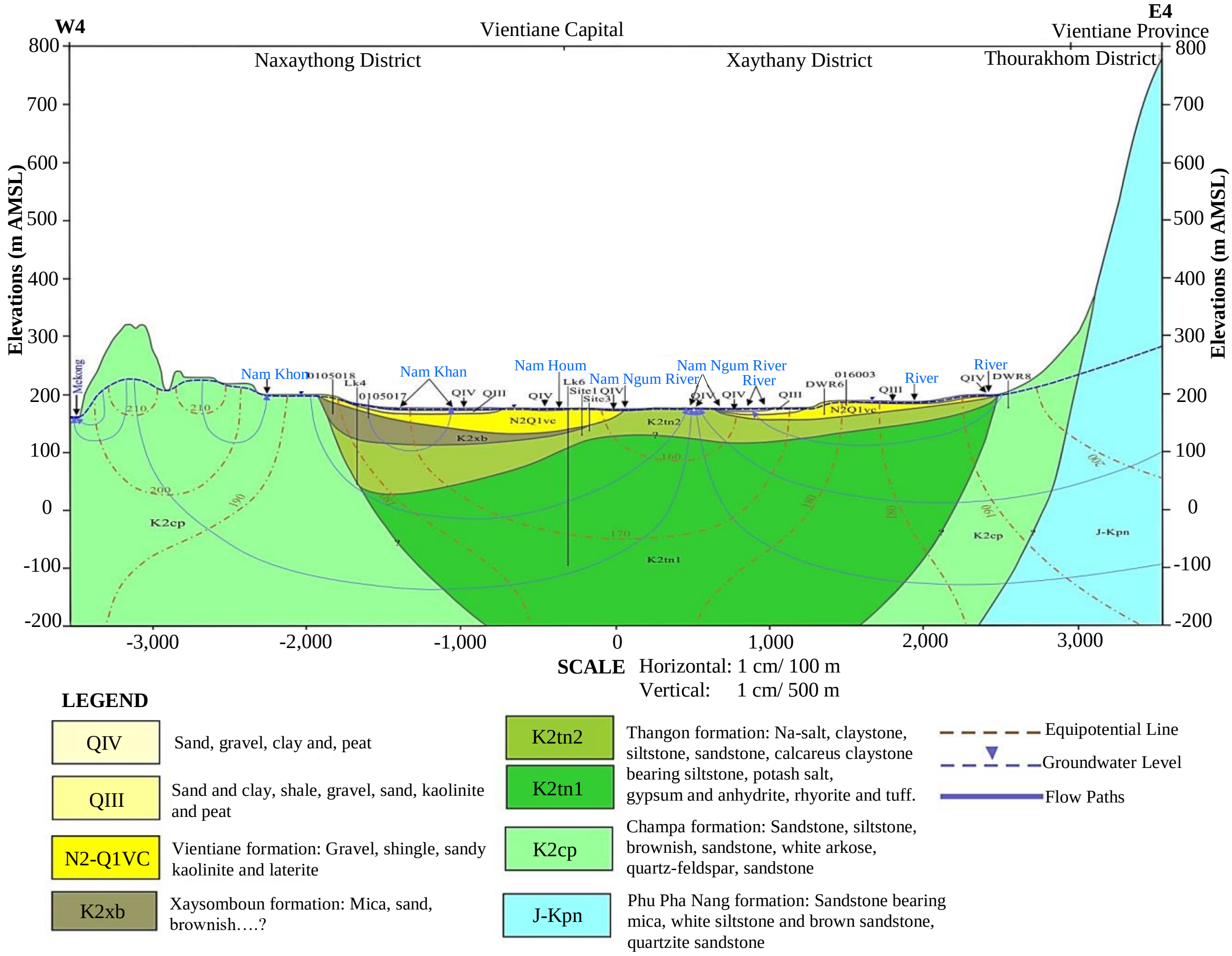

Figure 8 Cross-Section W4-E4

At Sri Chiangmai district, Nongkai Province in Thailand, there were the geology loggers K008 and K045 which were used to draw cross-section W5-E5 of the VTB. Also, there were geology loggers of the GMMVA1985 [8], such as LK8, LK31, LK35, and the geology at Ban Arkat [21]. There have been many types of research studies that have noted that the VBT is just one part of Khorat Basin. However, this matter has not been proven. This cross-section shows and connects geology units, such as QIII, K2nt, and K2cp. However, in the VTB, there is K2xb from LK8, LK35, and LK31 to Nam Ngum River. At LK35, there is a shallow depth of 378 m, and this log has many geology layers, such as N2-Q1vc, K2xb, K2nt3, K2nt2, K2nt1, and K2cp. Moreover, LK35 has appeared central to two faults, which means that this log was lifted out of the geology layers and that K2tn has been separated into three layers, such as K2tn3, K2tn2, and K2tn1. The Upper K2tn layer is K2xb, which shows good groundwater potential.

Finally, for cross-section W6-E6**,** the logger geology of Thailand was used, such as K046 and K045 as well as the LK30, LK18, and the LK21 data of the GMMVA1985 of Laos DoG [8]. This cross-section shows and connects four geology layers as follows: 1) the N2-Q1vc of Laos and the Qa of Thailand; 2) the K2xb of Laos and the Tpt of Thailand; 3) the K2tn3 of Laos and the Kms2 of Thailand, and 4) the K2tn2 of Laos and Kms1. The W2-E2 cross-section in Laos has K2tn1, in which K2tn1 is present at LK30 and LK21. The LK21 data at the last layer showed K2ns, which is suspected to be K2cp. The most serious problem found in the VTB is the occurrence of salty groundwater due to halite in Northern Thailand as well as in the Southern parts of the VTB. There are many deep wells that produce salty groundwater. Geographically speaking, the VTB is in an area that is like Northern Thailand, where the wells commonly produce salty groundwater.

The reference of the GMMVA1985 focused on investigations in the Vientiane Capital to find potassium. Even though geology loggers have recorded K2xb, this map did not show K2xb and did not link with the geology logger. The GMMVA1985 did not have a geology logger for the upstream of this basin and the Pak Ngum District in Vientiane Capital [8]. The most important aspect of this research is integrated multi-data sources to improve the groundwater map in VTB which it shows the detail of in Table 1. It is also interesting to note that the process of improving the geology map consisted of the three following parts in Figure 11: Part "A" was located upstream, Part "B" was located at the east of this basin, and Part "C" was located downstream near the mouth of the Nam Ngum River.

Firstly, the improving on hydrogeology map in the Vientiane Basin 2020 has integrated groundwater investigations around at Part "A" of Figure 11 in which the groundwater level is about 10-20 m but the GMMVA 1985 [8] is K2cp which K2cp or Kkk depth on the aquifer is about 50-400 m. The reference to the JICA [10] investigated distribution in Vientiane Province and identified the depth of the geology log to be between 20-40 m and to expand to Pho Village, Napoune Village, Napho Village, and Phon Savang Village in the Phonehong District. It is probable that the layer was formed by the old Nam Ngum River in the Alluvium or Diluvium Geological Age.

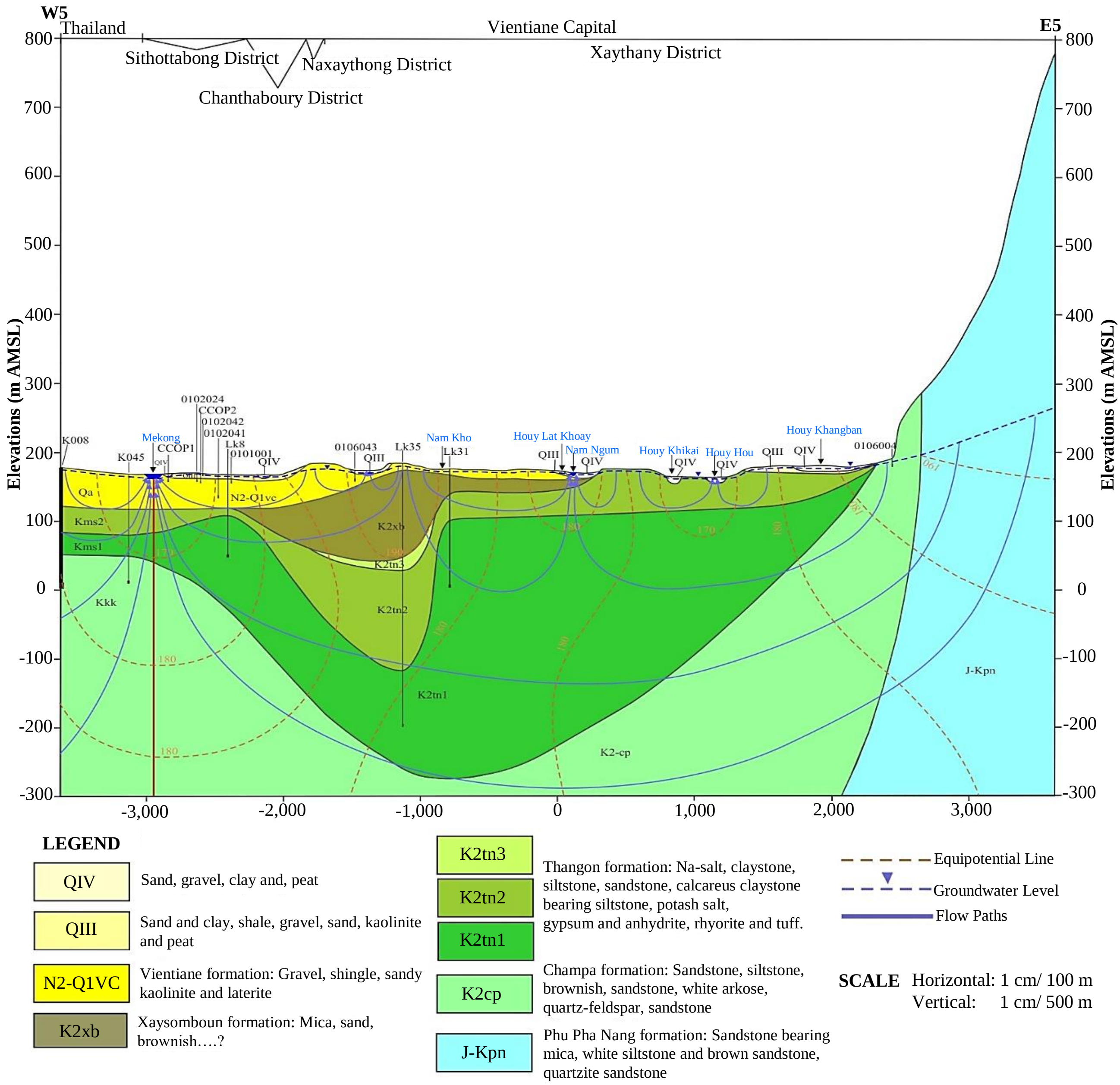

Figure 9 Cross-Section W5-E5

The significance, of this research, is integrated data from the research of Perttu et al. [14]; and Viossanges et al. [19]. The research of the Perttu et al. [14]; cross-session G-H between Naxou Village in the Phonehong District at site 19 and Nalongkhoun Village in the Naxaithong District at site 33 included N2-Q1vc and K2xb. In addition, site 37 was found to be K2xb, but the GMMVA1985 of Laos DoG showed K2cp on the map [8]. The project at Huaysone and Huay Sua [11] which covered Nagnang Village, Namkiang-Nua Village, and Naxap Village in the Xaythany District in the Laos capital, Vientiane, examined the hydro stratigraphics. It was determined that the best potential for feasibly extracting groundwater in the study area was designated to be Qa and Kkk when comparing the GMMVA1985 of Laos DoG [8] and the available cross-section of the Huaysone and Huay Sua project [11].

Further, the previous researcher were used geology data from Ekxang Village at the Phonhong District in Vientiane Province where they conducted drilling to carry out research on groundwater [15, 18]. At this location, the geology unit included Clay-Sand-Gravel. Therefore, this point, which is N2-Q1vc, is like the GMMVA 1985 of Laos DoG. Moreover, there has been Geophysics research to boost agricultural productivity and to enhance the livelihoods of smallholder farmers through improved groundwater management of the Vientiane Plain of Lao PDR. This research used geophysics at Ekxang Village, Thingnoung Village, and Viengkham Village in Phonhong District. At these locations, there are six sites, and the results of three sites indicated salt bodies Viossanges et al. [19].

Consequently, in the landscape at Thingnoung Village and Viengkham Village in Phonhong District, the unit geology of N2-Q1vc from the GMMVA 1985 [8] of the Laos DoG has been improved to become K2tn as noted on the updated geology map which shows the detail at Figure 11. In 2018, the DoG, CCOP, and DWR [21] was drilling to study the geology unit at Akat Village in the Sikhottabang District; and at Dongmakkhay Village in the Xaythany District. The wells at Akat Village are QIII and at Dongmakkhay Village, they are K2tn. When compared to the data of the GMMVA 1985 [8], both wells have linked data on geology. The final result of integrated and compared multi data sources in Table 3, in which Part “A”, is improved from K2cp to K2xb.

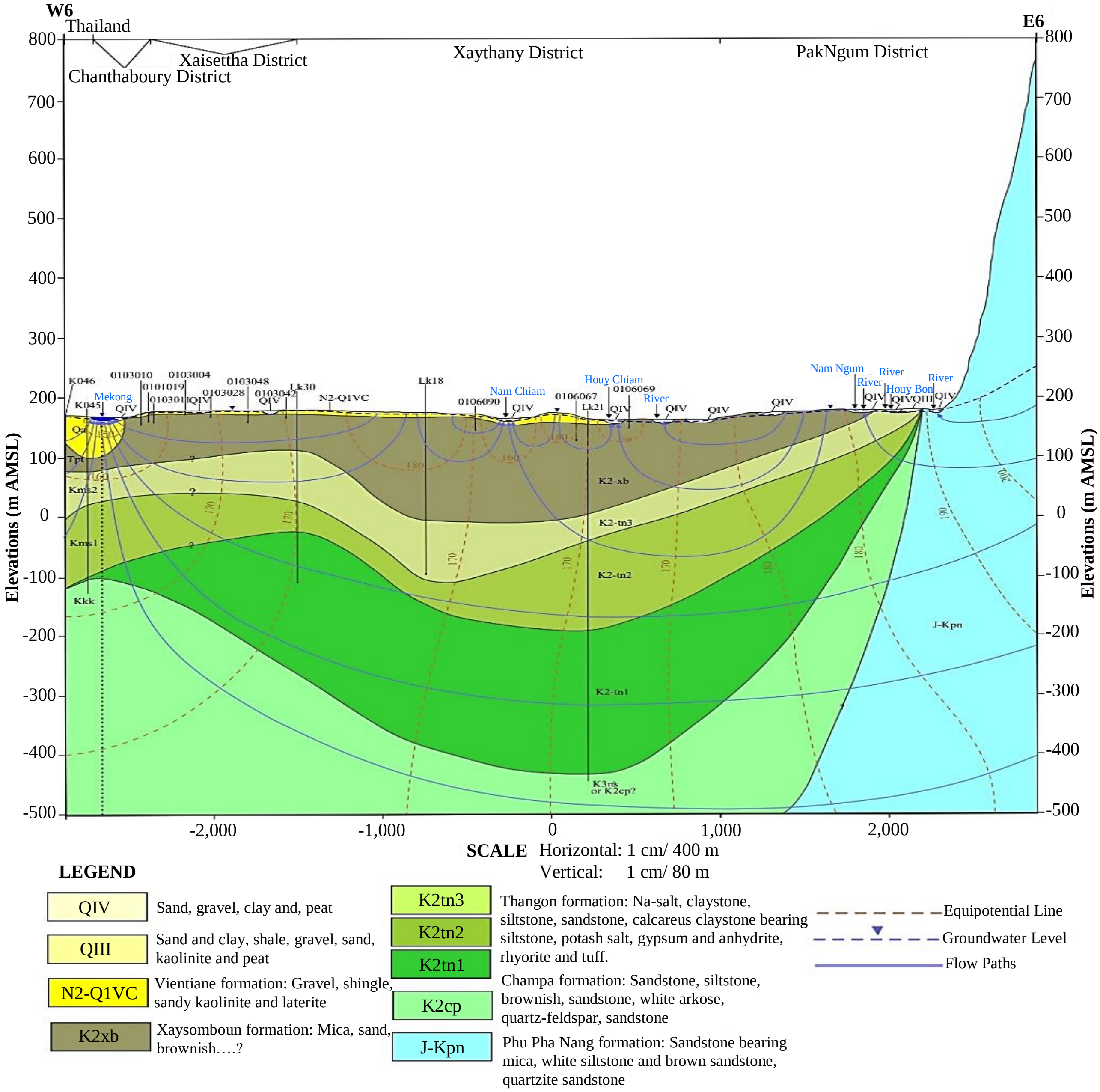

Figure 10 Cross-Section W6-E6

Part "B" of Figure 11 is in the east of the basin in the Thourakhom district in Vientiane Province and the Xathany district in the capital, Vientiane, geology unit data of the GMMVA 1985 [8] was noted to be QIV at Haiyoy-Mai Village and Nanokkhoum Village in the Xaythany District in Vientiane. The reference groundwater investigation at Thourakhom District has a groundwater level of about 6-18 m and local people have been told by the researcher that this District has good groundwater quantities and the ground is not deep. Ban Kuen Village in Thourakhom District is near Nam Ngum River and no geology log was done in this area. This village has been exploring salt (NaCl) mining and it is salt mining in a lesser way in Khoksa, a village in the Xaythany district. Additionally, nobody knew about the deep wells and area of this salt mining. However, a groundwater well near Ban Kuen was investigated; salt mining that has a depth of 18 m and TDS of 455 mg/l. The reference Table 3; salt at Ban Keun village may be deeper than 150 m. At the same time, the geology data of Perttu et al. [14]; at sites 8, 9, 10 and 11, included the geology unit N2-Q1vc. Also included was the geology data of the GMMVA 1985 [8] at Ban Nabo, Ban Bo, Ban Nala, Ban Phonkngam-Nafay and Ban Phonhong-Nafay at Thourakhom district in the Vientiane Province which was determined to be QIII. The most important, Perttu et al. [14]; at sites 5 and 6 showed K2xb in this area but this hydrogeological unit was not displayed at of the GMMVA 1985 [8] so it improved the hydrogeological map in VTB at Part "B" which shows the detail at cross-sections W2-E2 and W3-E3**.**

Part "C" of Figure 11 is a data analysis of the geology log 18 from the GMMVA 1985 [8] which includes LK18, LK21, LK25, LK30, and LK31 as well having a groundwater investigation that concluded that the groundwater level is about 20-25m. The GMMVA 1985 showed at Part "C" is N2-Q1vc which has a thickness of more than 10 m, so there have been improvements to the GMMVA 1985 at the Xathany and Xayxetha districts in Vientiane because N2-Q1vc covers the top of this area [8]. The reference Figure 10 showed on K2xb near LK21 at Ban Nabong Village and Ban Hadxaykham Village at Xathany District in Vientiane Capital.

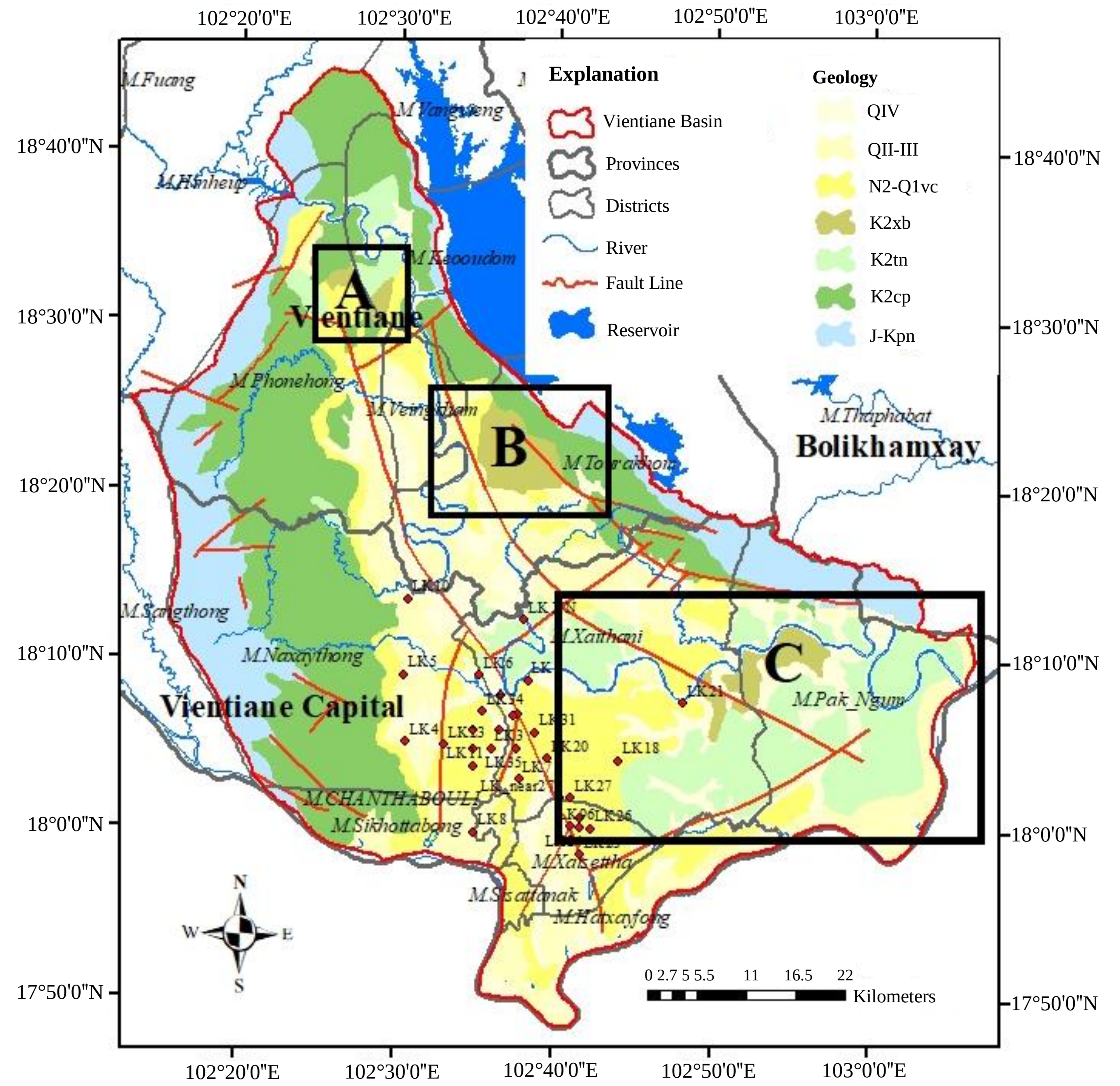

Figure 11 The hydrogeology map of the Vientiane Basin 2020

At Ban Khoksa-At the Xathany District, drilling takes place, and salt (NaCl) is produced under the brand name, "Salt Khoksa-At", but this area is far, about 2 km from LK18. In the GMMVA 1985 [8], it was observed that there is a central fault at Ban Khoksa-At, as well as one between the Mekong River and Nam Ngum River. The fault may have lifted the salt making it a salt dome, or an error may exist in the data between the geology logger and the GMMVA 1985 [8]. Therefore, Part "C" improved from N2-Q1vc to become K2xb.

3.3 Groundwater in Vientiane Basin

3.3.1 Groundwater expectation

Figure 12 shows that the groundwater expectation had four ranges: <2, 2 to 10, 10 to 20, and >20 m^3/hr. The reference potential of the hydrogeology unit is shown at Table 2. The expected groundwater range of 10 to 20 m^3/hr covers about 37.15% of the total river basin area, and this range is at the center of this basin in which the center of this basin covered N2-Q1vc unit and has an average volume of 5 to 10 m^3/hr. The range between 2-10 m^3/hr covers 16.47% and is at the foothills of the Phou Pha Nang Mountain at the west and is distributed in some areas at Pakngum in this basin. The range of >20 m^3/hr covers 19.56% of the total basin area and covers the Hatxayfong District, Pakngum District, and some parts of the KeoOudom and Thourakom Districts. Of the total basin area, 14.01% has a range of < 2 m^3/hr and is far away from the Phou Pha Nang Mountain of the basin. According to regional research Viossanges et al. [19] on a map of shallow aquifer productivity in Laos, the aquifer productivity bore well potential yields in the Vientiane Basin were shown to be between 0.0001 to 0.0015 m^3/hr at the center of the basin in the Xaythany District. The range of 0.0003 to 0.003 m^3/hr covers the long distance from the Mekong River to the Phou Pha Nang Mountain.

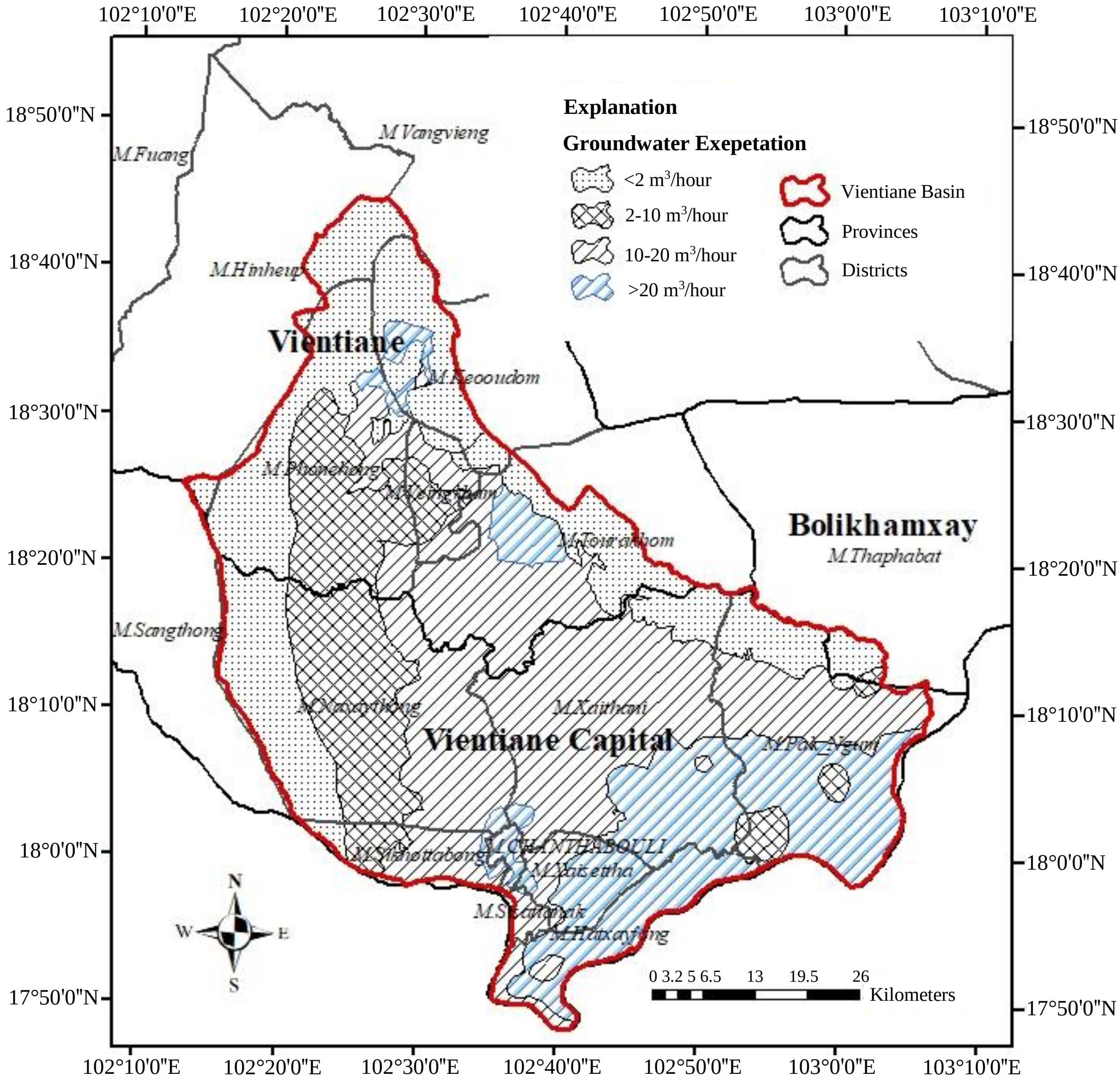

Figure 12 The groundwater expectation map of the Vientiane Basin

The regarding paper of Lacombe et al. [31], Viossanges et al. [19] and Department of irrigation of Laos (DOI) and International Water Management Instituted (IWMI) [15] used the specific yield method to estimate and develop groundwater storage in Laos which at VTB has aquifer potential borewell potential yields 0.0003 to 0.006 m^3/hr in Alluvial and aquifer potential borewell potential yields 0.0001 to 0.0015 m^3/hr in Sedimentary (Mesozoic). When compared between maps of shallow aquifer productive in Laos of Department of irrigation of Laos (DOI) and International Water Management Instituted (IWMI) [15], Viossanges et al. [19] and Lacombe et al. [31], and the groundwater expectation map in VTB 2020 which overall map has near output but the area at Xaythany District at a map of IWMI is aquifer potential borewell potential yields are low but the groundwater expectation map in VTB 2020 has groundwater expectation two levels such as 10 to 20 m^3/hr and >20 m^3/hr.

3.3.2 Groundwater quality

This research is an initiative for a groundwater quality map using TDS as the indicator of groundwater quality. This investigation has measured the TDS from 173 well which there has the depth vary between 5 to 60 m. The reference on groundwater use Department of Public Health of Vientiane Capital [20] and 173 wells investigated in VTB of this research had collected TDS between 10 mg/l at Songkhouakangsaen Village in Naxaythong District to 1,590 mg/l at Dontew Village in Xaythany District. The general, TDS of groundwater has a volume lower than 500 mg/l but it covered 96.33% of VTB. The TDS of groundwater has a volume between 501-1,500 mg/l covering 0.84% and the TDS of groundwater has a volume higher than 1,500 mg/l covering 2.83% of this basin (Figure 13).

Consequently, the TDS in this basin is low and has good water quality but this is only a basic parameter of water quality which needs more investigation on pH, Calcium (Ca), Magnesium (Mg), Iron (Fe), etc. The important point is that the TDS volume higher than 1,500 mg/l is downstream of this basin and it is the area that is very densely populated and developed industrially. If water demand needs more groundwater use in the future this basin will have the challenge of raising a layer of saline waters downstream of this basin.

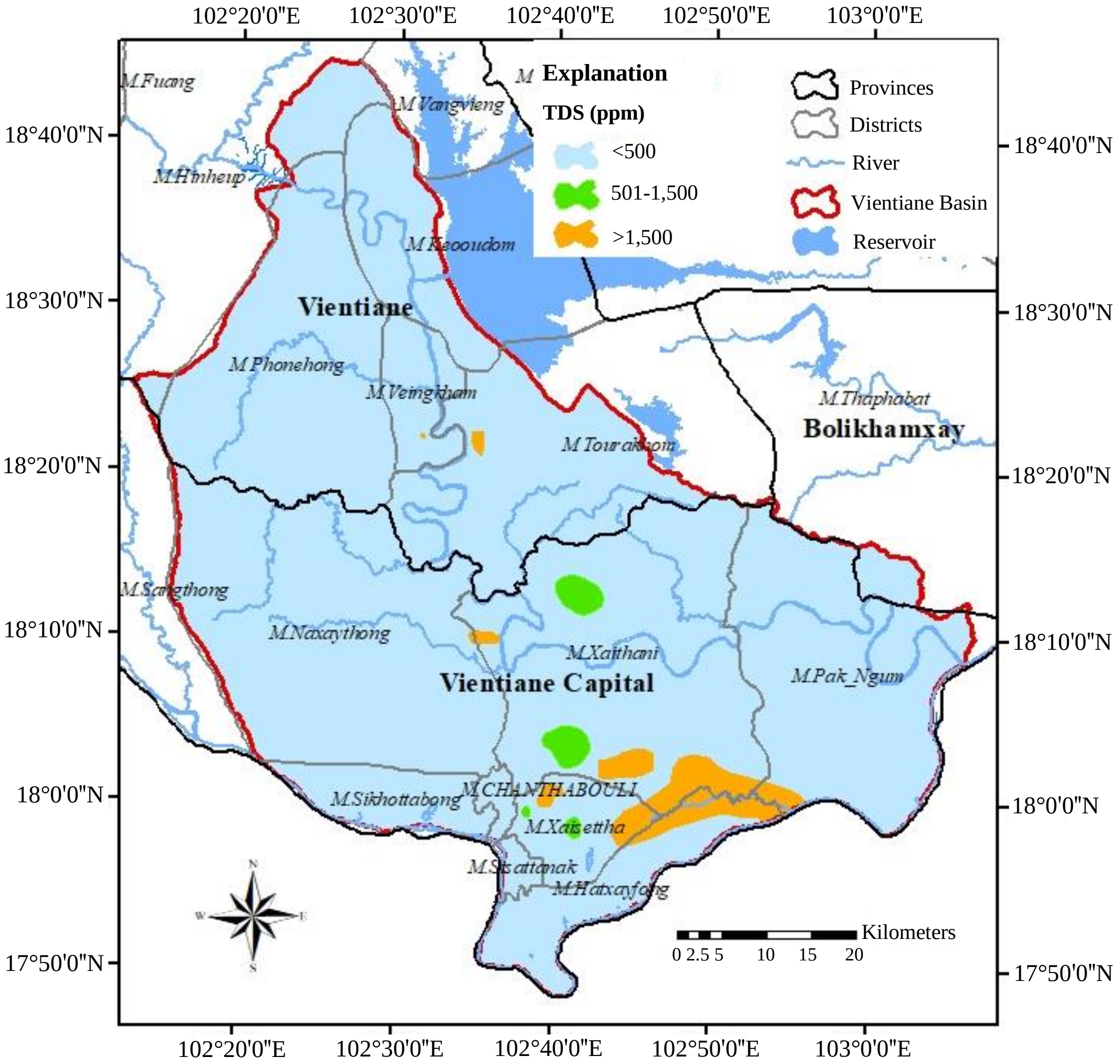

Figure 13 Map of TDS in groundwater of the Vientiane Basin

3.3.3 Groundwater potential

Due to this data, the most obvious part of the map is displayed in color tones representing two data sets: 1) groundwater quantity, which was calculated from the maximum yields of wells and 2) the Groundwater quality based on the salinity or TDS value. That data can be simply explained by the "the groundwater quality to salinity in the Vientiane Basin" as shown in Figure 14. The groundwater availability map shows most of the blue color in the basin in which the average TDS of groundwater is <500 mg/l and the expected well yield is 2 to10 m^3/hr, as well as covering the center and along the hills of Phou Pha Nang Mountains in the west and north of this basin. The expected well yields range from 10 to 20 m^3/hr and the TDS of groundwater is <500 mg/l, and these are distributed in the central and eastern portions of the Vientiane Basin, which has a higher demand for groundwater.

However, Khoksa-At Village in the Xaythany District and the landscape of the Houy Mak Hiey River in Hadxayfong District were determined to be saline and to have a low potential. Also, where the TDS of the groundwater was higher the 1,500 mg/l, the expected well yield was found to be more than 20 m^3/hr. In general, the groundwater in the VTB is in a good condition but there have been challenges with saline; soil collapse resulting from excavation mining; and water usage, which is greater than the groundwater potential. Therefore, groundwater management needs to be developed and data needs to be updated in the following areas of groundwater management: determining the hydrogeology, assessing groundwater demand, monitoring groundwater, planning for water allocation, and enforcing regulations.

4. Discussion

There is drilling and salt production at Samsa-At in Xaythany Village District, Vientiane Capital under the brand name, "Salt Veunkham". Samsa-At Village is located about 5 km from the SinoHydro Mining (Lao) Co., Ltd [13], which is located at Dongbongn Village in Xaythany District, Vientiane Capital. The salty characteristics can move anywhere and will cause a collapse of the geology given that there are many wetlands in the surrounding landscape [19]. Also, on page 55 of the JICA Project of 1993 [10], it is noted that Samsa-At Village is one part of the 'cross-section B-B' that is "K" or "K2tn". Furthermore, Ban Samsa-At is located near the Nam Ngum River and fault line, which means that it is possible that the geology moved and lifted up the salt in this area. Therefore, it is possible that in some parts of the Xaythany District and the Pak Ngum District, K_2tn still remains. The reference on research of Xayavong et al. [23] has been compared with the result of Perttu et al. [14]; which Viengthong Xayavong focus at PhonHong District in Vientiane Province in which both showed aquifer layer (N2Q1) in this district.

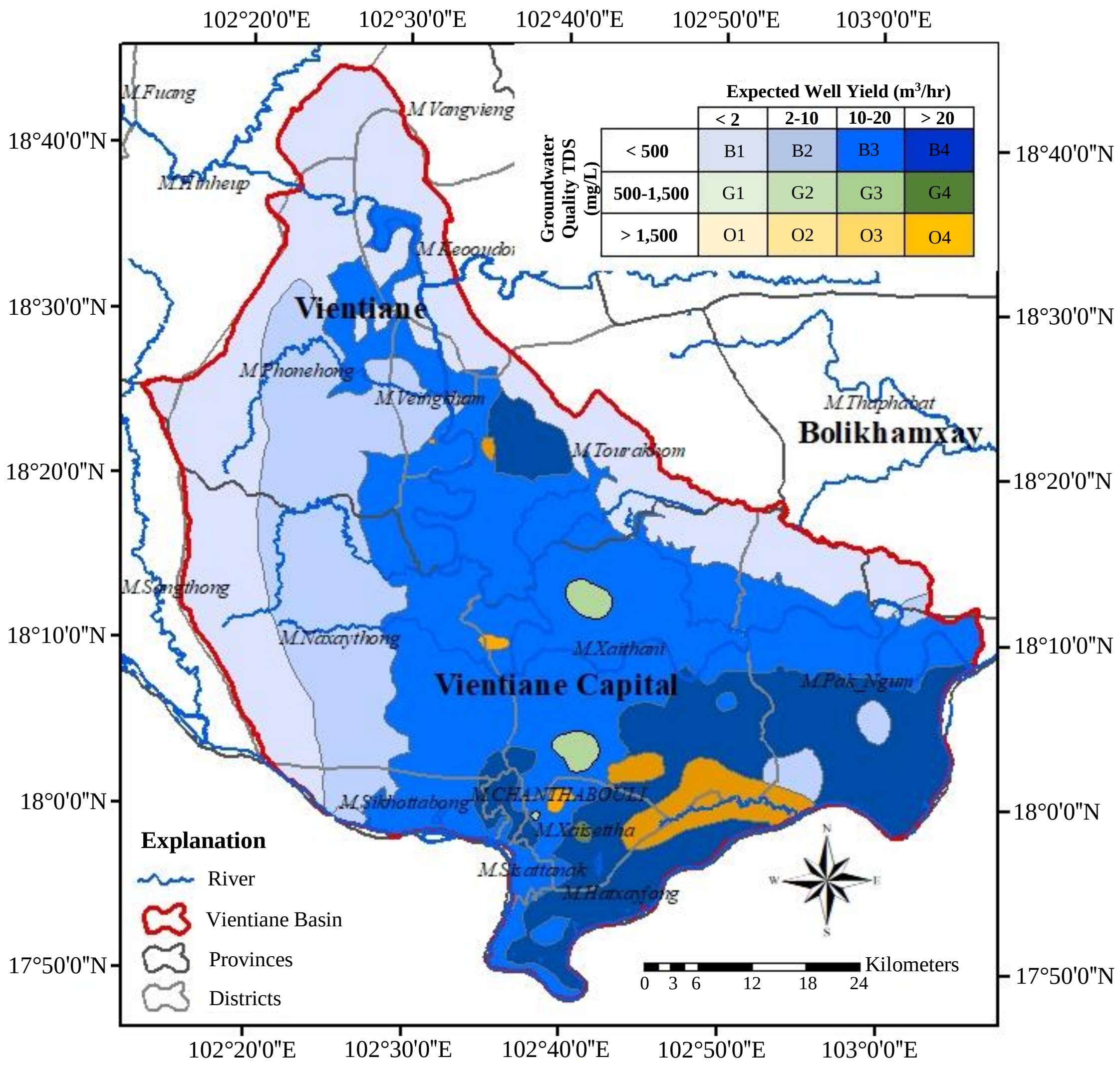

Figure 14 The groundwater potential map of the Vientiane Basin

Another important point is that the multi-data sources do not have information on geology, groundwater, and salt at Veunkam and Kheun Villages; both villages produced NaCl, but there is doubt that the both villages will be K2tn under N2-Q1vc. In 2014 and 2021, the International Union for the Conservation of Nature (IUCN) surveyed the Peat Land at Thoulakham District which the VTB maybe has large freshwater sources for the development of water supplies. Correspondingly, the water supply development at Pak Ngum District used groundwater but has no information on groundwater while water supply stations development is at low groundwater potential and the risk of salty water that has meant for some years that water supplies could not be produced. Unfortunately, ordinary people just know how to use groundwater but did not know about storage groundwater and Laos governance did not plan on a Managed Aquifer Recharge (MAR). The most significant feature is this research related to the history of the Naka area and sacred water at Thatlouang stupa at Xaysattha District, NakYai Temple at Sisattanak District, and Nong Sane Kham Temple at Hadxaythong District. When comparing with the groundwater level and water level of the Mekong River, it is near equal as well as compared with the river system of the VTB. Maybe this is an old river from a long time ago. This is one of all the data information to consider for the additional hydrogeology map of VTB in this research.

Finally, the regarding research of Viossanges et al. [19] it has three main maps included as 1) Aquifer Characteristics; 2) Mapping of Storage, Productivity and Recharge; and 3) Groundwater Potential. The Groundwater maps of Viossanges et al. [19] showed on aquifer unit of Alluvial Sediments which it covers at around downstream of the VTB and aquifer unit Alluvial Sediments are linked with area of N2-Q1vc of Laos DoG. However, the detail on the hydrogeological unit is very limited for support information to improve the groundwater map in this study.

It is also interesting to note that this paper applied multi-data resources to improve the hydrogeology maps of the VTB, through the systematic identification, mapping, and synthesis of the geology map, cross-section geology, groundwater flow, and groundwater potential. Therefore, this study demonstrated the K2xb on the hydrogeology map showing that K2xb is freshwater and that groundwater potential exists in the central and eastern portions of this basin. The important point, K2xb in the VTB is very limited but water demand is high. Naxaythong, Sithodtabong, and Hadxayfong Districts have been using groundwater at a layer of N2-Q1vc. The geology map separated K2tn into three classes: K2tn3, K2tn2, and K2tn1, while K2tn started at the mouth of a river basin.

5. Conclusions

An analysis of the hydrogeology, TDS, and groundwater use displayed for this basin showed the highest groundwater potential in the west at the upstream and in the eastern portion of the basin. However, it was limited, and that area was not in high demand.

Conversely, at the central portion of the basin near the Mekong River in the Chathaboury and Hadtxayfong Districts, there was higher groundwater potential at about 10 to 20 m^3/hr and TDS <500 mg/l. However, there were challenges with respect to the groundwater quality and salinity because by using the groundwater, there was higher groundwater potential, and there was also wastewater from the households. Moreover, around the Houy Maok Hieng River and in some parts in the center of the Xaythany District, there was salinity and lower groundwater potential >20 m^3/hr and TDS >1,500 mg/l.

However, this was an area with higher water demand. Consequently, legislation was developed to support the processing of the implementation of the Laos groundwater governance system, such as the water laws, regulations on water allocations and licensing, planning, management, and the development of groundwater in VTB.

Consequently, groundwater resources represent one of the choices that can be used to develop the water supply, but further investigation is needed to design a groundwater plan and the development of the groundwater map needs more investigation on hydrogeology in the central and upper VTB, pumping tests, groundwater level, and groundwater quality monitoring. In addition, groundwater management needs to be studied and assessed to identify groundwater use and to issue groundwater licenses. To issue groundwater licenses, information about groundwater potential and hydrogeology is needed. Additionally, the Laos government need to extend this work to improve the hydrogeological characterization in the VTB to support hydrogeological information to all groundwater managers and stakeholders across the country.

6. Acknowledgements

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