การประเมินเชิงพื้นที่ของความเสี่ยงต่อการปนเปื้อนและการกำหนดเขตป้องกันแหล่งน้ำบาดาลในอำเภอหนองเรือ จังหวัดขอนแก่น

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต

สาขาวิชาภูมิสารสนเทศ

มหาวิทยาลัยเทคโนโลยีสุรนารี

ปีการศึกษา 2553

SPATIAL ASSESSMENT OF GROUNDWATER CONTAMINATION RISK AND PROTECTION ZONING IN AMPHOE NONG RUA, CHANGWAT KHON KAEN

Jiradech Majandang

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Geoinformatics

Suranaree University of Technology

Academic Year 2010

SPATIAL ASSESSMENT OF GROUNDWATER CONTAMINATION RISK AND PROTECTION ZONING IN AMPHOE NONG RUA, CHANGWAT KHON KAEN

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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จิระเดช มาจันแดง : การประเมินเชิงพื้นที่ของความเสี่ยงต่อการปนเปื้อนและการกำหนดเขตป้องกันแหล่งน้ำบาดาลในอำเภอหนองเรือ จังหวัดขอนแก่น (SPATIAL ASSESSMENT OF GROUNDWATER CONTAMINATION RISK AND PROTECTION ZONING IN AMPHOE NONG RUA, CHANGWAT KHON KAEN) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร.สัญญา สราภิรมย์, 175 หน้า.

การศึกษาครั้งนี้มีวัตถุประสงค์เพื่อประเมินความเปราะบาง ความเสี่ยงและเขตป้องกันแหล่งน้ำบาดาลต่อการปนเปื้อนในอำเภอหนองเรือ จังหวัดขอนแก่น สารสนเทศที่ได้รับจากการศึกษาจะเป็นประโยชน์สำหรับการวางแผนจัดการและป้องกันแหล่งน้ำบาดาลอย่างมีประสิทธิภาพ แผนที่ความเปราะบางต่อการปนเปื้อนได้จากการประเมินด้วยวิธี SINTACS ซึ่งอาศัยตัวแปรทางสิ่งแวดล้อม 7 ตัวแปร ประกอบด้วยความลึกของระดับน้ำบาดาล การแทรกซึม เขตไม่อิ่มตัวด้วยน้ำ ดิน ชั้นหินอุ้มน้ำ สัมประสิทธิ์การยอมให้น้ำซึมผ่าน และความลาดชัน พื้นที่ที่มีระดับความเปราะบางต่อการปนเปื้อนสูงมากและสูงที่สุดพบบริเวณทิศตะวันตกเฉียงเหนือ ตะวันตกเฉียงใต้ และทางตอนกลางของพื้นที่ เนื่องจากพื้นที่เหล่านี้มีคุณลักษณะที่เอื้อต่อการปนเปื้อนคือ มีอัตราการแทรกซึมสูง เนื้อเม็ดดินมีขนาดใหญ่ และระดับน้ำบาดาลอยู่ตื้น ผลการประเมินสัมประสิทธิ์สหสัมพันธ์ทางสถิติระหว่างค่าความเข้มข้นของไนเตรตในน้ำบาดาลจากบ่อบาดาล 87 บ่อ กับระดับความเปราะบางต่อการปนเปื้อนที่ได้จากการประเมินโดย SINTACS แสดงความสัมพันธ์ทางบวกอย่างมีนัยสำคัญ โดยมีค่าเท่ากับ 0.51 และได้มีการวิเคราะห์ความอ่อนไหวเพื่อบ่งบอกถึงอิทธิพลของตัวแปรแต่ละตัวที่มีต่อแบบจำลอง

แผนที่ความเสี่ยงต่อการปนเปื้อนประเมินจากแผนที่ภาวะอันตราย ซึ่งแสดงพื้นที่ศักยภาพของการปนเปื้อนทั้งที่ทราบและไม่ทราบแหล่งที่มา ควบคู่กับแผนที่ความเปราะบางต่อการปนเปื้อน การประเมินแผนที่ภาวะอันตรายได้จากการรวม 3 แผนที่เข้าด้วยกัน ประกอบด้วย ภาวะอันตรายจากพื้นที่เกษตรกรรม ภาวะอันตรายจากเขตเมือง และภาวะอันตรายอื่นๆ ซึ่งวิธี NPSAHI ได้ถูกนำมาประยุกต์ในการประเมินภาวะอันตรายจากพื้นที่เกษตรกรรมที่ไม่ทราบแหล่งที่มา ภาวะอันตรายจากเขตเมืองประเมินจากปริมาณน้ำเสียชุมชน และภาวะอันตรายอื่นๆ ได้จากแผนที่การใช้ประโยชน์ที่ดิน ค่าถ่วงน้ำหนักของแหล่งปนเปื้อนทั้ง 5 กลุ่มในพื้นที่ศึกษา ได้จากการคำนวณด้วยแบบจำลองเชิงลำดับชั้นแบบคลุมเครือ โดยพิจารณาจากความเป็นพิษ การเคลื่อนที่ การสลายตัว และปริมาณของมลพิษ ผลการศึกษาพบว่าพื้นที่ศึกษาส่วนใหญ่แสดงระดับความเสี่ยงสูง โดยพื้นที่ที่มีระดับความเสี่ยงสูงมากส่วนใหญ่จะพบอยู่ในบริเวณทิศตะวันตกเฉียงเหนือและตะวันตกเฉียงใต้ของพื้นที่

เขตป้องกันแหล่งน้ำบาดาลซึ่งใช้ในการจัดลำดับความสำคัญเพื่อการป้องกันบ่อบาดาลที่ใช้ผลิตน้ำประปา ประเมินได้จากแผนที่ความเสี่ยงและมูลค่าเขตตรวจจับ โดยมูลค่าเขตตรวจจับสร้างจากชั้นของพื้นที่เขตตรวจจับ ซึ่งมีระยะเวลาการไหล 2 5 และ 12 ปี และมูลค่าทางเศรษฐกิจสังคมของบ่อบาดาลนั้นๆ ประเมินจากจำนวนครัวเรือนที่ใช้น้ำควบคู่กับแหล่งน้ำอื่นที่สามารถหาทดแทนได้ ผลการศึกษาพบว่าบ่อบาดาลที่บ้านโนนคูณ หมู่ 11 ตำบลโนนสะอาด เป็นบ่อที่ต้องการการป้องกันอย่างเร่งด่วนเป็นลำดับที่หนึ่ง

สาขาวิชาการรับรู้จากระยะไกล ลายมือชื่อนักศึกษา________________________

ปีการศึกษา 2553 ลายมือชื่ออาจารย์ที่ปรึกษา___________________

JIRADECH MAJANDANG : SPATIAL ASSESSMENT OF GROUNDWATER CONTAMINATION RISK AND PROTECTION ZONING IN AMPHOE NONG RUA, CHANGWAT KHON KAEN. THESIS ADVISOR : ASST. PROF. SUNYA SARAPIROME, Ph.D. 175 PP.

GIS/GROUNDWATER VULNERABILITY/GROUNDWATER CONTAMINATION RISK/ GROUNDWATER PROTECTION ZONING

The aim of this study is to assess groundwater vulnerability, contamination risk and protection zoning in Amphoe Nong Rua, Changwat Khon Kaen. The information obtained from the study can be very useful for efficient groundwater protection and management planning. The SINTACS method was used to assess the groundwater vulnerability of the area based on the seven environmental parameters which are depth to water, infiltration, unsaturated zone, soil, aquifer, hydraulic conductivity, and slope. Very high and extremely high vulnerability levels were mostly concentrated in the northwestern, southwestern, and central parts of the area. This is because of their characteristics on being high infiltration rate, coarse-texture soil and shallow depth to groundwater. The relationship of vulnerability levels and water quality was examined using the statistical correlation coefficient between the nitrate concentration in 87 wells and the SINTACS vulnerability levels. It showed significantly positive relation as high as 0.51. Sensitivity analyses were performed to obtain which parameters have more effect on the model result.

The risk map was assessed by coupling hazard map, which represents the potential contamination of both point and non-point sources, and the vulnerability map. The assessment of the hazard map was the result of the merging of 3 input map layers which were agricultural, urban, and other hazards. Non-Point Source Agricultural Hazard Indexes (NPSAHI) method was applied to evaluate the agricultural hazard. The quantity of domestic wastewater was used to represent the urban hazard. The other hazard sources were obtained from the land use map. The weights of 5 contamination source groups in the study area were calculated by use of the fuzzy hierarchical model with respect to toxicity, mobility, degradability, and volume. The result showed that the high level covered main parts of the study area. The very high risk level was mostly concentrated in the northwestern and southwestern parts of the area.

The protection zoning was analyzed to rank the protection priority of 83 groundwater wells reserved as sources of water work for the area. It was evaluated by coupling the risk map and capture zone value. The capture zone value was determined by coupling the tiers of capture zone area which contain 2, 5, and 12 years flowing paths and socio-economic value of wells that were evaluated using a number of household being supplied from the wells and alternative water source availability. The result showed that the well at Ban Non Khun, Mu 11, Tambon Non Sa-at was the first priority for protection urgency.

School of Remote Sensing   Student's Signature_____________________

Academic Year 2010   Advisor's Signature_____________________

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Jiradech Majandang

CONTENTS

CONTENTS (Continued)

Page

CONTENTS (Continued)

CONTENTS (Continued)

Page

CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

Table **Page**

LIST OF TABLES (Continued)

Table **Page**

LIST OF TABLES (Continued)

Table **Page**

LIST OF FIGURES

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF ABBREVIATIONS

AH	=	Agricultural Hazard
ANHI	=	Agricultural Nitrate Hazard Index
CFR	=	Calculated Fixed Radius
CF	=	Control Factors
CN	=	Curve Number
DCI	=	Danger of Contamination Index
DEM	=	Digital Elevation Model
DGR	=	Department of Groundwater Resources
DLD	=	Department of Livestock Development
DMR	=	Department of Mineral Resources
DOAE	=	Department of Agricultural Extension
DOPA	=	Department of Provincial Administration
GIS	=	Geographic Information System
HF	=	Hazard Factors
IDW	=	Inverse Distance Weight
IPA	=	Agricultural Hazard Index
IPNOA	=	Agricultural Nitrate Hazard Index
LDD	=	Land Development Department
MSL	=	Mean Sea Level
NPSAHI	=	Non-point Source Agricultural Hazard Indexes

LIST OF ABBREVIATIONS (Continued)

NRC	=	National Research Council
PCD	=	Pollution Control Department
PCSM	=	Point Count System Models
RTSD	=	Royal Thai Survey Division
SCS	=	Soil Conservation Service
SDWA	=	Safe Drinking Water Act
SNIFFER	=	Scotland and Northern Ireland Forum for Environmental Research
TMD	=	Thai Meteorological Department
TOT	=	Time of Travel
UH	=	Urban Hazard
USA	=	United States of America
USEPA	=	United States Environmental Protection Agency
USDA	=	United States Department of Agriculture
WHPA	=	Wellhead Protection Area
WHPP	=	Wellhead Protection Program
ZOC	=	Zone of Contribution
ZOI	=	Zone of Influence

GLOSSARY

Amphoe	=	district
Ban	=	village
Changwat	=	province
Lam	=	stream
Rongrian	=	school
Tambon	=	sub-district
Wat	=	monastery

CHAPTER I

INTRODUCTION

1.1 Background problem

Groundwater is one of the most important natural resources. Nowadays, it has been used heavily for agricultural and industrial activities according to the ever-increasing economic growth and seasonal or permanent lacking of surface water. This subsequently leads to increasing pollution into the resource. Therefore, good management and monitoring program are definitely required to protect and prevent groundwater from contamination.

Groundwater resource in Amphoe Nong Rua located at the west of Changwat Khon Kaen shows high possibility to be severely contaminated due to intensive use of groundwater and the specific land-use types of the area. Department of Groundwater Resources (DGR) reported that there have been up to 87 groundwater wells in the area which are managed as water work source (กรมทรัพยากรน้ำบาดาล, 2551). The supply goes for domestic consumption and even for drinking. Moreover, the groundwater quality analysis of 43.68% of the total number of wells showed pollutants in the amount that were over standard for drinking. The problems were that the volume of nitrate was over 45 mg/L for 28 wells, sulfate was over 250 mg/L for 9 wells, and Escherichia coli bacteria was found in 4 wells that exceeded the drinking water standard of groundwater (กรมควบคุมมลพิษ, 2552). The preparation of the groundwater contamination risk map and the groundwater protection zoning is significantly required in order that the pollution sources, contamination risk areas and certain time-period capture zone can be provided and applied to effective groundwater planning and management. This will result in improving maintaining groundwater quality and the quality of life within the area.

1.2 Research objectives

The main objectives of this study are:

1.2.1 To assess groundwater vulnerability.

1.2.2 To assess groundwater contamination risk.

1.2.3 To zone groundwater protection.

1.3 Scope of the study

Scope of the study will cover the followings:

1.3.1 The groundwater contamination sources are considered particularly from surface.

1.3.2 The groundwater contamination risk of the study will be concentrated on the intrinsic characteristics related to groundwater vulnerability of the area, not related to health risks which emphasizes on the presence of a particular contaminant in groundwater.

1.3.3 Wellhead protection and the groundwater value assessment will be operated only on groundwater wells supplying as water work source of the area.

1.3.4 SINTACS is the method applied to the groundwater vulnerability evaluation.

1.3.5 The capture zone area is delineated by the calculated fixed radius (CFR) method because of having limited data of aquifer parameters for flow equations.

1.4 The study area

1.4.1 Location

The study area, covering 10 Tambons in Amphoe Nong Rua, is located in the westerns part of Changwat Khon Kaen (Figure 1.1). The area falls between UTM WGS84 zone 48 209803E to 242171E and 1809787N to 1840400N with area extent of 534 square kilometers.

1.4.2 Physical characteristics

The topography of the area mainly consists of hilly terrain on the northeast and southwest with the highest elevation at 240 m above MSL (Figure 1.2). The terrain altitude gradually decreases to approximately 190 m above MSL in the middle part of the area which is the floodplain of the Lam Choen. The Lam Choen flows from the southwest to Ubolratana Dam at the northeast of the study area. The highest elevation of the area is 680 m above MSL at the Phu Meng appearing on the south of the area.

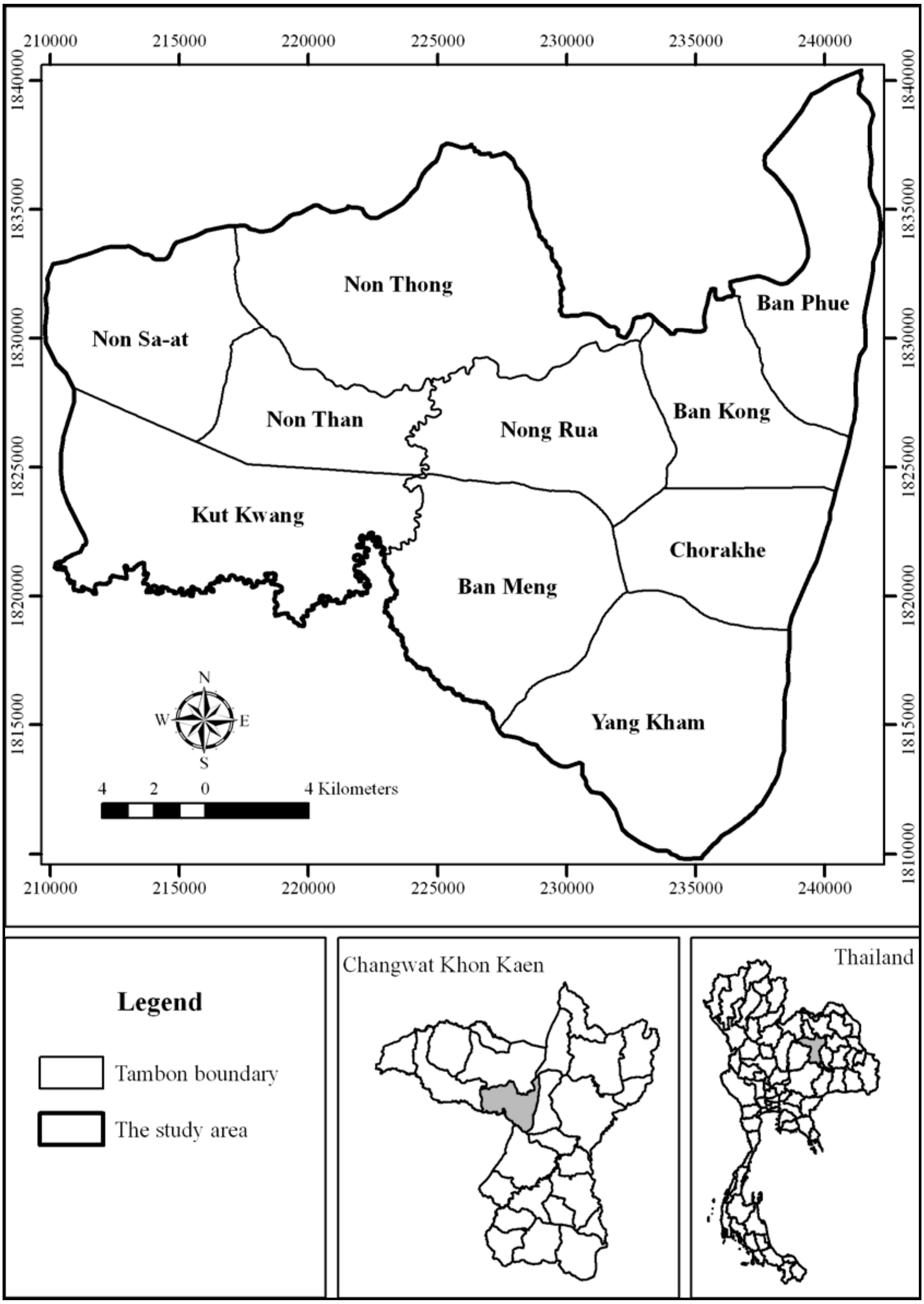


Figure 1.1 A map of the study area.

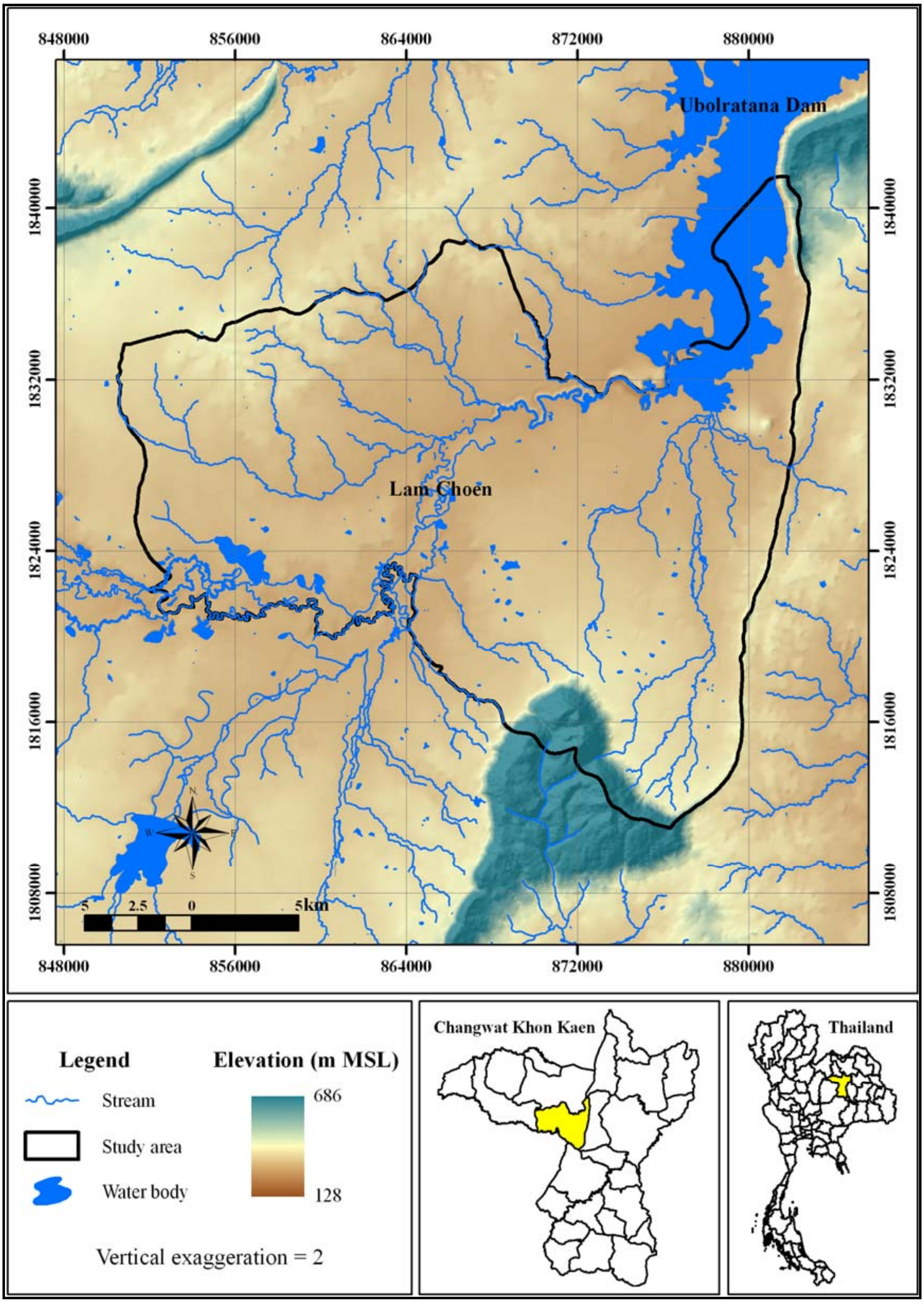


Figure 1.2 Topography of the study area.

1.4.3 Geology

Geology of the Khorat Plateau of which the study area is a part was reviewed by Assanee Meesook et al. (2002). The geology of the study area is characterized by four lithostratigraphic units as shown in Figure 1.3 (กรมทรัพยากรธรณี, 2522). The unit descriptions are as follows:

Nam Phong Formation (Trn) consists of reddish-brown siltstones, sandstones and claystones. The age of this formation is assigned to be Rhaetian (uppermost Triassic). It has been found in the north of the study area.

Phu Kradung Formation (Jpk) consists of maroon siltstones, claystones, sandstones and conglomerates. Calcrete nodules and caliches including silcrete nodules are often found on the top part of claystones. The Formation has been found covering main part and covered by the Quaternary alluvium at the middle part of the area. They expose on the west, the south and the eastern rim of the area. Photos of this rock unit from the field investigation are presented in Appendix B. The Middle to Upper Jurassic age is given to this Formation.

Phra Wihan Formation (Jpw) consists of yellowish-white, well-sorted and well-rounded, fine- to medium-grained quartzitic sandstones, siltstones, thin-bedded claystones, and conglomerates. The Formation is apparent at the southeast rim of the area and ranges in age from Upper Jurassic to Lower Cretaceous.

Alluvial Deposits (Qa) consists of Quaternary sand, silt, and clay. Its distribution is obviously found associated with the Lam Choen network.

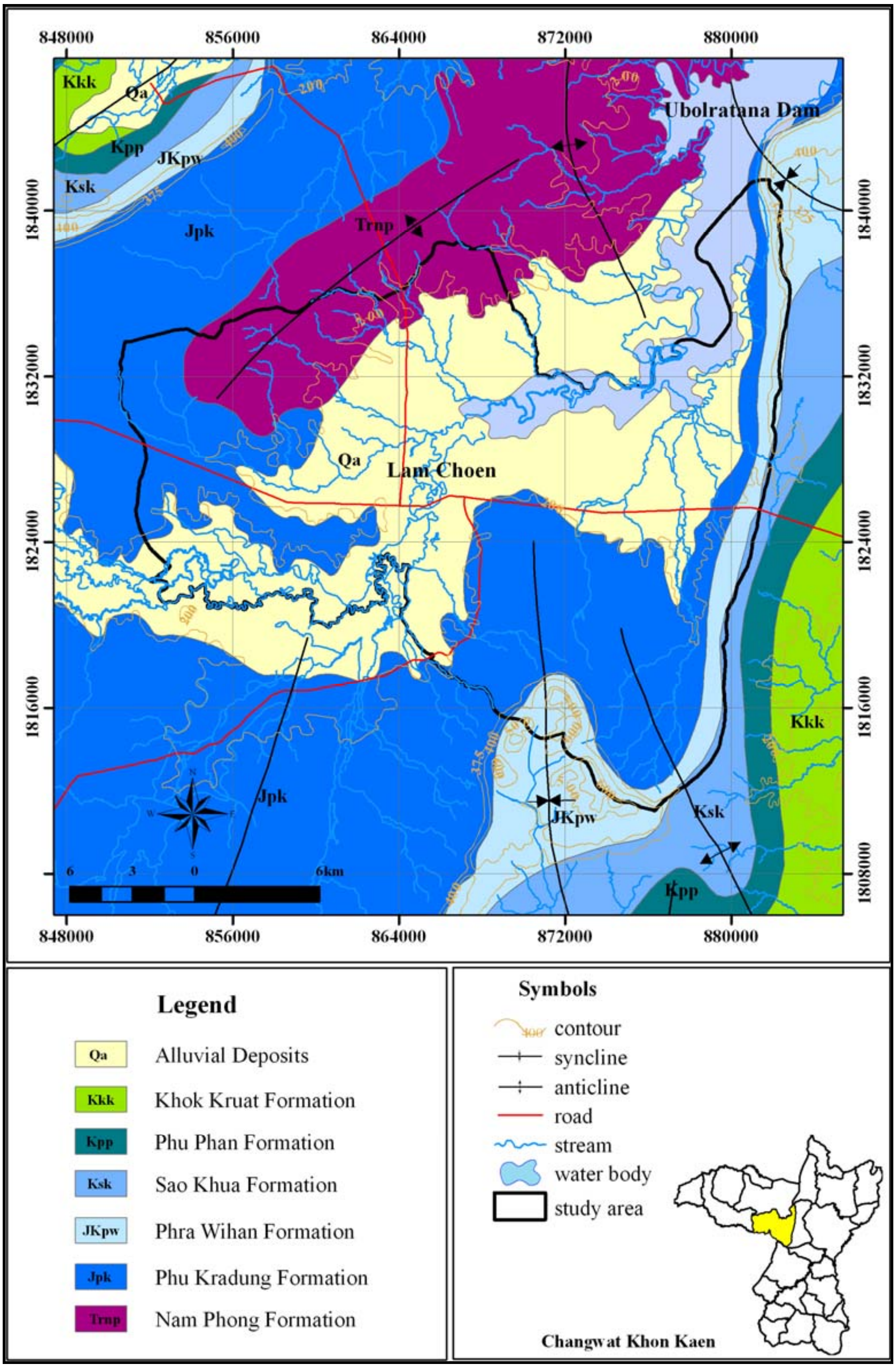


Figure 1.3 Geologic map of the study area.

Source: Department of Mineral Resources (กรมทรัพยากรธรณี, 2522)

Geological structure of the area is expressed mainly as a set of anticlines and synclines with axes oriented in N-S to SW-NE. Bedding of the rock sequences appears to be gentle dipping in the whole area and steeper to the east.

1.4.4 Hydrostratigraphic units

The hydrostratigraphic units of the study area were based on the groundwater map of 1:100,000 scale, produced by Groundwater Division, Department of Mineral Resources (กรมทรัพยากรธรณี, กองน้ำบาดาล, 2531). The main hydrostratigraphic unit of the study area is the Phu Kradung Unit (Figure 1.4). From the lithologic logging data of wells, this unit consists of shale, siltstone, and sandstone whereas Nam Phong Unit consists mainly of siltstone and sandstone only found at the north of the study area. The Phra Wihan Unit has been found covering as higher land in the southwest rim.

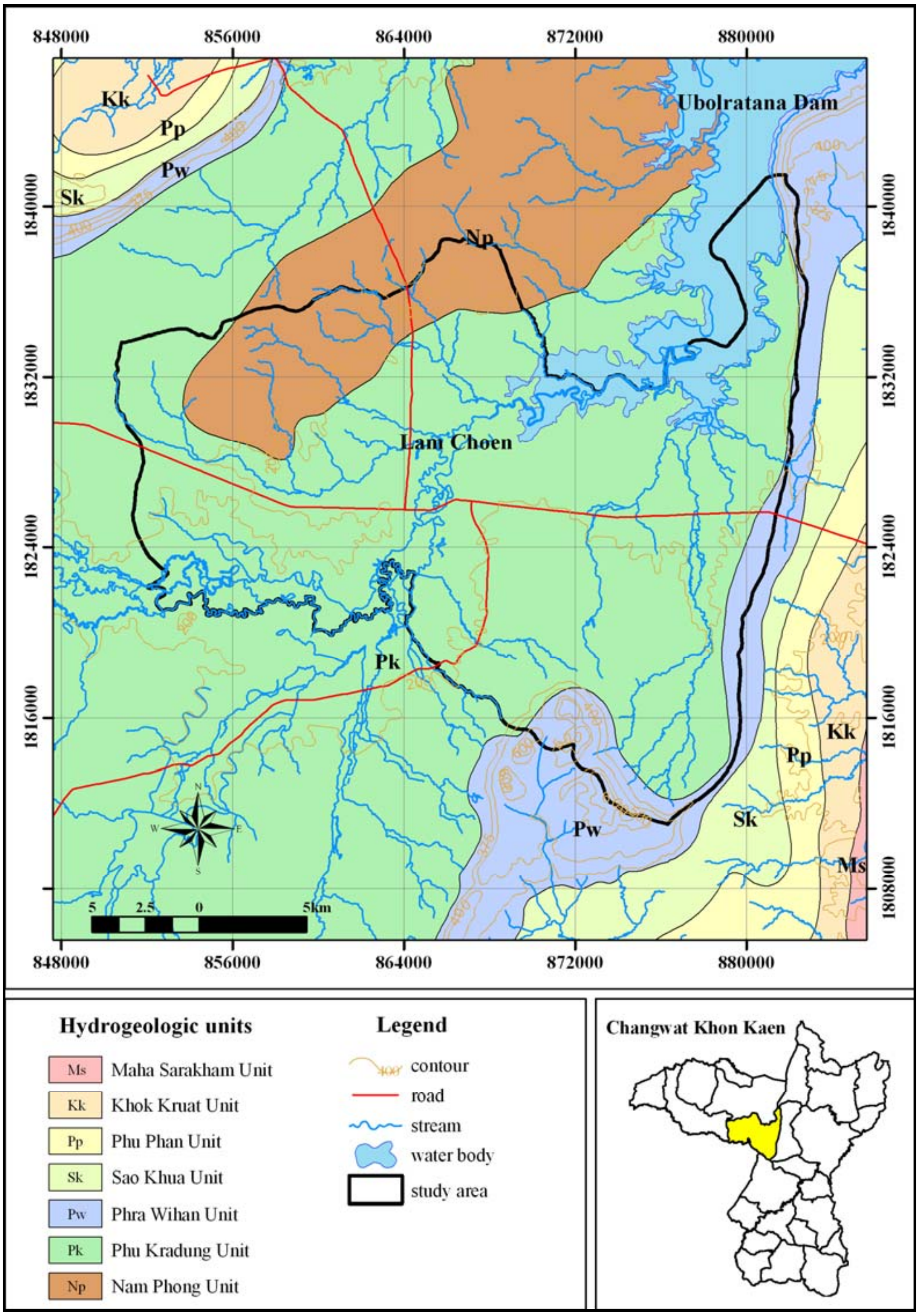


Figure 1.4 Hydrogeologic units distribution of the study area.

Source: Groundwater Division, Department of Mineral Resources (กรมทรัพยากรธรณี, กองน้ำบาดาล, 2531)

1.5 References

กรมควบคุมมลพิษ. (2551). ประกาศกระทรวงทรัพยากรธรรมชาติและสิ่งแวดล้อม เรื่อง กำหนดหลักเกณฑ์และมาตรการในทางวิชาการสำหรับการป้องกัน ด้านสาธารณสุขและการป้องกันในเรื่องสิ่งแวดล้อมเป็นพิษ พ.ศ. 2551 ตีพิมพ์ในราชกิจจานุเบกษา เล่ม 125 ตอนพิเศษ 85 ง ลงวันที่ 21 พฤษภาคม 2552.

กรมทรัพยากรธรณี. (2522). **แผนที่ธรณีวิทยาประเทศไทย 1:250,000 ระวางจังหวัดขอนแก่น**. กรุงเทพฯ: กรมทรัพยากรธรณี กระทรวงอุตสาหกรรม.

กรมทรัพยากรธรณี, กองน้ำบาดาล. (2531). **แผนที่น้ำบาดาลรายจังหวัด 1:100,000 ระวางจังหวัดขอนแก่น**. กรุงเทพฯ: กรมทรัพยากรธรณี กระทรวงอุตสาหกรรม.

กรมทรัพยากรน้ำบาดาล. (2551). **รายงานผลการปฏิบัติงานโครงการสำรวจและตรวจสอบคุณภาพน้ำของระบบประปาบาดาลทั่วประเทศ ปี 2551 จังหวัดขอนแก่น**. กรุงเทพฯ: กรมทรัพยากรน้ำบาดาล กระทรวงทรัพยากรธรรมชาติและสิ่งแวดล้อม.

Assanee Meesook, Varavudh Suteethorn, Pol Chaodumrong, Naramase Teerarungsigul, Apsorn Sardsud, and Terapon Wongprayoon. (2002). Mesozoic Rocks of Thailand: A Summary. In **The Symposium on Geology of Thailand** (pp 82-94). Bangkok: Department of Mineral Resources.

CHAPTER II

LITERATURE REVIEW

2.1 Groundwater contamination risk

Risk is considered as the probability or likelihood of an adverse effect, or an assessed threat to persons, the environment, and/or property, due to hazardous situations. It is an estimation of probability and severity of adverse consequences from an exposure of potential receptors to hazards due to a system failure, as represented in Figure 2.1 (Asante-Duah, 1998).

The term "risk assessment" describes a systematic process of analyzing risk. Risk assessment process considers estimating the likelihood of occurrence of adverse effect causing from exposures of humans and ecological receptors to chemical, physical, and/or biological agent that are present in the environment (Asante-Duah, 1998).

The risk assessment approach can be separated into three groups as the health risk, the environmental risk, and the engineering-based risk assessment (Gough, 2009). The health risk assessment is used to estimate the possible harm causing substance. The environmental risk assessment is to estimate the probability of harm to the integrity of the whole ecosystem. The engineering-based risk assessment bases on the statistical analysis of events and extrapolations.

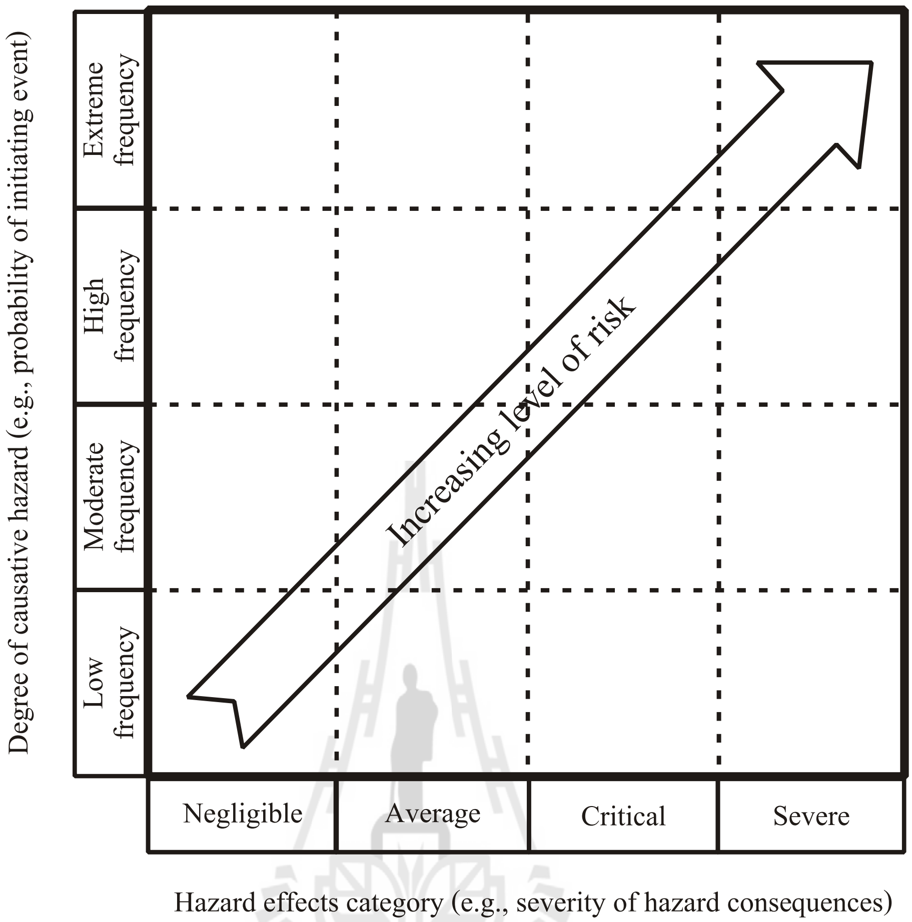


Figure 2.1 Conceptual categories of risk measures.

Source: Asante-Duah (1998).

The engineering-based risk assessment is applied in Earth science such as earthquakes, floods, landslide, contamination, etc. (Ducci, 1999). In the part of groundwater contamination risk, Morris and Foster (2000) defined as the probability that groundwater will become contaminated to an unacceptable level by human activities on the immediately overlying land surface. The evaluation of groundwater risk is defined as probability multiplied by consequence. The probability equates to the combination of the rating of the contamination sources and the consequence equates to the rating of groundwater vulnerability and groundwater value (Zaporozec, 2004). The following three map layers are required as input for producing a groundwater contamination risk map (Civita and De Maio, 2009; Corniello and Ducci, 2001; Ducci, 1999; Ducci, De Masi, and Priscoli, 2008; Zaporozec, 2004): groundwater hazard map, groundwater vulnerability map, and groundwater value map.

2.1.1 Groundwater hazard mapping

The groundwater hazard map is defined as information of existing and potential sources of groundwater contamination that impacts on groundwater by human activities. The groundwater contamination sources are considered in their locations, types, characteristics, and estimated magnitudes of impact on groundwater (Zaporozec, 2004).

Trevisan, Padovani, and Capri (2000) used a parametric approach to evaluate the hazard level of farming activities based on the definition of potential hazard indexes (Non-point Source Agricultural Hazard Indexes, NPSAHI). Two categories of parameters were considered: the hazard factors (HF), which represent all farming activities that cause or might cause an impact on groundwater (use of fertilizers and pesticides, application of livestock and poultry manure, food industry wastewater, and urban sludge), and the control factors (CF), which adapt the hazard factors to the characteristics of the site (geographical location, slope, agronomic practices, and type of irrigation). The potential hazard index (HI) is obtained by multiplying the different hazard factors by the control factors as shown in the equation:

$$HI = (HF_p + HF_f + HF_{te}) \times CF_{ap} \times CF_c \times CF_i \times CF_s \quad (2.1)$$

where the subscripts are: *p* = pesticides, *f* = fertilizers, *te* = trace elements, *ap* = agronomic practices, *c* = climate, *i* = irrigation content, and *s* = slope

Zaporozec (2004) proposed a general method for screening contamination sources according to the origin-based contamination source classification. A subdivision is made into sources given high, moderate, and low contamination potential rating.

Civita and De Maio (2009) suggested a Danger of Contamination Index (DCI) that is used to classify the level of contamination sources. The DCI is identified from the existing or potential of one or more contamination source points of which a contamination event of the groundwater can be determined.

2.1.2 Groundwater vulnerability mapping

The first introduction of the concept of groundwater vulnerability was in France by the end of the 1960s to create awareness of groundwater contamination. The general concept of groundwater vulnerability is based on the assumption that the physical environment provides some natural protection to groundwater against human impacts, especially with regard to contaminants entering the subsurface environment (Vrba and Zaporozec, 1994). The term "vulnerability" and "contamination" can be used alternatively [National Research Council (NRC), 1993; Vrba and Zaporozec, 1994; Scotland and Northern Ireland Forum for Environmental Research (SNIFFER), 2004; Zaporozec, 2004]. However, it can be summarized that groundwater vulnerability is the tendency or likelihood for contaminants to reach in the groundwater system after introduction at the ground surface. The groundwater vulnerability assessment for each area is based on the fundamental concept that some land areas are more vulnerable to groundwater contamination than others (Vrba and Zaporozec, 1994). Therefore, the vulnerability of groundwater is a relative, dimensionless property that is not directly measurable (Catchment, 2001), and does not include pollutant propagation and attenuation. Groundwater vulnerability deals only with the hydrogeologic setting and the natural hydrogeologic factors affecting the different pollutants in different ways depending on their interactions and chemical properties (Babiker, Mohamed, Hiyama, and Kato, 2005). There are two general types of vulnerability assessments. The first addresses specific vulnerability, which is referenced to a specific contaminant, contaminant class, or human activity. The second addresses intrinsic vulnerability, which does not consider the attributes and behavior of specific contaminants and is used for all pollutant sources.

The groundwater vulnerability assessment method can be divided into 3 categories (NRC, 1993) including: *index and overlay methods*, that are based on combining maps of various physiographic attributes (e.g., geology, soil, depth to water) controlling groundwater vulnerability of the region by assigning a numerical rating or score to each attribute; *process-based methods*, that examine vulnerability from a quantitative point of view by the governing equations for water flow and solute transport; and *statistical methods*, that incorporate data on known contaminated distribution areas (concentration or probability) and provide characterizations of contamination potential for the specific geographic area from which data were drawn.

Index and overlay methods are based on the assumption that a few major parameters largely control groundwater vulnerability. These parameters are known and can be evaluated. The result of this method is qualitative and relative. An index is evaluated by multiplying weigh and rating score and is ranked or classified. An index is used as the interpretation of the vulnerability information. Index and overlay methods are applied to several assessments such as GOD (Foster, 1987), DRASTIC (Aller, Bennet, Lehr, Petty, and Hackett, 1987), SINTACS (Civita, 1994), AVI (Van Stempvoort, Evert, and Wassenaar, 1993), and EPIK (Doerfliger and Zwahlen, 1995).

The advantage of these methods is that they provide relatively simple algorithms or decision trees and are appropriate for using geographic information system (GIS) as a tool. However, if various methods are used to assess in one area, the resulting maps can be often different and sometimes contradictory (Lobo-Ferreira and Oliveira, 2003; quoted in Lindström, 2005; Gogu, Hallet, and Dassargues, 2003).

2.1.3 Groundwater value mapping

Related to the groundwater contamination risk, the evaluation of the groundwater value should be considered how much its value could be as the supply resource. However, the valuation of groundwater is a complex process and a number of issues with high uncertainty have to be assessed (Zaporozec, 2004). Value map assessment has a negligible literature and yet is a very crucial point in groundwater contamination risk map evaluation (Ducci et al., 2008).

Zaporozec (2004) evaluated groundwater value rating that is developed using a matrix combining an aquifer classification system and user-defined variables. Civita and De Maio (2009) defined the value through two different factors: basic quality of the groundwater and socio-economic values of the resource. The socio-economic value of the resource is determined by the number of users served. The evaluation of the values is obtained by applying a matrix crossing the basic quality and the socio-economic value of the resource. Ducci (1999) suggested the evaluation of the socio-economic value considering the number of inhabitants served or amount of workers of industry consuming groundwater resource.

2.2 Wellhead protection

The Wellhead Protection Program (WHPP) was approved into law by the U.S. Congress as a part of the Safe Drinking Water Act (SDWA) of 1986. The aim of the WHPP is to protect the health of people using groundwater as a public drinking water source by providing a focus zone around public wells or well fields to prevent, detect and remediate groundwater contamination. Adverse impacts on groundwater quality occur where contamination finds its way into the well either from surface or subsurface sources. The area surrounding the well to drawn from which groundwater is known collectively as the Wellhead Protection Area (WHPA).

The purpose of WHPA delineation is to approximate the area through which water flows to a well so that management decisions regarding the control of contamination sources in that area can be implemented. The area through which water recharges a well is the zone of contribution (ZOC) where shows in Figure 2.2. In contrast, the zone of influence (ZOI) is the area affected by a pumping well, and coincides with the area extent of the cone of depression. The ZOI extends outward from the pumping well to the point of negligible drawdown (USEPA, 1991).

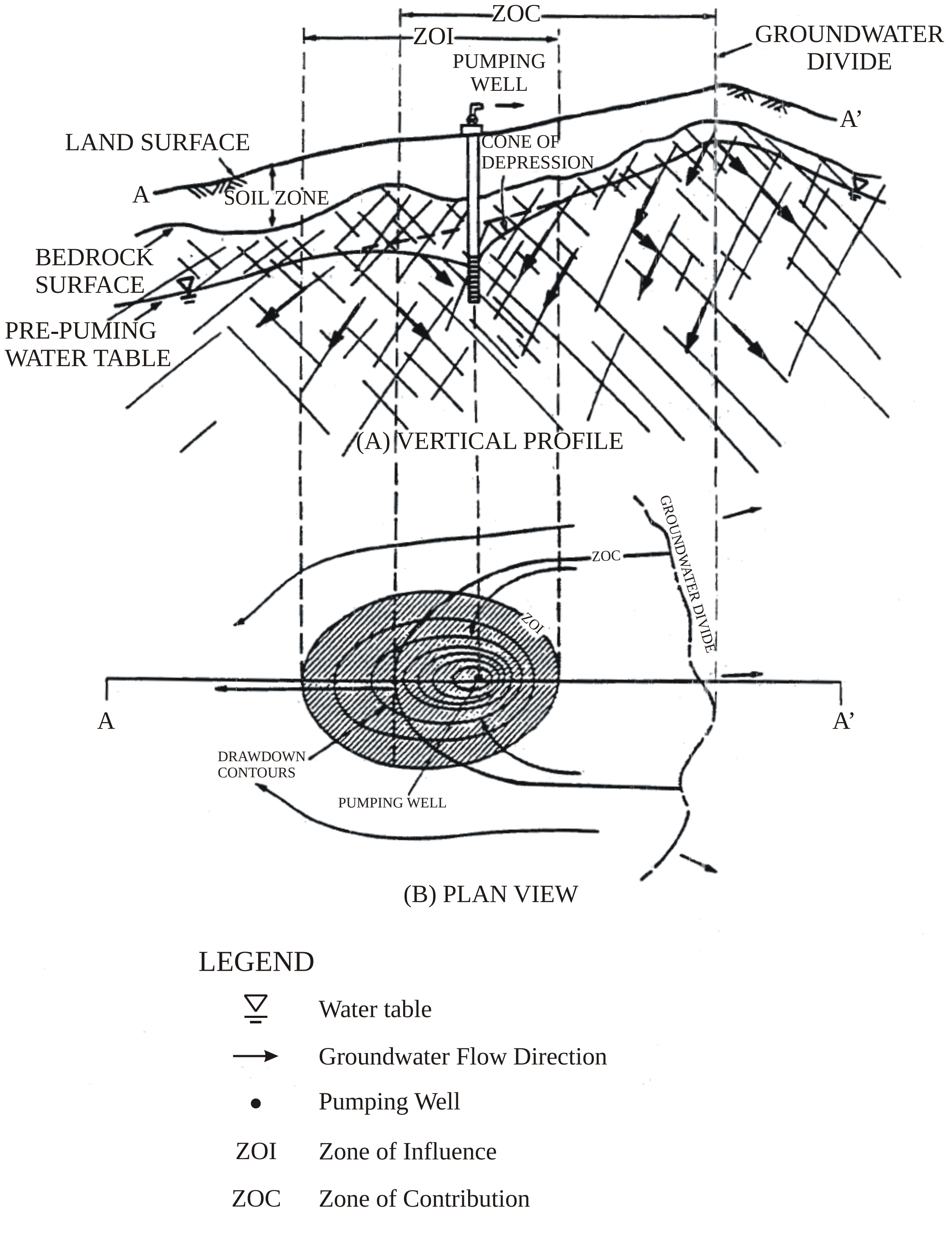


Figure 2.2 The capture zone in an unconfined aquifer with a sloping regional water table.

Source: USEPA (1991).

The WHPA delineation methods are classified into four major groups of generally increasing complexity (USEPA, 1994):

1) Geometric methods that involve the use of a pre-determined fixed radius and aquifer geometry without any special consideration of the flow system, or the use of simplified shapes that have been pre-calculated for a range of pumping and aquifer conditions (USEPA, 1994).

2) Simple analytical methods that allow calculation of distances for wellhead protection using equations that can be solved using a hand calculator or microcomputer spreadsheet program. These methods fall into two major groups, which are often used in combination time of travel (TOT) calculations and drawdown calculations (USEPA, 1994).

3) Hydrogeologic mapping, which involves identification of the zone of contribution (as defined by flow boundaries) based on geomorphic, geologic, hydrologic, and hydrochemical characteristics of an aquifer. This is often used in combination with simple analytical methods and is usually required when using more complex analytical and numerical computer flow and transport models (USEPA, 1994).

4) Computer modeling methods, which involve the use of more complex analytical or numerical solutions to groundwater flow and contaminant transport processes. These methods can be broadly grouped into simple and complex models (USEPA, 1994).

2.3 Related literatures

2.3.1 Groundwater contamination risk

Ducci (1999) used the ILWIS GIS to construct the groundwater contamination risk map in the Caserta sample area. It is located in the eastern part of the Piana Campana, in Southern Italy. The risk map was derived from the vulnerability map, which was evaluated by DRASTIC method; the hazard map, where the potential contaminating sources were identified; and the socio-economic value of the groundwater resource, represented by the wells. The groundwater quality map was used to verify the hazard and risk maps. The result showed that the correlation coefficients were low, around 0.3, because of the total independence of the maps, the large number of pixels and the impossibility of using probabilistic methods to predict the frequency of future groundwater contamination.

Corniello, Ducci, and Ruggieri (2007) assessed the Potential Agricultural Nitrate Contamination Risk as a map and verified this method by the spatial distribution of the Nitrate Concentration in the part of the highly urbanized Campania alluvial plain, located in southern Italy. The Potential Agricultural Nitrate Contamination Risk Map was constructed by using cross matrix system in terms of classes, hazard, and vulnerability. The hazard map was evaluated by the Agricultural Nitrate Hazard Index (ANHI) that was obtained by multiplying the hazard factors (HF) and the control factors (CF). The hazard factors represent all farming activities that cause, or might cause, an impact on soil quality in terms of nitrate (use of fertilizers, application of livestock and poultry manure, food industry wastewater and urban sludge). The control factors are the site characteristics (geographical location, climatic conditions, and agronomic practices). The vulnerability map used was prepared from previous studies that drawn up by the SINTACS method. The verifiable result shows a low spatial correlation. They explained that the source of the groundwater nitrate is not necessarily only related to intensive cropping or livestock, but also to leakage from the sewage network and old septic systems.

Belousova and Proskurina (2008) suggested principles of zoning a territory by the pollution hazard to groundwater that considered the pollution sources and their position in the environment. The pollution hazard classifications were proposed related to groundwater pollutants by their chemical and hydrochemical properties. The groundwater pollution risks are evaluated depending on the degree of hazard and the type of pollutants.

Ducci et al. (2008) constructed the groundwater contamination risk map of the aquifer of the Alburni karst area, Italy. The groundwater contamination risk was assessed by the combination of three layers: the vulnerability map, the hazard map, and the value map. The vulnerability map was evaluated by the COP method (Vias, Andreo, Perles, Carrasco, Vadillo, and Jimenez, 2006). The hazard map was prepared from the overlay of two maps: the Agricultural Hazard Index (IPA) map and the industrial DCI map. The value map was created by taking into account the natural high quality of the water and the importance of the aquifer. The result map shows the prevalent moderate degree of risk that is a consequence of a low hazard degree.

Capri et al. (2009) assessed the potential risk of contamination obtained by coupling the agricultural nitrate hazard index (IPNOA) and the groundwater vulnerability map. The IPNOA is a parametric index which is used to assess the potential hazard of nitrate contamination originating from agriculture on a regional scale. Two parameters were used to integrate: the hazard factors (HF), which represent all farming activities that cause, or might cause, an impact on soil quality in terms of nitrate, and the control factors (CF) which is the site characteristics. The groundwater vulnerability map was evaluated using the SINTACS R5 method.

Civita and De Maio (2009) evaluated the groundwater contamination risk using three map layers: the groundwater hazard map, the groundwater vulnerability map and the groundwater value map. The groundwater hazard map was constructed by using the Danger of Contamination Index (DCI) to classify contamination sources. The groundwater vulnerability map was assessed by the SINTACS method. The groundwater value map was defined by two different factors: basic quality of the groundwater and socio-economic values, which is determined by the number of users served. This method was used in Piedmont (Italy) in the Tanaro river valley, south of the city of Alessandris. The result presented the higher risk level that was found in correspondence to the north section of the oil pipe line.

Mimi and Assi (2009) presented the first application of all components of a comprehensive approach of the European COST action 620 to the groundwater underlying the Ramallah district, a karst hydrogeology system in Palestine. The risk map was construed by the interaction between the hazard map and the intrinsic groundwater vulnerability map, which was assessed by PI method (Goldscheider, Klute, Sturm, and Hotzl, 2000; quoted in Mimi and Assi, 2009) which is specifically used for the karst area. The prevalent low and very low risk area are classified in the result map corresponding to the absence of hazards and also due to low vulnerabilities.

2.3.2 Wellhead protection

Vieux, Mubaraki, and Brown (1998) developed a friendly interface between the GIS database and the WHPA Model, and delineated wellhead protection areas on the Concho Reserve in Canadian County, Oklahoma, US. A travel time of 10 years was adjusted for the capture zone delineation. Two models of operation were provided in this study: the forward and backward problems. The forward problem was used for selection and identification of the possible sources of contamination. The backward problem was used for the ensemble area of possible well sites for which no known sources of contamination exist. This system developed provides efficient management and protection of tribal drinking-water resources.

Harman, Allan, and Forsythe (2001) assessed the potential groundwater contamination sources and the human health risk within a wellhead protection area in Gaston County, North Carolina. The capture zone delineation adjusted a travel time of 10 years. The potential groundwater contamination sources were identified in the inventory by aerial photograph analyses, exploration of existing state and local databases, and windshield surveys. The human health risk (R) is calculated as follows:

$$L = L_1 + L_2 \tag{2.2}$$

$$S = Q + A + T \tag{2.3}$$

$$R = L + S \tag{2.4}$$

Where L = the likelihood

S = the severity

L_1 = Likelihood of a contaminant released from the source

L_2 = Likelihood that the contaminant reaches the well

Q = the quantity released from the source

A = attenuation of the contaminant due to transport

T = toxicity of the contaminant

2.4 Synthesis for the research approach

The result of the literature review can be concluded and used as a guide to establish the new approach for this research. The approach is focused on addition input data/information and their synthesized or analytical products, improving methodology which more fits to the study area and data availability, including developing or constructing the more useful output. The conclusion from the review and the research approach can be discussed and proposed as follows:

2.4.1 The review shows that the groundwater contamination risk map can be obtained by incorporating information on groundwater hazard map, groundwater vulnerability map, and groundwater value map.

2.4.2 Instead of generally considering types of land use, lately, the groundwater hazard mapping has been developed specifically for agricultural contamination assessment by combining farm activities and characteristics of agricultural area. This leads to the idea of separately assessing agricultural, urban, and other contaminations using their own related parameters and systematically merging them to be a groundwater hazard map. The more accurate map produced and more efficiency in further applying can be anticipated.

2.4.3 Instead of using the conventional DRASTIC model for groundwater vulnerability mapping, the research prefers SINTACS model which could provide more accuracy due to applying a different set of weights to different hydrogeologic scenarios.

2.4.4 The problem will be addressed to groundwater value mapping in a case that there is less variation of aquifer characteristics particularly in a small area, which will result in one or two classes of the map. This will send less effect and variation to the risk map. Information from groundwater hazard and vulnerability maps should be adequate for constructing the risk of contamination map.

2.4.5 Instead of considering the value of a major aquifer in the whole area, the research emphasizes on determining the capture zone value of each target well which should be more meaningful in incorporating with groundwater contamination risk map. The resulting capture zone value map will be more constructive for groundwater planning and management in terms of prioritized urgent protection zoning, monitoring network set up, remedial measure design, suitable land use planning and regulation establishment, etc.

2.5 References

Aller, L., Bennet, I., Lehr, J.H., Petty, R.J., and Hackett, G. (1987). **DRASTIC: a standardized system for evaluating ground water pollution potential**

using hydrogeologic settings. USA: U.S. Environmental Protection Agency.

Asante-Duah, D.K. (1998). **Risk Assessment in Environmental Management**. Chichester, UK: John Wiley & Sons.

Babiker, I.S., Mohamed, M.A.A., Hiyama, T., and Kato, K. (2005). A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. **Science of the Total Environment**. 345: 127-140.

Belousova, A.P. and Proskurina, I.V. (2008). Principles of zoning a territory by the hazard and risks of groundwater pollution. **Water Resources**. 35(1): 108-119.

Capri, E., Civita, M., Corniello, A., Cusimano, G., De Maio, M., Ducci, D., Fait, G., Fiorucci, A., Hauser, S., Pisciotta, A., Pranzini, G., Trevisan, M., Delgado Huertas, A., Ferrari, F., Frullini, R., Nisi, B., Offi, M., Vaselli, O., and Vassallo, M. (2009). Assessment of nitrate contamination risk: The Italian experience. **Journal of Geochemical Exploration**. 102: 71-86.

Catchment, L. (2001). **Groundwater vulnerability map explanatory notes**. Parramatta: NSW Department of Land and Water Conservation.

Civita, M. (1994). **Le carte della vulnerabilità degli acquiferi all'inquinamento**. Bologna: Teoria and practica (Aquifer vulnerability maps to pollution) Pitagora.

Civita, M. and De Maio, M. (2009). **Assessing Groundwater contamination risk using ArcInfo via GRID function** [On-line]. Available: http://proceedings.esri.com/library/userconf/proc97/proc97/to600/pap591/p591.htm.

Corniello, A. and Ducci, D. (2001). The risk contamination map of the aquifer underlying the Middle Volturno River plain. In **Proceedings of the 3rd International Conference on Future Groundwater at Risk Lisbon (Portugal), June 2001** (pp 25-33).

Corniello, A., Ducci, D., and Ruggieri, G. (2007). Areal identification of groundwater nitrate contamination sources in periurban areas. **Journal of Soils and Sediments**. 7(3): 159-166.

Doerfliger, N. and Zwahlen, F. (1995). **EPIK: a new method for outlining of protection areas in karst environment**. In: Günay, G. and Johnson, I. (eds) Proceedings 5th International symposium and field seminar on karst waters and environmental impacts. Antalya, Sep 1995, Balkema, Rotterdam, 117-123.

Ducci, D. (1999). GIS techniques for mapping groundwater contamination risk. **Natural Hazard**. 20: 279-294.

Ducci, D., De Masi, G., and Priscoli, G.D. (2008). Contamination risk of the Alburni Karst System (Southern Italy). **Engineering Geology**. 99: 109-120.

Foster, S.S.D. (1987). Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: van Duijvenbooden, W. and van Waegeningh, H.G. (eds) TNO Committee on Hydrological Research, The Hague.

Vulnerability of soil and groundwater to pollutants, Proceedings and Information. 38: 69-86.

Gogu, R.C., Hallet, V., and Dassargues, A. (2003). Comparison of aquifer vulnerability assessment techniques. Application to the Ne´blon river basin (Belgium). **Environmental Geology**. 44: 881-892.

Goldscheider, N., Klute, M., Sturm, S., and Hotzl, H. (2000). The PI method - a GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers. **Zeitschrift für angewandte Geologie**. 46(3): 157-166. quoted in Mimi, Z.A. and Assi, A. (2009). Intrinsic vulnerability, hazard and risk mapping for karst aquifers: A case study. **Journal of Hydrology**. 364: 298-310.

Gough, J.D. (2009). **Environmental Decision Making and Risk Management for Groundwater Systems**. [On-line]. Available:http://www.piercelaw.edu/risk/vol8/spring/gough.htm.

Lobo-Ferreira, L. and Oliveria, M.M. (2003). **On the Experience of Groundwater Vulnerability Assessment in Portugal. Aquifer Vulnerability and Risk, International Workshop**. Quoted in Lindström, R. (2005). **Groundwater vulnerability assessment using process-based models**. Ph.D. Dissertation, KTH Royal Institute of Technology.

Harman, W.A., Allan, C.J., and Forsythe, R.D. (2001). Assessment of potential groundwater contamination sources in a wellhead protection area. **Journal of Environmental Management**. 62: 271-282.

Mimi, Z.A. and Assi, A. (2009). Intrinsic vulnerability, hazard and risk mapping for karst aquifers: A case study. **Journal of Hydrology**. 364: 298-310.

Morris, B.L. and Foster, S.S. (2000). *Cryptosporidium* contamination hazard assessment and risk management for british groundwater sources. **Water Science and Technology**. 41(7): 67-77.

National Research Council. (1993). **Groundwater Vulnerability Assessment. Predicting Relative Contamination Potential Under Conditions of Uncertainty**. Washington: National Academy Press.

Scotland and Northern Ireland Forum for Environmental Research. (2004). **Development of a groundwater vulnerability screening methodology for the Water Framework Directive**. Edinburgh: SNIFFER.

Trevisan, M., Padovani, L., and Capri, E. (2000). Nonpoint-source agricultural hazard index: a case study of the province of Cremona, Italy. **Environmental Management**. 26(5): 577-584.

United States Environmental Protection Agency. (1991). **Delineation of wellhead protection areas in factured rocks**. Washington, DC: Office of Ground-Water Protection.

United States Environmental Protection Agency. (1994). **Handbook: Ground Water and Wellhead Protection**. Washington, DC: Office of Ground-Water Protection.

Van Stempvoort, D., Evert, L., and Wassenaar, L. (1993). Aquifer vulnerability index: A GIS compatible method for groundwater vulnerability mapping. **Canadian Water Resources Journal**. 18: 25-37.

Vias, J.M., Andreo, B., Perles, M.J., Carrasco, F., Vadillo, I., and Jimenez, P. (2006). Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method. **Hydrogeology Journal**. 14: 912-925.

Vieux, B.E., Mubaraki, M.A., and Brown, D. (1998). Wellhead protection area delineation using a coupled GIS and groundwater model. **Journal of Environmental Management**. 54: 205-214.

Vrba, J. and Zaporozec, A. (1994). **Guidebook on mapping groundwater vulnerability. International Association of Hydrogeologists (International Contributions to Hydrogeology 16)**. Hannover: Verlag Heinz Heise.

Zaporozec, A. (ed.). (2004). **Groundwater contamination inventory: A methodological guide**. Paris: UNESCO.

CHAPTER III

DATA COLLECTION AND PREPARATION

3.1 Data collection

This step covers existing data/information collection, evaluation, refinement, and summation. Field sampling program was designed to cover location identification and data collection procedure. There are several sources of previous and existing data/information, which are the Royal Thai Survey Division (RTSD), Land Development Department (LDD), Thai Meteorological Department (TMD), Department of Mineral Resources (DMR), Department of Groundwater Resources (DGR), Department of Livestock Development (DLD), and Department of Provincial Administration (DOPA). All data/information employed in the study are listed in Table 3.1.

Table 3.1 Data employed in the study covering Amphoe Nong Rua, Changwat Khon Kaen.

Data	Source/format	Year	Scale	Organization
Administrative boundary	Digital database	-	1:50,000	RTSD
Rainfall	Spread sheet	2009	All	TMD
Groundwater quality	Spread sheet	2008	All	DGR

Table 3.1 (Continued).

Data	Source/format	Year	Scale	Organization
Well data	Spread sheet	-	All	DGR
Hydrogeology	Digital database and field survey	1988	1:100,000	DGR, Researcher
Geology	Digital database	1979	1:250,000	DMR
Land use	Digital database	2008	1:25,000	LDD
Topography	Digital database	-	1:50,000	RTSD
Soil	Digital database	-	1:25,000	LDD
Pumping rate	Field survey	-	All	Researcher
Agricultural data: - Pesticides - Fertilizers	Field survey, and literature reviews	-	Attached to land use map	Researcher
Socio-economic value of productive well	Field survey, and literature reviews	-	All	Researcher
Watering system	Field survey, and literature reviews	-	Attached to land use map	Researcher
Agronomic practices	Field survey, and literature reviews	-	Attached to land use map	Researcher
Animal population	Spread sheet	2009	Attached to administrative boundary	DLD
Population	Spread sheet	2009	Attached to land use map	DOPA

3.2 Data preparation

GIS technique was used to prepare, manipulate, and determine the values of factors in the models. Some of the inputs were referred to acceptable existing information in literatures.

3.2.1 Rainfall data

Rainfall data was recorded by TMD. However, in the study area does not have any rain gauge station. Therefore, the annual rainfall was estimated by the average of annual rainfall data from stations at Amphoe Chum Phae, Phu Wiang, and Ban Fang, Changwat Khon Kaen which are around the study area. Table 3.2 shows the average annual rainfall from those stations. The average result of the study area from these annual rainfall data is about 1,209.9 mm/year.

3.2.2 Land use data

Land use map was used to estimate the infiltration value and to select the contaminant sources such as agricultural area, urban area, industrial area, municipal landfill, and livestock farm house within the study area. Digital land use map in 2008 was produced by LDD (กรมพัฒนาที่ดิน, 2551) and used for this study. It was updated by filed investigation and some land use types in the study area are illustrated in Figure 3.1. Table 3.3 shows the top 10 of high percentage of covering areas in the study area and land use map is shown in Figure 3.2. Paddy field and sugarcane are the major land use of the area and covering area about 54.50 and 12.28 percent, respectively.

Table 3.2 The average annual rainfall of all Amphoes around the study area.

Year	Average annual rainfall at Amphoe (mm/year)			Average
	Chum Phae	Phu Wiang	Ban Fang	
1989	1,059.7	1,348.6	956.4	1,121.6
1990	1,446.7	1,349.9	1,339.3	1,378.6
1991	2,114.6	1,104.7	957.9	1,392.4
1992	1,178.1	941.2	673.7	931.0
1993	830.7	772.3	893.8	832.3
1994	1,086.6	1,342.8	1,049.5	1,159.6
1995	1,583.9	900.2	-	1,242.1
1996	743.4	1,022.2	1,635.9	1,133.8
1997	450.5	975.1	-	712.8
1998	859.7	1,099.5	1,142.0	1,033.7
1999	700.4	1,174.6	1,144.0	1,006.3
2000	1,455.9	994.8	-	1,225.4
2001	944.8	1,379.8	1,198.1	1,174.2
2002	2,190.6	1,299.9	1,320.8	1,603.8
2003	2,443.7	995.2	-	1,719.5
2004	1,914.7	1,107.8	1,920.0	1,647.5
2005	1,343.0	759.2	921.7	1,008.0
2006	1,538.0	1,288.3	1,016.8	1,281.0
2007	332.1	1,102.2	1,484.4	972.9
2008	2,401.2	1,479.7	-	1,940.5
Average	1,330.9	1,121.9	1,177.0	1,209.9

a) Sugarcane

b) Pomelo

c) Jujube

d) Paddy field

e) Watermelon

f) Livestock farm house

Figure 3.1 Some land use types in the study area.

Table 3.3 The various land use types and their percentage of area cover.

Land use class	**Area cover**	
	km^2	**Percent**
Paddy field	290.76	54.51
Sugarcane	65.54	12.29
Deciduous forest	48.97	9.18
Water body	35.95	6.74
Scrub	28.19	5.28
Urban and Built-up land	24.58	4.61
Perennial	12.91	2.42
Marsh and Swamp	12.56	2.36
Cassava	5.03	0.94
Grass	4.39	0.82
Factory	1.67	0.31
Para rubber	1.02	0.19
Mango	0.62	0.12
Livestock farm house	0.37	0.07
Jujube	0.28	0.05
Watermelon	0.25	0.05
Garbage dump	0.14	0.03
Truck crop	0.11	0.02
Longan	0.06	0.01
Pomelo	0.05	0.01

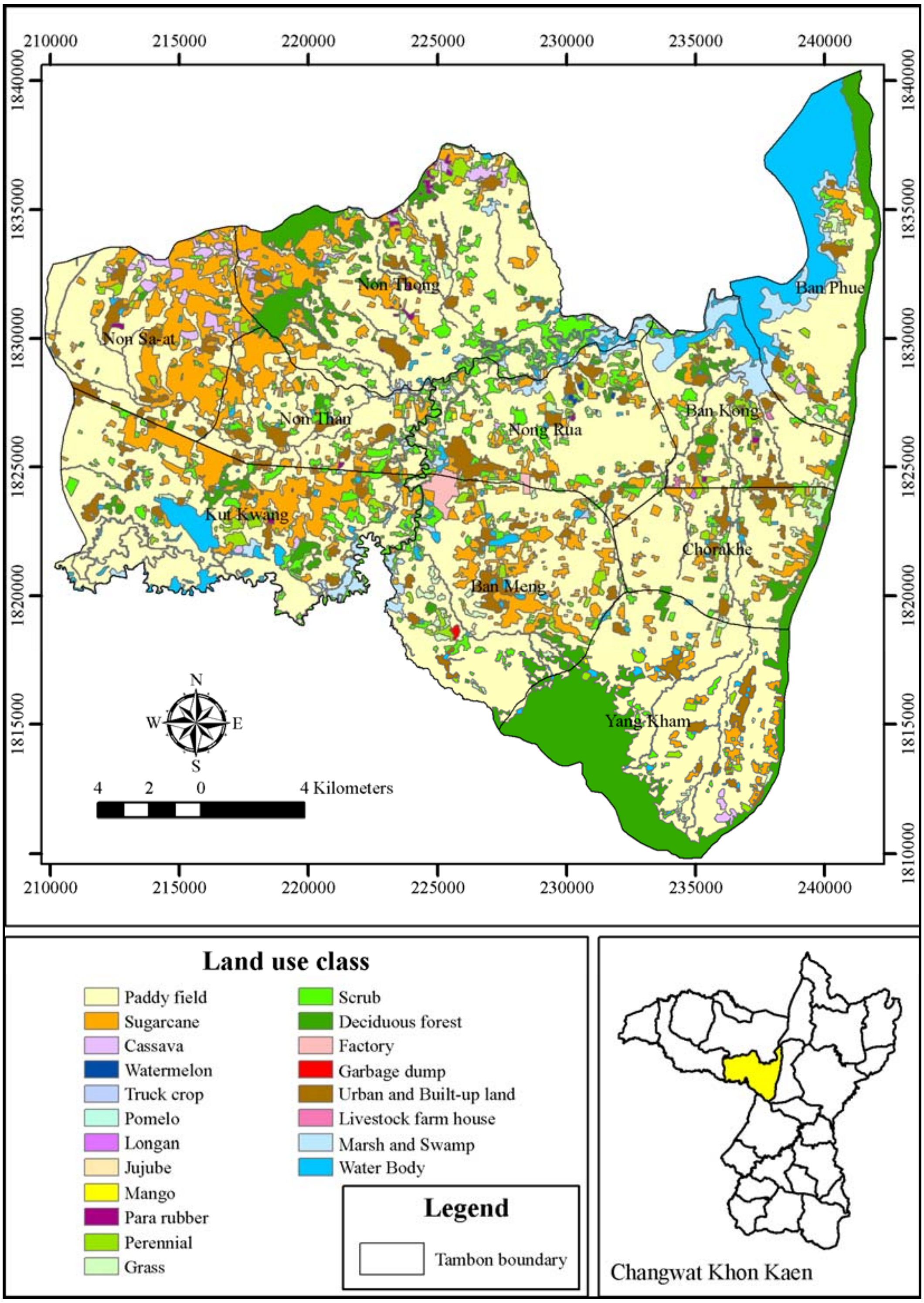


Figure 3.2 Land use map of the study area.

Source: LDD (กรมพัฒนาที่ดิน, 2551)

3.2.3 Soil texture data

Soil texture was obtained from digital soil group map of Changwat Khon Kaen produced by LDD (กรมพัฒนาที่ดิน, ม.ป.ป.). This map layer was employed to estimate the infiltration value and is one of the SINTACS factors. Figure 3.3 shows spatial distribution of soil texture in the study area.

3.3 References

กรมพัฒนาที่ดิน. (2551). **แผนที่การใช้ประโยชน์ที่ดิน จังหวัดขอนแก่น** [แฟ้มข้อมูล]. กรุงเทพฯ: กรมพัฒนาที่ดิน กระทรวงเกษตรและสหกรณ์.

กรมพัฒนาที่ดิน. (ม.ป.ป.). **แผนที่กลุ่มชุดดิน จังหวัดขอนแก่น** [แฟ้มข้อมูล]. กรุงเทพฯ: กรมพัฒนาที่ดิน กระทรวงเกษตรและสหกรณ์.

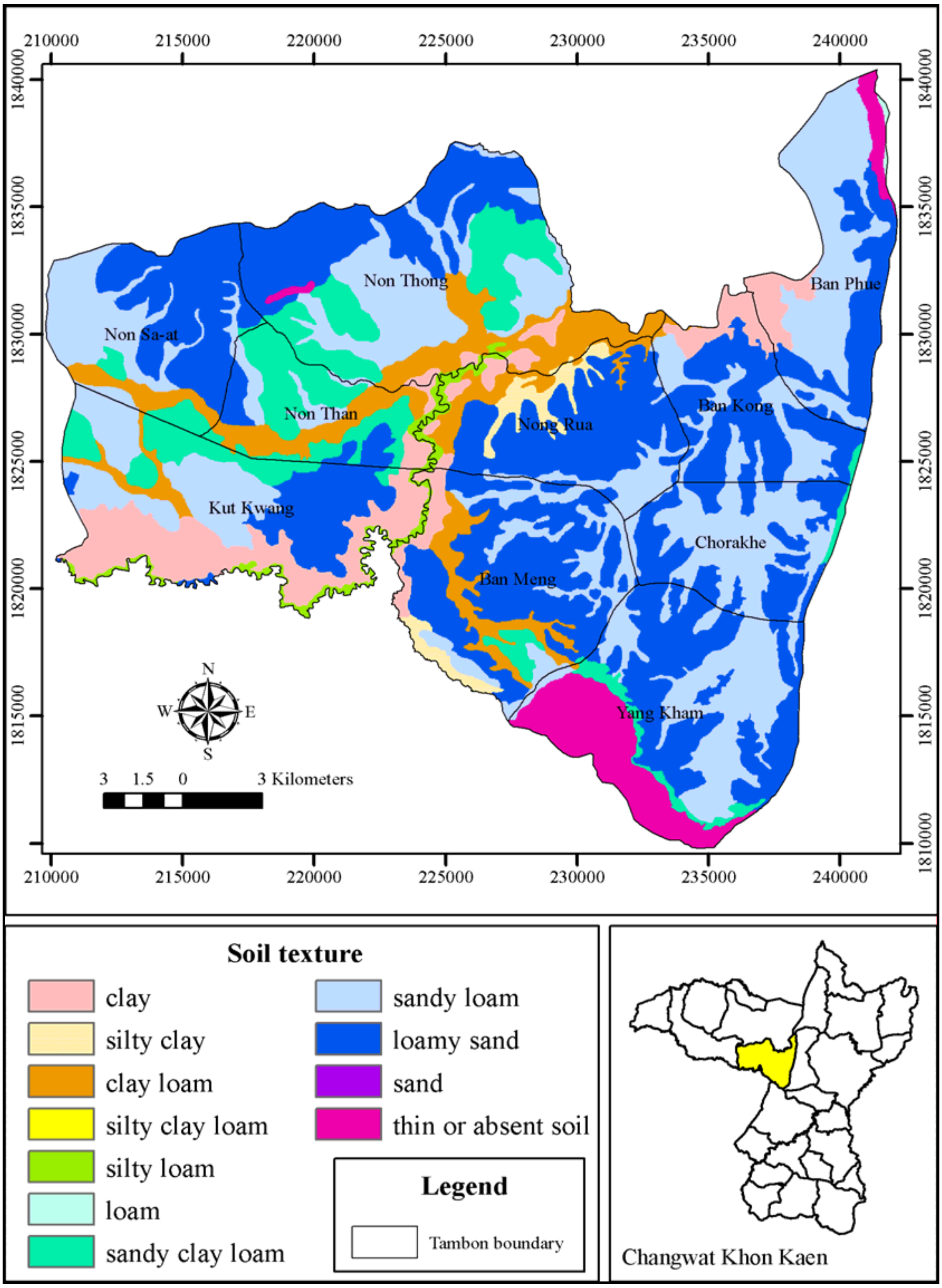


Figure 3.3 Soil texture map of the study area.

Source: LDD (กรมพัฒนาที่ดิน, ม.ป.ป.)

CHAPTER IV

GROUNDWATER VULNERABILITY

4.1 Abstract

The SINTACS approach was used to evaluate the intrinsic groundwater vulnerability in Amphoe Nong Rua, Changwat Khon Kaen. ArcGIS^{TM} as a tool of the Geographical Information System (GIS) was used to perform the organization, processing, and display all data layers. The approach is based on the seven environmental parameters, which are depth to water, infiltration, unsaturated zone, soil, aquifer, hydraulic conductivity, and slope. The vulnerability map shows six classes from very low to extremely high. High and moderate level dominated main part of the study area. The northwestern, southwestern, and central parts of the study area were covered by very high and extremely high levels. This should be because of their characteristics on being high infiltration rate, coarse-texture soil and shallow depth to groundwater. Both map removal and single parameter sensitivity analyses were performed to observe the effect of parameters to the model result. The statistical correlation coefficient showed significantly positive between the nitrate concentration in 87 wells and the SINTACS vulnerability level as high as 0.51. The result of this study is useful as basic data for strategic planning of groundwater quality management.

Keywords: GIS/SINTACS/Groundwater vulnerability/Nong Rua

4.2 Introduction

Nowadays, groundwater resource is the major source of water for domestic, agricultural, and industrial uses because of its acceptable chemical and biological characteristics. It is an only choice to solve water shortage problems, particularly where there is other water source. Therefore, the usage of groundwater resource must be cared and managed in terms of both quantity and quality to assure long term adequate and effectual supply. The contamination that causes groundwater quality degradation has to be seriously concerned. Once it was polluted, big time and budget are required to alleviate with incredibly high difficulty. To plan to protect groundwater resource properly, its vulnerability map is a very important tool for strategic planning of this management. It provides the priority of target areas for monitoring and protection.

Groundwater vulnerability deals only with the hydrogeologic setting and the natural hydrogeologic factors affecting the different pollutants in different ways depending on their interactions and chemical properties (Babiker, Mohamed, Hiyama, and Kato, 2005). Groundwater vulnerability concept is based on the assumption that the physical environment provides some natural protection to groundwater against human impacts, especially with regard to contaminants entering the subsurface environment. It is the tendency or likelihood for contaminants to reach into the groundwater system after introduction at the ground surface and based on the fundamental concept that some land areas are more vulnerable to groundwater contamination than others (Vrba and Zaporozec, 1994). Moreover, it is a relative, dimensionless property that is not directly measurable (Catchment, 2001), and does not include pollutant propagation and attenuation. There are two general types of vulnerability assessments. The first addresses specific vulnerability, which is referenced to a specific contaminant, contaminant class, or human activity. The second addresses intrinsic vulnerability, which does not consider the attributes and behavior of specific contaminants and is used for all pollutant sources.

Three categories of groundwater vulnerability assessment method are included (NRC, 1993): *index and overlay methods*, *process-based methods*, and *statistical methods* (see detail 2.1.2), *Index and overlay methods* are applied to groundwater vulnerability assessment in this study through SINTACS model.

The aim of this research is to assess the intrinsic groundwater vulnerability. Both map removal and single parameter methods are chosen to operate sensitivity analyses. The statistical correlation coefficient between vulnerability levels and the nitrate concentration from 87 wells was used to validate the result.

4.3 Research methods

4.3.1 Research procedure

The main steps of this part are shown in Figure 4.1. All data preparations and analyses were operated on raster-based GIS data. The details of each step can be explained as the followings.

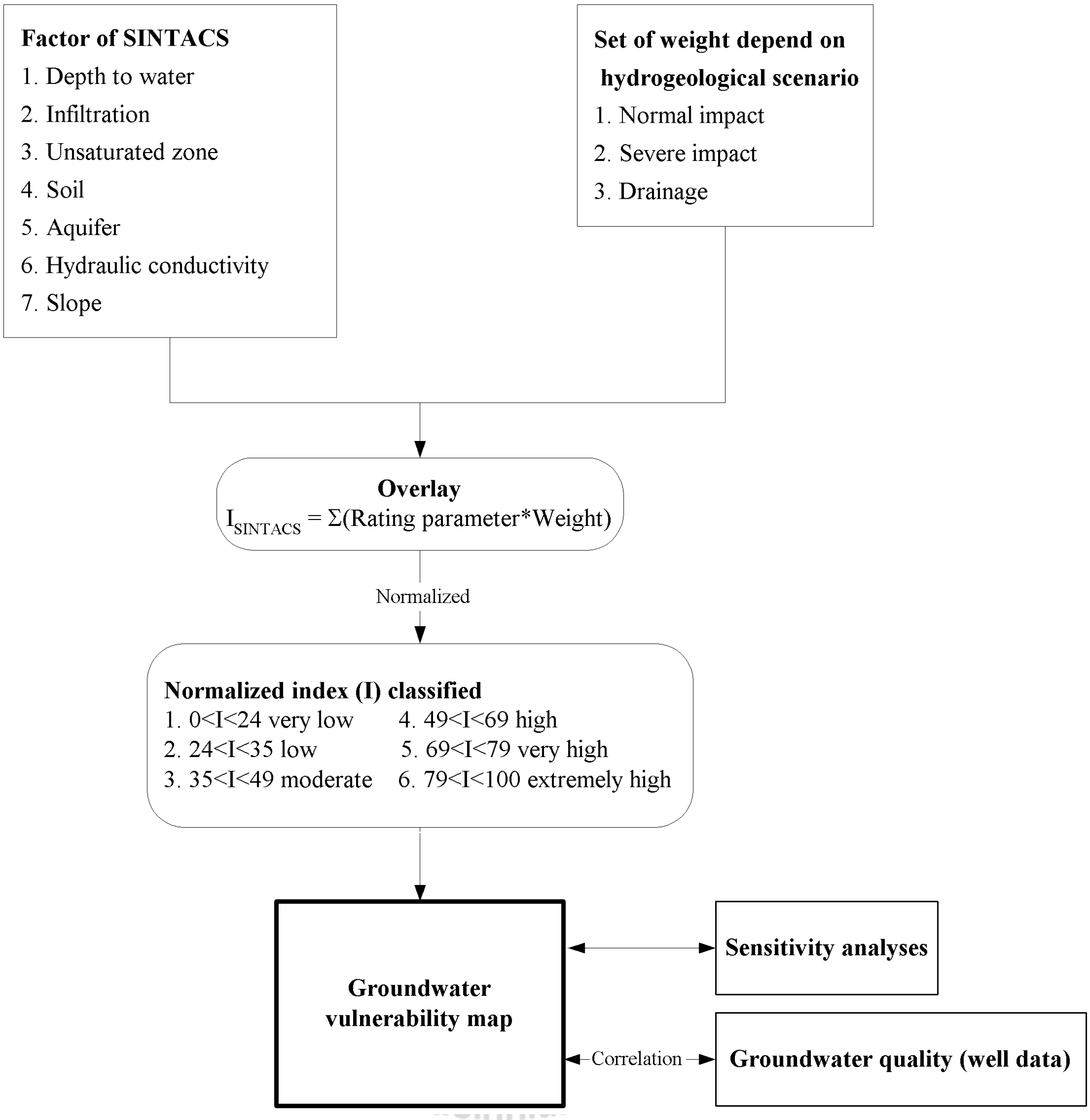


Figure 4.1 Overview of the research procedure for groundwater vulnerability assessment.

4.3.2 Groundwater vulnerability assessment

The SINTACS method was used in this study. It was developed by Civita (1994) and Civita and De Maio (1997 quoted in Al Kuisi, El-Naqa, and Hammouric, 2006) in order to assess the intrinsic groundwater vulnerability. The acronym SINTACS comes from the Italian names of the factors that are used:

Soggicenza (depth to groundwater), **I**nfiltrazione (effective infiltration), **N**on saturo (unsaturated zone attenuation capacity), **T**ipologia della copertura (soil/overburden attenuation capacity), **A**cquifero (saturated zone characteristics), **C**onducibilità (hydraulic conductivity), and **S**uperficie topografica (topographic surface slope). It is a Point Count System Models (PCSM) or Parameter Weighting and Rating Methods. The method is modified from DRASTIC which has been widely used in the USA. Moreover, its application is more suitable for assessment at a medium to small scale area than DRASTIC (Vrba and Zaporozec, 1994). Each factor is assigned a rating (R) from 0 to 10 (Figure 4.2) and a weight (W) from 0 to 5 (Table 4.1) which depends on hydrogeologic scenario.

Five hydrogeologic scenarios (weight strings) are suggested: normal impact, severe impact, drainage (by streams), karst (aquifers), and fissured (aquifers) (Civita and De Maio, 1997 quoted in Al Kuisi et al., 2006, 2004). Each criterion map of each factor was prepared to be GIS data layer in forms of 30×30 m grid size raster format. The SINTACS index (IS) is calculated for each grid element using the equation:

$$IS = \sum_{i=1}^{7} W_i \times R_i \tag{4.1}$$

The index ranges from 26 to 260. However, in order to facilitate interpretation of the results this data range has been normalized to 0-100. This normalization is divided into six classes as follows (Civita and De Maio, 2000): 0-24 very low (VL), 24-35 low (L), 35-49 moderate (M), 49-69 high (H), 69-79 very high (VH), and 79-100 extremely high (EH).

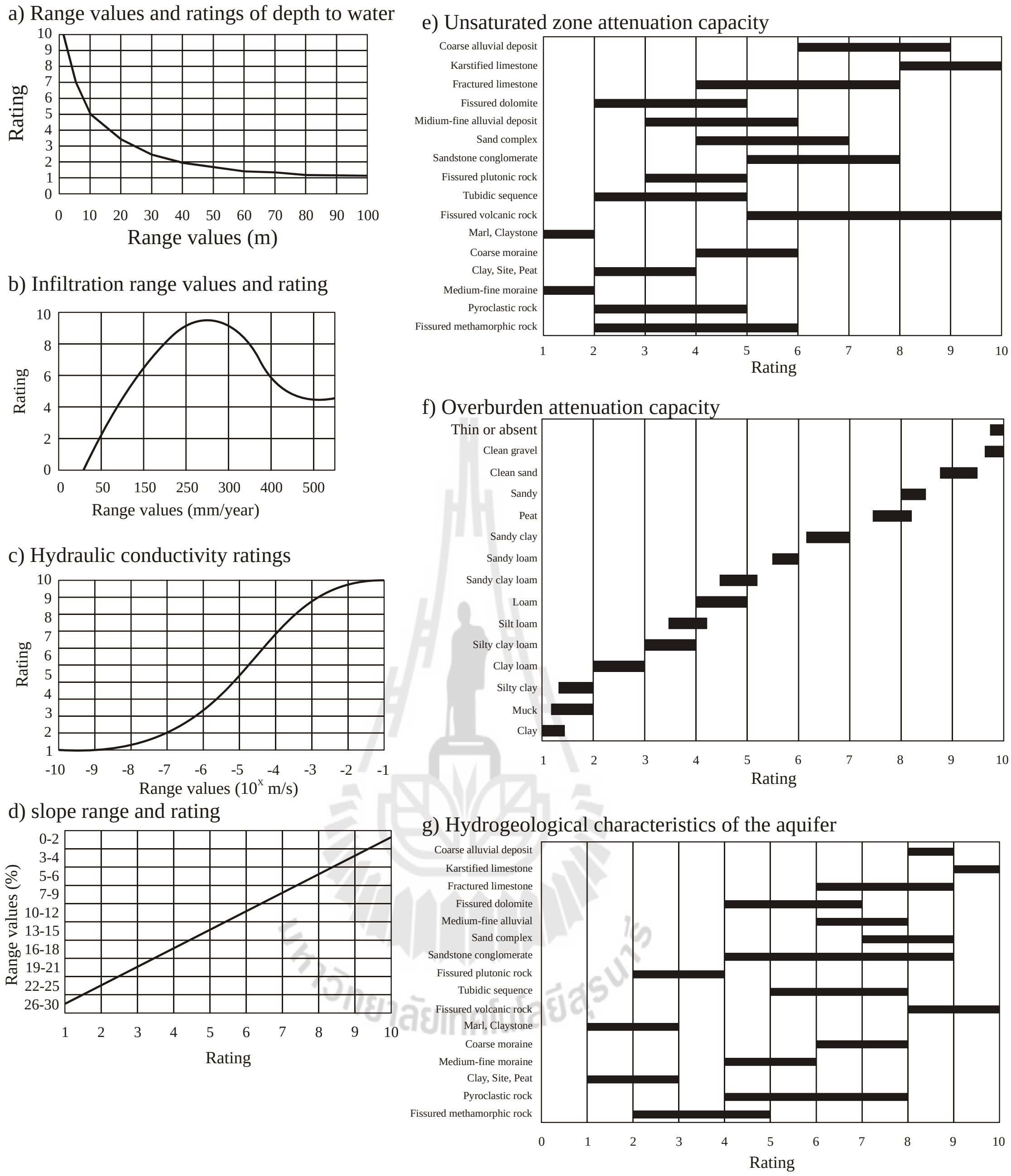


Figure 4.2 Rating graphs for parameters of the SINTACS method.

Source: Civita and De Maio (1997 quoted in Al Kuisi et al., 2006).

Table 4.1 Description of hydrogeologic scenarios and related weights for SINTACS.

hydrogeologic scenario	Description	weights						
		S	**I**	**N**	**T**	**A**	**C**	**S**
Normal impact	Barren areas, uncultivated or with spontaneous cultivations which however do not require the use of plant protection products or chemical fertilizers, unless in small doses, or irrigation practices. The breeding of a few wild animals, whether permanent or seasonal, often occurs in these areas.	5	4	5	3	3	3	3
Severe impact	Areas with cultivation that foresee abundant treatments with plant protection products, fertilizers, applications of fert-irrigations, sewage spreading, uncontrolled dumping of waste materials, lagoons, petrol pipelines, sewage deposits, etc.; active and abandoned industrial areas, urban areas or similar.	5	5	4	5	3	2	2
Drainage	From surface water bodies and shallow aquifer; depth to water areas subject to natural and man-made drainage networks; irrigation areas with large quantities of water, continuous or periodic outcropping areas of the unconfined piezometric surface.	4	4	4	2	5	5	2
Karst	Characterized by karst features.	2	5	1	3	5	5	5
Fissuring	Where hard rocks have elevated fracture indexes.	3	3	3	4	4	5	4

Source: Civita and De Maio (1997 quoted in Al Kuisi et al., 2006, 2004).

4.3.3 Sensitivity analyses

Sensitivity analysis is one way to acknowledge uncertainty in parameter estimation by observing change of results while using different sets of parameters and can help to determine the most important and influential parameters on the groundwater intrinsic vulnerability map. It is important both for the experts that implement a vulnerability model and for the users of vulnerability maps. The former can use sensitivity analysis for consistency evaluation of the analytical results. In addition, they can select the layers which are more critical for the analysis and require more detailed information and accuracy (Napolitano and Fabbri, 1996). Two types of sensitivity analyses employed in this study include map removal and single parameter analyses (Babiker, Mohamed, Hiyama, and Kato, 2005; Napolitano and Fabbri, 1996, and Sunya Sarapirome and Jiradech Majandang, 2008). These will imply that which parameter could more affect to the model result.

4.3.3.1 Map removal

The map removal is the sensitivity analysis performed by removing one parameter at a time for testing effect of that parameter to the model result of the study area. The purpose of the test is to identify which one(s) of parameters can be removed and it will not affect much on the model result.

1) It can be expressed as equation (4.2) (Babiker et al., 2005):

$$S = \left(\frac{\left| \frac{V}{N} - \frac{V'}{n} \right|}{V} \right) \times 100 \tag{4.2}$$

Where S is the sensitivity measurement expressed in terms of variation index, V and V' are the unperturbed and the perturbed vulnerability indices respectively, and *N* and *n* are the number of criterion maps used to compute *V* and *V'*. This operation is the cell-based analysis. A cell with very high or very low index of a removed parameter will show much effect on the variation index. According to Babiker et al. (2005), the mean of variation index in all cells of each parameter will be used to indicate which parameter can be less effect to the model result when removed. Any parameter with lower mean indicates the less effect.

2) As mentioned above, the result of comparison among removals can mislead when the mean of variation index in all cells of each removal is used. It will not completely reflect the spatial difference or similarity to the original model result. Therefore, the error matrix in terms of overall accuracy and Kappa coefficient is proposed for this study to compare vulnerability class of each removal to the original class of the model result. Any removal with higher overall accuracy and Kappa coefficient indicates less effect to the original model result when all cells are considered. Indexes of each removal are normalized and classified as same as carried out for the original model result.

4.3.3.2 Single parameter

The single parameter sensitivity analysis is the cell-based operation as well. Its purpose is to evaluate the average impact of each parameter on the vulnerability index of the study area. The evaluation is to compare the effective or normalized weight of each input parameter with the theoretical or model weight assigned. The effective weight was obtained using the following equation (Napolitano and Fabbri, 1996):

$$W = \left(\frac{P_r P_w}{V} \right) \times 100 \quad (4.3)$$

Where W refers to the effective weight of each parameter, P_r and P_w are the rating value and weight of each parameter, and V is the overall vulnerability index.

The purpose to use this analysis is to indicate that the criterion providing high effective weight will be the one which provides the high to very high rating when its spatial variation of the whole area is considered. It means that its category with high/very high rating covers main part of the area.

4.3.4 Correlation between vulnerability levels and the nitrate concentration in the well

The nitrate (NO_3) concentration in 87 groundwater wells was analyzed by DGR (กรมทรัพยากรน้ำบาดาล, 2551). These data were used to correlate to the groundwater vulnerability levels to observe the degree of corresponding between the surface characteristics and the water quality. The nitrate was used because of its common presence as pollutants from fertilizers, manures, and septic systems available in agricultural and urban areas. In addition, Hentati, Zairi, and Dhia (2010) suggested that nitrate behaves as a non-conservative solute and always shows higher variation compared to other solutes. Due to the data characteristics, Spearman's rank correlation coefficient (ρ) is applied to assess the relationship between the nitrate concentration in wells and the vulnerability levels. It measures how closely rankings of two variables agree with each other. It could be calculated by the following equation:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d^2}{n\left(n^2 - 1\right)} \qquad (4.4)$$

Where *d* is the difference in the ranks given to the two variable values for each item of data and *n* is the number of pairs.

4.4 Results and discussion

4.4.1 Factors of SINTACS method

The SINTACS method is based on the assessment and ratings of seven factors that includes depth to water, infiltration, unsaturated zone, soil, aquifer, hydraulic conductivity, and slope.

4.4.1.1 Depth to water

Depth to water is defined as the distance between the ground surface and the piezometric level (both for confined and unconfined aquifers). It determines the thickness of the unsaturated zone through which a contaminant must travel before reaching the aquifer and it may help to determine the duration of the attenuation process for oxidation by atmospheric oxygen. The SINTACS rating of this factor therefore decrease with an increase of the depth (Civita and De Maio, 2004).

Depth to water was estimated by interpolating information stored in well's database. These data were obtained from measured data during drilling test boreholes for artificial groundwater well that produced by DGR. Inverse distance weight (IDW) interpolation method was used to create this criterion map from data of 426 wells. The rating for these values was obtained from Figure 4.2a and shows in Table 4.2. Their spatial distribution is shown in Figure 4.3. The values of depth to water were ranged into 17 groups and the rating of each group was assigned from 1.5 to 9.5. The lower depth to water table was assigned the higher rating. The high rating area has been found covering the northwest, east, and central part of the study area.

Table 4.2 Depth to water range and rating value.

Depth to water (m)	rating
0.0-2.0	9.5
2.0-2.5	9.0
2.5-3.5	8.5
3.5-4.5	8.0
4.5-5.0	7.5
5.0-6.0	7.0
6.0-7.0	6.5
7.0-8.0	6.0
8.0-9.0	5.5
9.0-10.0	5.0
10.0-13.0	4.5
13.0-17.0	4.0
17.0-20.0	3.5
20.0-25.0	3.0
25.0-30.0	2.5
30.0-40.0	2.0
>40.0	1.5

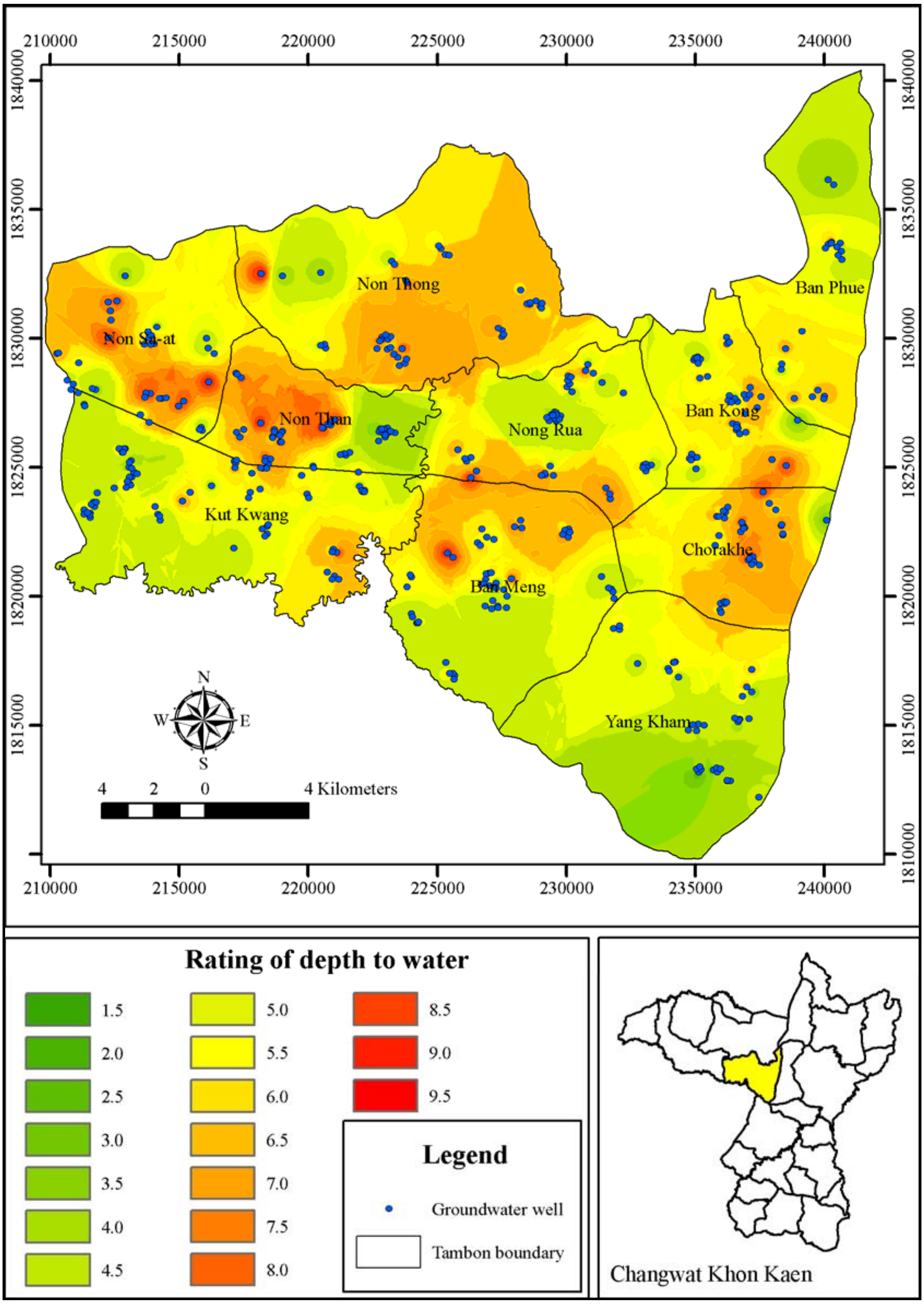


Figure 4.3 Spatial distribution of depth to water rating.

4.4.1.2 Infiltration

Infiltration is the movement of water from the surface through the soil as distinguished percolation (Linsley, Kohler, and Paulhus, 1988). It plays a very significant role in aquifer vulnerability assessment, because of its dragging down surface pollutants into the groundwater system. The water quantity available for dispersion and dilution in the unsaturated zone and then within the saturated zone is controlled by this factor. Direct infiltration is the only or widely prevalent component of net recharge in all the areas where there are no interflows aquifers linking to the surface water bodies or no irrigation practices using large water volumes (Civita and De Maio, 2004).

The mean annual infiltration (mm/year) is represented by the difference between the annual precipitation and runoff (Al Kuisi et al., 2006). The average of annual rainfall data in the study area is about 1,209.9 mm/year. For runoff values, it was calculated by the Soil Conservation Service (SCS) method (Soil Conservation Service, 1985).

The SCS runoff curve number method is one of the simplest and most efficient models to estimate the surface runoff, using rainfall, soil type, and land use data. The surface runoff according to this method is calculated using the formula:

$$Q = \frac{\left(P - I_a\right)^2}{\left(P - I_a\right) + S} \tag{4.5}$$

Where Q is the runoff (mm/year), P is the rainfall (mm/year), S is the potential maximum retention after runoff begins, and I_a is the initial abstraction.

Initial abstraction includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. Among several expressions to compute initial abstraction in a small watershed, the following empirical equation of relationship between the initial abstraction and the potential maximum retention after runoff begins will be used:

$$I_a = 0.2S \tag{4.6}$$

Replacing I_a from this equation in equation 4.5 will produce:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{4.7}$$

The potential maximum retention after runoff begins is related to soil and cover conditions of the watershed through the curve number (*CN*). This number can be given a value that range between 0 and 100. The relation between S and *CN* is given by:

$$S = \frac{25400}{CN} - 254 \tag{4.8}$$

The curve number value is depended on hydrologic soil groups and land use. Hydrologic soil groups are classified into four groups according to their soil texture [U.S. Department of Agriculture (USDA), 1986]. Group A includes sand, loamy sand, and sandy loam and group B includes silt loam and loam. Sandy clay loam belongs to group C and group D includes clay loam, silty clay loam, sandy clay, silty clay, and clay. The curve number values were modified by Tharapong Phetprayoon, Sunya Sarapirome, Charlie Navanugraha, and Sodchol Wonprasaid (2009) which are applied for this study. The summary of modified curve number values is shown in the Table 4.3.

Table 4.3 Modified curve number values of Nong Rua.

Land cover	**Assumption for appropriate to land use in the study area**	**Curve numbers for hydrologic soil group**			
		A	**B**	**C**	**D**
Row crop	Cassava, watermelon	72	81	88	91
	Sugarcane	49	69	79	84
Small grain	Paddy field	65	76	84	88
Pasture, grassland	Grass, pasture	68	79	86	89
Brush-grass mixture with brush the major element	Scrub	48	67	77	83
Woods-grass combination (orchard or tree farm)	Jujube, mango, perennial, para rubber, teak, eucalyptus, longan, pomelo	43	65	76	82
Forest	Disturbed deciduous	36	60	73	79
	Dense deciduous	30	55	70	77
Impervious and water surface	Water body, marsh, swamp	98	98	98	98
Farmstead-building	Livestock farm house	59	74	82	86
Urban districts	City, Town, Commercial, institutional land	89	92	94	95

Source: Tharapong Phetprayoon, Sunya Sarapirome, Charlie Navanugraha, and Sodchol Wonprasaid (2009).

The infiltration values in the study area are between 6.20 and 502.63 mm/year and were ranged into 16 groups. The rating for these ranges was obtained from Figure 4.2b and shows in Table 4.4. Figure 4.4 shows the spatial distribution of infiltration rating over the study area. The main part of the study area is covered by rating value above 6. The low rating value is mostly concentrated both sides of streams and water body.

Table 4.4 Infiltration range and rating value.

Infiltration values (mm/year)	rating
0-25	1
25-40	2
40-65	3
65-90	4
90-110	5
110-135	6
135-165	7
165-190	8
190-235	9
235-275	9.5
275-315	9
315-350	8
350-375	7
375-400	6
400-435	5
435-510	4

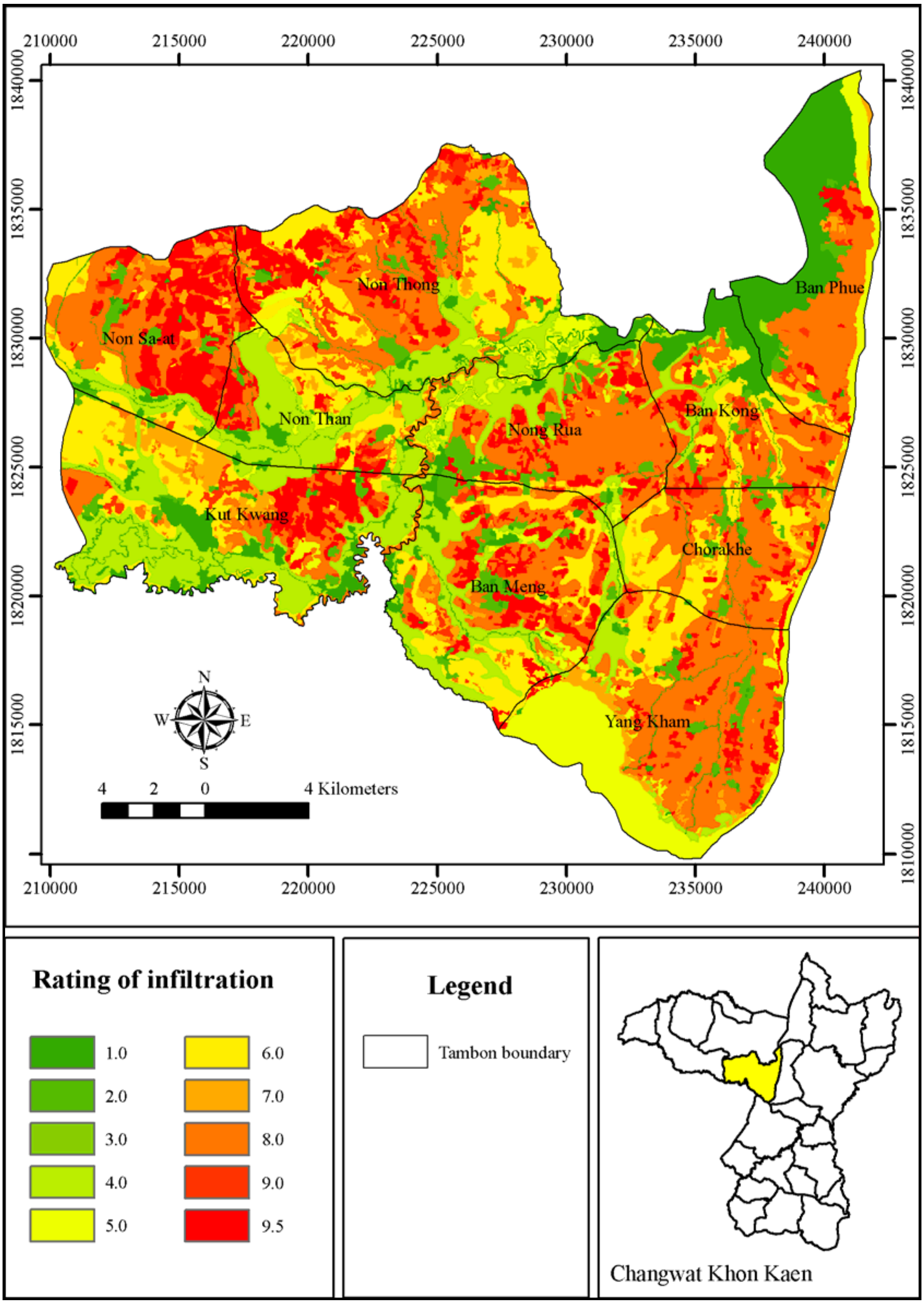


Figure 4.4 Spatial distribution of infiltration rating.

4.4.1.3 Unsaturated zone

The unsaturated zone is the second defense layer of the hydrogeologic system below the soil horizon and above the piezometric surface. The attenuation capacity of unsaturated zone is assessed starting from the hydro-lithologic features (texture, mineral composition, grain size, fracturing, karst development, etc.) (Civita and De Maio, 2004).

The drill logging information of 215 groundwater wells of DGR was used to interpret the unsaturated zone. The unsaturated zone in the study area consists of alternated different lithologic units with variable thicknesses. The unit rating in the unsaturated zone was obtained from Figure 4.2e and given in Table 4.5. The rating of the unsaturated zone can be estimated using equation 4.9.

$$\bar{x} = \frac{\sum_{i=1}^{n} W_i x_i}{\sum_{i=1}^{n} W_i} \tag{4.9}$$

Where $\bar{x}$ is the weighted mean, W_i is the thicknesses of lithologic unit i, x_i is the rating of unit i, and n is the number of lithologic units.

The rating values of unsaturated zone calculated by equation 4.9 ranges from 2.00 to 6.95. IDW interpolation method was used to generate this criterion map from wells. Figure 4.5 shows the spatial distribution of these ratings. The study area shows trend of low rating values.

Table 4.5 Lithologic unit and rating value of the unsaturated zone.

Lithologic unit	rating
shale	2
siltstone	4
sandstone	5
clay	2.5
laterite	3
silt	3.5
sandy clay	6
sand	7

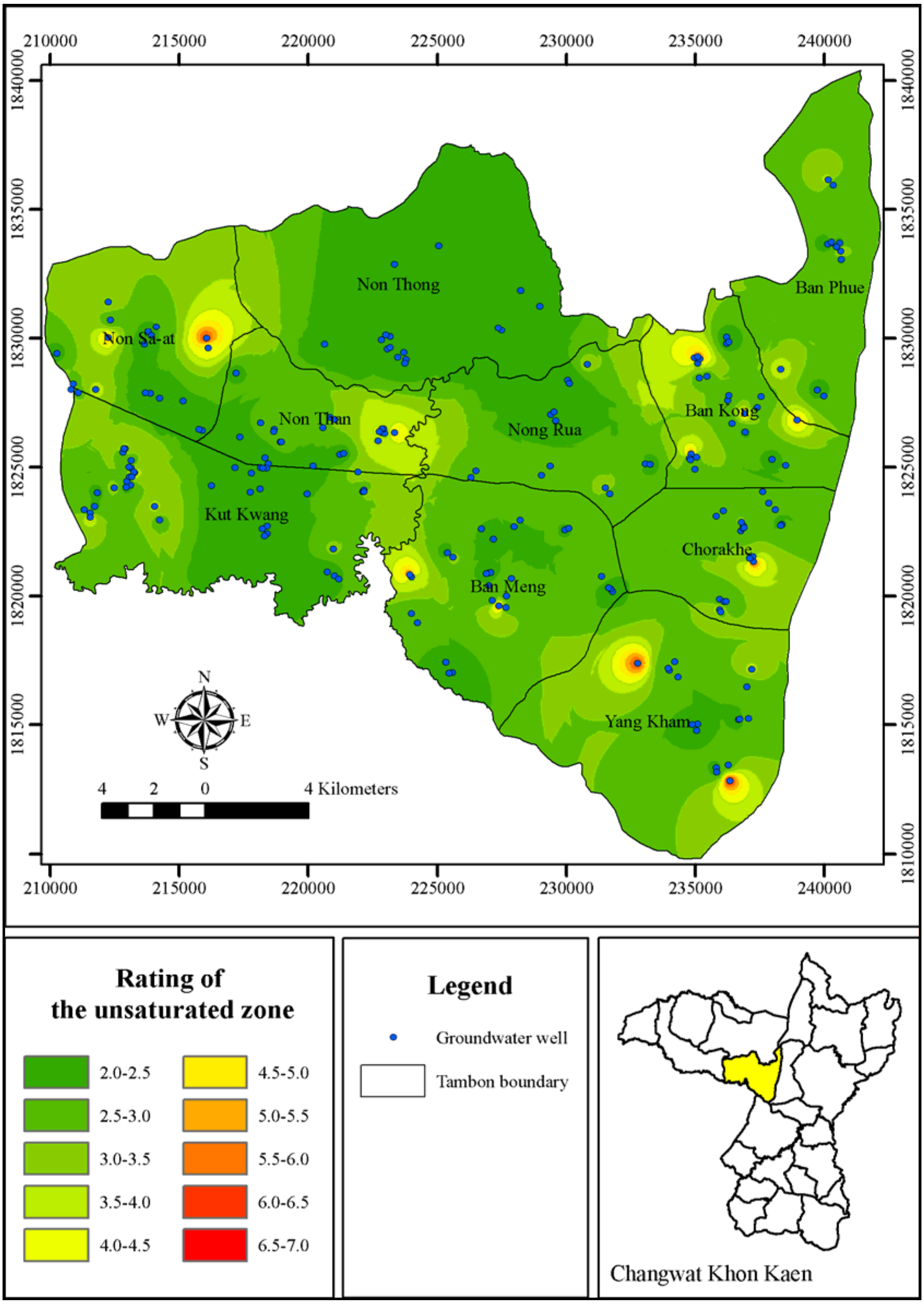


Figure 4.5 Spatial distribution of the unsaturated zone rating.

4.4.1.4 Soil

Soil is the first defense layer of the hydrogeologic system above the unsaturated zone. The significant impact of soil on the amount of recharge is how good to allow it to infiltrate into the ground and hence indicates the ability of a contaminant to move vertically into the unsaturated zone. A several important processes (filtration, biodegradation, sorption, and volatilization) take place inside the soil that built up the attenuation capacity of a contaminant traveling inside a hydrogeologic system (Civita and De Maio, 2004). The soil texture characteristics are effective to the groundwater intrinsic vulnerability. The presence of fine texture materials such as silts and clays can relatively decrease soil permeability and restrict contaminant migration (Al Kuisi et al., 2006).

Soil information was obtained from LDD. These data were rated according to Figure 4.2f. Table 4.6 shows rating value of this factor. From Figure 4.6, the study area shows high rating value as majority. The low rating value is mostly concentrated along both sides of streams where finer texture is present.

Table 4.6 Soil texture and rating value.

Soil texture	rating
clay	1.0
silty clay	2.0
clay loam	3.0
silty clay loam	3.5
silty loam	4.0
loam	4.5
sandy clay loam	5.0
sandy loam	6.0
loamy sand	8.0
sand	8.5
thin or absent	9.5

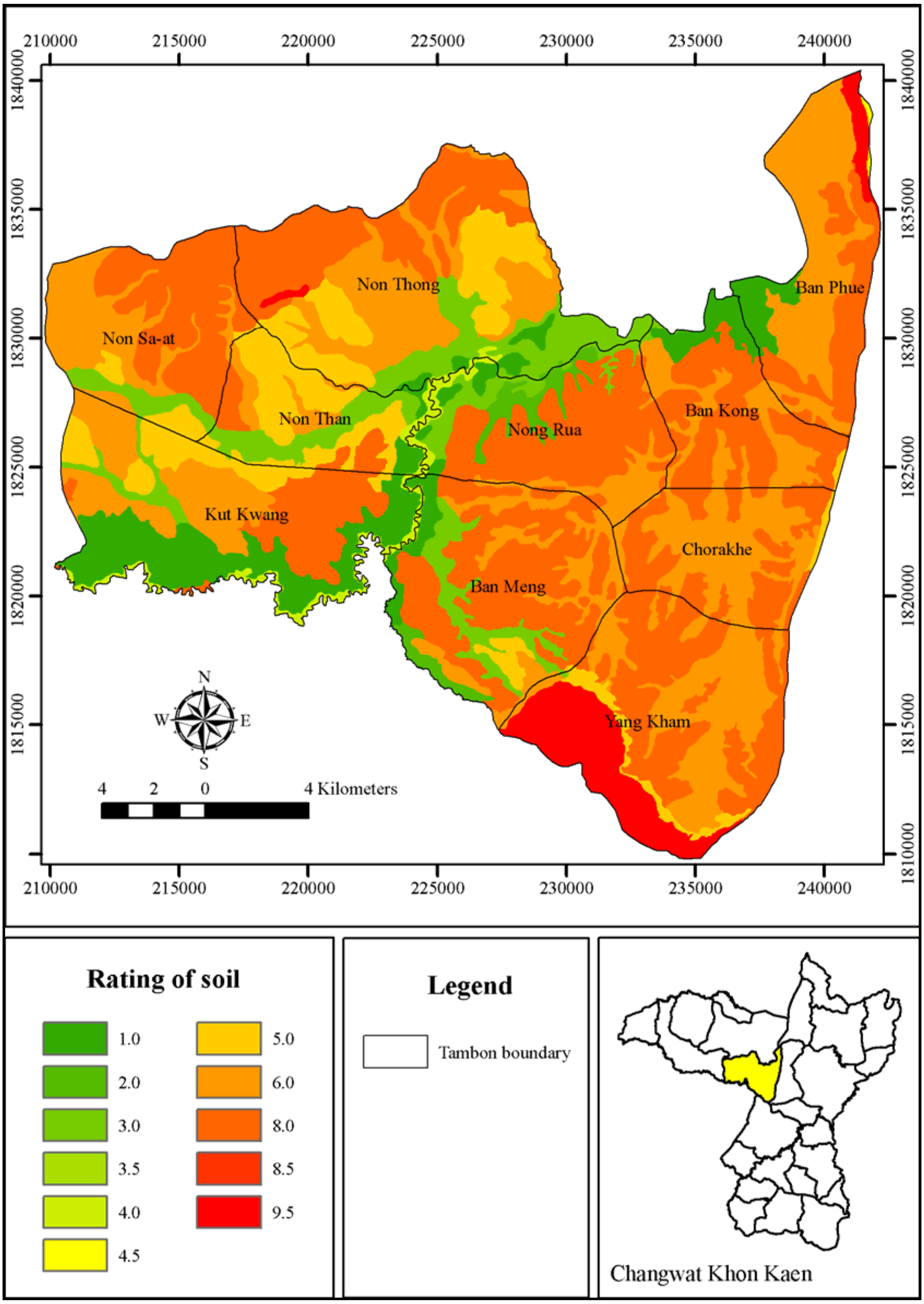


Figure 4.6 Spatial distribution of soil rating.

4.4.1.5 Aquifer

For vulnerability assessment models, the aquifer characteristics describe the process that takes place below the piezometric level when a contaminant is mixed with groundwater with a loss of a small or more relevant part of its original concentration during the traveling through soil and the unsaturated thickness. Basically, these processes are: molecular and cinematic dispersion, dilution, sorption and chemical reactions between the rock and the contaminants (Civita and De Maio, 2004).

Three different rock types generally appear in aquifers of the study area. They include shale, siltstone, and sandstone. Their boundaries are hardly able to identify. However, they can be determined using the drill logging information of 210 groundwater wells. The thickness of each rock type aquifer was attained by IDW interpolation method. The rating of aquifer can be estimated using equation 4.10.

$$\bar{x} = \frac{\sum_{i=1}^{n} W_i x_i}{\sum_{i=1}^{n} W_i} \tag{4.10}$$

Where $\bar{x}$ is the weighted mean, W_i is the thicknesses of rock type i, x_i is the rating of rock type i and n is the number of rock types.

The aquifer rating value for each type can be obtained from Figure 4.2g which are 2, 4, and 6 for shale, siltstone, and sandstone, respectively. The spatial distribution of each type of aquifer thickness shows in Figure 4.7. Figure 4.8

shows the spatial distribution of aquifer rating. The study area mainly shows low rating value. The high value appears as scattering small patches over the study area.

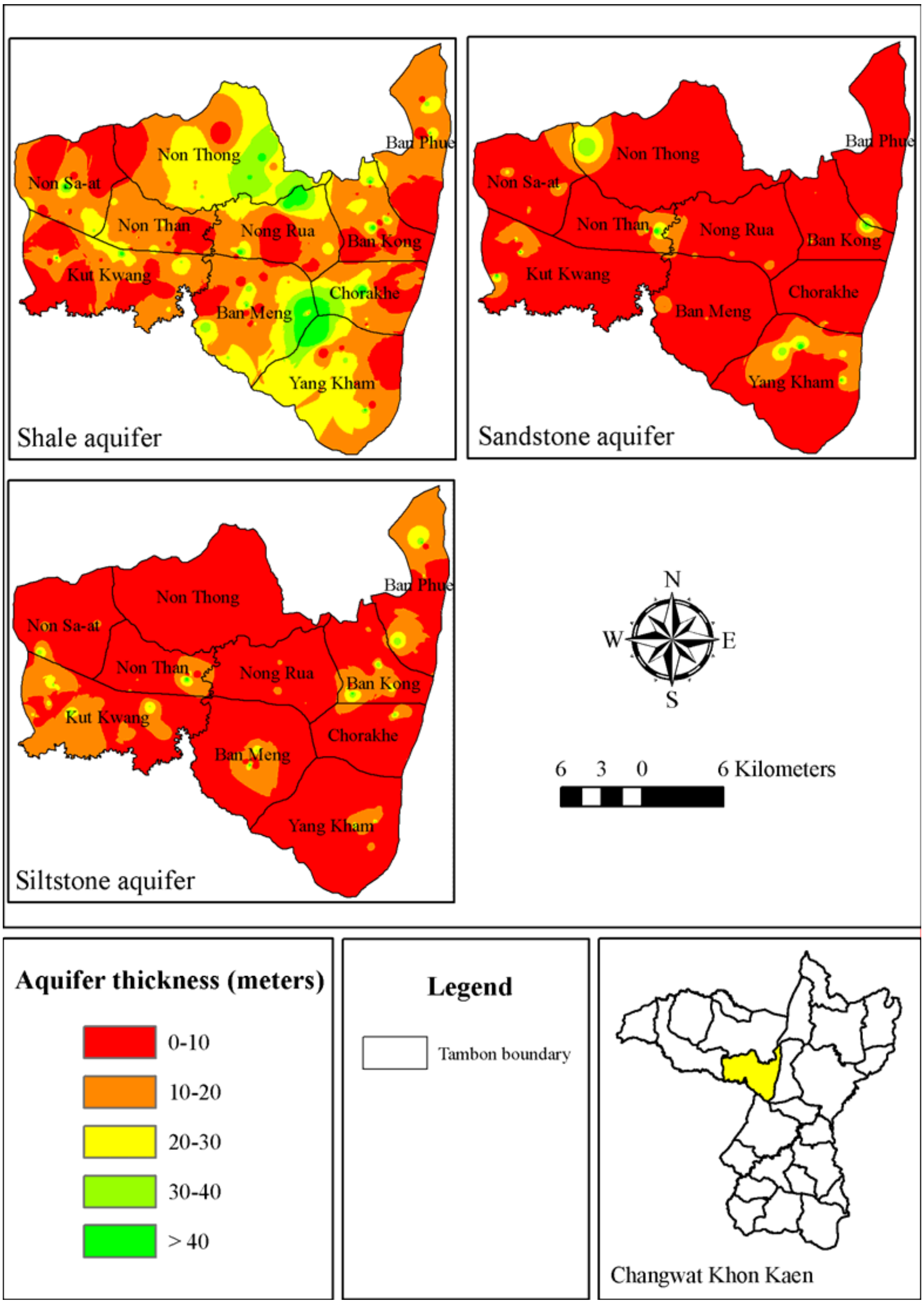


Figure 4.7 Aquifer thickness of the study area.

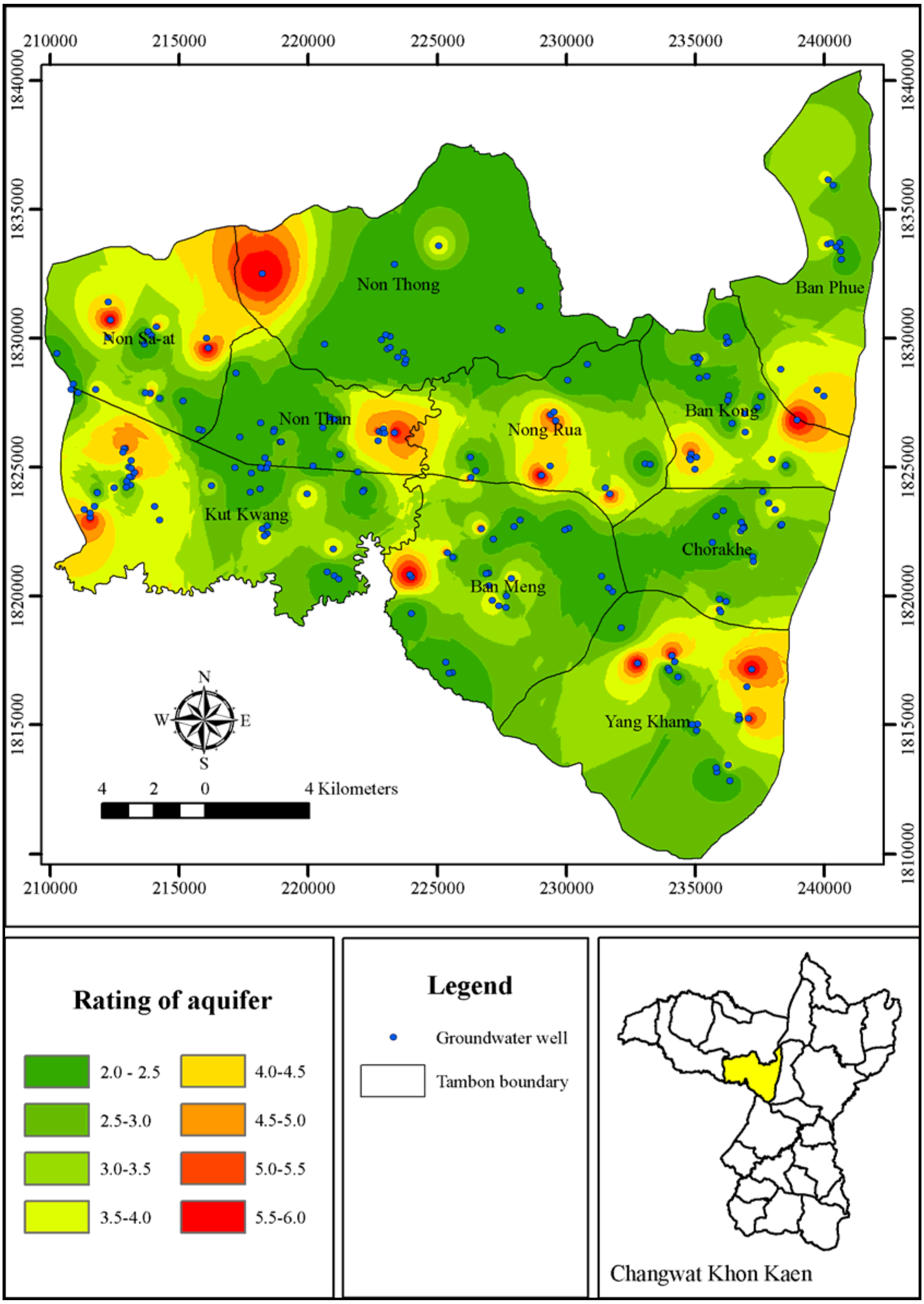


Figure 4.8 Spatial distribution of aquifer rating.

4.4.1.6 Hydraulic conductivity

Hydraulic conductivity refers to the ability of aquifer materials to transmit water, which in turn controls the rate of ground water flow under a given hydraulic gradient (Aller et al., 1987). High hydraulic conductivity is associated with high vulnerable to contaminations. Because the hydraulic conductivity controls the rate at which a contaminant will be moved away from the point at which it enters to the aquifer.

Due to the limitation of pumping test data, the hydraulic conductivity (K) for this study was estimated by a simple well test value. It could be calculated by the following equation (USEPA, 1994):

$$K = \frac{T}{b} = 2,000 \times \frac{specific\ capacity}{b} \qquad (4.11)$$

Where T is transmissivity (in gallons per day per foot) and b is the aquifer thickness (in foot).

The aquifer thickness was determined by the screen length. Transmissivity is estimated based on specific capacity measurements. However, they are commonly low because of well construction details such as screen length is less than the thickness of the aquifer (USEPA, 1994). Specific capacity could be calculated by the following equation:

$$specific\ capacity = \frac{Q}{wd} \qquad (4.12)$$

Where Q is discharge rate (in gallons per minute), and wd is well drawdown (in foot) which is the difference of the static water surface and the lowest water surface when pumped.

The hydraulic conductivity was calculated using equation 4.11 with data from 111 groundwater wells (กรมทรัพยากรน้ำบาดาล, ม.ป.ป.). It ranges from 3.73×10^{-2} to 3.00×10^{-6} m/s. The thematic map layer of hydraulic conductivity was generated by IDW interpolation method. The rating of hydraulic conductivity was obtained from Figure 4.2c and shown in Table 4.7. Its spatial distribution is displayed in Figure 4.9. The area obviously shows high rating value. The highest covers the northern and northwestern parts of the study area while the lower is common in the eastern part.

Table 4.7 Hydraulic conductivity range and rating value.

Hydraulic conductivity (m/s)	rating
3.9×10^{-6} – 5.5×10^{-6}	4.50
5.5×10^{-6} – 1.0×10^{-5}	5.00
1.0×10^{-5} – 1.8×10^{-5}	5.50
1.8×10^{-5} – 3.0×10^{-5}	6.00
3.0×10^{-5} – 5.0×10^{-5}	6.50
5.0×10^{-5} – 9.0×10^{-5}	7.00
9.0×10^{-5} – 1.5×10^{-4}	7.50
1.5×10^{-4} – 2.0×10^{-4}	7.75
2.0×10^{-4} – 3.0×10^{-4}	8.00
3.0×10^{-4} – 4.5×10^{-4}	8.25
4.5×10^{-4} – 6.0×10^{-4}	8.50
6.0×10^{-4} – 1.0×10^{-3}	8.75
1.0×10^{-3} – 1.5×10^{-3}	9.00
1.5×10^{-3} – 2.5×10^{-3}	9.25
2.5×10^{-3} – 4.5×10^{-3}	9.50
4.5×10^{-3} – 4.0×10^{-2}	9.75

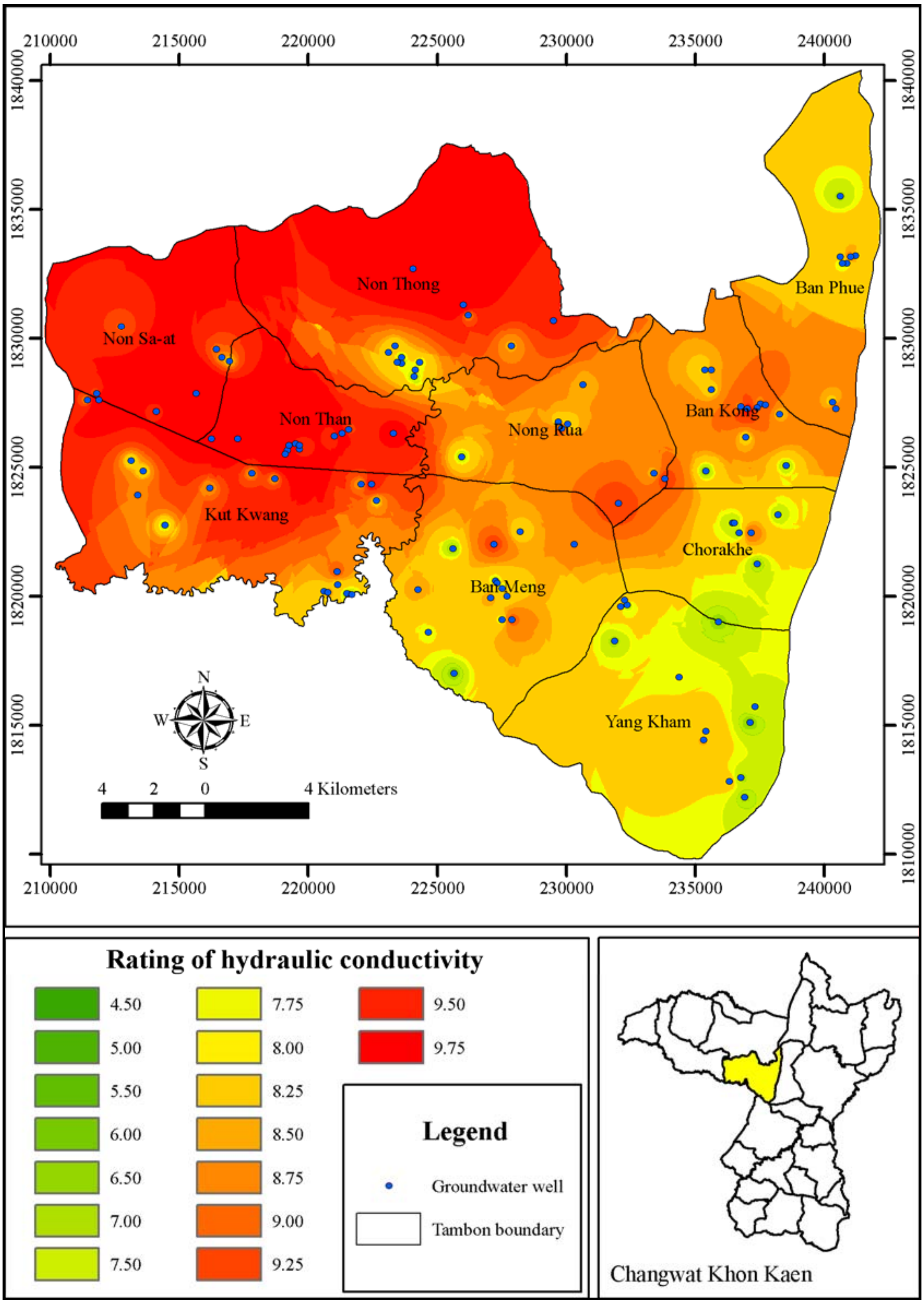


Figure 4.9 Spatial distribution of hydraulic conductivity rating.

4.4.1.7 Slope

The topographic slope in vulnerability assessment helps to control the likelihood that a pollutant will run off or remain on the surface in one area long enough to infiltrate (Aller et al., 1987). In practices, high rating is assigned to slight slope. The low slope areas tend to retain water for longer period of time, which allows a greater infiltration or recharge water and a greater potential for contaminant migration. Areas of steep terrain help to control runoff of pollutants and their infiltration into the groundwater (Al-Amoush, Hammouri, Zunic, and Salameh, 2010). The slope may be a genetic factor apart from the type of soil and its thickness, and can indirectly determine the attenuation potential of the hydrogeologic system (Civita and De Maio, 2004).

The percent slope for this study was generated from DEM that constructed by Chaiyapon Keeratikasikorn and Itthi Trisirisatyawong (ชัยพล กีรติกสิกร และอิทธิ ตริสิริสัตยวงศ์, 2550) from SRTM data version 3.0. The rating for percent slope was obtained from Figure 4.2d and shown in Table 4.8. Their spatial distribution is shown in Figure 4.10. The main rating value of the study area is high because the study area is apparently flat.

Table 4.8 Slope range and rating value.

Slope (percent)	rating
0-2	9.5
2-4	8.5
4-6	7.5
6-9	6.5
9-12	5.5
12-15	4.5
15-18	3.5
18-21	2.5
21-25	1.5
25-30	1.0

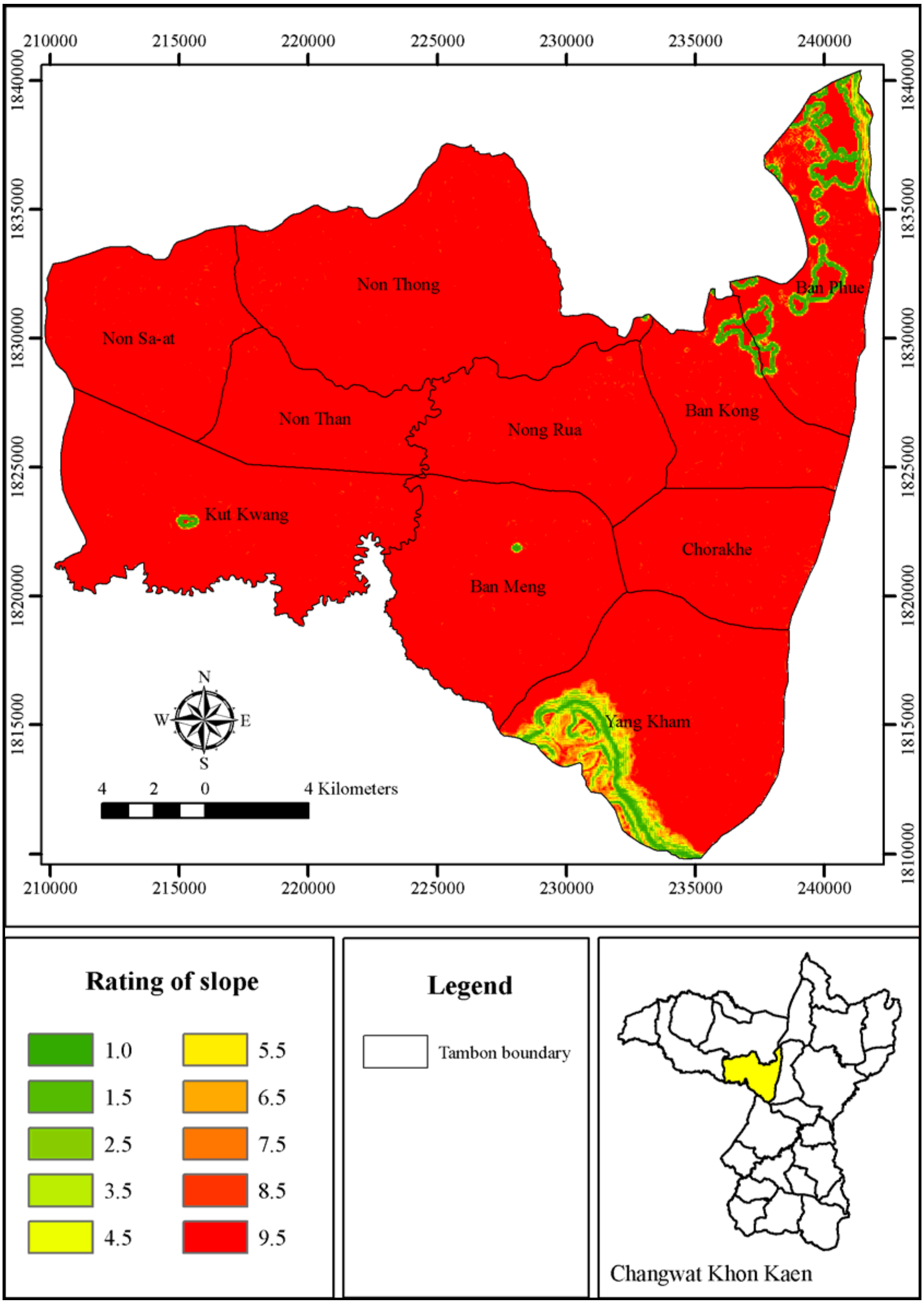


Figure 4.10 Spatial distribution of slope rating.

4.4.2 Weighting based on different hydrogeologic scenarios

Only three hydrogeologic scenarios exist in the study area. They include normal impact, severe impact, and drainage (Figure 4.11). For this study, the hydrogeologic scenarios by definition were considered and prepared based on land use. The normal impact scenario consists of grass, deciduous forest, perennial, scrub, pasture, teak, and eucalyptus while the severe impact scenario consists of paddy field, truck crop, cassava, field crop, watermelon, sugarcane, jujube, para rubber, mango, longan, pomelo, livestock farm house, build-up land, institutional land, and village area. Water body, marsh, and swamp are assigned to be in drainage scenario. The weight string values were obtained from Table 4.1 and shown in Table 4.9.

Table 4.9 The set of weights for factors depending on different hydrogeologic scenarios.

hydrogeologic scenario	**Land use in study area**	**Weights**						
		S	**I**	**N**	**T**	**A**	**C**	**S**
Normal impact (95.26, 6.77)	Grass, deciduous forest, perennial, scrub, pasture, teak, eucalyptus	5	4	5	3	3	3	3
Severe impact (1,262.83, 89.78)	Paddy field, truck crop, cassava, field crop, watermelon, sugarcane, jujube, para rubber, mango, livestock farm house, longan, pomelo, build-up land, institutional land, village	5	5	4	5	3	2	2
Drainage (48.52, 3.45)	Water body, marsh, swamp	4	4	4	2	5	5	2

Remark: numeric values in parentheses are covering area (km^2, %).

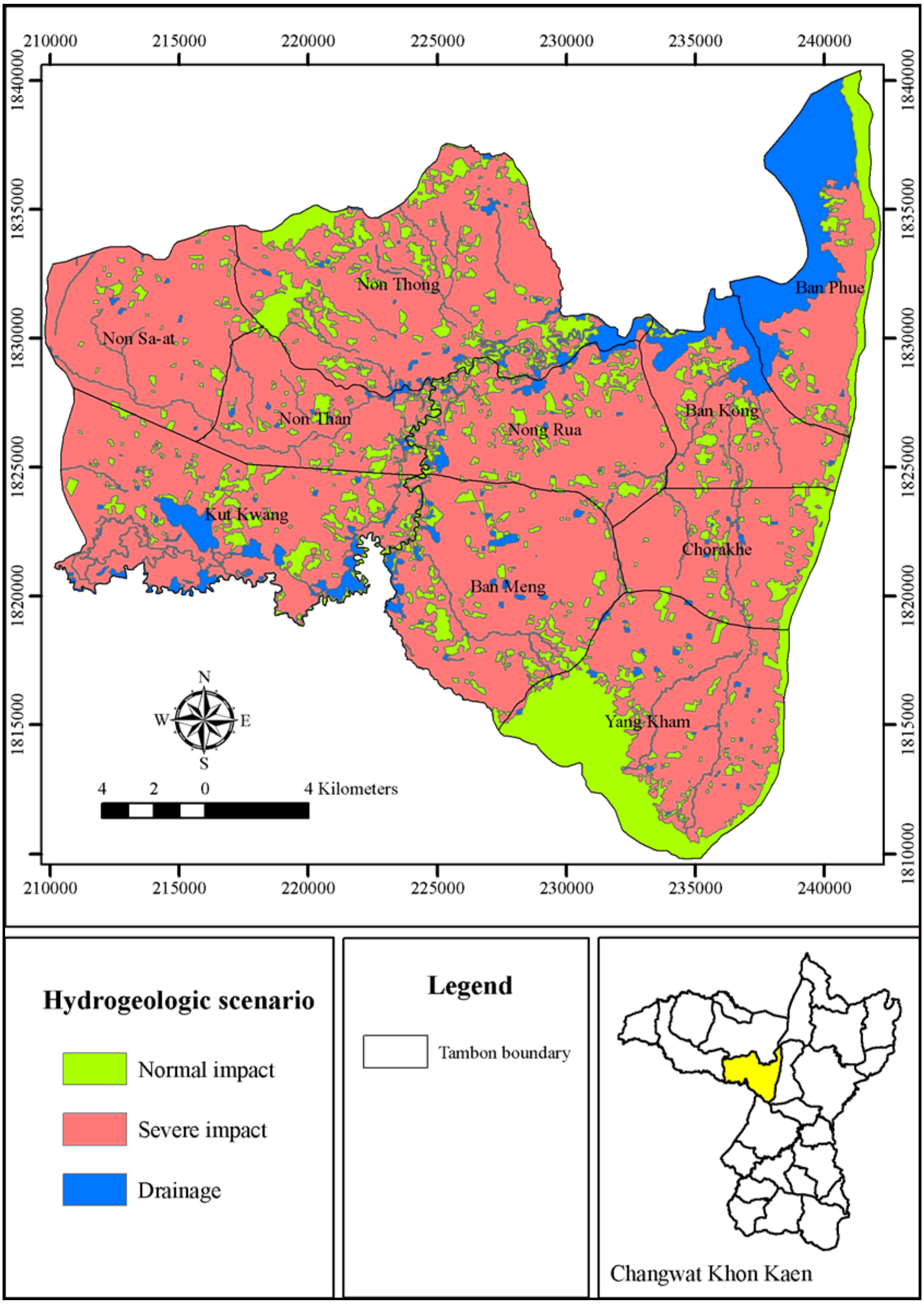


Figure 4.11 Hydrogeologic scenarios of the study area.

4.4.3 Groundwater vulnerability map

The final intrinsic groundwater vulnerability index of each grid was calculated using the equation 4.1. The obtained index values range between 83.33 and 194.10. However, to facilitate interpretation of the results, they were normalized to be between 0-100 and separated to be 6 classes of vulnerability, from very low to extremely high. The area cover of each class is shown in Table 4.10. Figure 4.12 shows the final vulnerability map using the SINTACS method.

The major vulnerability levels of the study area are high (45.54%) and moderate (21.59%). These levels have been found covering all parts of the study area. Low (13.10%) and very low (8.61%) are mostly concentrated along streams of the study area such as Lam Choen, Huai Bu Na, and Huai Lua. This should be because of the presence of clay rich soil both sides of streams and causing low rating in soil and infiltration for the SINTACS method. The area having very high (8.21%) and extremely high (2.95%) levels are in the northwest, southwest, and central part of the study area. The high infiltration rate, coarse-texture soil, and shallow depth to water express high effect to these levels.

Table 4.10 Intrinsic groundwater vulnerability levels and their percentage of area cover.

Intrinsic index levels	Normalized index	Area cover	
		km^2	Percent
Very low (VL)	0-24	45.90	8.61
Low (L)	24-35	69.87	13.10
Moderate (M)	35-49	115.13	21.59
High (H)	49-69	242.82	45.54
Very high (VH)	69-79	43.76	8.21
Extremely high (EH)	79-100	15.72	2.95

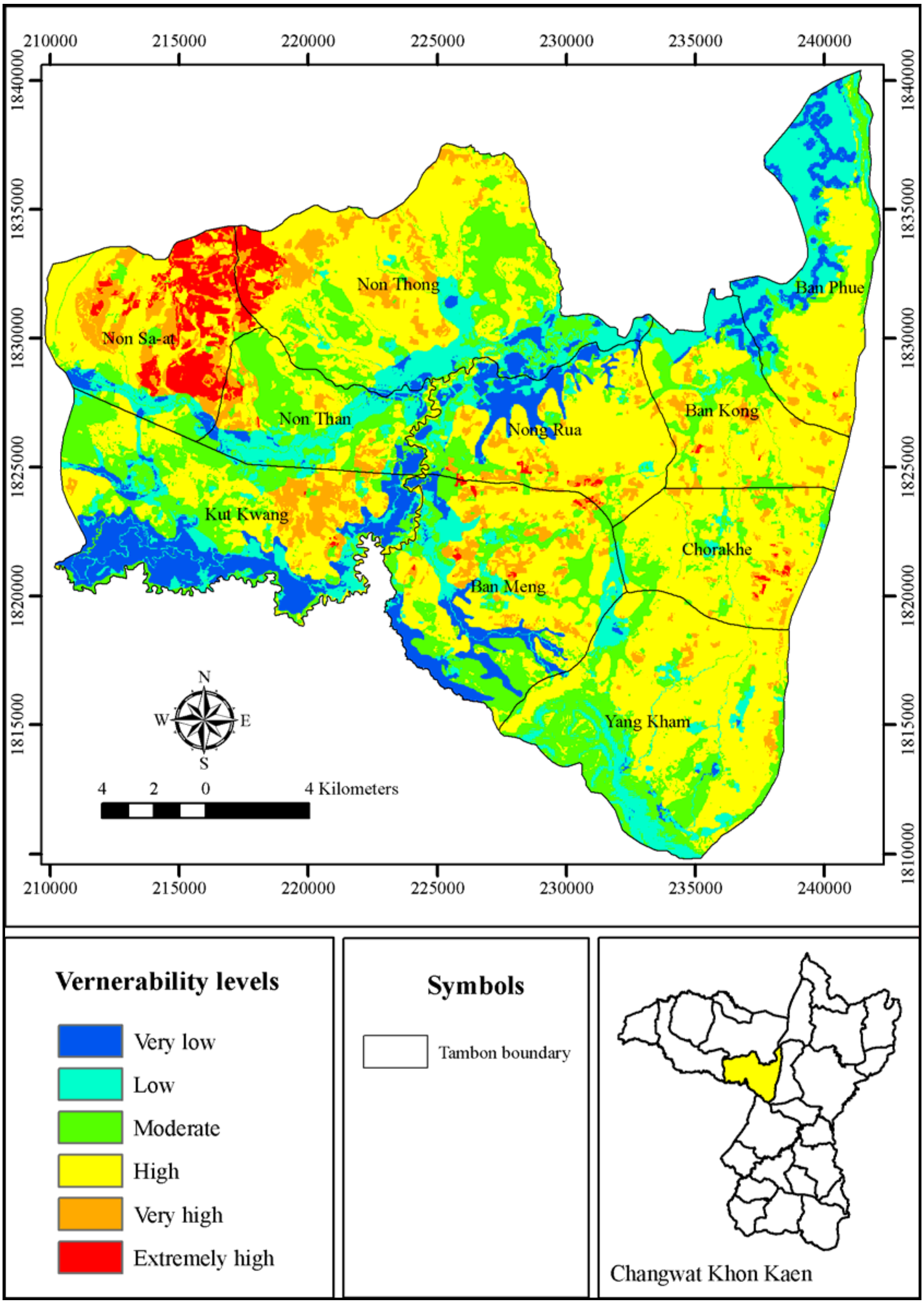


Figure 4.12 The SINTACS groundwater vulnerability map of the study area.

4.4.4 Sensitivity analyses

4.4.4.1 Map removal

Map removal sensitivity analysis performs removing one criterion at a time to determine its effect to the model result.

1) Based on Babiker et al. (2005), the effect is expressed in term of variation index. The statistical analysis of the variation index was applied to all pixels within the model domain using equation 4.2. Table 4.11 shows the statistical summary of variation index resulting from each parameter removal. The highest variation index with the mean of 1.20% is associated with the removal of aquifer. The parameters showing high variation index consist of depth to water, unsaturated zone, soil, and infiltration, as their index means are 0.92%, 0.96%, 1.00%, and 1.13%, respectively. Slope and hydraulic conductivity have the lowest means of variation indexes which are 0.43% and 0.73%.

Table 4.11 Statistical summary of the map removal sensitivity analysis.

Variation index (%)	Parameter removed						
	Depth to water	Infiltration	Unsaturated zone	Soil	Aquifer	Hydraulic conductivity	Slope
Mean	0.92	1.13	0.96	1.00	1.20	0.73	0.43
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	3.99	3.59	1.65	4.17	1.81	5.47	2.16
S.D.	0.64	0.69	0.31	0.47	0.39	0.98	0.36

2) The overall accuracy and Kappa coefficient of each parameter removal is presented in Table 4.12. Error matrixes of all comparisons are

presented in the Appendix A. The ranking of the removals based on these two statistic values are the same. The highest and the second highest overall accuracy and Kappa coefficient fall into unsaturated zone (90% and 86%) and slope (85% and 79%). This indicates that these two parameters contain low to very low spatial variation and will not affect much to the original result when removed.

Table 4.12 Overall accuracy and Kappa coefficient of each parameter removal.

Accuracy assessment	Parameter removed						
	Depth to water	**Infiltration**	**Unsaturated zone**	**Soil**	**Aquifer**	**Hydraulic conductivity**	**Slope**
Overall accuracy (%)	65	55	90	54	76	55	85
Kappa coefficient (%)	51	32	86	34	67	38	79

4.4.4.2 Single parameter

The single parameter sensitivity analysis for this study is separated into three parts following different hydrogeologic scenarios. The effective weight was obtained from the equation 4.3. Table 4.13 shows the statistics of the single parameter sensitivity analysis. However, the result from the above map removal analysis indicates that unsaturated zone and slope are stable or very low in terms of spatial variation. Thus, they are not necessary to be considered in the single parameter analysis. The parameter showing obviously higher effective weight than the theoretical weight is the hydraulic conductivity. The parameter showing lower effective weight than the theoretical weight is the aquifer. The depth to water and soil show the least difference between the effective and the theoretical weights. For infiltration parameter, severe impact and normal impact scenarios show the least difference between the effective and the theoretical weights. But the drainage scenario shows lower effective weights than the theoretical weights because the very low rating of this parameter was assigned in the drainage scenario. From the result, it was confirmed that the main area was provided high rates of hydraulic conductivity or is covered with its categories with high rates. However, using a simple well test might be a reason leading to this result. If hydraulic conductivity from pumping test is used, the more accurate result can be expected. The trend of low rating values was existed for the aquifer while the depth to water, infiltration, and soil showed median rating values.

For the single parameter analysis of the depth to water, the areas with high effective fall into the central and the east of the study area (Figure 4.13a). The areas having high effective of the infiltration parameter appear in the northwest, the southwest, and the central (Figure 4.13b). These areas agree with the extremely high and very high vulnerability. The unsaturated zone parameter with lower spatial variation is shown Figure 4.13c. For soil parameter, the main area tends to have moderate value of effective while low value area is mostly concentrated both sides of Lam Choen which is the main stream of the study area (Figure 4.13d). The high effective areas of aquifer agree with hydraulic conductivity. They are mostly concentrated both sides of streams and nearby water bodies in the study area (Figures 4.13e and 4.13f). The slope parameter containing more stable or lower spatial variation is shown in Figure 4.13g.

Table 4.13 Statistics of the single parameter sensitivity analysis.

Parameter	Scenario	Theoretical weight	Theoretical weight (%)	Effective weight (%)			
				Mean	Min	Max	S.D.
Depth to water	Severe impact	5	19.23	20.34	7.13	38.25	4.11
	Normal impact	5	19.23	18.28	10.32	32.14	3.00
	Drainage	4	15.38	17.78	9.56	26.75	2.70
Infiltration	Severe impact	5	19.23	20.01	3.50	35.82	5.77
	Normal impact	4	15.38	16.01	2.88	29.30	4.44
	Drainage	4	15.38	3.41	2.46	4.31	0.25
Unsaturated zone	Severe impact	5	19.23	8.03	4.40	20.78	1.67
	Normal impact	5	19.23	10.08	5.71	19.79	1.81
	Drainage	4	15.38	9.69	6.38	17.89	1.44
Soil	Severe impact	5	19.23	18.76	4.29	39.28	4.90
	Normal impact	3	11.54	13.85	2.27	25.96	5.32
	Drainage	2	7.69	6.72	1.50	17.70	3.71
Aquifer	Severe impact	3	11.54	6.62	3.50	17.02	1.87
	Normal impact	3	11.54	6.46	3.41	12.52	1.45
	Drainage	5	19.23	12.49	7.43	21.27	2.22
Hydraulic conductivity	Severe impact	2	7.69	12.84	7.28	21.00	2.12
	Normal impact	3	11.54	18.35	12.32	26.30	1.85
	Drainage	5	19.23	36.42	20.06	47.10	2.74
Slope	Severe impact	2	7.69	13.40	1.34	22.17	2.23
	Normal impact	3	11.54	16.96	2.38	26.43	4.73
	Drainage	2	7.69	13.49	1.68	18.20	4.48

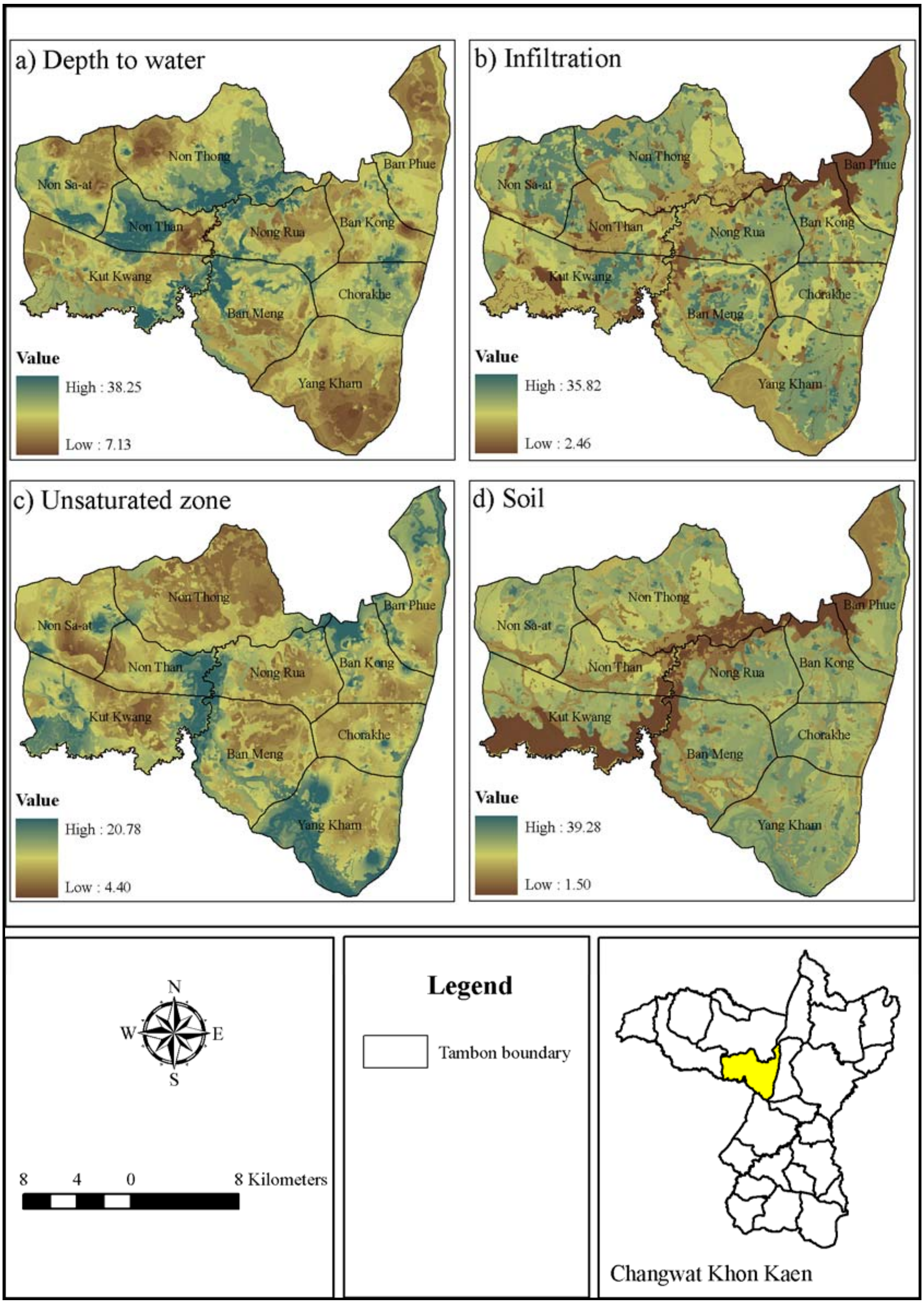


Figure 4.13 Spatial distribution of single parameter of: a) depth to water, b) infiltration, c) unsaturated zone, and d) soil.

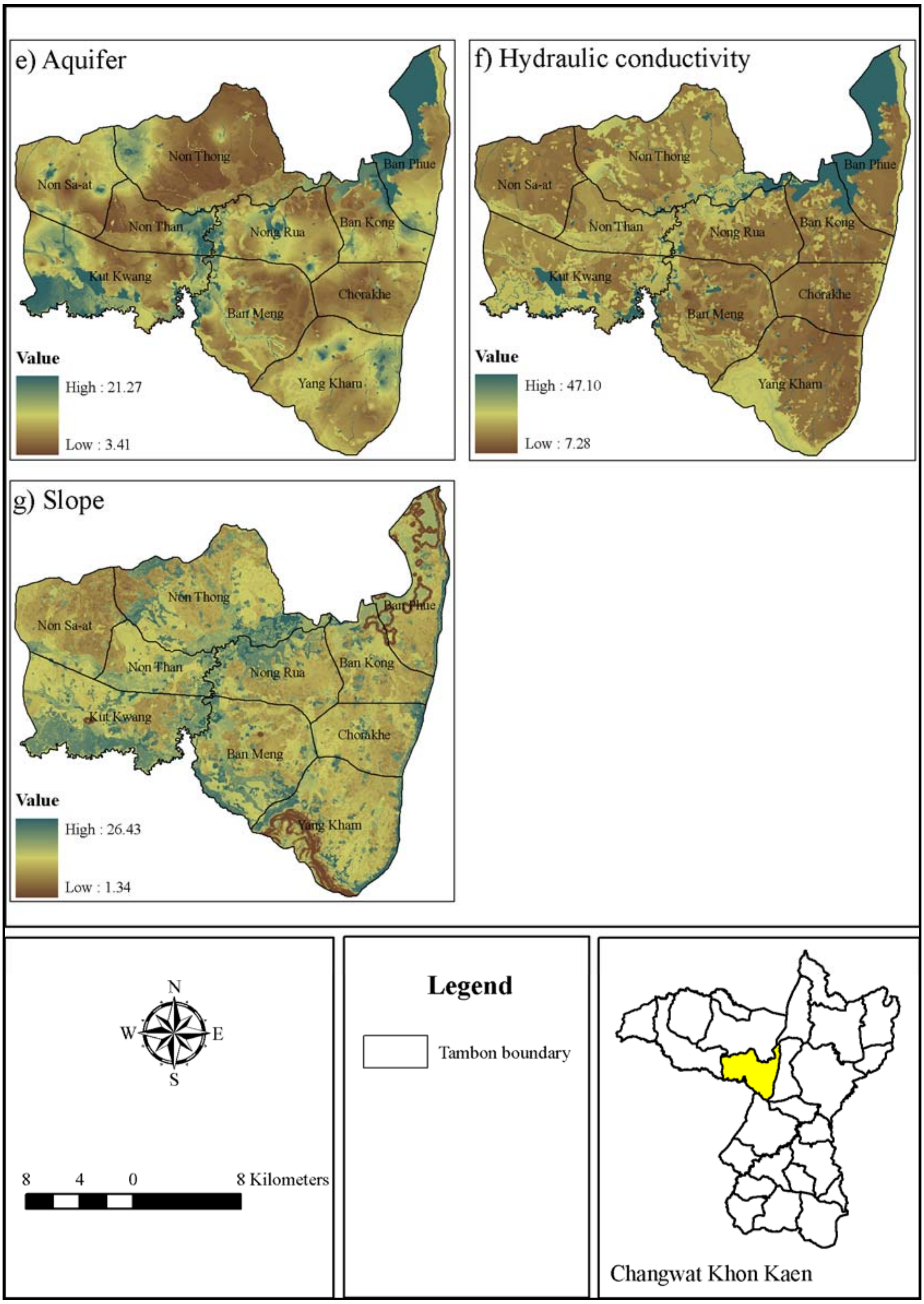


Figure 4.13 Spatial distribution of single parameter of: e) aquifer, f) hydraulic conductivity, and g) slope.

4.4.5 Correlation between vulnerability levels and the nitrate concentration in the well

In order to evaluate the validity of the constructed SINTACS vulnerability map, a correlation was made between the vulnerability levels and the nitrate concentration in the wells. Figure 4.14 and Table 4.14 show the distribution of nitrate concentration in the vulnerability levels. The numbers of wells found within very low, low, moderate, and high vulnerability areas are 9, 22, 43, and 13, respectively. Unfortunately, there is no information of nitrate concentration in very high and extremely high vulnerability areas. The concentration recorded varies from 0.9 to 410 mg/L. There are 59 wells having nitrate concentration lower than 45 mg/L which is the drinking water standard level of groundwater (กรมควบคุมมลพิษ, 2551). There are 28 wells having the concentration over this level. There are numbers of wells with concentration over the standard level found in the moderate (13 wells), high (12 wells), and very low (3 wells) vulnerability areas. The statistical correlation coefficient was calculated to determine the relationship between the nitrate concentration in the wells and their SINTACS vulnerability levels. The groundwater nitrate concentration shows a significantly positive correlation with the vulnerability level as high as 0.51.

It is very interesting to note that there are studies dealing with the correlation between vulnerability levels and the nitrate concentration in wells. Some cases showed poor or unclear correlations (Ducci, 1999; Al-adamat, Foster, and Baban, 2003; Stigter, Ribeirr, and Carvalho Dill, 2006; Almasri, 2008; Debernardi, De Luca, and Lasagna, 2008).

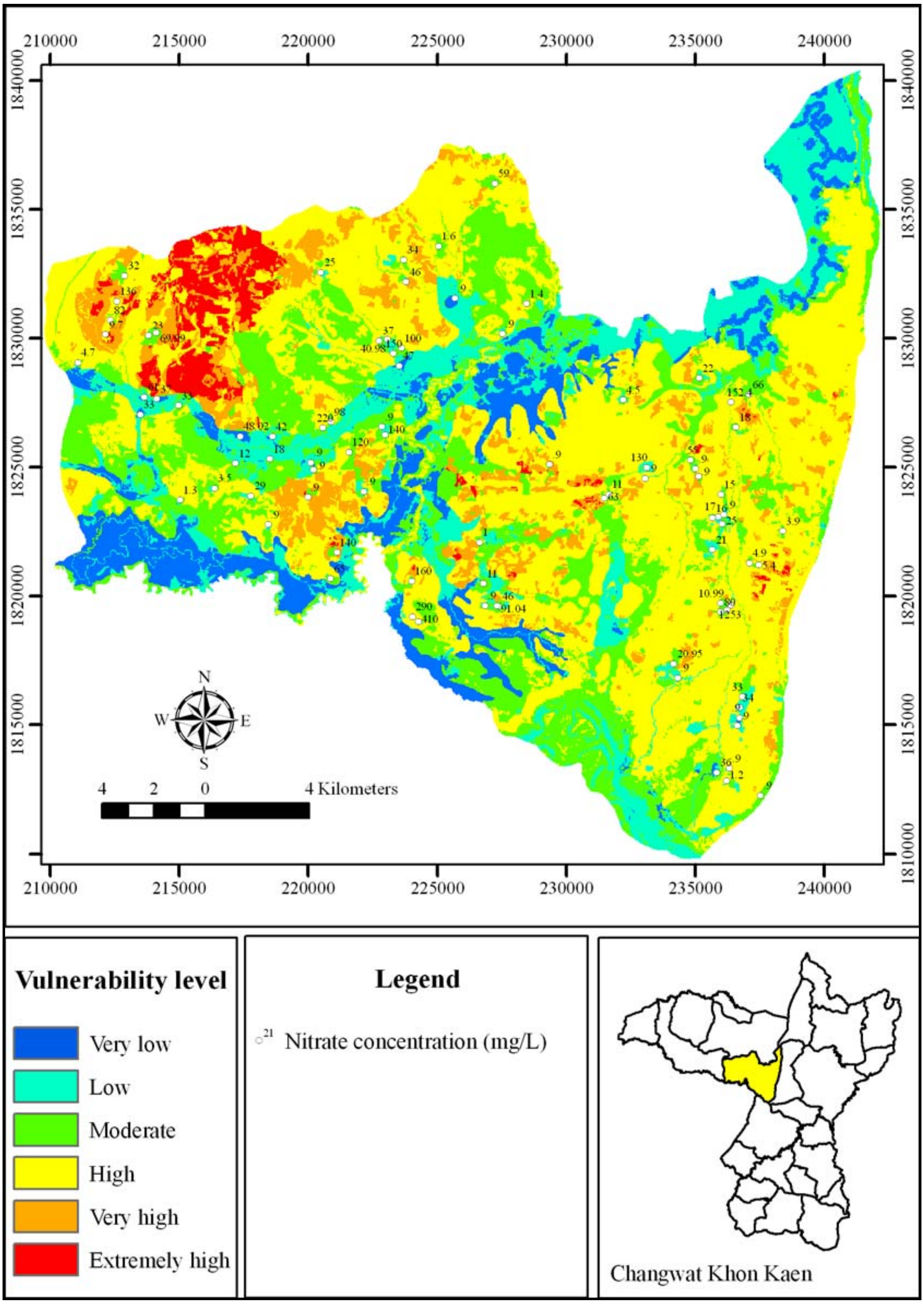


Figure 4.14 Distribution of nitrate concentration in the vulnerability levels.

Table 4.14 The vulnerability levels and the nitrate concentration in wells.

Vulnerability level	Lab NO.	Place	Mu	Tambon	UTM_E	UTM_N	NO_3 (mg/L)
Very low	1913/51	Wat Pho Si	16	Non Thong	225684	1831545	0.90
	2033/51	Rongrian Ban Nong Wa	3	Yang Kham	236637	1814948	0.90
	2105/51	Ban Non Sa-nga	16	Kut Kwang	217190	1825136	12.00
	2094/51	Ban Non Sila	13	Non Sa-at	213491	1827022	33.00
	2034/51	Wat Ban Don Khaem	4	Yang Kham	235836	1813143	36.00
	2103/51	Ban Non Khun	11	Non Sa-at	214142	1827626	37.00
	1901/51	Ban Non Thong	19	Non Thong	223540	1828909	47.00
	1855/51	Wat Ban Wa	3	Non Than	217363	1826180	48.02
	2095/51	Ban Khok Klang	5	Non Sa-at	213653	1827699	61.00
Low	2144/51	Rongrian Ban Nong Sa	4	Ban Kong	235004	1824921	0.90
	2018/51	Ban Hua Na	2	Chorakhe	236116	1823137	0.90
	1914/51	Wat Chumphon	1	Kut Kwang	222162	1824046	0.90
	2088/51	Ban Nong Kung	15	Kut Kwang	220210	1824889	0.90
	2090/51	Ban Kut Kwang	4	Kut Kwang	218442	1822761	0.90
	1851/51	Ban Kut Chim	8	Non Than	222848	1826550	0.90
	1912/51	Rongrian Ban Kut Khaen	8	Non Thong	227535	1830156	0.90
	2032/51	Wat Ban Nong Wa	3	Yang Kham	236719	1815257	0.90
	2037/51	Rongrian Ban Don Khaem	4	Yang Kham	236312	1813300	0.90
	2038/51	Rongrian Ban Nong Waeng	10	Yang Kham	234320	1816798	0.90
	2092/51	Ban Nong Waeng	18	Kut Kwang	216380	1824169	3.50
	2042/51	Ban Nong Kung	4	Nong Rua	232201	1827583	4.50
	2102/51	Ban Phon Sawan	12	Non Sa-at	211094	1829034	4.70
	2017/51	Ban Hua Na	12	Chorakhe	235898	1823066	17.00
	1918/51	Ban Non Than Noi	12	Non Than	218524	1825304	18.00
	2022/51	Ban Nong Paen	8	Chorakhe	235669	1821788	21.00
	2149/51	Ban Nong Mek	5	Ban Kong	235154	1828434	22.00
	1907/51	Rongrian Ban Huai Sai	13	Non Thong	220490	1832548	25.00
	2091/51	Wat Arun Sawang Amphawan	14	Kut Kwang	217782	1823867	29.00
	2104/51	Ban Don Han	9	Non Sa-at	214981	1827378	33.00
	2031/51	Ban Yang Kham	13	Yang Kham	236721	1815642	34.00
	1854/51	Ban Non Than	1	Non Than	218614	1826167	42.00
Moderate	2143/51	Wat Ban Nong Sa	4	Ban Kong	235124	1824625	0.90
	2110/51	Rongrian Ban Nong No Pracha San	8	Ban Meng	226848	1819612	0.90
	2089/51	Ban Nong Kung	15	Kut Kwang	219987	1823820	0.90
	2106/51	Ban Pueai	6	Non Than	220102	1825159	0.90
	2044/51	Ban Sa-at	7	Nong Rua	233056	1824553	0.90
	2045/51	Rongrian Nong Hai Pracha Rat	9	Nong Rua	229362	1825088	0.90
	2036/51	Rongrian Mattayomtaladyaiwittaya	0	Yang Kham	237535	1812251	0.90
	2107/51	Ban Nong Kung Noi	13	Ban Meng	226649	1822075	1.00
	2035/51	Ban Nong Na Wong	9	Yang Kham	236209	1812821	1.20
	2093/51	Ban Non Du	5	Kut Kwang	215050	1823718	1.30
	1911/51	Ban Phai Noi	11	Non Thong	228472	1831337	1.40
	1909/51	Ban Nong Nok Khian	7	Non Thong	225047	1833569	1.60
	2029/51	Ban Khok Klang	7	Chorakhe	238392	1822511	3.90
	2028/51	Ban Hua Buen	5	Chorakhe	237106	1821266	4.90

Table 4.14 (Continued).

Vulnerability level	Lab NO.	Place	Mu	Tambon	UTM_E	UTM_N	NO_3 (mg/L)
Moderate	2027/51	Ban Bueng Sawang	11	Chorakhe	237464	1821206	5.40
	2023/51	Ban Nong Hoi	6	Chorakhe	235970	1819717	10.99
	2108/51	Ban Meng	2	Ban Meng	226802	1820475	11.00
	2041/51	Wat Non Phanit	8	Nong Rua	231670	1823940	11.00
	2024/51	Rongrian Ban Nong Hoi	6	Chorakhe	236381	1819635	12.00
	2019/51	Ban Hua Na	2	Chorakhe	235995	1823920	15.00
	2021/51	Ban Hua Na	3	Chorakhe	235667	1823018	16.00
	2141/51	Ban Tha Li	7	Ban Kong	236577	1826533	18.00
	2039/51	Wat Sawang Pho Si	7	Yang Kham	234164	1817354	20.95
	2097/51	Rongrian Ban Nong Lum Phuk	6	Non Sa-at	213822	1830091	23.00
	2020/51	Ban Hua Na	3	Chorakhe	236045	1822792	25.00
	2100/51	Ban Non Waeng	7	Non Sa-at	212892	1832426	32.00
	2030/51	Ban Yang Kham	13	Yang Kham	236816	1816071	33.00
	1908/51	Ban Sap Charoen	18	Non Thong	223709	1833041	34.00
	1903/51	Ban Non Thong	1	Non Thong	222755	1829879	37.00
	1904/51	Ban Non Thong	15	Non Thong	223071	1829947	40.98
	1906/51	Wat Ban Dong Noi	14	Non Thong	223789	1832177	46.00
	2025/51	Wat Nong Hoi	13	Chorakhe	236224	1819441	53.00
	2142/51	Ban Nong Sa	4	Ban Kong	234824	1825259	55.00
	1910/51	Rongrian Ban Nong Khuean Chang	6	Non Thong	227229	1836007	59.00
	1916/51	Rongrian Khanuan Nakhon	3	Kut Kwang	220867	1820668	65.00
	2147/51	Wat Pho Thong	2	Ban Kong	237090	1827800	66.00
	2096/51	Wat Sawang Phaithun	14	Non Sa-at	214121	1830193	69.99
	2026/51	Ban Nong Hoi	9	Chorakhe	235990	1819370	80.00
	1905/51	Ban Non Thong	20	Non Thong	223623	1829594	100.00
	2043/51	Ban Sa-at	7	Nong Rua	233115	1824973	130.00
	1850/51	Rongrian Ban Kut Chim	7	Non Than	222980	1826236	140.00
	1902/51	Ban Non Thong	10	Non Thong	223296	1829384	150.00
	2109/51	Wat Sabaeng	11	Ban Meng	224029	1820573	160.00
High	2101/51	Ban Nong Hai	2	Non Sa-at	212153	1830125	9.70
	2111/51	Ban Nong No	8	Ban Meng	227390	1819595	46.00
	2040/51	Ban Sala Thong	12	Nong Rua	231480	1823791	63.00
	2098/51	Ban Non Sawan	10	Non Sa-at	212338	1830700	82.00
	2112/51	Ban Nong No	8	Ban Meng	227329	1819606	91.04
	1852/51	Ban Na	6	Non Than	220876	1826735	98.00
	1856/51	Wat Ban Non Sa-at	11	Non Than	221587	1825560	120.00
	2099/51	Ban Non Sa-at	15	Non Sa-at	212587	1831428	136.00
	1915/51	Ban Khok Sung	2	Kut Kwang	221114	1821685	140.00
	2146/51	Ban Pueai	3	Ban Kong	236391	1827506	152.40
	1853/51	Wat Ban Na Pueai	5	Non Than	220576	1826504	220.00
	2114/51	Ban Hat	10	Ban Meng	224044	1819191	290.00
	2113/51	Ban Hat	10	Ban Meng	224272	1819003	410.00

Debernardi et al. (2008) explained why high vulnerability area are found associated with low nitrate concentrations while high nitrate concentrations can be found in low vulnerability area. The explanations are as follows:

High vulnerability found associated with low nitrate concentrations can depend on:

1) A low nitrate input from the soil which causes a low nitrate concentration in groundwater, even if the aquifer is highly vulnerable;

2) When there are high nitrate inputs, low nitrate concentrations in groundwater can be a consequence of an aquifer with a high dilution capacity. This allows a mixing of the contaminant with the groundwater and a following reduction of concentrations due to the dilution process.

Low vulnerability found associated with high nitrate concentrations can depend on:

1) The presence of areas with high nitrate concentrations in the upstream groundwater. Nitrates can also be detected in the downstream groundwater even where vulnerability is low.

2) The presence of an aquifer with a low dilution capacity. The contaminant does not mix easily with groundwater and there are no important reduction phenomena of nitrate concentrations.

3) High nitrogenous compound inputs to the aquifer.

Moreover, the fastest way to contaminate groundwater is through a well. The poor groundwater well management and well construction provide a direct path for contamination to travel from the surface to the aquifer. It is one of all reasons why high nitrate concentrations can be found in low vulnerability area.

In case of high vulnerability associated with low nitrate concentration available in this study, there was only an obvious well with low nitrate concentration (9.7 mg/L) found in the groundwater well at Ban Nong Hai, Mu 2, Tambon Non Sa-at. The case can be explained by the field investigation that this well is located at the position with low nitrate input and no surrounding environmental influence. For another case, the association of high nitrate concentrations with low vulnerability area is not generally and specifically apparent in the study.

Since physical and chemical processes play a role in nitrate pollution in aquifers. In particular, dilution and denitrification are neither described nor taken into consideration by these methods of vulnerability analysis. Important attenuation phenomena of contaminants, which reduce pollutant concentrations, are not evaluated (Debernardi et al., 2008).

However, SINTACS method is still useful for assessing the intrinsic vulnerability. This method analyzes a series of parameters which affects the vulnerability of aquifers, without taking physical processes into consideration. Therefore, it cannot assess and measure quantitatively and temporally the phenomena, which occur in the soil and subsoil and which reduce the contaminant concentration.

As discussed above, it can be concluded that the validation of groundwater vulnerability map of an area using any concentration(s) in it is still debatable. According to Debernardi et al. (2008), their explanation above can have both positively and negatively an effect on the correlation result. Other facts have to be mentioned are that they are not or hardly practicable or predictable from where pollutant input on the surface will go to that well and how long it takes to travel to the aquifer. Then, an exact position where and the period of time when pollutant was input on the surface and send an effect to groundwater concentration(s) observed from a well at the time measured cannot be specified. These all can affect to the correlation result. It cannot be assured that the vulnerability class at the surface can completely correspond to water quality in the well located in that class.

Even though, the validation of groundwater vulnerability is still debatable as discussed, sensitivity analysis was performed in this study so as to gain more useful information. The result can tell which parameters provide more effect to the result. The more effect they provide, the more serious care is needed when they are collected and prepared. In addition, the areas with high weights and ratings of parameters are useful information for groundwater protection planning.

4.5 Conclusions

The SINTACS method was used to evaluate the intrinsic groundwater vulnerability. This evaluation was based on the assessment and ratings of seven parameters, which include depth to water, infiltration, unsaturated zone, soil, aquifer, hydraulic conductivity, and slope. In addition, three weight strings that depend on hydrogeologic scenario existent in the study area which include normal impact, severe impact, and drainage. The SINTACS index varied between 83.33 and 194.10 and was normalized to be 0 to 100. The normalized index was divided into 6 groups of vulnerability, from very low to extremely high. High and moderate levels dominated

45.53% and 21.48% of the study area. Low and very low levels dominated 13.09% and 8.74% and are mostly concentrated both sides of streams such as Lam Choen, Huai Bu Na, and Huai Lua. Very high (8.21%) and extremely high levels (2.95%) are found in the northwest, southwest, and central of the study area. They are characterized and influenced by high infiltration rate, coarse-texture soil, and shallow depth to water.

The map removal sensitivity analyses based on variation index showed that slope and hydraulic conductivity were lowly sensitive whereas aquifer, depth to water, unsaturated zone, soil, and infiltration were highly sensitive. Based on error matrix, it is obvious that the unsaturated zone and slope were lowly sensitive. It means that both unsaturated zone and slope contain very low spatial variation and can be removed because of their low effect to the model result. From different point of view, the single parameter sensitivity analysis showed that the hydraulic conductivity was highly sensitive whereas the aquifer was lowly sensitive. The depth to water, infiltration, and soil showed moderately sensitive. The results imply that in this area the hydraulic conductivity in all scenarios should be considered more seriously when specific remedial measure to protect groundwater vulnerability is planned.

The statistical correlation coefficient between the nitrate concentration in wells and the SINTACS vulnerability map showed a significantly positive correlation as high as 0.51.

Conclusively, groundwater vulnerability map effectually provides information on high potential areas prone to groundwater contamination on the basis of different hydrogeologic conditions. Together with criterion maps, they are very useful information for identifying the priority of target areas and proper method for management and protection.

4.6 References

กรมควบคุมมลพิษ. (2551). ประกาศกระทรวงทรัพยากรธรรมชาติและสิ่งแวดล้อม เรื่อง กำหนดหลักเกณฑ์และมาตรการในทางวิชาการสำหรับการป้องกัน ด้านสาธารณสุขและการป้องกันในเรื่องสิ่งแวดล้อมเป็นพิษ พ.ศ. 2551 ตีพิมพ์ในราชกิจจานุเบกษา เล่ม 125 ตอนพิเศษ 85 ง ลงวันที่ 21 พฤษภาคม 2552.

กรมทรัพยากรน้ำบาดาล. (2551). **รายงานผลการปฏิบัติงานโครงการสำรวจและตรวจสอบคุณภาพน้ำของระบบประปาบาดาลทั่วประเทศ ปี 2551 จังหวัดขอนแก่น**. กรุงเทพฯ: กรมทรัพยากรน้ำบาดาล กระทรวงทรัพยากรธรรมชาติและสิ่งแวดล้อม.

กรมทรัพยากรน้ำบาดาล. (ม.ป.ป.). ข้อมูลบ่อบาดาล [แฟ้มข้อมูล]. กรุงเทพฯ: กรมทรัพยากรน้ำบาดาล กระทรวงทรัพยากรธรรมชาติและสิ่งแวดล้อม.

ชัยพล กีรติกสิกร และอิทธิ ตริสิริรัสัตยวงศ์. (2550). การสร้างแบบจำลองความสูงความละเอียด 30 เมตร จากข้อมูล SRTM 3 ความละเอียด 90 เมตร ด้วยวิธีโพลีโนเมียลสองตัวแปรกำลังสาม [CD-ROM]. ใน **การประชุมวิชาการ การแผนที่และภูมิสารสนเทศแห่งชาติประจำปี 2550**. กรุงเทพฯ: สำนักงานพัฒนาเทคโนโลยีอวกาศและภูมิสารสนเทศ (องค์การมหาชน) กระทรวงวิทยาศาสตร์และเทคโนโลยี.

Al-Adamat, R.A.N., Foster, I.D.L., and Baban, S.M.J. (2003). Groundwater vulnerability and risk mapping for the Basaltic aquifer of the Azraq basin of Jordan using GIS, Remote sensing and DRASTIC. **Applied Geography**. 23: 303-324.

Al-Amoush, H., Hammouri, N.A., Zunic, F., and Salameh, E. (2010). Intrinsic vulnerability assessment for the alluvial aquifer in the Northern Part of Jordan Valley. **Water Resources Management**. 24: 3461-3485.

Al Kuisi, M., El-Naqa, A., and Hammouri, N. (2006). Vulnerability mapping of shallow groundwater aquifer using SINTACS model in the Jordan Valley area, Jordan. **Environmental Geology**. 50: 651-667.

Aller, L., Bennet, I., Lehr, J.H., Petty, R.J., and Hackett, G. (1987). **DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings**. USA: U.S. Environmental Protection Agency.

Almasri, M.N. (2008). Assessment of intrinsic vulnerability to contamination for Gaza coastal aquifer, Palestine. **Journal of Environmental Management**. 88: 577-593.

Babiker, I.S., Mohamed, M.A.A., Hiyama, T., and Kato, K. (2005). A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. **Science of the Total Environment**. 345: 127-140.

Civita, M. (1994). **Le carte della vulnerabilità degli acquiferi all'inquinamento**. Bologna: Teoria and practica (Aquifer vulnerability maps to pollution) Pitagora.

Civita, M. and De Maio, M. (1997). **SINTACS. Un sistema parametrico per la valutazione e la cartografia della vulnerabilita` degli acquiferi all'inquinamento. Metodologia and Automatizzazione, vol. 60**. Bologna: Pitagora Editrice. Quoted in Al Kuisi, M., El-Naqa, A., and Hammouric N. (2006). Vulnerability mapping of shallow groundwater aquifer using

SINTACS model in the Jordan Valley area, Jordan. **Engineering Geology**. 50: 651-667.

Civita, M. and De Maio, M. (2000). **Valutazione e cartografia automatica della vulnerabilità degli acquiferi all'inquinamento con il sistema parametrico - SINTACS R5 - A new parametric system for the assessment and automatic mapping of ground water vulnerability to contamination**. Bologna: Quaderni e Tecniche di Protezione ambientale. Quoted in Agenzia Nazionale per la Protezione dell'Ambiente. (2001). **Linee-guida per la redazione e l'uso delle carte della vulnerabilità degli acquiferi all'inquinamento**. Roma: ANPA.

Civita, M. and De Maio, M. (2004). Assessing and mapping groundwater vulnerability to contamination: The Italian "combined" approach. **Geofísica Internacional**. 43(4): 513-532.

Debernardi, L., De Luca, D.A., and Lasagna, M. (2008). Correlation between nitrate concentration in groundwater and parameters affecting aquifer intrinsic vulnerability. **Environmental Geology**. 55: 539-558.

Ducci, D. (1999). GIS techniques for mapping groundwater contamination risk. **Natural Hazard**. 20: 279-294.

Kraemer, S.R., Haitjema, H.M., and Kelson, V.A. (2007). **Working with WhAEM2000 Capture Zone Delineation for a City Wellfield in a Valley Fill Glacial Outwash Aquifer Supporting Wellhead Protection**. Washington: U.S. Environmental Protection Agency.

Linsley, R.K., Kohler, M.A., and Paulhus, J.L.H. (1988). **Hydrology for Engineers**. Singapore: McGraw-Hill.

Lodwick, W.A., Monson, W., and Svoboda, L. (1990). Attribute error and sensitivity analysis of map operations in geographical informations systems: suitability analysis. **International Journal of Geographical Information Science**. 4: 413-428.

Hentati, I., Zairi, M., and Dhia, H.B. (2010, June). A statistical and geographical information system analysis for groundwater intrinsic vulnerability: a validated case study from Sfax–Agareb, Tunisia. **Water and Environment Journal**. 1-12.

Napolitano, P. and Fabbri, A.G. (1996). Single-parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS. In **Proceedings of Vienna Conference** (pp 559-566). Wallingford: IAHS Pub.

Soil Conservation Service. (1985). **National engineering handbook. Section 4-Hydrology**. Washington, DC: U.S. Department of Agriculture.

Stigter, T.Y., Ribeirr, L., and Carvalho Dill, A.M.M. (2006). Evaluation of an intrinsic and a specific vulnerability assessment method in comparison with groundwater salinisation and nitrate contamination levels in two agricultural regions in the south of Portugal. **Hydrogeology Journal**. 14: 79-99.

Sunya Sarapirome and Jiradech Majandang. (2008). Groundwater Vulnerability Mapping Using a GIS-based DRASTIC Model at Lam Takhong Subbasin, Nakhon Ratchasima, Thailand. In **Proceedings of the International Symposia on Geoscience Resources and Environments of Asian**

Terranes (GREAT 2008), 4th IGCP 516, and 5th APSEG (pp 559-564). Bangkok: Department of Geology, Chulalongkorn University.

Tharapong Phetprayoon, Sunya Sarapirome, Charlie Navanugraha, and Sodchol Wonprasaid. (2009). Surface Runoff Estimation Using Grid-Based Curve Number Method in The Upper Lam Phra Phloeng Watershed, Thailand [CD-ROM]. In **30th Asian Conference on Remote Sensing, October 18-23, 2009, Beijing, China**. Beijing: Asian Association on Remote Sensing.

United States Department of Agriculture. (1986). **Urban Hydrology for Small Watersheds**. Washington, DC: U.S. Department of Agriculture.

United States Environmental Protection Agency. (1994). **Handbook: Ground Water and Wellhead Protection**. Washington, DC: Office of Ground-Water Protection.

Vrba, J. and Zaporozec, A. (1994). **Guidebook on mapping groundwater vulnerability. International Association of Hydrogeologists (International Contributions to Hydrogeology 16)**. Hannover: Verlag Heinz Heise.

CHAPTER V

GROUNDWATER CONTAMINATION RISK

5.1 Abstract

The groundwater contamination risk map was assessed by coupling the vulnerability map and the hazard map. The assessment of the hazard map was the result of the merging of three input map layers which are agricultural hazard, urban hazard, and other hazard. Non-Point Source Agricultural Hazard Indexes (NPSAHI) method was applied to evaluate the agricultural hazard. The quantity of domestic wastewater value was used to represent the urban hazard. The other hazard sources were obtained from land use map. The weights of five contamination source groups in the study area were calculated by the fuzzy hierarchical model with respect to toxicity, mobility, degradability, and volume. The final result of risk map shows that high level mainly covers of the study area. The very high risk level is mostly concentrated in the northwestern and southwestern parts of the study area. The statistical correlation coefficient between the nitrate concentration in the wells and the groundwater risk levels showed a significantly positive correlation (0.49). The result of this study is a useful tool to determine the target area on the basis of hydrogeologic conditions and human impacts for developing and designing the protection planning of groundwater resources.

Keywords: GIS/Groundwater contamination risk/NPSAHI/Nong Rua

5.2 Introduction

Groundwater contamination risk map is a tool to manage the quality of groundwater resource. Morris and Foster (2000) defined groundwater contamination risk as the probability that groundwater will become contaminated to an unacceptable level by human activities on the immediately overlying land surface. The risk map is evaluated by multiplication between probability and consequence. The probability is represented by groundwater hazard and groundwater vulnerability represents the consequence.

The concept of groundwater vulnerability is based on the assumption that the physical environment provides some natural protection to groundwater against human impacts, especially with regard to contaminants entering the subsurface environment (Vrba and Zaporozec, 1994). However, this method considers only the physical characteristics of the area. It does not take groundwater hazard into account. Zaporozec (2004) defined groundwater hazard as potential sources of contamination that impacts on groundwater by human activities. Most land use activities have provides major sources of diffuse groundwater contamination such as urban, municipal, industrial, and agricultural area. The groundwater contamination sources are considered in their locations, types, characteristics, and estimated magnitudes of impact on groundwater.

The aim of this research is to assess the groundwater contamination risk by coupling the groundwater vulnerability map and the groundwater hazard map. The intrinsic groundwater vulnerability is assessed by the SINTACS approach. The groundwater hazard map is evaluated by the merging of point and non-point contamination sources.

5.3 Research methods

5.3.1 Research procedure

The main steps of this part are shown in Figure 5.1. All preparations and analyses were operated on raster based GIS data. Details of each step can be explained as follows.

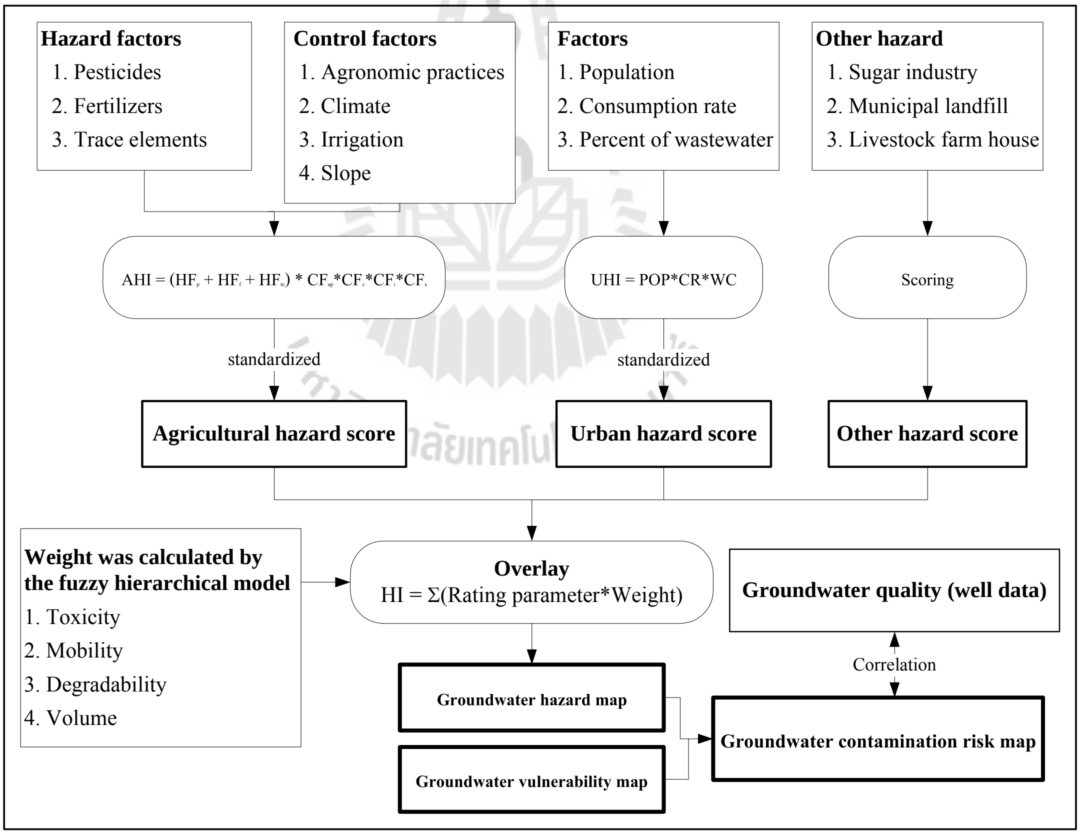


Figure 5.1 Overview of the research procedure for groundwater contamination risk assessment.

5.3.2 Groundwater hazard mapping

The construction of groundwater hazard mapping can be divided into three parts which include agricultural hazard, urban hazard, and other hazard evaluation. They will be prepared in terms of indexes and later standardized, merged by weighting, and ranked to be a hazard map. All of map layers are used to evaluate the groundwater hazard map in the framework of GIS in this study that has been divided into 30×30 m pixel. The groundwater hazard index is calculated for each grid element using the equation:

$$HI = \sum_{i=1}^{5} W_i \times S_i \tag{5.1}$$

Where HI is the hazard index, W_i is the weight of contaminant source group i, and S_i is the hazard score of source group i.

5.3.3 Agricultural hazard score evaluation

Non-point Source Agricultural Hazard Indexes (NPSAHI) method (Trevisan et al., 2000) was adapted to evaluate the agricultural hazard score. It is a parametric method. The evaluation of the hazard level by farming activities is based on the definition of potential hazard indexes. Two categories of parameters were considered: the hazard factors (HF), which represent all farming activities that cause or might cause an impact on groundwater (use of fertilizers and pesticides, application of livestock and poultry manure), and the control factors (CF), which adapt the hazard factors to the characteristics of the site (geographical location, slope, agronomic practices, and type of irrigation). The hazard factors are rated from the estimated ranges of the total loading defined as quantity per hectare per year of distributed substance and each factor is assigned a score from 0 to 5 (Table 5.1).

Table 5.1 The *HF* classes for agrochemicals and trace elements.

Pesticides (HF_p)		Fertilizers (HF_f)		Trace elements (HF_{te})	
Range (kg/ha/yr)	Score	Range (kg/ha/yr)	Score	Range (kg/ha/yr)	Score
0-0.5	0	0-25	0	0-10.4	0
0.5-1.5	1	25-75	1	10.4-51.9	1
1.5-2.5	2	75-125	2	51.9-103.9	2
2.5-4.5	3	125-225	3	103.9-207.9	3
4.5-6.5	4	225-325	4	207.9-519.7	4
> 6.5	5	> 325	5	> 519.7	5

Source: Trevisan et al. (2000).

The ranges of fertilizers and pesticides are calculated from the amount of the total using per hectare per year of each agricultural area. However, the fertilizers refer only to the amount of nitrogen (N) and phosphorus (P_2O_5). For trace elements, the overall amount of animal sewage produced in each sub-district was calculated from the account of animal types and numbers. Therefore, the quantity of sewage distributed per hectare was obtained, assuming a distribution on agricultural area in given sub-district (Trevisan et al., 2000). Table 5.2 shows standard live weight values of animal husbandry and average manure yields (dung and urine) as percentages of live weight. Overcash, Humenik, and Miner (1983) suggested the amount of total dry solid of manure production per 453.51 kg live animal weight per day of poultry, swine, and cattle are about 11.16, 3.67, and 3.22 kg, respectively. Finally, the quantity of distributed trace elements for each sewage types was calculated using literature data that shows in Table 5.3. Data obtained for pesticides, fertilizers, and trace elements have been added together in order to obtain the total value of *HF* (HF_p + HF_f + HF_{te}), ranging from 0 to 15 by overlaying the land use map and the map of the Tambon boundary.

Table 5.2 Standard live weight values of animal husbandry and average manure yields (dung and urine) as percentages of live weight.

Species	Daily manure yield as % of live weight		Live weight (kg)
	dung	urine	
Poultry	4.5	4.5	1.5-2
Swine	2.0	3.0	30-75
Cattle	5.0	4.0-5.0	135-800

Source: Werner, Stohr, and Hees (1989).

Table 5.3 Concentrations of trace elements (mg kg^{-1}DW) in animal wastes.

Animal waste	Trace elements																	
	As	**Ba**	**Be**	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Mn**	**Mo**	**Pb**	**Sb**	**Se**	**Sn**	**Ti**	**V**	**Zn**	**Ni**
Cattle	**2**	305	0.03	**3.4**	2.2	**15.2**	**46.5**	**0.1**	161	49	**15.7**	0.08	0.32	7.4	129	8	**151.9**	**14.1**
Poultry	**3.8**	57	0.03	**3.4**	1.2	**46**	**102**	**0.13**	242	7.2	**20.6**	0.1	0.66	4.1	27	4.3	**308.9**	**15.9**
Swine	**12.8**	-	-	**4.8**	11	**46.6**	**472.6**	**0.12**	168	34	**10.1**	-	-	-	-	-	**843.3**	**12.5**

Remark Bold numbers refer to Luo, Ma, Zhang, Wei, and Zhu (2009).

Normal numbers refer to Adriano (2001).

The hazard can be increased or decreased by the control factors (CF) which are modifying factors ranging from 0.90 to 1.10. The CF depended upon geographical location, slope, agronomic practices, and type of irrigation. The parameters and the values assigned on the basis of expert judgment are shown in Table 5.4 (Trevisan et al., 2000).

Table 5.4 Control factors and related values.

Control factors	Hazard decrease		Reference conditions (CF = 1)		Hazard increase	
Agronomic practices (CF_{ap})	No tillage (0.94); minimum tillage (0.96); orchards (grass regeneration; 0.98); Integrated Pest Manag. (0.92)		Traditional tillage; orchards (tilled soil)		Sludge application (1.10)	
Climate (CF_c)	Temperature (annual mean)	Precipitation (mm/yr)	Temperature (annual mean)	Precipitation (mm/yr)	Temperature (annual mean)	Precipitation (mm/yr)
	13-14°C	600-700 (0.96)	12-13°C	600-800	6-15°C	>1200 (1.10)
	>16°C	500-900 (0.98)			12°C	800-1000 (1.04)
	15-17°C	<600 (0.94)			14-16°C	950-1100 (1.06)
					13°C	1050-1150 (1.08)
					15-16°C	600-1000 (1.02)
Irrigation (CF_i)			No irrigation		Submersion (1.06); flowing (1.04); aspersion (1.02)	
Slope (CF_s)	>24% (0.96); 5–24% (0.98)		0–5%			

Remark: *CF* values are in parentheses.

Source: Trevisan et al. (2000).

Traditional tilling is established as a common condition for agronomic practices and sludge application leads to increase the CF. The conditions of agronomic practice effective to hazard decrease include no tillage, minimum tillage, orchards (grass regeneration), and integrated pest management. The climatic conditions affect to contaminant leaching into groundwater that the hazard raises with increasing rainfall and decreasing temperature (Trevisan et al., 2000). The irrigation refers to the watering plants methods. No irrigation represents the normal reference condition. Submersion, flowing, and aspersion irrigation system are effect to increase the *CF*. Because the irrigation may provide a chance to input water into the soil and drag down surface pollutants into the groundwater system. The reference condition of slope is less than 5% and the hazard decreases with slope more than 5%.

The agricultural hazard (*AH*) score is obtained by multiplying the different hazard factors by the control factors as shown in following the equation (Trevisan et al., 2000).

$$AH = (HF_p + HF_f + HF_{te}) \times CF_{ap} \times CF_c \times CF_i \times CF_s \quad (5.2)$$

Where HF_p is the hazard factor for pesticides; HF_f is the hazard factor for fertilizers; HF_{te} is the hazard factor for trace elements; CF_{ap} is the control factor for agronomic practices; CF_c is the control factor for climate; CF_i is the control factor for irrigation; and CF_s is the control factor for slope.

The *AH* are standardized by dividing each raw score with the highest score value. These hazard scores result in the groundwater hazard map based on agricultural activities.

5.3.4 Urban hazard score evaluation

For this study, the urban hazard is referred to the quantity of domestic wastewater which can be calculated by the following equation.

$$UH = POP \times CR \times WC \quad (5.3)$$

Where *UH* is the quantity of domestic wastewater (m^3/person/day), *POP* is the population, *CR* is the consumption rate (m^3/person/day), and *WC* is the percent of wastewater.

Finally, the urban hazard score is standardized by dividing each score value by the highest value. This results in the groundwater hazard map based on waste water consumption.

5.3.5 Other hazard sources

Other hazard sources are referred to the other potential contaminant sources such as factory, municipal landfill, and livestock farm house that cause or might cause an impact on groundwater. They can be obtained from land use map. The score of these contaminant sources will be assigned as 1 for producing the groundwater hazard map.

5.3.6 Weighting of different contaminant sources

The fuzzy hierarchical model is applied to calculate weight value for merging the hazard maps. $A=(a_{ij})_{h\times n}$ and $B=(b_{jk})_{n\times m}$ are matrices that represent, respectively, the demand of *h* environmental indices relatively to *n* offering parameters represented by *m* location alternatives in the domain (Nobre, Rotunno, Mansur, Nobre, and Cosenza, 2007). The environmental index here is the weight of contaminant sources (h=1) that is calculated by this model. 4 parameters, which are toxicity, mobility, degradability and volume, are chosen to evaluate the weight of contaminant sources (n=4). Within the study area, contaminant sources are divided into 5 groups (m=5) which are agriculture, urban, industry, municipal landfill, and livestock farm house. Toxicity was handled by assigning a higher value to the weight of contaminant sources of compounds such as benzene which is known as carcinogen. Its mobility was represented by organic carbon partition coefficient (K_{oc}) and water solubility (S_w). The smaller the polarity of the compound, the greater the K_{oc} and the smaller the S_w are. As such, the contaminant will have a higher capacity to be absorbed by organic matter and requires a longer period to reach the aquifer. Therefore, a smaller value of weight will be assigned. Degradability was represented in terms of its half-life ($t_{1/2}$). Larger $t_{1/2}$ values suggest that more contaminant mass is likely to reach the aquifer. Volume was represented by amount of pollutant which produced by the contaminant sources.

Assuming that $F=\{ f_i \mid i=1,..., n\}$ is a finite set of parameters that evaluate the weight of contaminant sources, which are toxicity, mobility, degradability and volume. Then the fuzzy set $\tilde{A}$ in f is a set of ordinate pairs represented as $\tilde{A}=\{ f, \mu_A(f) |f \in F \}$, where $\tilde{A}$ is a fuzzy representation of the demand matrix $\mathbf{A}=(a_{ij})_{h\times n}$ and $\mu_A(f)$ is the membership function representing the level of importance of the parameters, such as *critical, conditional, not very conditional or irrelevant* (Table 5.5). Likewise, the fuzzy set $\tilde{B}=\{ f, \mu_B(f) |f \in F \}$, where $\tilde{B}$ is a fuzzy representation of the offering matrix $\mathbf{B}=(b_{jk})_{n\times m}$ and $\mu_B(f)$ is the membership function that represents the level of availability of the parameters by different type of contaminant sources, indicated by *excellent, good, fair, weak* (Table 5.6). The membership functions assume numeric values in the range of [0,1]. The product matrix $\mathbf{C}=(c_{ik})_{h\times m}=\mathbf{A}\otimes\mathbf{B}$ represents the comparison between demand and availability of each parameter. The matrices **A** and **B** assume, arbitrarily, the linguistic values ■, □, ▪, ▫ (see Tables 5.5 and 5.6). The elements of $(a_{ij})_{h\times n} \otimes (b_{jk})_{n\times m}$ can also be expressed by numerical values of their membership functions. The operator in Table 5.7 is used to obtain the product matrix **C** (Nobre et al., 2007).

Table 5.5 Demand matrix (A) and the level of importance of the parameters.

Parameters/attributes	**Toxicity**	**Mobility**	**Degradability**	**Amount/volume**
Index	f_1	f_2	f_3	f_4
Weights of contaminant sources (weights offered by potential sources)	□	■	■	▪

Where ■ is Critical, □ is Conditional, ▪ is Not very conditional, and ▫ is Irrelevant.

Source: Nobre et al. (2007).

Table 5.6 The offering matrix (B) and the level of each parameter.

Contaminant sources groups	**Indices of the offering matrix B**			
	f_1	f_2	f_3	f_4
Agriculture (agrochemicals, nitrate)	■	▪	■	▪
Urban area (nitrate, faecal coliform bacteria, boron, virus)	▪	□	▪	▪
Industry (aromatic and chlorinated organics, heavy metals)	■	□	■	■
Municipal landfill (nitrate, heavy metals, bacteria)	□	■	□	■
Livestock farm house (nitrate, faecal coliform bacteria, virus)	▪	▪	▪	■

Where ■ is Excellent, □ is Good, ▪ is Fair, and ▫ is Weak.

Source: Nobre et al. (2007).

Table 5.7 Fuzzy operators (⊗) for obtained the product matrix **C.**

$(a_{ij})/(b_{jk})$	■	□	▪	▫
■	1	0	0	0
□	1+1/n	1	0	0
▪	1+2/n	1+1/n	1	0
▫	1+3/n	1+2/n	1+1/n	1

Source: Nobre et al. (2007).

The resulting weight matrix $\Delta = (\delta_{ik})_{h\times m}$, reflects the state of abundance or its lack related to the sources at various locations and is given by the equation (Nobre et al., 2007):

$$\Delta = (\delta_{ik})_{h\times m} = \frac{(c_{ik})_{h\times m}}{DF} \tag{5.4}$$

Where *DF* is the demand factor, given by the sum of the highest of fuzzy number of each parameter in the demand matrix A, which is equal to 3.4.

Finally, the weight matrix result was calculated with respect to its toxicity, mobility, degradability, and volume for 5 groups of contaminant sources. This results in integrated groundwater hazard map.

5.3.7 Groundwater contamination risk mapping

The groundwater contamination risk map was assessed by coupling the groundwater hazard map and the groundwater vulnerability map by attribute matrix system method (Table 5.8).

Table 5.8 The combine matrix of vulnerability and hazard maps for the risk assessment.

Vulnerability	**Hazard**					
	Other area	VL	L	M	H	VH
VL	VL	VL	L	L	M	M
L	VL	L	L	M	M	H
M	L	L	M	M	H	H
H	L	M	M	H	H	VH
VH	M	M	H	H	VH	VH
EH	M	H	H	VH	VH	VH

Where VL is very low, L is low, M is moderate, H is high, VH is very high, and EH is extremely high.

5.3.8 Correlation between risk levels and the nitrate concentration

In order to consider how reasonable the risk level was assigned to the area, groundwater risk levels were correlated with the nitrate concentration data from 87 groundwater wells. Due to the data characteristics, Spearman's rank correlation coefficient (ρ) is applied to assess the relationship between the nitrate concentration in wells and the risk levels. It measures how closely rankings of two variables agree with each other. It could be calculated by the following equation:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d^2}{n\left(n^2 - 1\right)} \tag{5.5}$$

Where *d* is the difference in the ranks given to the two variable values for each item of data and *n* is the number of pairs.

5.4 Results and discussion

5.4.1 Agricultural hazard score

The agricultural areas were obtained from land use. The actual annual loading of pesticides and fertilizers data of the area has never been surveyed by any researcher or organization and is difficult to be investigated. Therefore, the guide for agriculture from the Department of Agricultural Extension (DOAE) and some literatures were used to estimate these data. Tables 5.9 and 5.10 show the estimated annual loading of pesticides and fertilizers for given land use classes in the study area. The amount of “use” indicates main types of pesticides for a certain class of land use while the amount of “sum” indicates total of them being applied. The scores of these can be obtained from Table 5.1. Watermelon planting area shows the highest rating of annual loading of pesticides and fertilizers while sugarcane and longan planting area show trend of high rating. The lower rating is appeared in paddy field, jujube, and pomelo planting area. Table 5.11 shows the dry weight of manure produced in each sub-district, which was assumed to be applied within it. Table 5.12 shows the trace elements values of each sub-district in the study area. The trace elements values of all sub-districts were much lower than 14 kg/ha/yr and negligible. Thus, they were rated to be zero for the whole area. All scores of hazard factors of each spatial unit were summed up. Figure 5.2 shows the spatial distribution of hazard factors in the study area.

Table 5.9 Annual loading of pesticides for given land use classes in the study area.

Land use classes	Pesticides name	Amount		Score
		Use (g/rai/yr)	Sum (kg/ha/yr)	
Paddy field (กรมส่งเสริมการเกษตร, 2553ก)	Copper (II) sulfate	1,000.00	6.25	4
Para rubber (กรมส่งเสริมการเกษตร, 2553ฉ)	Glyphosate	410.00	2.56	3
Mango (กรมส่งเสริมการเกษตร, 2553ง)	Carbendazim	80.00	1.00	1
	Paraquat	80.00		
Sugarcane (กรมส่งเสริมการเกษตร, 2553ฌ)	Atrazine	720.00	4.50	4
Longan (กรมส่งเสริมการเกษตร, 2553ช)	Metalaxyl+Mancozeb	200.00	3.37	3
	Carbaryl	180.00		
	Sulphur powder	160.00		
Jujube (กรมส่งเสริมการเกษตร, 2553ค)	Carbaryl	180.00	1.62	2
	Dinocap	80.00		
Cassava (กรมส่งเสริมการเกษตร, 2553จ)	Metolachlor	250	1.56	2
Watermelon (สนธยา ชินอาจ, 2545)	Methomyl	1745.76	11.90	5
	Metallic copper+Mancozeb	156.78		
Pomelo (กรมส่งเสริมการเกษตร, 2553ซ)	Copper oxychloride	240.00	2.19	2
	Paraquat	110.40		

Table 5.10 Annual loading of fertilizers for given land use classes in the study area.

Land use classes	Fertilizer formula	Amount			Score
		Use (kg/rai/yr)	Use ($N+P_2O_5$, kg/rai/yr)	Sum ($N+P_2O_5$, kg/ha/yr)	
Paddy field	16-16-8	25	8	78.75	2
(กรมส่งเสริมการเกษตร, 2553ก)	46-0-0	10	4.6		
Para rubber	20-10-12	17.6	5.28	225.5	4
(กรมส่งเสริมการเกษตร, 2553ฉ)	30-5-18	88	30.8		
Mango	16-16-6	75	24	150	3
(กรมส่งเสริมการเกษตร, 2553ง)					
Sugarcane	16-16-8	116.65	37.33	233.3	4
(สงัด ทองภูธรณ์, 2550)					
Longan	15-15-15	75	22.5	428.12	5
(กรมส่งเสริมการเกษตร, 2553ช)	46-0-0	75	34.5		
	0-46-0	25	11.5		
Jujube	15-15-15	128	38.4	240	4
(กรมส่งเสริมการเกษตร, 2553ค)					
Cassava	15-15-15	7.5	46.88	75.63	2
(กรมส่งเสริมการเกษตร, 2553จ)	46-0-0	4.6	28.75		
Watermelon	10-10-20	150	45	281.25	4
(กรมส่งเสริมการเกษตร, 2553ข)					
Pomelo	15-15-15	22.5	51.5	321.88	4
(กรมส่งเสริมการเกษตร, 2553ซ)	46-0-0	11.5			
	12-24-12	4.5			
	13-13-21	13			

Table 5.11 The dry weight (DW) of manure produced in sub-district.

Tambon	Agricultural area (ha)	Number of			liveweight (kg)			Dry weight of manure produced (kg/day)		
		Poultry	Swine	Cattle	Poultry	Swine	Cattle	Poultry	Swine	Cattle
Ban Kong	2,199.50	51,200			102,400			2,519.87		
Ban Phue	1,775.39	134,364	550	60	268,728	41,250	27,000	6,612.87	333.81	191.70
Ban Meng	4,729.30	41,360			82,720			2,035.58		
Yang Kham	4,288.01	10,000			20,000			492.16		
Nong Rua	3,270.72	5,000			10,000			246.08		
Non Than	2,407.53		2650			198,750			1,608.37	

Table 5.12 The trace elements values of each sub-district in the study area.

Tambon	Concentrations of TE (mg/day DW)			TE total (mg/day)	TE total (kg/day)	TE total (kg/yr)	TE total (kg/ha/yr)
	Poultry	Swine	Cattle				
Ban Kong	2,127,572.46			2,127,572.46	2.13	776.56	0.35
Ban Phue	5,583,381.76	539,381.60	174,629.57	6,297,392.93	6.30	2,298.55	1.29
Ban Meng	1,718,679.63			1,718,679.63	1.72	627.32	0.13
Yang Kham	415,541.50			415,541.50	0.42	151.67	0.04
Nong Rua	207,770.75			207,770.75	0.21	75.84	0.02
Non Than		2,598,838.63		2,598,838.63	2.60	948.58	0.39

For the control factors, the score values can be obtained from Table 5.4. Table 5.13 shows scores of types of agronomic practice and irrigation of agricultural land use in the study area. Traditional tillage is the reference condition that has no influence on the agricultural hazard index calculation. The grass regeneration of orchards is the control factor decrease condition. This condition has been established in mango, longan, jujube, and pomelo planting area.

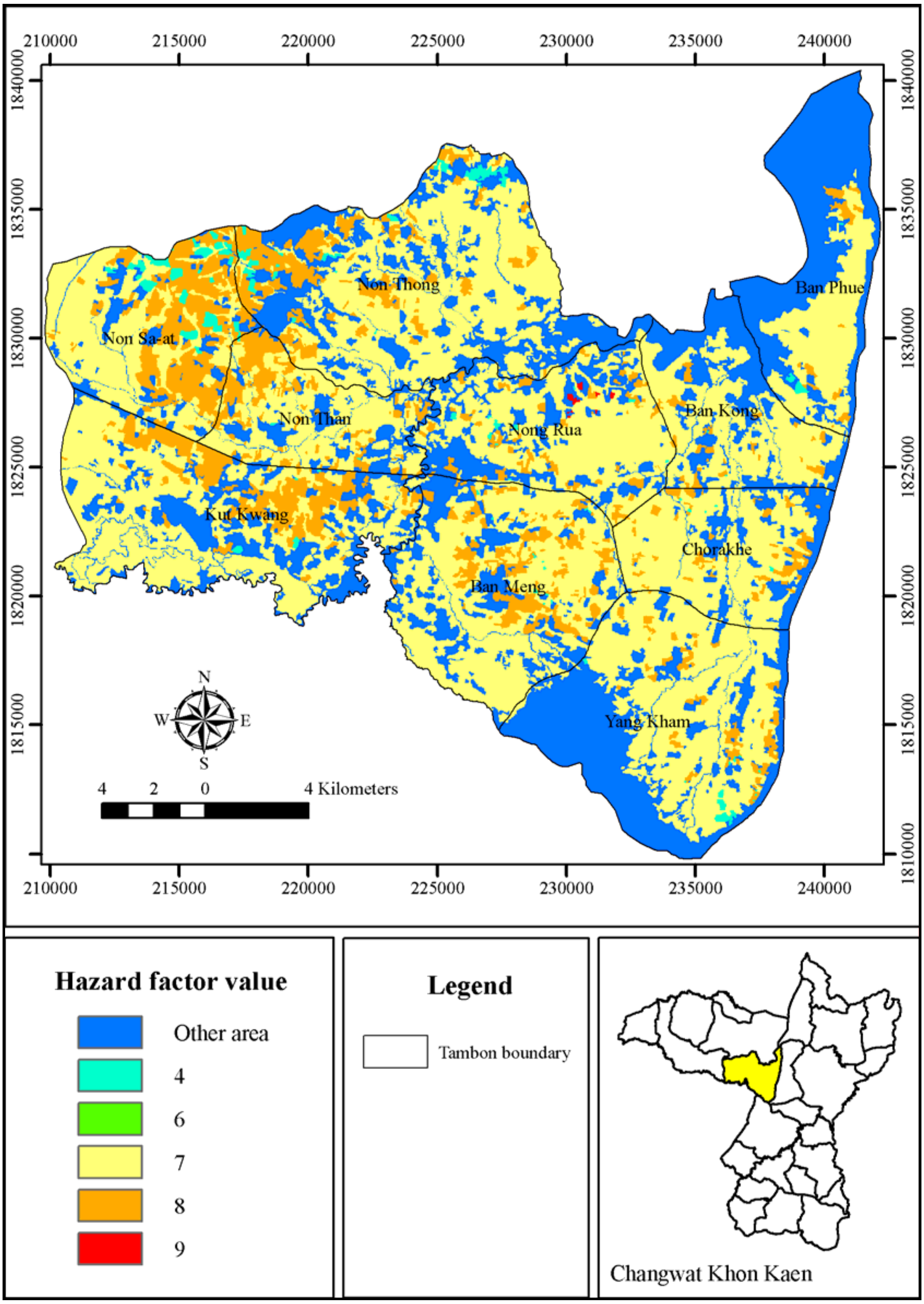


Figure 5.2 The spatial distribution of hazard factors in the study area.

Table 5.13 The scores of types of agronomic practice and irrigation of the study area.

Land use class	**Agronomic practice**		**Irrigation**	
	Type	**Score**	**Type**	**Score**
Paddy field	Traditional tillage	1.00	Submersion	1.06
Para rubber	Traditional tillage	1.00	No Irrigation	1.00
Mango	Orchards; grass regeneration	0.98	Aspersion	1.02
Sugarcane	Traditional tillage	1.00	Flowing	1.04
Longan	Orchards; grass regeneration	0.98	Aspersion	1.02
Jujube	Orchards; grass regeneration	0.98	Aspersion	1.02
Cassava	Traditional tillage	1.00	No Irrigation	1.00
Watermelon	Traditional tillage	1.00	Aspersion	1.02
Pomelo	Orchards; grass regeneration	0.98	Aspersion	1.02

For the irrigation methods, no irrigation is found in para rubber and cassava planting area. Submersion method of irrigation found in paddy field planting area is assigned with the highest score. The sugarcane planting area has trend for flowing irrigation method and aspersion irrigation method is established in mango, longan, jujube, watermelon, and pomelo planting area. For this study, the climate control factor is not counted because of its negligible variation in such a small area like this. The major slope in the study area is less than 5% which has no influence on the index result either.

Lastly, the scores of agricultural hazard were obtained using equation 5.2. They range from 3.92 to 9.18. After that they were standardized by dividing by the highest value which is 9.18. The spatial distribution of standardized AH score in the study area is shown in Figure 5.3. This information was further used for the groundwater hazard map construction.

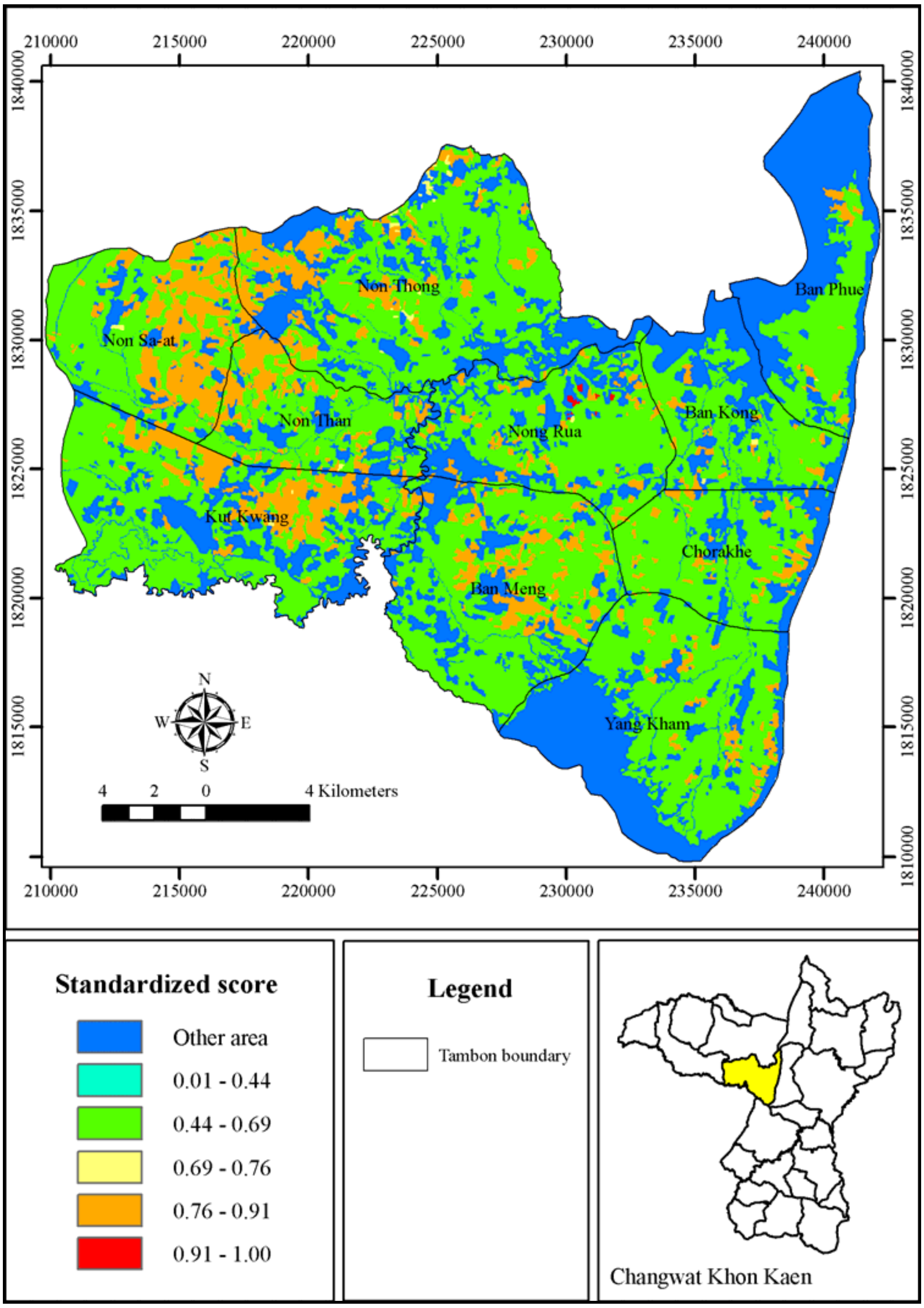


Figure 5.3 The spatial distribution of standardized AH score in the study area.

5.4.2 Urban hazard score

The urban areas were obtained from land use map. In 2002, Suthiraphon Nimitkunphaibun, Trirong Pimpa, and Rungnapha Yiamsakhon (สุธิราพร นิมิตกุลไพบูลย์, ไตรรงค์ ปิมปา, และรุ่งนภา เยี่ยมสาคร, 2545) reported that average consumption rate of the village water work in Changwat Khon Kaen has been 0.04265 m^3/person/day. Pollution Control Department (กรมควบคุมมลพิษ, 2545) estimated that the percent of wastewater generation was 80% of consumption. The population data was obtained from DOPA. From these data, the quantity of domestic wastewater could be calculated using equation 5.3.

The quantity of domestic wastewater of urban areas ranges from 1.02 to 152.07 m^3/day. It was standardized by dividing by the highest score which is 152.07. The spatial distribution of standardized UH score in the study area is shown in Figure 5.4. This information was further used for the groundwater hazard map construction.

5.4.3 Other hazard sources

The other hazard sources were obtained from land use map. Figure 5.5 shows the location of other hazard sources in the study area. They include sugar industry, municipal landfill, and livestock farm house. The sugar industry is one of the potential contaminant sources found in the study area. There exist 2 municipal landfills and 34 livestock farm houses in the study area. A score of 1 was assigned to each other hazard sources and were further used for the groundwater hazard map construction.

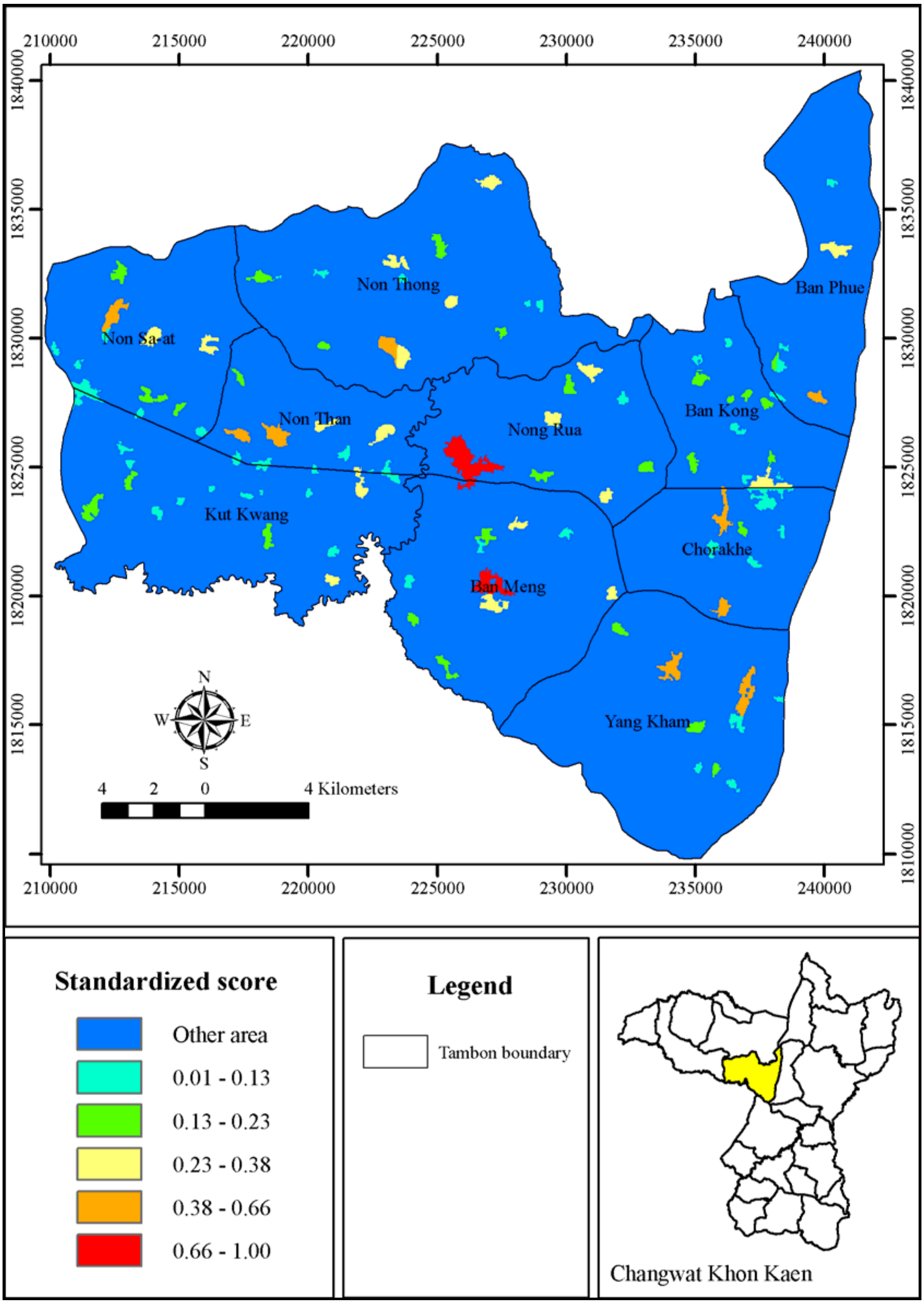


Figure 5.4 The spatial distribution of standardized UH score in the study area.

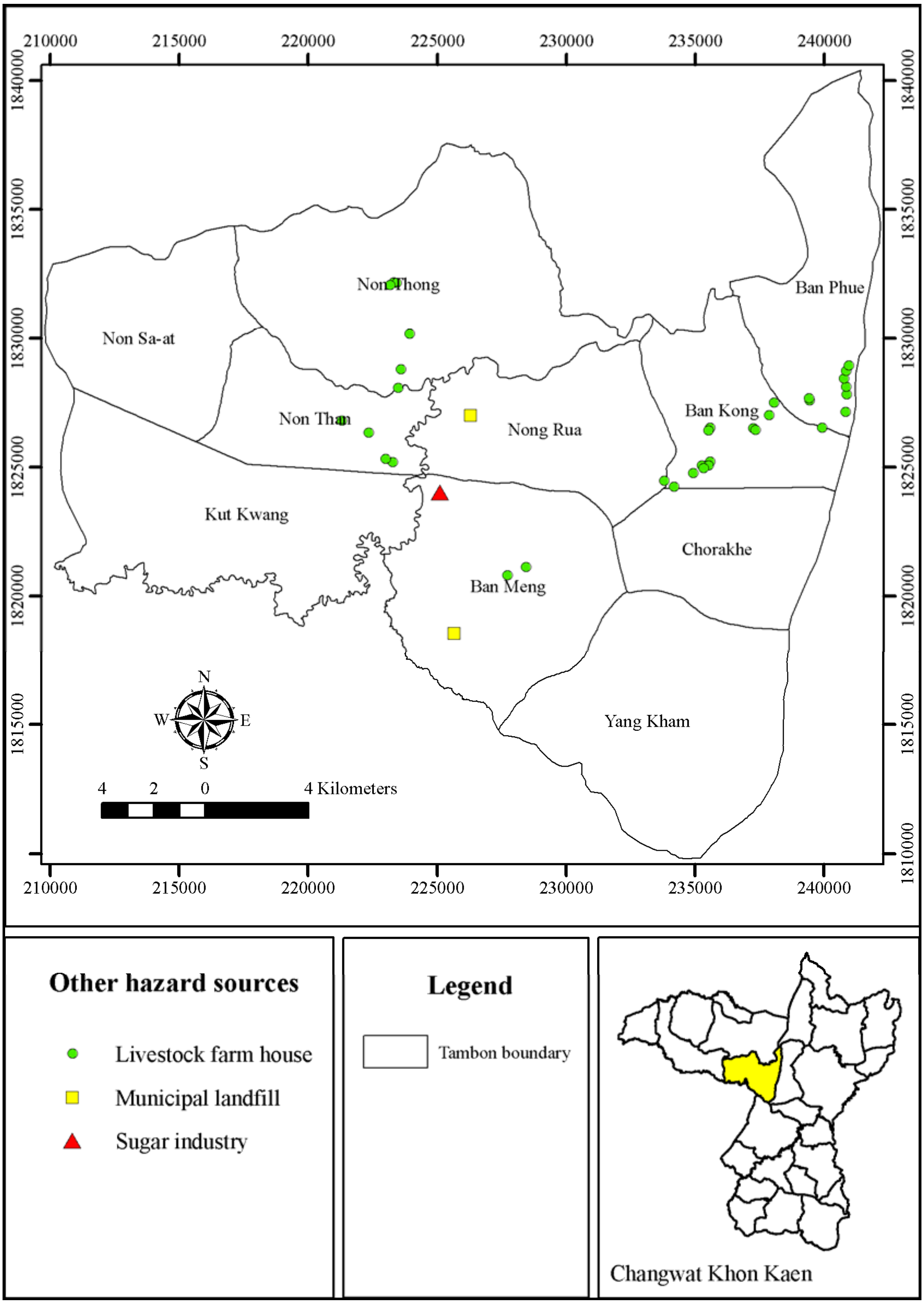


Figure 5.5 The location of other hazard sources in the study area.

5.4.4 Weights of contaminant sources

The hazard weight of each contaminant source was calculated as mentioned in 5.3.6. The resulting weights are shown in Table 5.14. The highest hazard weight is 1.10 for the industry group. The urban area group possesses the lowest hazard weight which is 0.29. The other sources groups, consisting of municipal landfills, agriculture, and livestock farm house, have weights of 1.03, 0.96, and 0.44, respectively.

Table 5.14 Hazard weight of each contaminant sources group.

	Contaminant sources group				
	Agriculture	**Urban area**	**Industry**	**Municipal landfill**	**Livestock farm house**
Hazard weight	0.96	0.29	1.1	1.03	0.44

5.4.5 Groundwater hazard map

Overlay operation according to equation 5.1 resulted in groundwater hazard map which contains varying potential hazard index between 0.002 and 1.100. The 5 levels of index from very low to very high and the percent area cover are shown in Table 5.15. Figure 5.6 shows the final resulting groundwater hazard map.

Moderate potential hazard covers main part of the area (54.58%). Low and very low potential cover area about 1.13% and 4.43%, respectively, whereas high and very high potential are found covering 12.48% and 0.34% of the area, respectively. The sugar industry, municipal landfill, and watermelon planting area are fallen into the very high level of potential hazard.

Table 5.15 Groundwater hazard levels and their percentages of area cover.

Hazard level	Hazard index range	Area cover	
		km^2	**Percent**
Other area	-	144.16	27.04
Very low	0.0-0.3	23.59	4.43
Low	0.3-0.5	6.03	1.13
Moderate	0.5-0.7	291.03	54.58
High	0.7-0.9	66.56	12.48
Very high	0.9-1.1	1.82	0.34

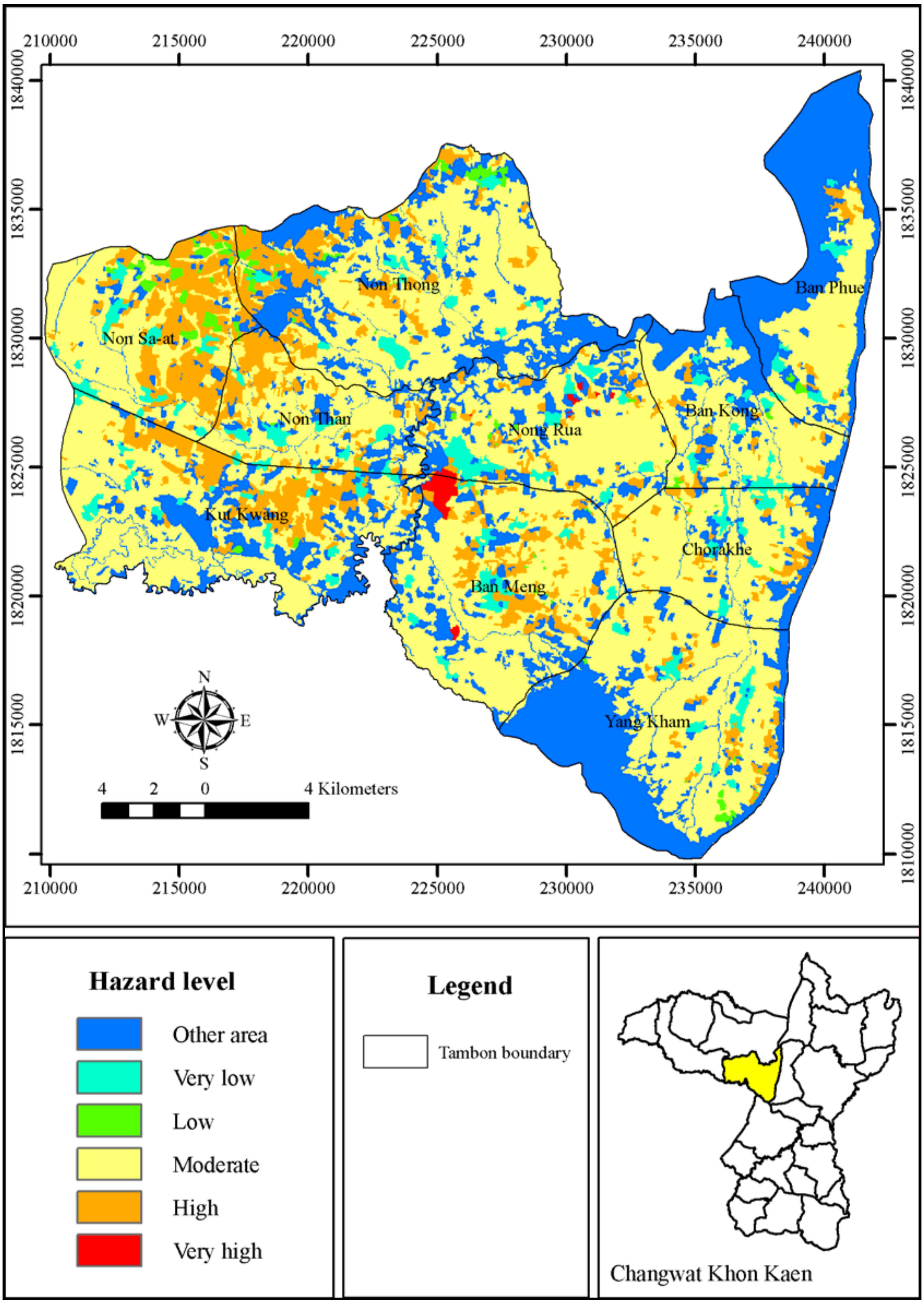


Figure 5.6 The groundwater hazard map.

5.4.6 Groundwater contamination risk map

Groundwater contamination risk map is the integration of groundwater hazard and vulnerability maps. The attribute matrix combination of both map levels expressed in Table 5.8 was used to combine them. The 5 levels of contamination risk map and their percentage of area cover are shown in Table 5.16. The groundwater contamination risk map is shown in Figure 5.7.

The high level of groundwater contamination risk mainly covers 37.48% of the study area. Very low level, covering 8.85%, is mostly concentrated at water bodies. Low and moderate levels have been found covering 26.90% and 18.96% of the area respectively. Undoubtedly, the area having very high risk level agrees with very high and extremely high vulnerability areas. This level covers 7.80% of the area and is mostly concentrated in the northwestern and southwestern parts of the study area.

Table 5.16 Groundwater contamination risk levels and their percentages of area cover.

Contamination risk level	**Area cover**	
	km^2	**Percent**
Very low	47.21	8.85
Low	143.46	26.90
Moderate	101.09	18.96
High	199.85	37.48
Very high	41.61	7.80

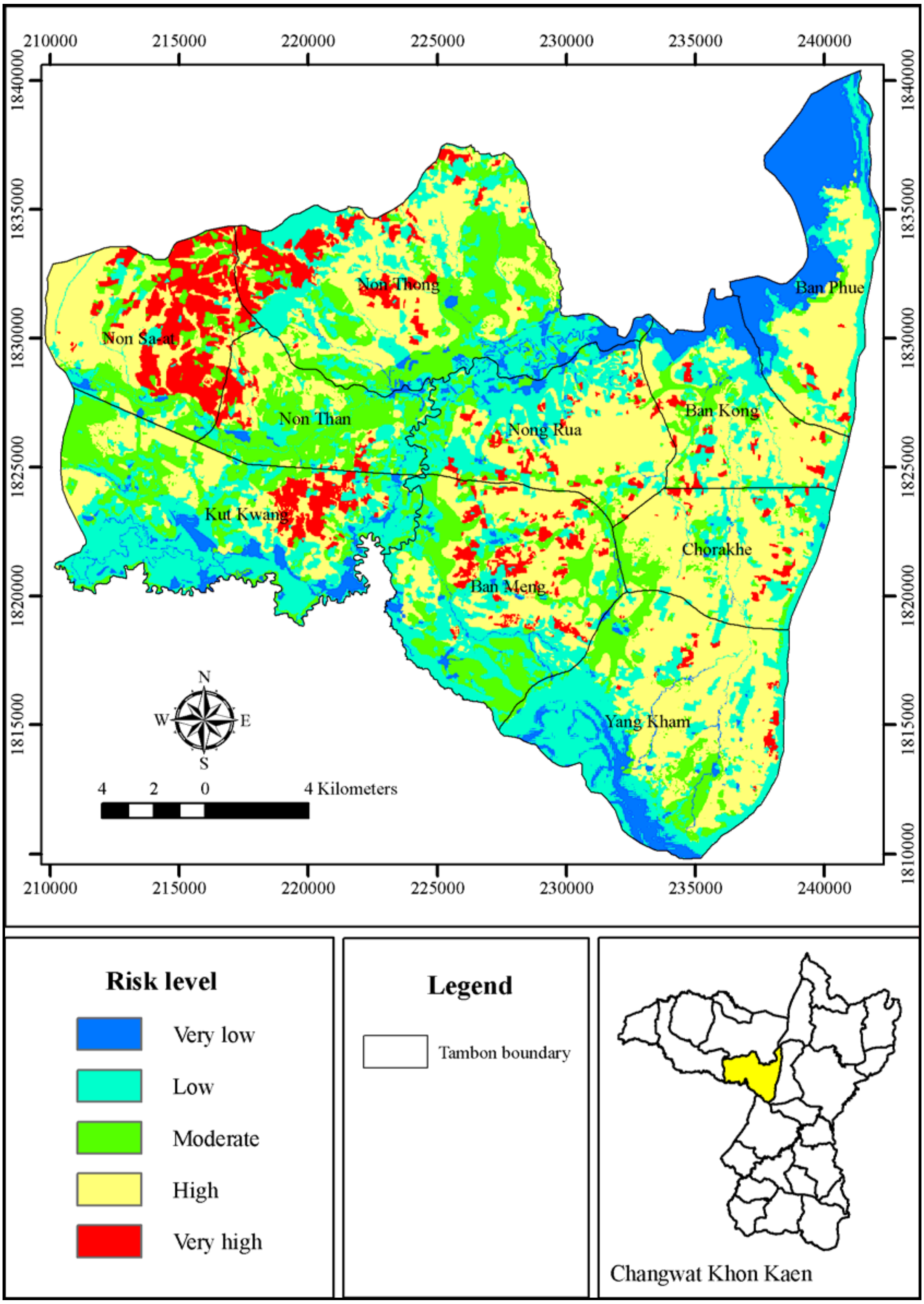


Figure 5.7 The groundwater contamination risk map.

5.4.7 Comparison between risk levels and nitrate concentration

Figure 5.8 and Table 5.17 show distribution of wells with nitrate concentration in the groundwater risk levels. The numbers of existing wells found within areas of very low, low, and moderate risk levels are 10, 64, and 13, respectively. Unfortunately, no well has been existed in high and very high risk areas. The statistical correlation coefficient of nitrate concentration in wells and their corresponding risk levels was calculated and resulted in 0.49. Conclusively, the groundwater nitrate concentration shows a significantly positive correlation with the risk level. Noticeably, if wells could exist in high and very high risk areas this correlation will be able to change to be more accurate.

5.5 Conclusions

Groundwater hazard map was constructed to represent the integration of spatial distribution of the potential hazard level of contamination sources. Three map layers including agricultural hazard, urban hazard, and other hazard are required as input for producing this map. NPSAHI method was applied to evaluate the agricultural hazard. The hazard factors, which represent all farming activities that cause or might cause an impact on groundwater, and the control factors, which adapt the hazard factors to the characteristics of the site, are two parameters employed in consideration for this method. The urban hazard is represented by the quantity of domestic wastewater value. The other hazard sources including sugar industry, municipal landfill, and livestock farm house were obtained from land use map.

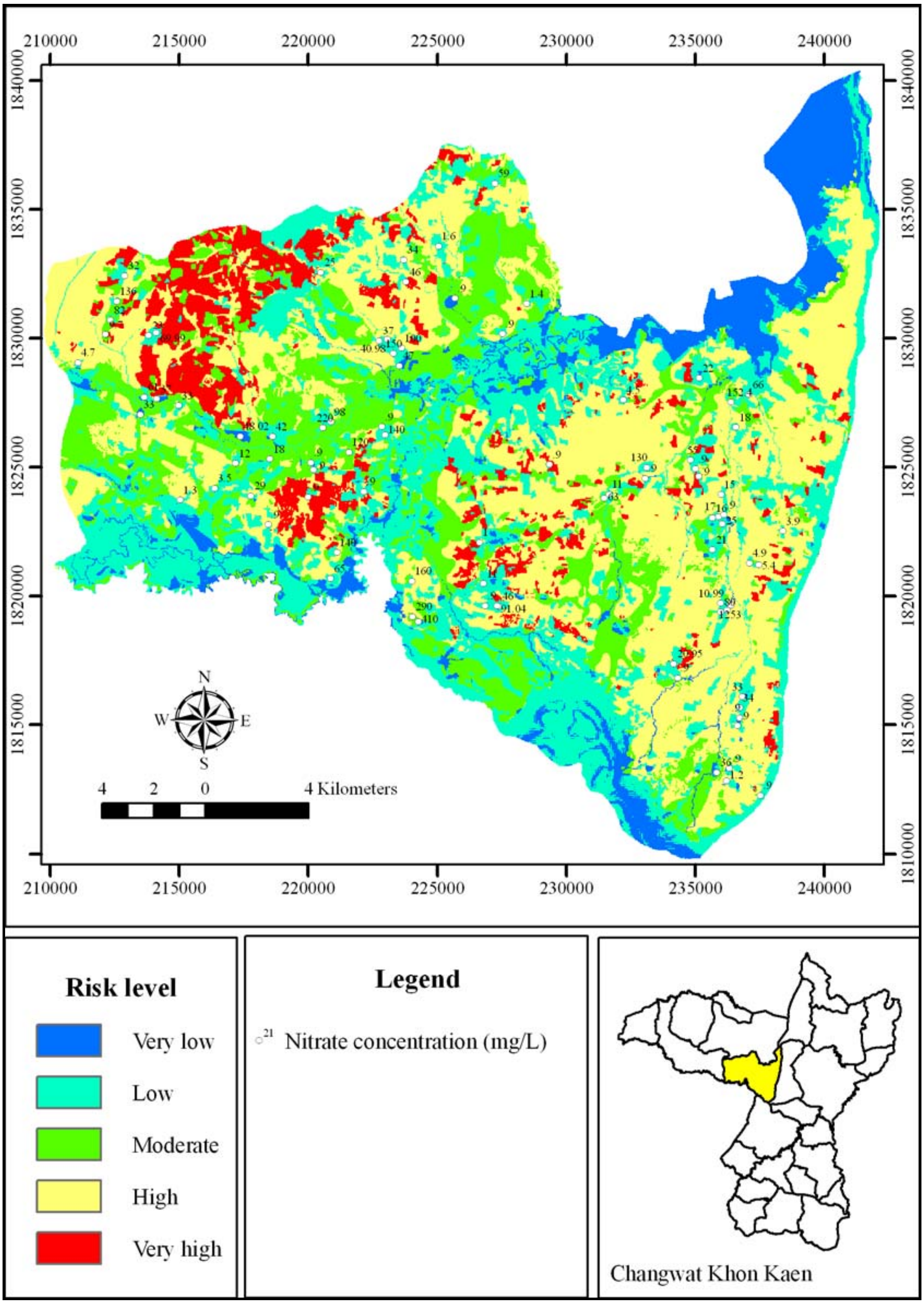


Figure 5.8 Distribution of nitrate concentration in wells and the risk levels.

Table 5.17 The risk levels and the nitrate concentration in well.

Risk level	Lab No.	Place	Mu	Tambon	UTM_E	UTM_N	NO_3 (mg/L)
Very low	1913/51	Wat Pho Si	16	Non Thong	225684	1831545	0.90
	2033/51	Rongrian Ban Nong Wa	3	Yang Kham	236637	1814948	0.90
	2037/51	Rongrian Ban Don Khaem	4	Yang Kham	236312	1813300	0.90
	2105/51	Ban Non Sa-nga	16	Kut Kwang	217190	1825136	12.00
	2094/51	Ban Non Sila	13	Non Sa-at	213491	1827022	33.00
	2034/51	Wat Ban Don Khaem	4	Yang Kham	235836	1813143	36.00
	2103/51	Ban Non Khun	11	Non Sa-at	214142	1827626	37.00
	1901/51	Ban Non Thong	19	Non Thong	223540	1828909	47.00
	1855/51	Wat Ban Wa	3	Non Than	217363	1826180	48.02
	2095/51	Ban Khok Klang	5	Non Sa-at	213653	1827699	61.00
Low	1851/51	Ban Kut Chim	8	Non Than	222848	1826550	0.90
	1912/51	Rongrian Ban Kut Khaen	8	Non Thong	227535	1830156	0.90
	1914/51	Wat Chumphon	1	Kut Kwang	222162	1824046	0.90
	2018/51	Ban Hua Na	2	Chorakhe	236116	1823137	0.90
	2032/51	Wat Ban Nong Wa	3	Yang Kham	236719	1815257	0.90
	2036/51	Rongrian Mattayomtaladyaiwittaya	0	Yang Kham	237535	1812251	0.90
	2038/51	Rongrian Ban Nong Waeng	10	Yang Kham	234320	1816798	0.90
	2044/51	Ban Sa-at	7	Nong Rua	233056	1824553	0.90
	2045/51	Rongrian Nong Hai Pracha Rat	9	Nong Rua	229362	1825088	0.90
	2088/51	Ban Nong Kung	15	Kut Kwang	220210	1824889	0.90
	2089/51	Ban Nong Kung	15	Kut Kwang	219987	1823820	0.90
	2090/51	Ban Kut Kwang	4	Kut Kwang	218442	1822761	0.90
	2106/51	Ban Pueai	6	Non Than	220102	1825159	0.90
	2110/51	Rongrian Ban Nong No Pracha San	8	Ban Meng	226848	1819612	0.90
	2143/51	Wat Ban Nong Sa	4	Ban Kong	235124	1824625	0.90
	2144/51	Rongrian Ban Nong Sa	4	Ban Kong	235004	1824921	0.90
	2107/51	Ban Nong Kung Noi	13	Ban Meng	226649	1822075	1.00
	2035/51	Ban Nong Na Wong	9	Yang Kham	236209	1812821	1.20
	2093/51	Ban Non Du	5	Kut Kwang	215050	1823718	1.30
	1911/51	Ban Phai Noi	11	Non Thong	228472	1831337	1.40
	1909/51	Ban Nong Nok Khian	7	Non Thong	225047	1833569	1.60
	2092/51	Ban Nong Waeng	18	Kut Kwang	216380	1824169	3.50
	2029/51	Ban Khok Klang	7	Chorakhe	238392	1822511	3.90
	2042/51	Ban Nong Kung	4	Nong Rua	232201	1827583	4.50
	2102/51	Ban Phon Sawan	12	Non Sa-at	211094	1829034	4.70
	2028/51	Ban Hua Buen	5	Chorakhe	237106	1821266	4.90
	2027/51	Ban Bueng Sawang	11	Chorakhe	237464	1821206	5.40
	2023/51	Ban Nong Hoi	6	Chorakhe	235970	1819717	10.99
	2041/51	Wat Non Phanit	8	Nong Rua	231670	1823940	11.00
	2108/51	Ban Meng	2	Ban Meng	226802	1820475	11.00
	2024/51	Rongrian Ban Nong Hoi	6	Chorakhe	236381	1819635	12.00
	2019/51	Ban Hua Na	2	Chorakhe	235995	1823920	15.00
	2021/51	Ban Hua Na	3	Chorakhe	235667	1823018	16.00
	2017/51	Ban Hua Na	12	Chorakhe	235898	1823066	17.00
	1918/51	Ban Non Than Noi	12	Non Than	218524	1825304	18.00

Table 5.17 (Continued).

Risk level	Lab No.	Place	Mu	Tambon	UTM_E	UTM_N	NO_3 (mg/L)
Low	2141/51	Ban Tha Li	7	Ban Kong	236577	1826533	18.00
	2039/51	Wat Sawang Pho Si	7	Yang Kham	234164	1817354	20.95
	2022/51	Ban Nong Paen	8	Chorakhe	235669	1821788	21.00
	2149/51	Ban Nong Mek	5	Ban Kong	235154	1828434	22.00
	2097/51	Rongrian Ban Nong Lum Phuk	6	Non Sa-at	213822	1830091	23.00
	1907/51	Rongrian Ban Huai Sai	13	Non Thong	220490	1832548	25.00
	2020/51	Ban Hua Na	3	Chorakhe	236045	1822792	25.00
	2091/51	Wat Arun Sawang Amphawan	14	Kut Kwang	217782	1823867	29.00
	2100/51	Ban Non Waeng	7	Non Sa-at	212892	1832426	32.00
	2030/51	Ban Yang Kham	13	Yang Kham	236816	1816071	33.00
	2104/51	Ban Don Han	9	Non Sa-at	214981	1827378	33.00
	1908/51	Ban Sap Charoen	18	Non Thong	223709	1833041	34.00
	2031/51	Ban Yang Kham	13	Yang Kham	236721	1815642	34.00
	1903/51	Ban Non Thong	1	Non Thong	222755	1829879	37.00
	1904/51	Ban Non Thong	15	Non Thong	223071	1829947	40.98
	1854/51	Ban Non Than	1	Non Than	218614	1826167	42.00
	1906/51	Wat Ban Dong Noi	14	Non Thong	223789	1832177	46.00
	2025/51	Wat Nong Hoi	13	Chorakhe	236224	1819441	53.00
	2142/51	Ban Nong Sa	4	Ban Kong	234824	1825259	55.00
	1910/51	Rongrian Ban Nong Khuean Chang	6	Non Thong	227229	1836007	59.00
	1916/51	Rongrian Khanuan Nakhon	3	Kut Kwang	220867	1820668	65.00
	2147/51	Wat Pho Thong	2	Ban Kong	237090	1827800	66.00
	2096/51	Wat Sawang Phaithun	14	Non Sa-at	214121	1830193	69.99
	2026/51	Ban Nong Hoi	9	Chorakhe	235990	1819370	80.00
	1905/51	Ban Non Thong	20	Non Thong	223623	1829594	100.00
	2043/51	Ban Sa-at	7	Nong Rua	233115	1824973	130.00
	1850/51	Rongrian Ban Kut Chim	7	Non Than	222980	1826236	140.00
	1902/51	Ban Non Thong	10	Non Thong	223296	1829384	150.00
	2109/51	Wat Sabaeng	11	Ban Meng	224029	1820573	160.00
Moderate	2101/51	Ban Nong Hai	2	Non Sa-at	212153	1830125	9.70
	2111/51	Ban Nong No	8	Ban Meng	227390	1819595	46.00
	2040/51	Ban Sala Thong	12	Nong Rua	231480	1823791	63.00
	2098/51	Ban Non Sawan	10	Non Sa-at	212338	1830700	82.00
	2112/51	Ban Nong No	8	Ban Meng	227329	1819606	91.04
	1852/51	Ban Na	6	Non Than	220876	1826735	98.00
	1856/51	Wat Ban Non Sa-at	11	Non Than	221587	1825560	120.00
	2099/51	Ban Non Sa-at	15	Non Sa-at	212587	1831428	136.00
	1915/51	Ban Khok Sung	2	Kut Kwang	221114	1821685	140.00
	2146/51	Ban Pueai	3	Ban Kong	236391	1827506	152.40
	1853/51	Wat Ban Na Pueai	5	Non Than	220576	1826504	220.00
	2114/51	Ban Hat	10	Ban Meng	224044	1819191	290.00
	2113/51	Ban Hat	10	Ban Meng	224272	1819003	410.00

The fuzzy hierarchical model was applied to calculate the hazard weight of each contaminant sources with respect to its toxicity, mobility, degradability, and volume. The final result of groundwater hazard map showed values range from 0.002 to 1.100, which was divided into five levels from very low to very high. The moderate level of the hazard map dominated main part of the area. Land use classes fallen into the very high level include sugar industry, municipal landfill, and watermelon planting area.

Groundwater contamination risk map was evaluated by coupling the hazard map and the vulnerability map by attribute matrix system method. The final result of risk map contains five risk levels from very low to very high. High risk level dominated main part of the area. The very high risk area agrees with very high and extremely high vulnerability areas and mostly concentrated in the northwestern and southwestern part of the study area. The statistical correlation coefficient between the nitrate concentration in the wells and the groundwater risk levels showed a significantly positive correlation (0.49).

The result of this study is a useful tool for developing and designing the protection planning of these resources. It showed areas of the highest potential for groundwater contamination on the basis of hydrogeologic conditions and human impacts.

5.6 References

กรมควบคุมมลพิษ. (2545). **น้ำเสียชุมชนและระบบบำบัดน้ำเสีย**. กรุงเทพฯ: กรมควบคุมมลพิษ กระทรวงวิทยาศาสตร์ เทคโนโลยีและสิ่งแวดล้อม.

กรมส่งเสริมการเกษตร. (2553ก). **ข้าวเหนียว** [ออนไลน์]. ได้จาก: http://agritech.doae.go.th/agri-media/book-file/book-rice/RB002.pdf.

กรมส่งเสริมการเกษตร. (2553ข). **แตงโม** [ออนไลน์]. ได้จาก: http://agritech.doae.go.th/agri-media/book-file/book-rice/RB011.pdf.

กรมส่งเสริมการเกษตร. (2553ค). **พุทรา** [ออนไลน์]. ได้จาก: http://fs.doae.go.th/เนื้อหาถ่ายทอดFS%20ปี49/ไม้ผล/พุทรา%20.doc.

กรมส่งเสริมการเกษตร. (2553ง). **มะม่วง** [ออนไลน์]. ได้จาก: http://fs.doae.go.th/เนื้อหาถ่ายทอดFS%20ปี49/ไม้ผล/มะม่วง.doc.

กรมส่งเสริมการเกษตร. (2553จ). **มันสำปะหลัง** [ออนไลน์]. ได้จาก: http://agritech.doae.go.th/agri-media/book-file/book-rice/RB026.pdf.

กรมส่งเสริมการเกษตร. (2553ฉ). **ยางพารา** [ออนไลน์]. ได้จาก: http://agritech.doae.go.th/agri-media/book-file/book-fruit/MU001.pdf.

กรมส่งเสริมการเกษตร. (2553ช). **ลำใย** [ออนไลน์]. ได้จาก: http://fs.doae.go.th/เนื้อหาถ่ายทอดFS%20ปี49/ไม้ผล/ลำไย.doc.

กรมส่งเสริมการเกษตร. (2553ซ). **ส้มโอ** [ออนไลน์]. ได้จาก: http://fs.doae.go.th/เนื้อหาถ่ายทอดFS%20ปี49/ไม้ผล/ส้มโอ.doc.

กรมส่งเสริมการเกษตร. (2553ฌ). **อ้อยโรงงาน** [ออนไลน์]. ได้จาก: http://fs.doae.go.th/เนื้อหาถ่ายทอดFS%20ปี49/พืชไร่อุตสาหกรรม/อ้อยโรงงาน.doc.

สงัด ทองภูธรณ์. (2550). **การตัดสินใจปลูกอ้อยในพื้นที่นาของเกษตรกรในอำเภอหนองเรือ จังหวัดขอนแก่น**. วิทยานิพนธ์ปริญญาเกษตรศาสตรมหาบัณฑิต แขนงวิชาส่งเสริมการเกษตร สาขาวิชาส่งเสริมการเกษตรและสหกรณ์ มหาวิทยาลัยสุโขทัยธรรมาธิราช.

สนธยา ชินอาจ. (2545). **การใช้สารกำจัดศัตรูพืชในการปลูกแตงโม ผลกระทบต่อกิจกรรมของจุลินทรีย์ดิน และผลผลิตอันดับแรกของบ่อน้ำ: กรณีศึกษา บ้านหลุบหญ้าคา ตำบลดอนหัน อำเภอเมือง จังหวัดขอนแก่น**. วิทยานิพนธ์ปริญญาวิทยาศาสตรมหาบัณฑิต สาขาวิชาทรัพยากรการเกษตรและสิ่งแวดล้อม บัณฑิตวิทยาลัย มหาวิทยาลัยขอนแก่น.

สุธีราพร นิมิตกุลไพบูลย์, ไตรรงค์ ปิมปา, และรุ่งนภา เยี่ยมสาคร. (2545). **อัตราการใช้น้ำ และพฤติกรรมการใช้น้ำของประชาชนจากระบบประปาหมู่บ้านของกรมอนามัย**. กรุงเทพฯ: กรมอนามัย กระทรวงสาธารณสุข.

Adriano, D.C. (2001). **Trace elements in the terrestrial environments: biogeochemistry, bioavailability, and risks of metals** (2nd ed.). USA: Springer-Verlag New York.

Luo, L., Ma, Y., Zhang, S., Wei, D., and Zhu, Y.G. (2009). An inventory of trace element inputs to agricultural soils in China. **Journal of Environmental Management**. 90: 2524-2530.

Morris, B.L. and Foster, S.S. (2000). *Cryptosporidium* contamination hazard assessment and risk management for british groundwater sources. **Water Science and Technology**. 41(7): 67-77.

Nobre, R.C.M., Rotunno Filho, O.C., Mansur, W.J., Nobre, M.M.M., and Cosenza, C.A.N. (2007). Groundwater vulnerability and risk mapping using GIS, modeling and a fuzzy logic tool. Journal **of Contaminant Hydrology**. 94: 277-292.

Overcash, M.R., Humenik, F.J., and Miner, J.R. (1983). **Source is Livestock Waste Management** (Vol. I). Boca Raton, Florida: CRC Press.

Trevisan, M., Padovani, L., and Capri, E. (2000). Nonpoint-source agricultural hazard index: a case study of the province of Cremona, Italy. **Environmental Management**. 26(5): 577-584.

Vrba, J. and Zaporozec, A. (1994). **Guidebook on mapping groundwater vulnerability. International Association of Hydrogeologists (International Contributions to Hydrogeology 16)**. Hannover: Verlag Heinz Heise.

Werner, U., Stohr, U., and Hees, N. (1989). **Biogas Plants in Animal Husbandry**. Braunschweig, Germany: Friedr. Vieweg & Sohn Velagsgesellschaft mbH.

Zaporozec, A. (ed.). (2004). **Groundwater contamination inventory: A methodological guide**. Paris: UNESCO.

CHAPTER VI

GROUNDWATER PROTECTION ZONING

6.1 Abstract

The protection priority of groundwater wells, reserved for water work source in Amphoe Nong Rua, Changwat Khon Kaen, was assessed based on hydrogeologic conditions, human impacts, and socio-economic value. Groundwater protection urgency zoning was analyzed to rank this priority. It was analyzed through the operation of combination matrix system of contamination risk map and capture zone value. The capture zone value was determined by the combination matrix between the tier of capture zone area and the socio-economic value. The calculated fixed radius method was used to delineate the capture zone. The boundaries of capture zone were separated into three tiers consisting of tier 1 (2 years flowing path), tier 2 (5 years), and tier 3 (12 years). The socio-economic value within the capture zone area was evaluated dependent on a number of household being supplied from the wells and alternative water source availability. The final result of protection zoning showed that the well at Ban Non Khun, Mu 11, Tambon Non Sa-at was the first priority protection urgency. The result can be used as a tool to help discriminate preference or priority of wells for strategic planning and groundwater contamination and protection study.

Keywords: GIS/Groundwater protection zoning/Capture zone/Nong Rua

6.2 Introduction

Groundwater is regarded as the important source of domestic water work in Amphoe Nong Rua, Changwat Khon Kaen especially in area that does not have other water sources. Therefore, for long term adequate supply, groundwater wells reserved as water work source must be protected according to how urgent they are prone to contamination. Once it was polluted. Immense time and budget are required to alleviate with incredibly high difficulty. The protection of this resource is the first step for groundwater quality management.

The aim of this research is to determine the protection priority required by groundwater wells for water work source. The groundwater protection of each well was zoned and evaluated by coupling the risk map and the capture zone value map. The risk map defines the probability that groundwater will become contaminated to an unacceptable level by human activities on the immediately overlying land surface. It was assessed by coupling the groundwater vulnerability and hazard maps. The capture zone value was determined by the combination matrix between the tier of capture zone area and the socio-economic value of groundwater well. The capture zone area is the delineation of approximate well-surrounding area through which groundwater flows to wells in different specific ranges of time. The socio-economic of groundwater well was assessed by coupling the number of households and alternative water source availability.

6.3 Research methods

6.3.1 Research procedure

The main steps of the research procedure are shown in Figure 6.1. Details of each step can be explained as follows.

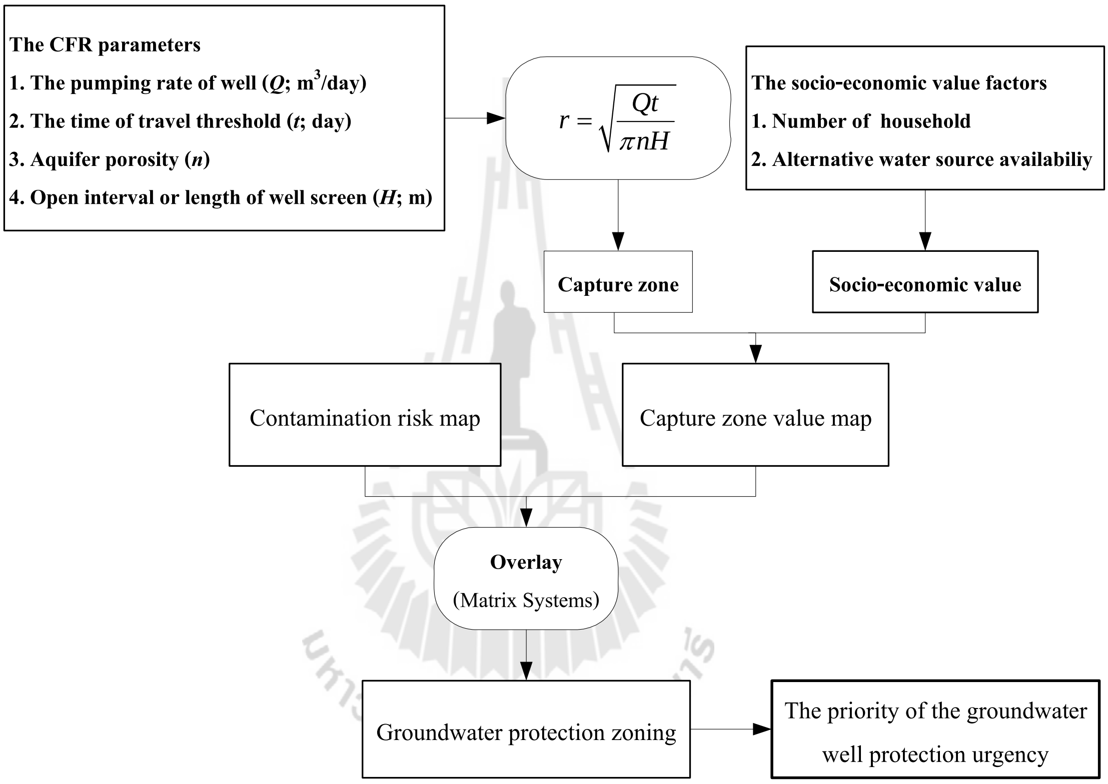


Figure 6.1 The research procedure of groundwater protection zoning.

6.3.2 Capture zone calculation

Due to the limitation of data on aquifer parameters for flow equations, time, and economic constraints, the calculated fixed radius (CFR) method was chosen to delineate the capture zone for this study. This method is based on simple hydrogeologic principles and only aquifer parameter required is porosity. In addition, it is appropriate for a confined aquifer as exists in the study area and is best using for the first step approach. Moreover, this method was suggested to serve for the Portuguese law which stated that all groundwater extraction wells designed for public water supply shall have a zone of immediate protection (Moinante and Lobo-Ferreira, 2005). The CFR value can be calculated by using the following formula (USEPA, 1994):

$$r = \sqrt{\frac{Qt}{\pi n H}} \qquad (6.1)$$

Where r is the CFR value, Q is the pumping rate of well (m^3/day), t is the time of travel threshold (day), n is aquifer porosity, and H is open interval or length of well screen (m).

The capture zone areas were separated into three tiers according to Spayd and Johnson (2003). The outer boundaries of these tiers will have the following time of travel (TOT) to the well: Tier 1 equal to two years, tier 2 equal to five years, and tier 3 equal to twelve years.

The outer boundary of tier 1 is two years that provides a reasonable margin of safety beyond the 170 and 270 days figures. On the one hand, bacteria from the source can stay in and pollute groundwater not longer than 170 days TOT. On the other hand, viruses can survive in groundwater for up to 270 days. Generally, a TOT represents an average because of pollution does not move in a uniform front. Once a pollution plume gets too close to a water supply well, it has tendency to impact or contaminate on water quality, but not quantity.

The five years TOT boundary of tier 2 was assigned based on the smearing effect observed in pollution plumes that caused by adsorption or desertion and the variable rate of pollutants travel through pores.

The last one, the boundary of tier 3 is twelve years. The purpose of this time span set up is to ensure sufficient monitoring of potential pollution sources so that responses may be made. The assignment of tier 3 is based on a preliminary analysis of pollution cases indicated that a TOT of 10 to 15 years encompasses the full length of most pollution plumes identified (Spayd and Johnson, 2003).

6.3.3 The socio-economic value evaluation

Evaluation of the socio-economic values of groundwater wells depends on a number of households being supplied from the wells and alternative water source availability. The alternative water sources are referred to the other sources of water supply able to apply when groundwater is contaminated and not suitable for human consumption. The combined-attribute matrix method used to evaluate the socio-economic value is shown in Table 6.1.

Table 6.1 The combined matrix of a number of households and alternative water source availability for the socio-economic value evaluation.

Alternative water source	Number of households				
	< 50	50-120	120-300	300-750	> 750
None	VL	L	M	H	VH
Surface water	VL	VL	L	M	H
Water work from surface water	VL	VL	VL	L	M

Where VL is very low, L is low, M is moderate, H is high, and VH is very high.

6.3.4 The capture zone value assessment

The capture zone value was assessed by coupling the tier and socio-economic value in the respective capture zone area by combined-attribute matrix method (Table 6.2). A tier closer to a well has higher value.

Table 6.2 The combined matrix of the tier and socio-economic value for capture zone value assessment.

Socio-economic value	The tier of capture zone		
	Tier 1	**Tier 2**	**Tier 3**
VL	L	VL	VL
L	M	L	VL
M	H	M	L
H	VH	H	M
VH	VH	VH	H

Where VL is very low, L is low, M is moderate, H is high, and VH is very high.

6.3.5 Groundwater protection zoning assessment

To achieve the groundwater protection urgency zoning, the groundwater contamination risk map and capture zone value map were combined through matrix system operation (Table 6.3). The operation was performed on different tiers of capture zones of wells. Finally, the urgency protection of wells were considered and ranked according to their combined levels of risk and value of the tier 1 in particular. The higher the level, the more protection urgency is.

Table 6.3 The combined matrix of groundwater contamination risk and capture zone value levels for groundwater protection zoning assessment.

Contamination risk	Capture zone value				
	VL	L	M	H	VH
VL	VL	L	L	M	M
L	L	L	M	M	H
M	L	M	M	H	H
H	M	M	H	H	VH
VH	M	H	H	VH	VH

Where VL is very low, L is low, M is moderate, H is high, and VH is very high.

6.4 Results and Discussion

6.4.1 Capture zone

The capture zone was calculated from equation 6.1. The pumping rate of well was obtained from the field investigation and interview (The examples of groundwater wells from the field investigation are presented in Appendix B). Because of the information limitation of some wells, the aquifers of wells were interpreted and projected from the near wells. In addition, the aquifer porosity was obtained from the literature data (USEPA, 1994) and is 0.03, 0.12, and 0.27 for shale, siltstone, and sandstone aquifers, respectively. The open interval or length of well screen was assigned to 3 m, the lowest value existing in the study area, for wells lacking in this information. Table 6.4 shows capture zone radiuses of wells calculated by CFR method and Figures 6.1 to 6.9 show examples of the capture zone areas of Tambon

Kut Kwang, Chorakhe, Non Thong, Non Than, Non Sa-at, Ban Kong, Ban Meng, Yang Kham, and Nong Rua, respectively. The capture zone of well no. 71 at Wat Sabaeng, Mu 11, Tambon Ban Meng is the smallest areal extent covering 6,323, 15,825, and 38,005 m^2 in tier 1, 2, and 3, respectively. The largest areal extent of capture zone shows at the well no. 48 at Ban Khok Klang, Mu 5, Tambon Nong Sa-at covering 547,332, 1,368,490, and 3,284,612 m^2 in tier 1, 2, and 3, respectively.

Table 6.4 The capture zone radiuses of wells calculated by CFR method.

No.	UTM_E	UTM_N	PLACE	MU	TAMBON	Aquifer	Pumping rate (m^3/day)	Porosity	Screen length (m)	Radius of (m)		
										Tier 1	Tier 2	Tier 3
1	222169	1824046	Wat Chumphon	1	Kut Kwang	sandstone	30.80	0.27	4.00	81.43	128.74	199.45
2	221114	1821685	Ban Khok Sung	2	Kut Kwang	siltstone	22.73	0.12	3.00	121.16	191.58	296.79
3	220867	1820668	Rongrian Khanuan Nakhon	3	Kut Kwang	shale	10.73	0.03	3.00	166.51	263.28	407.87
4	218452	1822761	Ban Kut Kwang	4	Kut Kwang	shale	32.90	0.03	6.00	206.14	325.93	504.93
5	215050	1823718	Ban Non Du	5	Kut Kwang	siltstone	20.83	0.12	6.00	82.02	129.68	200.90
6	218307	1824711	Ban Hin Lat	12	Kut Kwang	shale	17.73	0.03	6.00	151.34	239.29	370.71
7	217782	1823867	Wat Arun Sawang Amphawan	14	Kut Kwang	shale	15.93	0.03	6.00	143.45	226.82	351.39
8	220210	1824889	Ban Nong Kung	15	Kut Kwang	shale	3.20	0.03	6.00	64.29	101.65	157.47
9	219987	1823820	Ban Nong Kung	15	Kut Kwang	shale	14.97	0.03	6.00	139.03	219.83	340.56
10	217190	1825136	Ban Non Sa-nga	16	Kut Kwang	shale	15.10	0.03	3.00	197.50	312.27	483.77
11	216380	1824169	Ban Nong Waeng	18	Kut Kwang	shale	11.57	0.03	6.00	122.23	193.26	299.39
12	236116	1823137	Ban Hua Na	2	Chorakhe	shale	32.57	0.03	6.00	205.09	324.28	502.37
13	235995	1823920	Ban Hua Na	2	Chorakhe	shale	7.97	0.03	3.00	143.45	226.82	351.39
14	236045	1822792	Ban Hua Na	3	Chorakhe	siltstone	32.17	0.12	6.00	101.91	161.14	249.64
15	235667	1823018	Ban Hua Na	3	Chorakhe	shale	4.47	0.03	3.00	107.42	169.84	263.11
16	237106	1821266	Ban Hua Buen	5	Chorakhe	shale	16.73	0.03	3.00	207.91	328.73	509.26
17	235970	1819717	Ban Nong Hoi	6	Chorakhe	shale	14.40	0.03	6.00	136.38	215.63	334.05
18	236384	1819635	Rongrian Ban Nong Hoi	6	Chorakhe	shale	32.77	0.03	3.00	290.93	460.00	712.63
19	238392	1822511	Ban Khok Klang	7	Chorakhe	siltstone	25.07	0.12	6.00	89.97	142.25	220.37
20	235669	1821788	Ban Nong Paen	8	Chorakhe	shale	19.37	0.03	3.00	223.67	353.65	547.87
21	235990	1819370	Ban Nong Hoi	9	Chorakhe	shale	16.97	0.03	6.00	148.03	234.06	362.61
22	237464	1821206	Ban Bueng Sawang	11	Chorakhe	shale	20.10	0.03	3.00	227.86	360.28	558.15
23	235898	1823066	Ban Hua Na	12	Chorakhe	shale	19.57	0.03	6.00	158.97	251.36	389.40
24	236224	1819441	Wat Nong Hoi	13	Chorakhe	shale	18.93	0.03	3.00	221.15	349.67	541.71
25	222755	1829879	Ban Non Thong	1	Non Thong	shale	56.50	0.03	3.00	382.03	604.05	935.78

Table 6.4 (Continued).

No.	UTM_E	UTM_N	PLACE	MU	TAMBON	Aquifer	Pumping rate (m^3/day)	Porosity	Screen length (m)	Radius of (m)		
										Tier 1	Tier 2	Tier 3
26	227229	1836007	Rongrian Ban Nong Khuean Chang	6	Non Thong	siltstone	85.00	0.12	3.00	234.29	370.45	573.89
27	225047	1833569	Ban Nong Nok Khian	7	Non Thong	siltstone	39.67	0.12	6.00	113.17	178.94	277.22
28	227531	1830156	Rongrian Ban Kut Khaen	8	Non Thong	shale	38.77	0.03	12.00	158.22	250.18	387.57
29	223296	1829384	Ban Non Thong	10	Non Thong	shale	20.83	0.03	3.00	231.98	366.80	568.24
30	228472	1831337	Ban Phai Noi	11	Non Thong	shale	10.50	0.03	3.00	164.69	260.40	403.41
31	220490	1832548	Rongrian Ban Huai Sai	13	Non Thong	shale	20.43	0.03	6.00	162.45	256.86	397.93
32	223789	1832177	Wat Ban Dong Noi	14	Non Thong	shale	16.67	0.03	3.00	207.49	328.07	508.25
33	225684	1831545	Wat Pho Si	16	Non Thong	shale	47.93	0.03	6.00	248.82	393.41	609.47
34	223709	1833041	Ban Sap Charoen	18	Non Thong	shale	30.62	0.03	3.00	281.23	444.66	688.86
35	223540	1828909	Ban Non Thong	19	Non Thong	shale	18.90	0.03	3.00	220.96	349.36	541.23
36	223623	1829594	Ban Non Thong	20	Non Thong	shale	45.37	0.03	3.00	342.33	541.27	838.53
37	218614	1826167	Ban Non Than	1	Non Than	shale	111.27	0.03	6.00	379.09	599.39	928.58
38	217363	1826180	Wat Ban Wa	3	Non Than	shale	53.33	0.03	3.00	371.17	586.87	909.18
39	220569	1826504	Wat Ban Na Pueai	5	Non Than	shale	50.57	0.03	6.00	255.56	404.08	625.99
40	220876	1826735	Ban Na	6	Non Than	shale	32.13	0.03	3.00	288.11	455.54	705.71
41	222980	1826236	Rongrian Ban Kut Chim	7	Non Than	siltstone	67.60	0.12	3.00	208.94	330.36	511.79
42	222848	1826550	Ban Kut Chim	8	Non Than	sandstone	21.33	0.27	4.00	67.77	107.15	165.99
43	223107	1826342	Wat Ban Kut Chim	8	Non Than	siltstone	21.67	0.12	3.00	118.29	187.03	289.75
44	223343	1826312	Ban Kut Chim	8	Non Than	sandstone	13.67	0.27	3.00	62.63	99.03	153.41
45	221587	1825560	Wat Ban Non Sa-at	11	Non Than	shale	29.17	0.03	3.00	274.49	434.00	672.35
46	218524	1825304	Ban Non Than Noi	12	Non Than	shale	13.63	0.03	3.00	187.66	296.72	459.68
47	212153	1830125	Ban Nong Hai	2	Non Sa-at	siltstone	31.30	0.12	3.00	142.17	224.80	348.25
48	213653	1827699	Ban Khok Klang	5	Non Sa-at	shale	67.47	0.03	3.00	417.46	660.07	1022.58
49	213822	1830091	Rongrian Ban Nong Lum Phuk	6	Non Sa-at	shale	20.00	0.03	6.00	160.72	254.12	393.69
50	213965	1829929	Ban Nong Lum Phuk	6	Non Sa-at	shale	13.33	0.03	6.00	131.23	207.49	321.44

Table 6.4 (Continued).

No.	UTM_E	UTM_N	PLACE	MU	TAMBON	Aquifer	Pumping rate (m^3/day)	Porosity	Screen length (m)	Radius of (m)		
										Tier 1	Tier 2	Tier 3
51	212735	1832514	Ban Non Waeng	7	Non Sa-at	siltstone	11.67	0.12	6.00	61.38	97.05	150.34
52	212896	1832426	Ban Non Waeng	7	Non Sa-at	siltstone	11.67	0.12	3.00	86.80	137.24	212.62
53	214981	1827378	Ban Don Han	9	Non Sa-at	shale	45.67	0.03	6.00	242.86	384.00	594.89
54	212338	1830700	Ban Non Sawan	10	Non Sa-at	sandstone	66.40	0.27	3.00	138.05	218.28	338.15
55	214142	1827626	Ban Non Khun	11	Non Sa-at	shale	17.23	0.03	6.00	149.19	235.89	365.44
56	211094	1829034	Ban Phon Sawan	12	Non Sa-at	shale	18.13	0.03	3.00	216.43	342.20	530.14
57	213491	1827022	Ban Non Sila	13	Non Sa-at	shale	20.83	0.03	3.00	231.98	366.80	568.24
58	214121	1830193	Wat Sawang Phaithun	14	Non Sa-at	shale	26.13	0.03	3.00	259.82	410.81	636.43
59	212587	1831428	Ban Non Sa-at	15	Non Sa-at	siltstone	27.23	0.12	3.00	132.62	209.68	324.84
60	237090	1827800	Wat Pho Thong	2	Ban Kong	shale	44.43	0.03	3.00	338.79	535.67	829.86
61	236391	1827506	Ban Pueai	3	Ban Kong	shale	31.67	0.03	3.00	286.01	452.22	700.57
62	235124	1824625	Wat Ban Nong Sa	4	Ban Kong	siltstone	43.33	0.12	6.00	118.29	187.03	289.75
63	234824	1825259	Ban Nong Sa	4	Ban Kong	siltstone	7.67	0.12	6.00	49.75	78.67	121.87
64	235345	1828245	Ban Nong Mek	5	Ban Kong	shale	31.73	0.03	3.00	286.31	452.69	701.31
65	236577	1826533	Ban Tha Li	7	Ban Kong	shale	18.00	0.03	3.00	215.63	340.94	528.19
66	226802	1820475	Ban Meng	2	Ban Meng	siltstone	17.47	0.12	3.00	106.21	167.93	260.15
67	227390	1819595	Ban Nong No	8	Ban Meng	siltstone	32.33	0.12	6.00	102.18	161.56	250.28
68	227329	1819606	Ban Nong No	8	Ban Meng	siltstone	18.17	0.12	3.00	108.31	171.26	265.31
69	224272	1819003	Ban Hat	10	Ban Meng	shale	10.50	0.03	4.00	142.63	225.51	349.36
70	224044	1819191	Ban Hat	10	Ban Meng	shale	23.83	0.03	3.00	248.12	392.32	607.78
71	224029	1820573	Wat Sabaeng	11	Ban Meng	sandstone	14.07	0.27	6.00	44.93	71.04	110.06
72	226649	1822075	Ban Nong Kung Noi	13	Ban Meng	shale	13.17	0.03	3.00	184.42	291.60	451.74
73	236836	1816181	Ban Yang Kham	1	Yang Kham	siltstone	41.93	0.12	3.00	164.56	260.19	403.09
74	236719	1815257	Wat Ban Nong Wa	3	Yang Kham	shale	32.27	0.03	3.00	288.70	456.48	707.18
75	235836	1813143	Wat Ban Don Khaem	4	Yang Kham	shale	56.33	0.03	6.00	269.74	426.49	660.72

Table 6.4 (Continued).

No.	UTM_E	UTM_N	PLACE	MU	TAMBON	Aquifer	Pumping rate (m^3/day)	Porosity	Screen length (m)	Radius of (m)		
										Tier 1	Tier 2	Tier 3
76	234320	1816798	Rongrian Ban Nong Waeng	10	Yang Kham	shale	60.93	0.03	3.00	396.74	627.30	971.80
77	236816	1816071	Ban Yang Kham	13	Yang Kham	siltstone	24.73	0.12	3.00	126.38	199.83	309.57
78	232201	1827583	Ban Nong Kung	4	Nong Rua	shale	28.33	0.03	3.00	270.54	427.75	662.67
79	233108	1824973	Ban Sa-at	7	Nong Rua	shale	12.80	0.03	6.00	128.58	203.30	314.95
80	232949	1824975	Rongrian Ban Sa-at	7	Nong Rua	shale	12.80	0.03	6.00	128.58	203.30	314.95
81	233056	1824553	Ban Sa-at	7	Nong Rua	shale	12.80	0.03	3.00	181.84	287.51	445.41
82	231670	1823940	Wat Non Phanit	8	Nong Rua	sandstone	18.97	0.27	6.00	52.17	82.49	127.79
83	231480	1823791	Ban Sala Thong	12	Nong Rua	sandstone	63.20	0.27	3.00	134.68	212.95	329.90

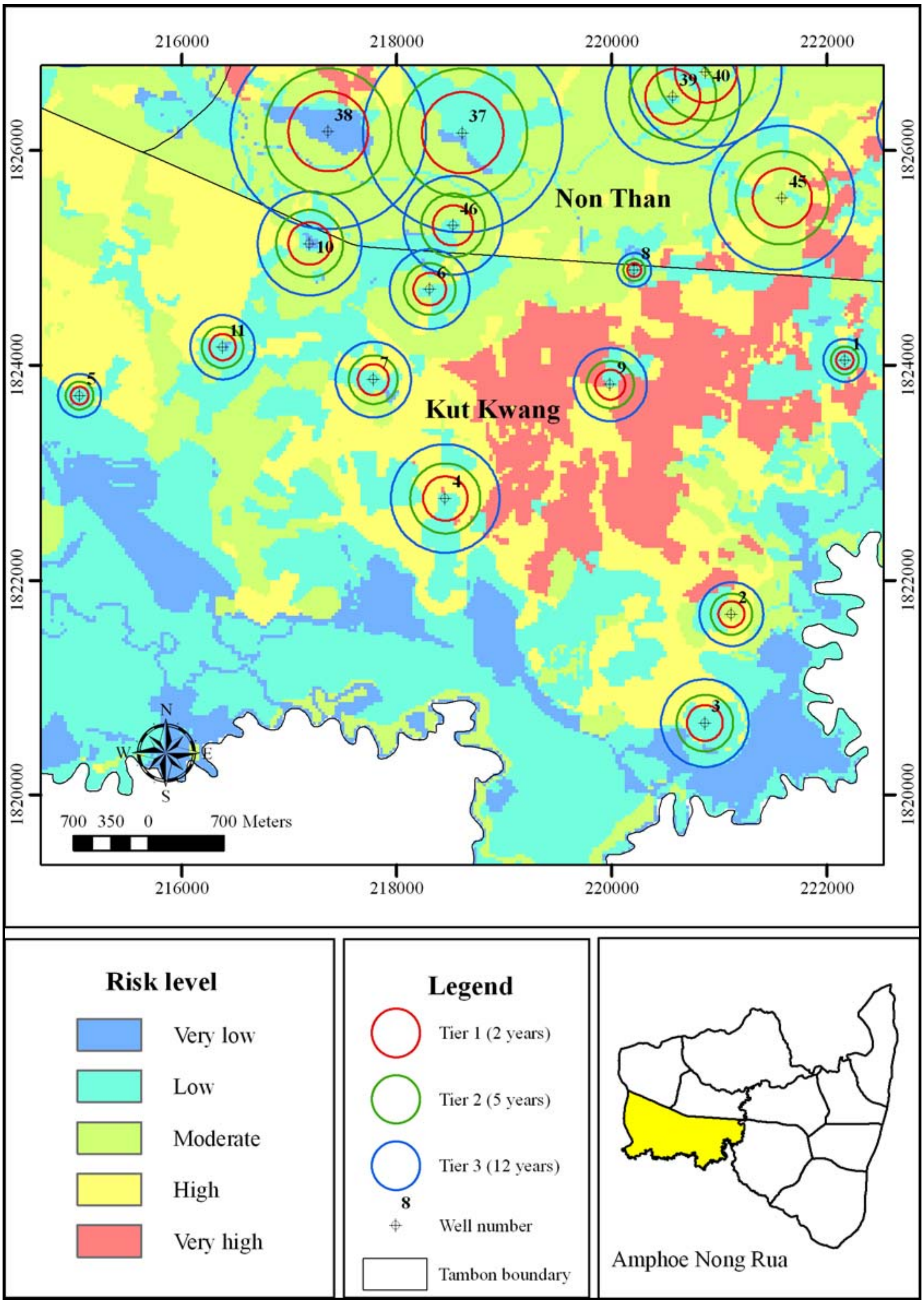


Figure 6.2 The capture zone areas of wells in Tambon Kut Kwang.

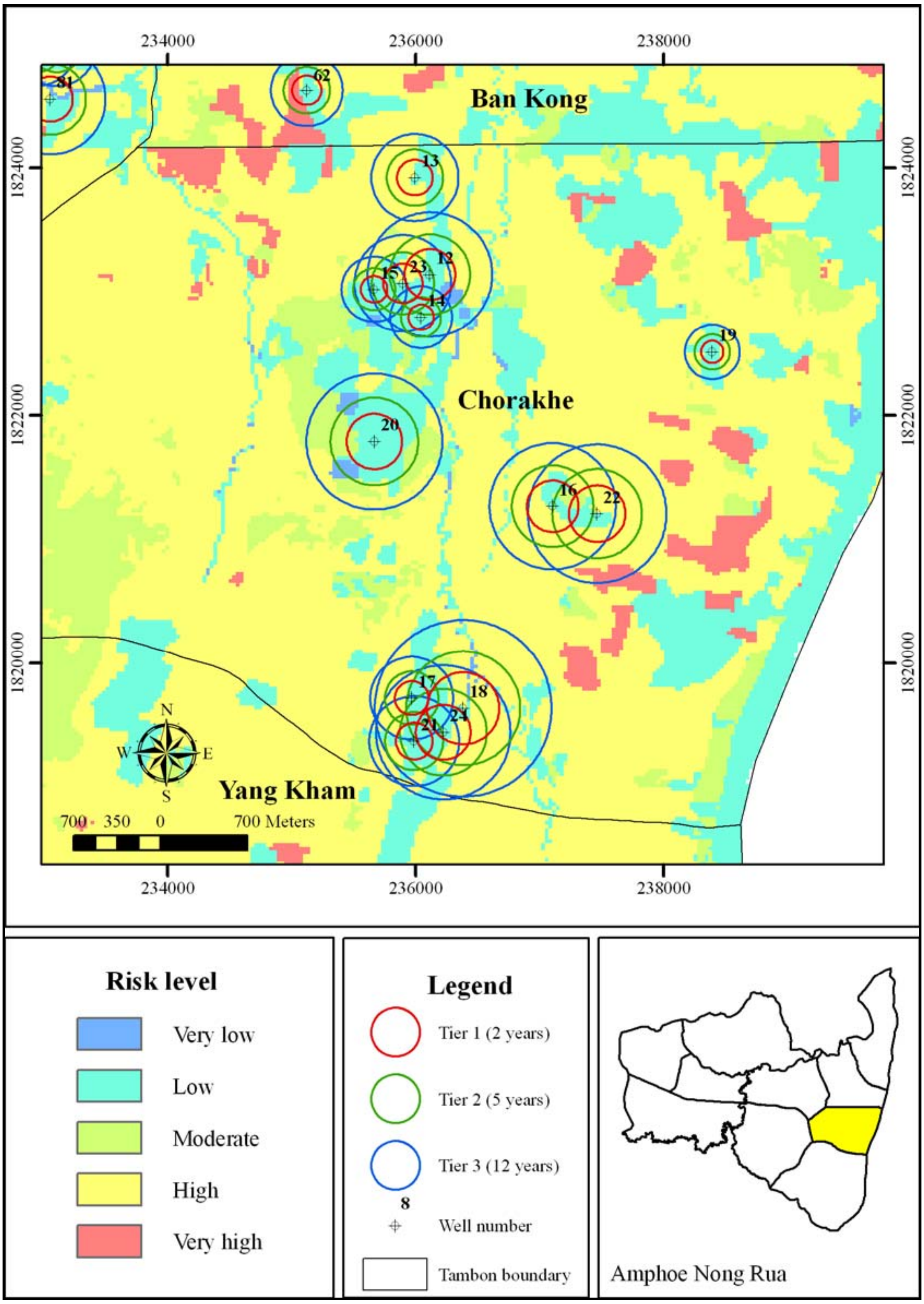


Figure 6.3 The capture zone areas of wells in Tambon Chorakhe.

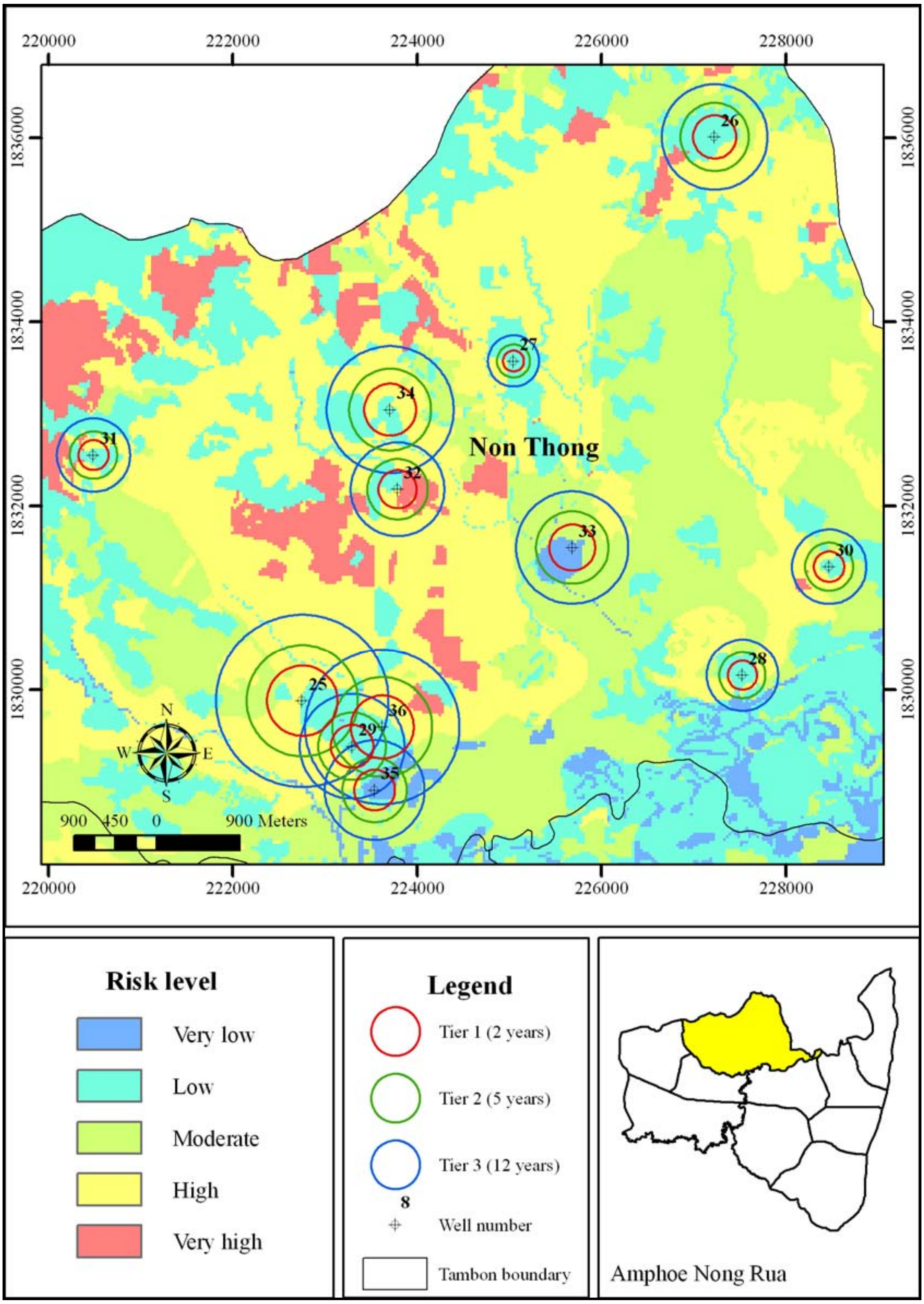


Figure 6.4 The capture zone areas of wells in Tambon Non Thong.

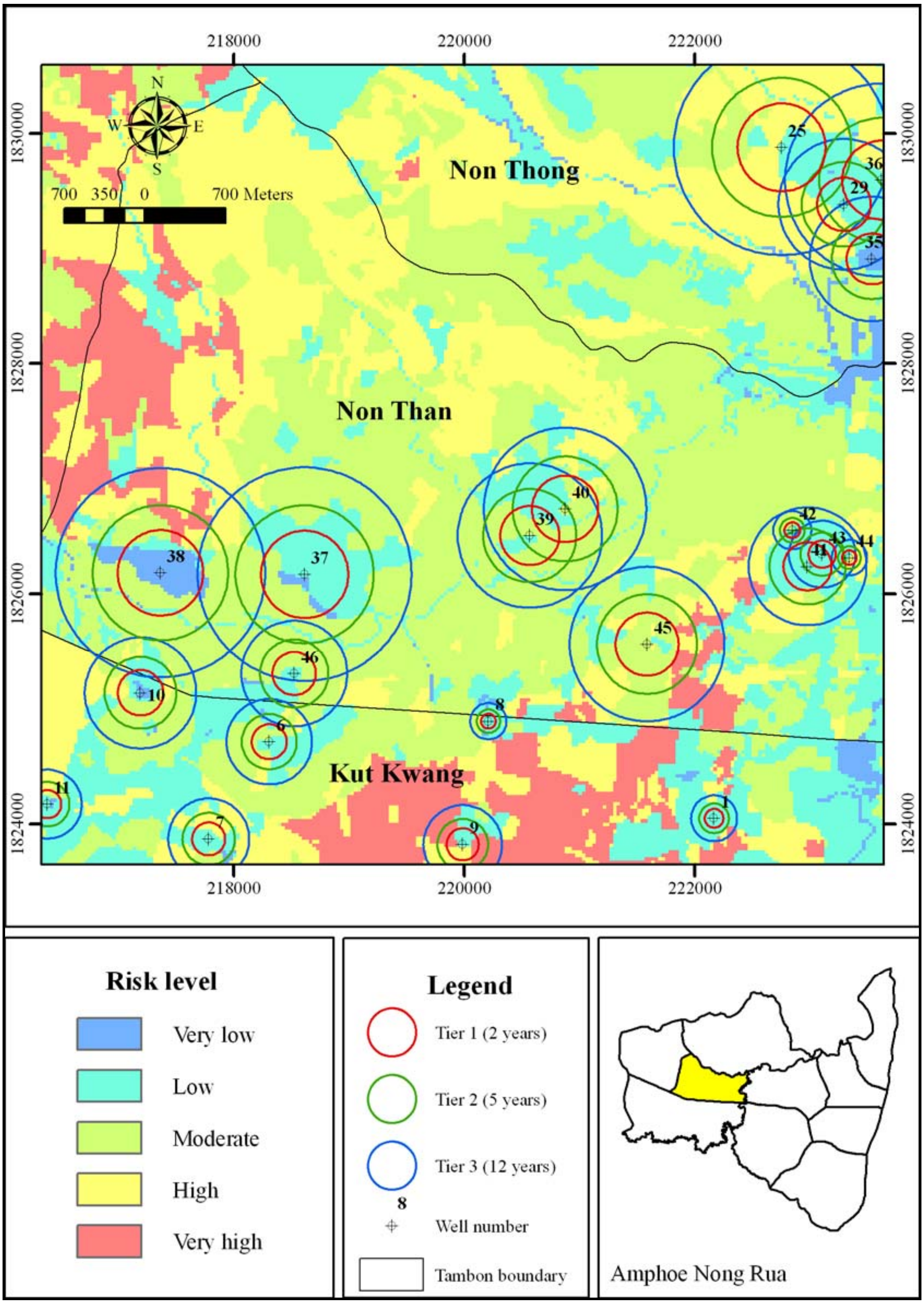


Figure 6.5 The capture zone areas of wells in Tambon Non Than.

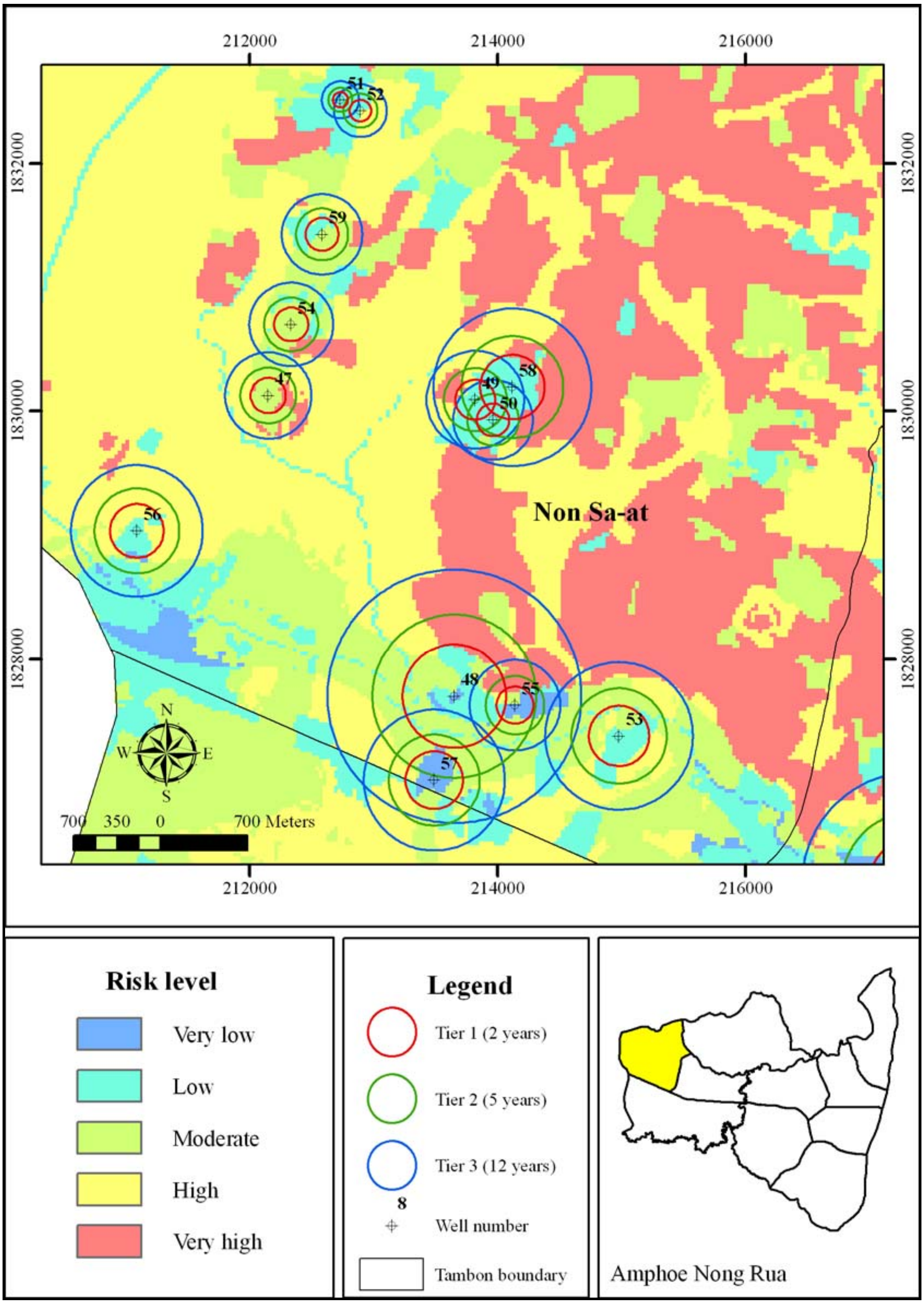


Figure 6.6 The capture zone areas of wells in Tambon Non Sa-at.

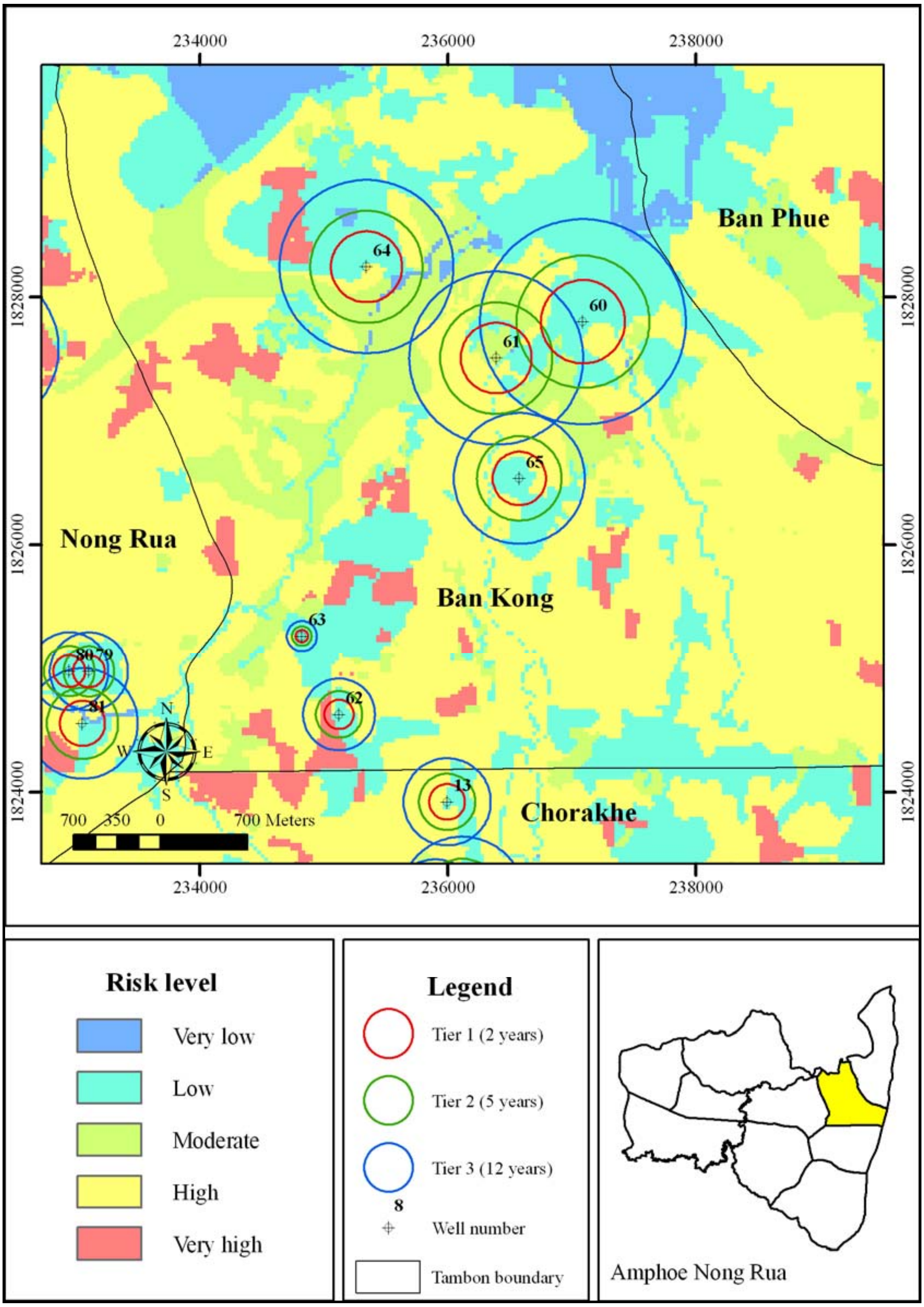


Figure 6.7 The capture zone areas of wells in Tambon Ban Kong.

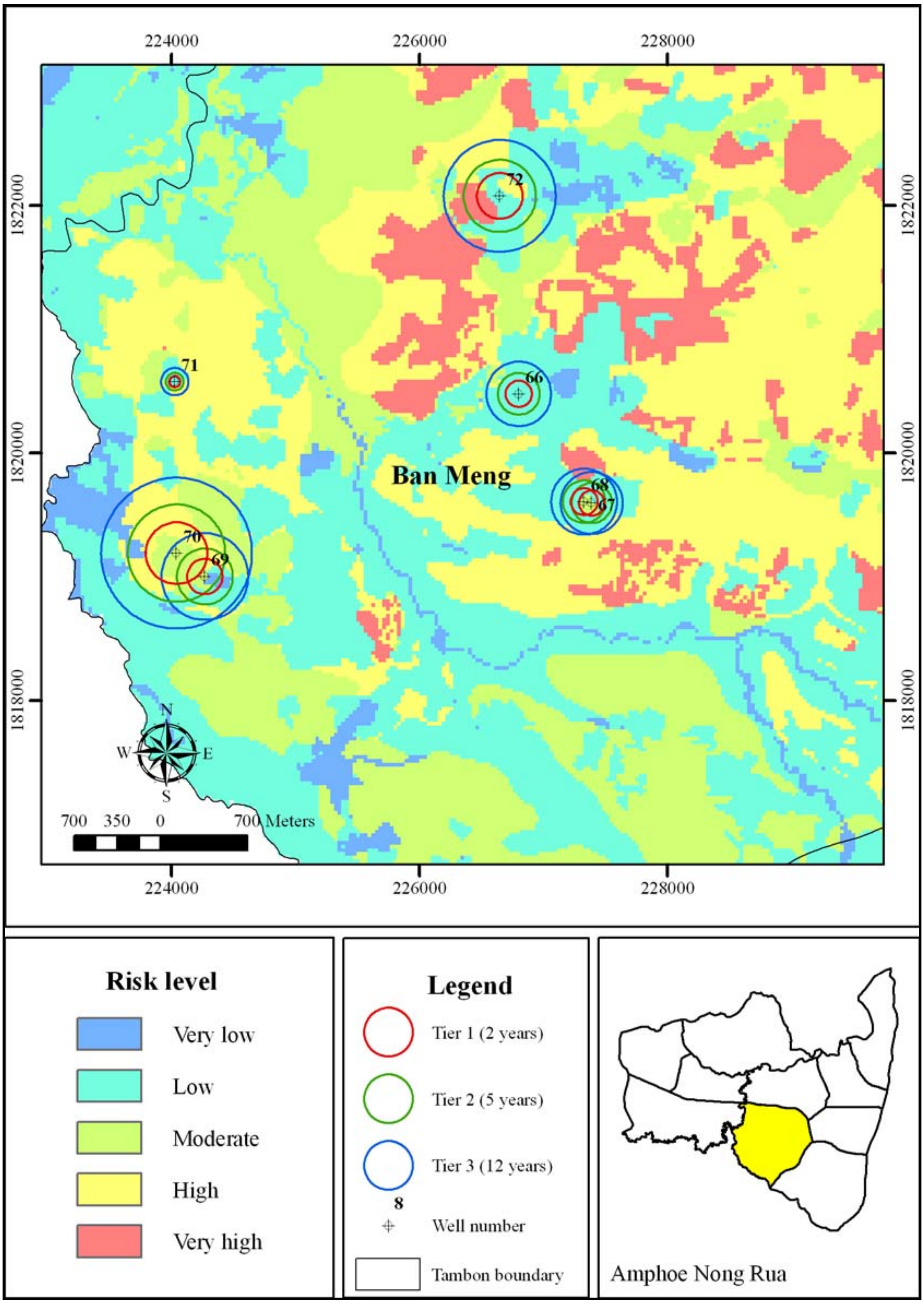


Figure 6.8 The capture zone areas of wells in Tambon Ban Meng.

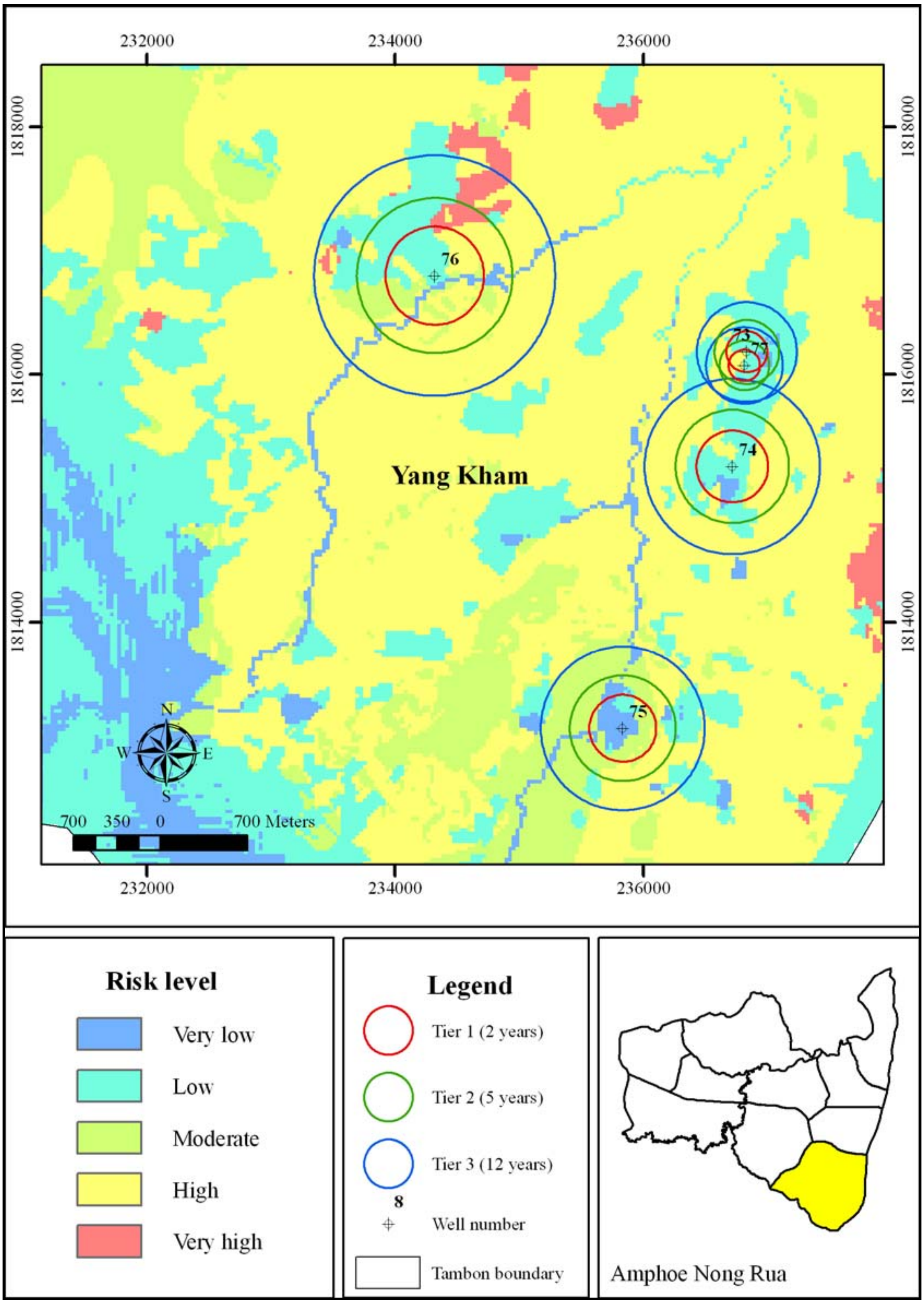


Figure 6.9 The capture zone areas of wells in Tambon Yang Kham.

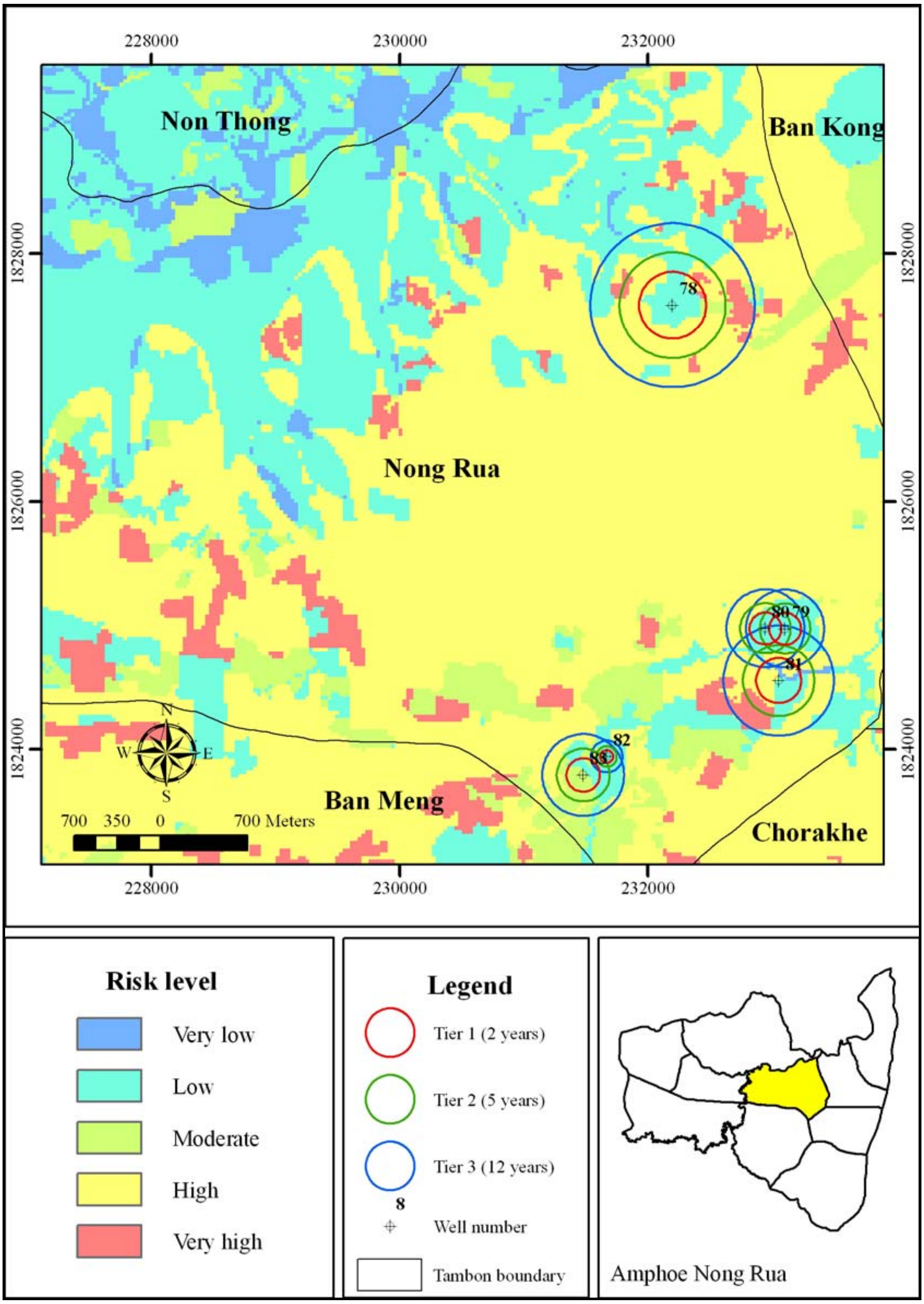


Figure 6.10 The capture zone areas of wells in Tambon Nong Rua.

6.4.2 The socio-economic value

The number of households in the study area was obtained from field investigation and varied between 10 and 230. A groundwater well supplying water work to the lowest number of households is the well no. 8 at Ban Nong Kung, Mu 5, Tambon Kut Kwang. The well no. 37 at Ban Non Than, Mu 1, Tambon Non Than is supplying water work to the highest number of households. Table 6.5 shows the number of households, alternative water sources, and socio-economic levels of wells. It is apparent that 33 wells in the study area provide low level of the socio-economic value. 27 and 23 wells with very low and moderate socio-economic levels are present.

Table 6.5 The number of households, alternative water sources, and socio-economic levels of wells.

No.	Place	Mu	Tambon	Number of household	Alternative water source	Level
1	Wat Chumphon	1	Kut Kwang	177	Surface water	L
2	Ban Khok Sung	2	Kut Kwang	122	None	M
3	Rongrian Khanuan Nakhon	3	Kut Kwang	91	None	L
4	Ban Kut Kwang	4	Kut Kwang	165	None	M
5	Ban Non Du	5	Kut Kwang	80	Surface water	VL
6	Ban Hin Lat	12	Kut Kwang	82	Surface water	VL
7	Wat Arun Sawang Amphawan	14	Kut Kwang	77	Surface water	VL
8	Ban Nong Kung	15	Kut Kwang	10	None	VL
9	Ban Nong Kung	15	Kut Kwang	55	Surface water	VL
10	Ban Non Sa-nga	16	Kut Kwang	70	None	L
11	Ban Nong Waeng	18	Kut Kwang	49	Surface water	VL
12	Ban Hua Na	2	Chorakhe	159	None	M
13	Ban Hua Na	2	Chorakhe	62	None	L
14	Ban Hua Na	3	Chorakhe	173	None	M
15	Ban Hua Na	3	Chorakhe	36	None	VL
16	Ban Hua Buen	5	Chorakhe	99	None	L
17	Ban Nong Hoi	6	Chorakhe	72	None	L
18	Rongrian Ban Nong Hoi	6	Chorakhe	154	None	M
19	Ban Khok Klang	7	Chorakhe	84	None	L
20	Ban Nong Paen	8	Chorakhe	102	Surface water	VL
21	Ban Nong Hoi	9	Chorakhe	130	None	M

Table 6.5 The number of households, alternative water sources, and socio-economic levels of wells (Continued).

No.	Place	Mu	Tambon	Number of household	Alternative water source	Level
22	Ban Bueng Sawang	11	Chorakhe	97	None	L
23	Ban Hua Na	12	Chorakhe	122	None	M
24	Wat Nong Hoi	13	Chorakhe	142	None	M
25	Ban Non Thong	1	Non Thong	188	None	M
26	Rongrian Ban Nong Khuean Chang	6	Non Thong	200	Surface water	L
27	Ban Nong Nok Khian	7	Non Thong	132	None	M
28	Rongrian Ban Kut Khaen	8	Non Thong	129	Surface water	L
29	Ban Non Thong	10	Non Thong	95	None	L
30	Ban Phai Noi	11	Non Thong	42	None	VL
31	Rongrian Ban Huai Sai	13	Non Thong	72	None	L
32	Wat Ban Dong Noi	14	Non Thong	67	None	L
33	Wat Pho Si	16	Non Thong	150	None	M
34	Ban Sap Charoen	18	Non Thong	167	None	M
35	Ban Non Thong	19	Non Thong	60	Surface water	VL
36	Ban Non Thong	20	Non Thong	151	None	M
37	Ban Non Than	1	Non Than	230	None	M
38	Wat Ban Wa	3	Non Than	189	None	M
39	Wat Ban Na Pueai	5	Non Than	180	None	M
40	Ban Na	6	Non Than	107	Surface water	VL
41	Rongrian Ban Kut Chim	7	Non Than	225	None	M
42	Ban Kut Chim	8	Non Than	60	None	L
43	Wat Ban Kut Chim	8	Non Than	50	None	L
44	Ban Kut Chim	8	Non Than	30	None	VL
45	Wat Ban Non Sa-at	11	Non Than	79	Surface water	VL
46	Ban Non Than Noi	12	Non Than	116	None	L
47	Ban Nong Hai	2	Non Sa-at	113	None	L
48	Ban Khok Klang	5	Non Sa-at	205	None	M
49	Rongrian Ban Nong Lum Phuk	6	Non Sa-at	60	Surface water	VL
50	Ban Nong Lum Phuk	6	Non Sa-at	40	Surface water	VL
51	Ban Non Waeng	7	Non Sa-at	146	Surface water	L
52	Ban Non Waeng	7	Non Sa-at	146	Surface water	L
53	Ban Don Han	9	Non Sa-at	152	Surface water	L
54	Ban Non Sawan	10	Non Sa-at	221	Surface water	L
55	Ban Non Khun	11	Non Sa-at	92	None	L
56	Ban Phon Sawan	12	Non Sa-at	70	Surface water	VL
57	Ban Non Sila	13	Non Sa-at	68	None	L
58	Wat Sawang Phaithun	14	Non Sa-at	97	Surface water	VL
59	Ban Non Sa-at	15	Non Sa-at	83	Surface water	VL
60	Wat Pho Thong	2	Ban Kong	143	Water work from surface water	VL
61	Ban Pueai	3	Ban Kong	130	Water work from surface water	VL

Table 6.5 The number of households, alternative water sources, and socio-economic levels of wells (Continued).

No.	Place	Mu	Tambon	Number of household	Alternative water source	Level
62	Wat Ban Nong Sa	4	Ban Kong	130	None	M
63	Ban Nong Sa	4	Ban Kong	29	None	VL
64	Ban Nong Mek	5	Ban Kong	174	Water work from surface water	VL
65	Ban Tha Li	7	Ban Kong	76	None	L
66	Ban Meng	2	Ban Meng	148	Surface water	L
67	Ban Nong No	8	Ban Meng	160	Surface water	VL
68	Ban Nong No	8	Ban Meng	87	Surface water	VL
69	Ban Hat	10	Ban Meng	48	Surface water	VL
70	Ban Hat	10	Ban Meng	116	None	L
71	Wat Sabaeng	11	Ban Meng	117	None	L
72	Ban Nong Kung Noi	13	Ban Meng	65	None	L
73	Ban Yang Kham	1	Yang Kham	186	Surface water	VL
74	Wat Ban Nong Wa	3	Yang Kham	173	None	M
75	Wat Ban Don Khaem	4	Yang Kham	211	Surface water	L
76	Rongrian Ban Nong Waeng	10	Yang Kham	223	Surface water	L
77	Ban Yang Kham	13	Yang Kham	112	Surface water	VL
78	Ban Nong Kung	4	Nong Rua	78	None	L
79	Ban Sa-at	7	Nong Rua	150	None	M
80	Rongrian Ban Sa-at	7	Nong Rua	150	None	M
81	Ban Sa-at	7	Nong Rua	150	None	M
82	Wat Non Phanit	8	Nong Rua	145	Surface water	L
83	Ban Sala Thong	12	Nong Rua	196	Surface water	L

6.4.3 Capture zone value

The capture zone value was assessed using the combination matrix between the kinds of tier and the socio-economic value of capture zone obtained from Table 6.2. Table 6.6 shows the capture zone value level of each tier of wells in the study area. Tier 1 was considered more important than the other tiers because of its shortest path length. 23 groundwater wells with high capture zone value level were considered as the first priority for urgent groundwater contamination protection. The second priority falls into 33 groundwater wells that show moderate capture zone value level. The last priority is for 27 groundwater wells with low capture zone value level.

Table 6.6 The capture zone value level of each tier of wells.

No.	UTM_E	UTM_N	Place	Mu	Tambon	Capture zone value		
						Tier 1	Tier 2	Tier 3
1	222169	1824046	Wat Chumphon	1	Kut Kwang	M	L	VL
2	221114	1821685	Ban Khok Sung	2	Kut Kwang	H	M	L
3	220867	1820668	Rongrian Khanuan Nakhon	3	Kut Kwang	M	L	VL
4	218452	1822761	Ban Kut Kwang	4	Kut Kwang	H	M	L
5	215050	1823718	Ban Non Du	5	Kut Kwang	L	VL	VL
6	218307	1824711	Ban Hin Lat	12	Kut Kwang	L	VL	VL
7	217782	1823867	Wat Arun Sawang Amphawan	14	Kut Kwang	L	VL	VL
8	220210	1824889	Ban Nong Kung	15	Kut Kwang	L	VL	VL
9	219987	1823820	Ban Nong Kung	15	Kut Kwang	L	VL	VL
10	217190	1825136	Ban Non Sa-nga	16	Kut Kwang	M	L	VL
11	216380	1824169	Ban Nong Waeng	18	Kut Kwang	L	VL	VL
12	236116	1823137	Ban Hua Na	2	Chorakhe	H	M	L
13	235995	1823920	Ban Hua Na	2	Chorakhe	M	L	VL
14	236045	1822792	Ban Hua Na	3	Chorakhe	H	M	L
15	235667	1823018	Ban Hua Na	3	Chorakhe	L	VL	VL
16	237106	1821266	Ban Hua Buen	5	Chorakhe	M	L	VL
17	235970	1819717	Ban Nong Hoi	6	Chorakhe	M	L	VL
18	236384	1819635	Rongrian Ban Nong Hoi	6	Chorakhe	H	M	L
19	238392	1822511	Ban Khok Klang	7	Chorakhe	M	L	VL
20	235669	1821788	Ban Nong Paen	8	Chorakhe	L	VL	VL
21	235990	1819370	Ban Nong Hoi	9	Chorakhe	H	M	L
22	237464	1821206	Ban Bueng Sawang	11	Chorakhe	M	L	VL
23	235898	1823066	Ban Hua Na	12	Chorakhe	H	M	L
24	236224	1819441	Wat Nong Hoi	13	Chorakhe	H	M	L
25	222755	1829879	Ban Non Thong	1	Non Thong	H	M	L
26	227229	1836007	Rongrian Ban Nong Khuean Chang	6	Non Thong	M	L	VL
27	225047	1833569	Ban Nong Nok Khian	7	Non Thong	H	M	L
28	227531	1830156	Rongrian Ban Kut Khaen	8	Non Thong	M	L	VL
29	223296	1829384	Ban Non Thong	10	Non Thong	M	L	VL
30	228472	1831337	Ban Phai Noi	11	Non Thong	L	VL	VL
31	220490	1832548	Rongrian Ban Huai Sai	13	Non Thong	M	L	VL
32	223789	1832177	Wat Ban Dong Noi	14	Non Thong	M	L	VL
33	225684	1831545	Wat Pho Si	16	Non Thong	H	M	L
34	223709	1833041	Ban Sap Charoen	18	Non Thong	H	M	L
35	223540	1828909	Ban Non Thong	19	Non Thong	L	VL	VL
36	223623	1829594	Ban Non Thong	20	Non Thong	H	M	L
37	218614	1826167	Ban Non Than	1	Non Than	H	M	L

Table 6.6 The capture zone value level of each tier of wells (Continued).

No.	UTM_E	UTM_N	Place	Mu	Tambon	Capture zone value		
						Tier 1	Tier 2	Tier 3
38	217363	1826180	Wat Ban Wa	3	Non Than	H	M	L
39	220569	1826504	Wat Ban Na Pueai	5	Non Than	H	M	L
40	220876	1826735	Ban Na	6	Non Than	L	VL	VL
41	222980	1826236	Rongrian Ban Kut Chim	7	Non Than	H	M	L
42	222848	1826550	Ban Kut Chim	8	Non Than	M	L	VL
43	223107	1826342	Wat Ban Kut Chim	8	Non Than	M	L	VL
44	223343	1826312	Ban Kut Chim	8	Non Than	L	VL	VL
45	221587	1825560	Wat Ban Non Sa-at	11	Non Than	L	VL	VL
46	218524	1825304	Ban Non Than Noi	12	Non Than	M	L	VL
47	212153	1830125	Ban Nong Hai	2	Non Sa-at	M	L	VL
48	213653	1827699	Ban Khok Klang	5	Non Sa-at	H	M	L
49	213822	1830091	Rongrian Ban Nong Lum Phuk	6	Non Sa-at	L	VL	VL
50	213965	1829929	Ban Nong Lum Phuk	6	Non Sa-at	L	VL	VL
51	212735	1832514	Ban Non Waeng	7	Non Sa-at	M	L	VL
52	212896	1832426	Ban Non Waeng	7	Non Sa-at	M	L	VL
53	214981	1827378	Ban Don Han	9	Non Sa-at	M	L	VL
54	212338	1830700	Ban Non Sawan	10	Non Sa-at	M	L	VL
55	214142	1827626	Ban Non Khun	11	Non Sa-at	M	L	VL
56	211094	1829034	Ban Phon Sawan	12	Non Sa-at	L	VL	VL
57	213491	1827022	Ban Non Sila	13	Non Sa-at	M	L	VL
58	214121	1830193	Wat Sawang Phaithun	14	Non Sa-at	L	VL	VL
59	212587	1831428	Ban Non Sa-at	15	Non Sa-at	L	VL	VL
60	237090	1827800	Wat Pho Thong	2	Ban Kong	L	VL	VL
61	236391	1827506	Ban Pueai	3	Ban Kong	L	VL	VL
62	235124	1824625	Wat Ban Nong Sa	4	Ban Kong	H	M	L
63	234824	1825259	Ban Nong Sa	4	Ban Kong	L	VL	VL
64	235345	1828245	Ban Nong Mek	5	Ban Kong	L	VL	VL
65	236577	1826533	Ban Tha Li	7	Ban Kong	M	L	VL
66	226802	1820475	Ban Meng	2	Ban Meng	M	L	VL
67	227390	1819595	Ban Nong No	8	Ban Meng	L	VL	VL
68	227329	1819606	Ban Nong No	8	Ban Meng	L	VL	VL
69	224272	1819003	Ban Hat	10	Ban Meng	L	VL	VL
70	224044	1819191	Ban Hat	10	Ban Meng	M	L	VL
71	224029	1820573	Wat Sabaeng	11	Ban Meng	M	L	VL
72	226649	1822075	Ban Nong Kung Noi	13	Ban Meng	M	L	VL
73	236836	1816181	Ban Yang Kham	1	Yang Kham	L	VL	VL
74	236719	1815257	Wat Ban Nong Wa	3	Yang Kham	H	M	L
75	235836	1813143	Wat Ban Don Khaem	4	Yang Kham	M	L	VL
76	234320	1816798	Rongrian Ban Nong Waeng	10	Yang Kham	M	L	VL
77	236816	1816071	Ban Yang Kham	13	Yang Kham	L	VL	VL
78	232201	1827583	Ban Nong Kung	4	Nong Rua	M	L	VL
79	233108	1824973	Ban Sa-at	7	Nong Rua	H	M	L
80	232949	1824975	Rongrian Ban Sa-at	7	Nong Rua	H	M	L

Table 6.6 The capture zone value level of each tier of wells (Continued).

No.	UTM_E	UTM_N	Place	Mu	Tambon	Capture zone value		
						Tier 1	Tier 2	Tier 3
81	233056	1824553	Ban Sa-at	7	Nong Rua	H	M	L
82	231670	1823940	Wat Non Phanit	8	Nong Rua	M	L	VL
83	231480	1823791	Ban Sala Thong	12	Nong Rua	M	L	VL

6.4.4 Groundwater protection zoning

The groundwater protection zoning of the area was constructed through the combined matrix operation of contamination risk and capture zone value levels as illustrated in Table 6.3. The zones with highest protection level were found at 32 wells. Moderate and low were found at 48 and 3 wells, respectively. This result was used to range the percent area cover of the highest protection level zone of each groundwater well. Table 6.7 shows the priority of the groundwater well protection urgency. The well with the first priority protection urgency is the well number 55 at Ban Non Khun, Mu 11, Tambon Non Sa-at and the one with the last priority is the well number 63 at Ban Nong Sa, Mu 4, Tambon Ban Kong.

Table 6.7 The priority of the groundwater well protection urgency.

Priority	Well No.	Place	Mu	Tambon	Protection zoning level	Ratio
1	62	Wat Ban Nong Sa	4	Ban Kong	High	14.27
2	81	Ban Sa-at	7	Nong Rua	High	12.53
3	4	Ban Kut Kwang	4	Kut Kwang	High	11.37
4	34	Ban Sap Charoen	18	Non Thong	High	10.65
5	18	Rongrian Ban Nong Hoi	6	Chorakhe	High	10.21
6	25	Ban Non Thong	1	Non Thong	High	8.28
7	48	Ban Khok Klang	5	Non Sa-at	High	7.82
8	36	Ban Non Thong	20	Non Thong	High	7.74
9	32	Wat Ban Dong Noi	14	Non Thong	High	6.50
10	74	Wat Ban Nong Wa	3	Yang Kham	High	5.54
11	12	Ban Hua Na	2	Chorakhe	High	5.27
12	24	Wat Nong Hoi	13	Chorakhe	High	5.06

Table 6.7 The priority of the groundwater well protection urgency (Continued).

Priority	Well No.	Place	Mu	Tambon	Protection zoning level	Ratio
13	23	Ban Hua Na	12	Chorakhe	High	4.92
14	2	Ban Khok Sung	2	Kut Kwang	High	4.39
15	72	Ban Nong Kung Noi	13	Ban Meng	High	3.56
16	38	Wat Ban Wa	3	Non Than	High	3.04
17	47	Ban Nong Hai	2	Non Sa-at	High	2.31
18	21	Ban Nong Hoi	9	Chorakhe	High	1.85
19	27	Ban Nong Nok Khian	7	Non Thong	High	1.52
20	55	Ban Non Khun	11	Non Sa-at	High	1.36
21	31	Rongrian Ban Huai Sai	13	Non Thong	High	0.49
22	78	Ban Nong Kung	4	Nong Rua	High	0.23
23	76	Rongrian Ban Nong Waeng	10	Yang Kham	High	0.16
24	39	Wat Ban Na Pueai	5	Non Than	High	0.07
25	80	Rongrian Ban Sa-at	7	Nong Rua	High	0.07
26	54	Ban Non Sawan	10	Non Sa-at	High	0.02
27	9	Ban Nong Kung	15	Kut Kwang	Moderate	51.44
28	79	Ban Sa-at	7	Nong Rua	Moderate	47.43
29	41	Rongrian Ban Kut Chim	7	Non Than	Moderate	47.25
30	58	Wat Sawang Phaithun	14	Non Sa-at	Moderate	38.00
31	22	Ban Bueng Sawang	11	Chorakhe	Moderate	37.23
32	37	Ban Non Than	1	Non Than	Moderate	33.24
33	33	Wat Pho Si	16	Non Thong	Moderate	33.11
34	70	Ban Hat	10	Ban Meng	Moderate	30.66
35	16	Ban Hua Buen	5	Chorakhe	Moderate	30.13
36	13	Ban Hua Na	2	Chorakhe	Moderate	26.24
37	65	Ban Tha Li	7	Ban Kong	Moderate	24.35
38	53	Ban Don Han	9	Non Sa-at	Moderate	21.58
39	14	Ban Hua Na	3	Chorakhe	Moderate	19.07
40	17	Ban Nong Hoi	6	Chorakhe	Moderate	17.46
41	75	Wat Ban Don Khaem	4	Yang Kham	Moderate	15.87
42	45	Wat Ban Non Sa-at	11	Non Than	Moderate	15.25
43	52	Ban Non Waeng	7	Non Sa-at	Moderate	14.53
44	57	Ban Non Sila	13	Non Sa-at	Moderate	14.10
45	50	Ban Nong Lum Phuk	6	Non Sa-at	Moderate	13.62
46	10	Ban Non Sa-nga	16	Kut Kwang	Moderate	13.53
47	83	Ban Sala Thong	12	Nong Rua	Moderate	13.15
48	26	Rongrian Ban Nong Khuean Chang	6	Non Thong	Moderate	12.08
49	29	Ban Non Thong	10	Non Thong	Moderate	11.94
50	19	Ban Khok Klang	7	Chorakhe	Moderate	11.36
51	46	Ban Non Than Noi	12	Non Than	Moderate	11.33
52	49	Rongrian Ban Nong Lum Phuk	6	Non Sa-at	Moderate	11.32
53	28	Rongrian Ban Kut Khaen	8	Non Thong	Moderate	10.59
54	30	Ban Phai Noi	11	Non Thong	Moderate	10.35
55	44	Ban Kut Chim	8	Non Than	Moderate	8.95

Table 6.7 The priority of the groundwater well protection urgency (Continued).

Priority	Well No.	Place	Mu	Tambon	Protection zoning level	Ratio
56	56	Ban Phon Sawan	12	Non Sa-at	Moderate	8.90
57	3	Rongrian Khanuan Nakhon	3	Kut Kwang	Moderate	8.16
58	64	Ban Nong Mek	5	Ban Kong	Moderate	7.73
59	68	Ban Nong No	8	Ban Meng	Moderate	6.68
60	59	Ban Non Sa-at	15	Non Sa-at	Moderate	6.41
61	61	Ban Pueai	3	Ban Kong	Moderate	6.18
62	77	Ban Yang Kham	13	Yang Kham	Moderate	6.17
63	71	Wat Sabaeng	11	Ban Meng	Moderate	5.29
64	42	Ban Kut Chim	8	Non Than	Moderate	4.89
65	1	Wat Chumphon	1	Kut Kwang	Moderate	4.31
66	67	Ban Nong No	8	Ban Meng	Moderate	4.27
67	7	Wat Arun Sawang Amphawan	14	Kut Kwang	Moderate	4.18
68	60	Wat Pho Thong	2	Ban Kong	Moderate	4.02
69	73	Ban Yang Kham	1	Yang Kham	Moderate	3.81
70	40	Ban Na	6	Non Than	Moderate	1.48
71	69	Ban Hat	10	Ban Meng	Moderate	1.14
72	11	Ban Nong Waeng	18	Kut Kwang	Moderate	0.94
73	35	Ban Non Thong	19	Non Thong	Moderate	0.64
74	15	Ban Hua Na	3	Chorakhe	Moderate	0.59
75	8	Ban Nong Kung	15	Kut Kwang	Moderate	0.40
76	5	Ban Non Du	5	Kut Kwang	Moderate	0.06
77	43	Wat Ban Kut Chim	8	Non Than	Moderate	0.05
78	66	Ban Meng	2	Ban Meng	Moderate	0.02
79	20	Ban Nong Paen	8	Chorakhe	Low	67.66
80	6	Ban Hin Lat	12	Kut Kwang	Low	61.19
81	82	Wat Non Phanit	8	Nong Rua	Low	54.21
82	51	Ban Non Waeng	7	Non Sa-at	Low	41.65
83	63	Ban Nong Sa	4	Ban Kong	Low	27.58

6.5 Conclusions

Groundwater protection urgency zoning is excellent decision making tool to rank groundwater wells required to be protected on the basis of hydrogeologic conditions, human impacts and socio-economic value. The priority of groundwater wells to be protected was determined by the zoning constructed by the combined matrix operation of the contamination risk and the capture zone value levels. This result showed that the well at Ban Non Khun, Mu 11, Tambon Non Sa-at was the first priority protection urgency. The capture zone value of groundwater wells was determined by the combined matrix between the kind of tier of capture zone and the socio-economic value level. The result showed that 23 groundwater wells with high capture zone value level were considered as the first priority for urgent groundwater contamination protection. The capture zone was delineated by the CFR method because of limitation on data of aquifer parameters for flow equations. The boundaries of capture zone were separated into three tiers consisting of tier 1 (2 years flowing path), tier 2 (5 years), and tier 3 (12 years). The socio-economic value level within the capture zone was evaluated dependent on a number of households being supplied from the wells and alternative water source availability. Moderate level was the highest socio-economic value found at 23 wells from the study area that.

The priority of groundwater wells for protection urgency is useful information to target wells which great care should be taken and should be focused on the protection of groundwater contamination.

6.6 References

Moinante, M.J. and Lobo-Ferreira, J.P. (2005). On wellhead protection assessment methods and a case-study application in Montemor-o-Novo, Portugal. In J.P.L. Ferreira and J.M.P. Vieira (ed.). **Proceedings of the Fourth InterCeltic Colloquium on Hydrology and Management of Water Resources, Guimaraes, Portugal, 4-11 July 2005** (pp 181-190). Portugal: Pitsumeikan University.

Spayd, S.E. and Johnson, S.W. (2003). **Guidelines for Delineation of Well Head Protection Areas in New Jersey**. New Jersey: New Jersey Geological Survey.

United States Environmental Protection Agency. (1994). **Handbook: Ground Water and Wellhead Protection**. Washington, DC: Office of Ground-Water Protection.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Groundwater is regarded as an important source of domestic water work in Amphoe Nong Rua located at the west of Changwat Khon Kaen. The deteriorate opportunity of its quality can be varied depending on the specific land use types including intrinsically physical properties of the area. Thus, to protect the groundwater properly and efficiently, its vulnerability and risk maps were established as significantly required. In addition, the groundwater zoning for urgent protection was developed to rank groundwater wells according to their values employed as the water work supplying source. From those results, all objectives of the study are achieved. The information obtained is very useful for groundwater protection and extraction planning related to the land use and physical properties of the area.

Groundwater vulnerability map was assessed by the use of SINTACS method based on the indexes cooperating on weighting and rating of seven parameters which are intrinsic properties of the area. These include the depth to water, infiltration, unsaturated zone, soil, aquifer, hydraulic conductivity, and slope. The vulnerability map was divided into six classes from very low to extremely high. The areas with very high and extremely high vulnerability are found in the northwest, southwest, and central of the study area. They are influenced by specific characteristics of the areas which are high infiltration rate, coarse-texture soil, and shallow depth to water.

The map removal sensitivity analyses based on variation index showed that slope and hydraulic conductivity were lowly sensitive whereas aquifer, depth to water, unsaturated zone, soil, and infiltration were highly sensitive. Based on error matrix, it is obvious that the unsaturated zone and slope were lowly sensitive. It means that both unsaturated zone and slope contain very low spatial variation and can be removed because of their low effect to the model result. From different point of view, the single parameter sensitivity analysis showed that the hydraulic conductivity was highly sensitive whereas the aquifer was lowly sensitive. The results imply that in this area the hydraulic conductivity in all scenarios should be considered more seriously when specific remedial measure to protect groundwater vulnerability is planned.

To validate the result, the statistical correlation coefficient between the nitrate concentration in wells and the SINTACS vulnerability map was performed. This resulted in a significantly positive correlation as high as 0.51.

Groundwater contamination risk map was evaluated by coupling the groundwater hazard map and groundwater vulnerability map using attribute matrix system method. The hazard map was constructed by the integration of spatial distribution of the potential hazard level of contamination sources from point and non-point sources. Three map layers including agricultural, urban, and other hazards were required as input for producing this map. NPSAHI method was applied to evaluate the agricultural hazard. The urban hazard was represented by the quantity of domestic wastewater value. The other hazard sources including sugar industry, municipal landfill, and livestock farm house were obtained from the land use map. The fuzzy hierarchical model was applied to calculate the hazard weight of each contaminant sources with respect to its toxicity, mobility, degradability, and volume. The resulting hazard map showed five levels from very low to very high. Land use classes fallen into the very high level include sugar industry, municipal landfill, and watermelon planting area. The final result of risk map contains five risk levels from very low to very high. High risk level dominated main part of the area. The very high risk area agrees with very high and extremely high vulnerability areas and mostly concentrated in the northwestern and southwestern parts of the study area. The statistical correlation coefficient between the nitrate concentration in the wells and the groundwater risk levels showed a significantly positive correlation (0.49).

Groundwater protection zoning was constructed by use of the combined matrix operation of the contamination risk and the capture zone value levels. The result provided ranking of the protection priority of groundwater wells. The capture zone value of groundwater wells was determined by the combined matrix between the kind of tier of capture zone and the socio-economic value. The CFR method was used to delineate the capture zone. The socio-economic value level within the capture zone was evaluated dependent on a number of households being supplied from the wells and alternative water source availability.

Groundwater vulnerability and risk maps are useful tools for identifying the priority of target areas and proper methods for management and protection. The vulnerability map shows the tendency or likelihood of contaminants to reach the groundwater system after their introduction at the ground surface on the basis of hydrogeologic conditions. The risk map shows the areas of greatest potential for groundwater contamination on the basis of different hydrogeologic conditions and human impacts. The priority of groundwater wells for urgent protection is excellent in providing the target wells for strategic planning and studying groundwater contamination in detail. This leads to assist in groundwater resource protection from quality degradation.

7.2 Recommendations

From the experience gained from this study, the recommendations for further study that could expect to yield better results are as follows.

1) A simple well test value was used to estimate hydraulic conductivity. This may cause uncertainty in vulnerability map. Therefore, the better result of the vulnerability could be expected if hydraulic conductivity from the pumping test is used.

2) Due to the limited time and budget, the annual loading data of pesticides and fertilizers were extracted from the guideline for agriculture and some literatures. Therefore, if they are systematically surveyed and collected based on plots, better result of the hazard could be expected.

3) In the future as data on parameters will become more available and accurate, namely local and regional water tables, aquifer recharge, well interference, hydrogeologic boundaries, aquifer heterogeneity, and aquifer anisotropy, the most appropriate and high accuracy mode for WHPA delineation could be performed using

the three-dimensional model. Then, the more accurate capture zone delineation could be expected.

4) Almost all of the factors employed in the hazard map construction are considered definitely lowly to moderately dynamic in terms of changing with time. Therefore, the hazard map, the derivative contamination risk map, and the groundwater wells for urgent protection should be reevaluated from time to time or when obvious change occurs to those relevant factors. Although the groundwater vulnerability map was constructed from intrinsic properties of the area which are considered more likely to be stable, it might have to be updated when more accurate data are available with time.

5) The statistical correlation coefficient between the nitrate concentration in wells and the SINTACS vulnerability map should be more frequently conducted. With adequate correlation data, they might assist in observing the corresponding relationship between what happen on the surface and water quality in the aquifer.

APPENDICES

APPENDIX A

ERROR MATRIX FOR COMPARISON OF ORIGINAL AND MAP REMOVAL VULNERABILITIES

Table A.1 Error matrix to compare original groundwater vulnerability and the one with depth to water (unit: pixel).

Vernerability Levels		Original						Total
		Very low	**Low**	**Moderate**	**High**	**Very high**	**Extremly high**	
When removed depth to water	**Very low**	28,116	5,061	7				33,184
	Low	22,465	23,209	2,569				48,243
	Moderate	416	49,311	73,398	4,281			127,406
	High		57	51,951	214,957	2,288	6	269,259
	Very high				48,042	27,385	1,376	76,803
	Extremly high				2,516	18,950	16,090	37,556
Total		50,997	77,638	127,925	269,796	48,623	17,472	592,451
Producer's Accuracy (%)		55	30	57	80	56	92	
User's Accuracy (%)		85	48	58	80	36	43	

Overall accuracy = 65% and Kappa coefficient = 51%

Table A.2 Error matrix to compare original groundwater vulnerability and the one with infiltration (unit: pixel).

Vernerability Levels		Original						Total
		Very low	Low	Moderate	High	Very high	Extremly high	
When removed infiltration	Very low	26,679	117	122				26,918
	Low	20,899	16,415	3,241	134			40,689
	Moderate	3,419	42,282	70,394	59,066	331		175,492
	High		18,824	53,467	204,174	42,926	13,953	333,344
	Very high			701	5,741	5,206	2,896	14,544
	Extremly high				681	160	623	1,464
Total		50,997	77,638	127,925	269,796	48,623	17,472	592,451
Producer's Accuracy (%)		52	21	55	76	11	4	
User's Accuracy (%)		99	40	40	61	36	43	

Overall accuracy = 55% and Kappa coefficient = 32%

Table A.3 Error matrix to compare original groundwater vulnerability and the one with unsaturated zone (unit: pixel).

Vernerability Levels		Original						Total
		Very low	Low	Moderate	High	Very high	Extremly high	
When removed unsaturated zone	Very low	50,165	7,274	9				57,448
	Low	832	68,072	11,569				80,473
	Moderate		2,292	108,531	12,633			123,456
	High			7,816	253,350	7,406	3	268,575
	Very high				3,813	39,118	2,927	45,858
	Extremly high					2,099	14,542	16,641
Total		50,997	77,638	127,925	269,796	48,623	17,472	592,451
Producer's Accuracy (%)		98	88	85	94	80	83	
User's Accuracy (%)		87	85	88	94	85	87	

Overall accuracy = 90% and Kappa coefficient = 86%

Table A.4 Error matrix to compare original groundwater vulnerability and the one with soil (unit: pixel).

Vernerability Levels		Original						Total
		Very low	Low	Moderate	High	Very high	Extremly high	
When removed soil	Very low	2,962	6,725	91				9,778
	Low	39,378	18,229	22,526	40			80,173
	Moderate	8,657	45,706	82,114	56,747			193,224
	High		6,978	23,194	195,473	28,203		253,848
	Very high				17,410	15,747	14,662	47,819
	Extremly high				126	4,673	2,810	7,609
Total		50,997	77,638	127,925	269,796	48,623	17,472	592,451
Producer's Accuracy (%)		6	23	64	72	32	16	
User's Accuracy (%)		30	23	42	77	33	37	

Overall accuracy = 54% and Kappa coefficient = 34%

Table A.5 Error matrix to compare original groundwater vulnerability and the one with aquifer (unit: pixel).

Vernerability Levels		Original						Total
		Very low	Low	Moderate	High	Very high	Extremly high	
When removed aquifer	Very low	47,602	10,648	22				58,272
	Low	3,395	56,717	7,507				67,619
	Moderate		10,273	80,759	1,667			92,699
	High			39,637	221,112	322		261,071
	Very high				47,017	28,019	266	75,302
	Extremly high					20,282	17,206	37,488
Total		50,997	77,638	127,925	269,796	48,623	17,472	592,451
Producer's Accuracy (%)		93	73	63	82	58	98	
User's Accuracy (%)		82	84	87	85	37	46	

Overall accuracy = 76% and Kappa coefficient = 67%

Table A.6 Error matrix to compare original groundwater vulnerability and the one with hydraulic conductivity (unit: pixel).

Vernerability Levels		Original						Total
		Very low	Low	Moderate	High	Very high	Extremly high	
When removed hydraulic conductivity	Very low	8,832	29,058	2,367				40,257
	Low	41,726	11,498	10,803	84			64,111
	Moderate	439	37,082	45,801	984			84,306
	High			68,954	212,754	4,566		286,274
	Very high				55,974	32,813	572	89,359
	Extremly high					11,244	16,900	28,144
Total		50,997	77,638	127,925	269,796	48,623	17,472	592,451
Producer's Accuracy (%)		17	15	36	79	67	97	
User's Accuracy (%)		22	18	54	74	37	60	

Overall accuracy = 55% and Kappa coefficient = 38%

Table A.7 Error matrix to compare original groundwater vulnerability and the one with slope (unit: pixel).

Vernerability Levels		Original						Total
		Very low	Low	Moderate	High	Very high	Extremly high	
When removed slope	Very low	43,578	6,298					49,876
	Low	7,046	61,943	14,277				83,266
	Moderate	373	9,397	110,349	33,838			153,957
	High			3,299	234,409	12,414		250,122
	Very high				1,549	35,222	1,625	38,396
	Extremly high					987	15,847	16,834
Total		50,997	77,638	127,925	269,796	48,623	17,472	592,451
Producer's Accuracy (%)		85	80	86	87	72	91	
User's Accuracy (%)		87	74	72	94	92	94	

Overall accuracy = 85% and Kappa coefficient = 79%

APPENDIX B

PHOTOS FROM FIELD INVESTIGATION

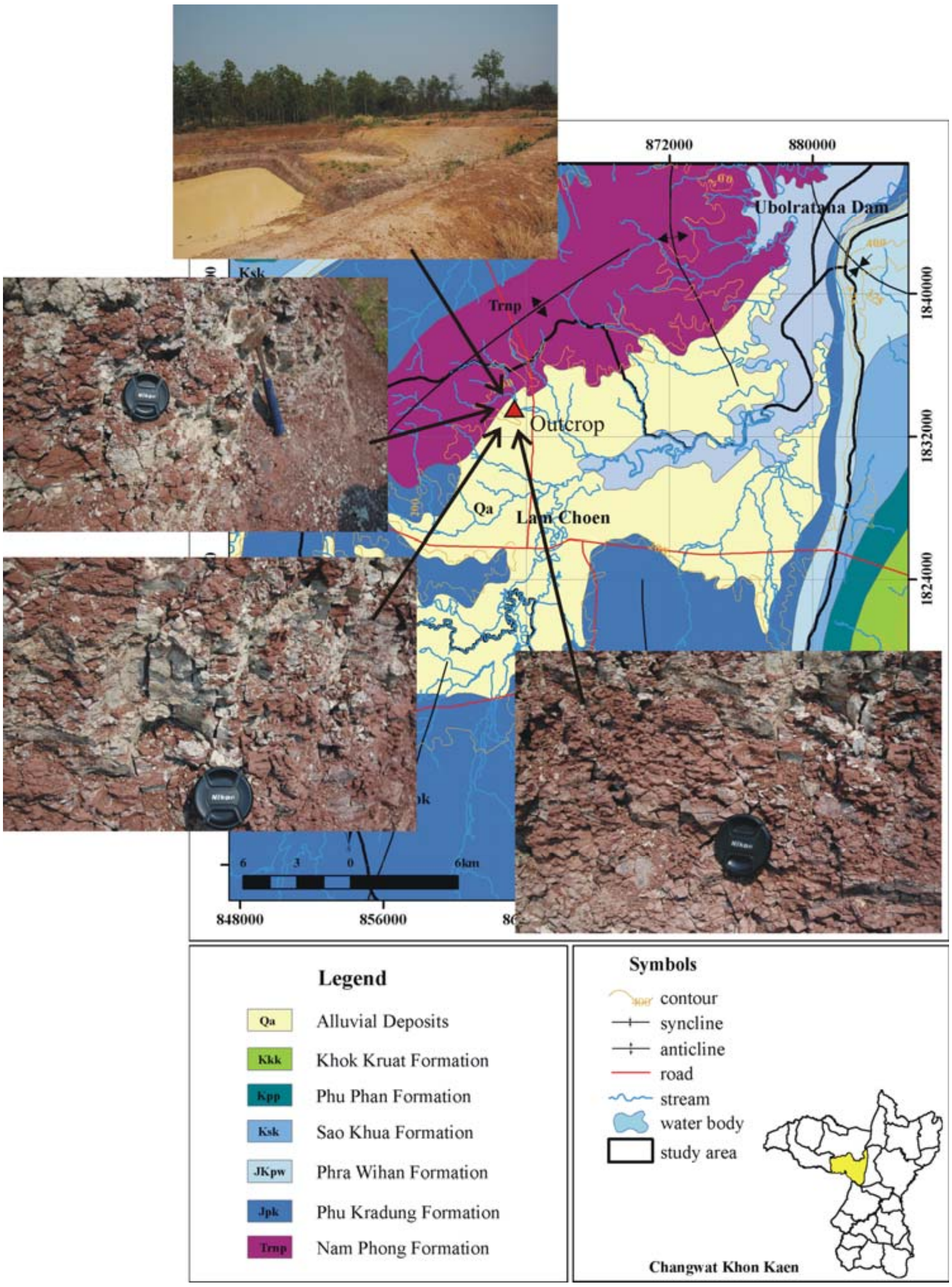
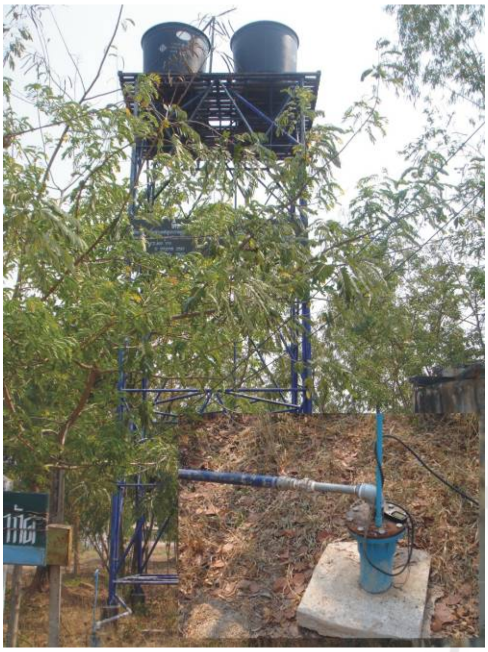


Figure B.1 Outcrops of Phu Kradung Formation in the study area.



Well No. 8 Ban Nong Kung, Mu 15, Tambon Kut Kwang

Well No. 14 Ban Hua Na, Mu 3, Tambon, Chorakhe

Well No. 18 Rongrian Ban Nong Hoi, Mu 6, Tambon Chorakhe

Well No. 64 Ban Nong Mek, Mu 5, Tambon Ban Kong

Figure B.2 The examples of wells supplying as water work source in the study area.

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