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VULNERABILITY ASSESSMENT OF GROUNDWATER RESOURCES IN THE LAMPANG BASIN OF NORTHERN THAILAND

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This study utilized the geographic information system technique and the DRASTIC method to assess the vulnerability of groundwater resources to contamination in the Lampang basin in northern Thailand. The area encompassed the Muang Lampang District, Hang Chat District, Ko Kha District, and Mae Tha District. The DRASTIC groundwater vulnerability map shows regional groundwater areas that are sensitive to contamination on the basis of hydrogeologic conditions. Seven hydrogeologic factors were used for vulnerability assessment. These are depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and aquifer hydraulic conductivity. These vulnerability factors were reclassified to vulnerability scores by using ArcView software to compute scales, ranges, and ratings. The vulnerability map shows that areas covered by Holocene unconsolidated sediments, the Qa aquifer unit, have the highest DRASTIC indices and are the most vulnerable to contamination. Pleistocene unconsolidated sediments, the Qt aquifer unit, have moderate to moderately high DRASTIC indices and contamination vulnerability. The areas of lowest contamination vulnerability are underlain by unconsolidated to semi-consolidated Tertiary sediments, the T aquifer unit.

INTRODUCTION

The Lampang basin is a large drainage basin located in northern Thailand. Major populated areas within the Lampang basin include the Muang Lampang District, Hang Chat District, Ko Kha District, and Mae Tha District. Groundwater is an important source of water supply for domestic, agricultural, and industrial use in the basin. The Thai National Committee on Irrigation and Drainage (2002) estimated that more than 50 percent of the total water supply is obtained from groundwater resources. This is especially so in the Hang Chat District, which lacks surface water for municipal water supplies. The groundwater usage in the basin is increasing as a result of city expansion and industrial growth. In the future, groundwater contamination could become a serious problem. A groundwater vulnerability assessment of the basin is needed to manage and reduce the contamination of groundwater resources.

The International Association of Hydrologists (1994) proposed the definition of vulnerability as an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts. The ultimate goal of a vulnerability map is a subdivision of an area into several units that show the differential potential for a specified purpose and use. Results of a vulnerability assessment are portrayed on a map that shows various homogeneous areas, each of which has unique levels of vulnerability, and do not represent absolute values. The most widely used groundwater vulnerability mapping method is an empirical model called DRASTIC. The DRASTIC model was developed for the U. S. Environmental Protection Agency by Aller et al. (1987) of the National Water Well Association to be a standardized system for evaluating groundwater vulnerability to pollution. The DRASTIC model has been used to produce maps in many parts of the United States (United States Geological Survey, 1999; Harman et al., 2000; Osborn et al., 1998; Kumar et al., 2003), in Portugal (Lobo-Ferreira and Oliveira, 2003), in Israel (Secunda et al., 1998), in Sweden (Rosen, 1994), in Australia (Piscopo, 2001), and in Jordan (Al-Adamat et al., 2003). The primary purpose of DRASTIC is to provide assistance in resource allocation and prioritization of many types of groundwater-related activities. It also is a practical education tool. DRASTIC can be used to set priorities of areas to conduct groundwater monitoring. For example, a monitoring system might be installed in areas where aquifer vulnerability is high and land use suggests a potential source of pollution. DRASTIC can also be used with other information, such as land use, potential sources of contamination, and beneficial uses of an aquifer, to identify areas where special attention or protection efforts are warranted. The DRASTIC model has four assumptions: 1) the contaminant is introduced at the ground surface, 2) the contaminant is flushed into the groundwater by precipitation, 3) the contaminant has the mobility of water, and 4) the area being evaluated by DRASTIC is 100 acres or larger (Osborn et al., 1998; Wyoming Water Resource Center, 1998, 1998a; Piscopo, 2001).

The purpose of this study was to provide a vulnerability map and information on the groundwater resource in the Lampang basin, which, in turn, could be incorporated into groundwater protection planning. The DRASTIC model was used to compute the relative vulnerability of groundwater to contamination from surface sources of pollution. The model results can be used to provide assistance in planning groundwater-related activities. Maps were developed by using the geographic information system computer mapping hardware and software to combine data layers. Groundwater vulnerability was determined by assigning point ratings to the individual data layers and then adding the point ratings together when these layers were combined into a vulnerability map.

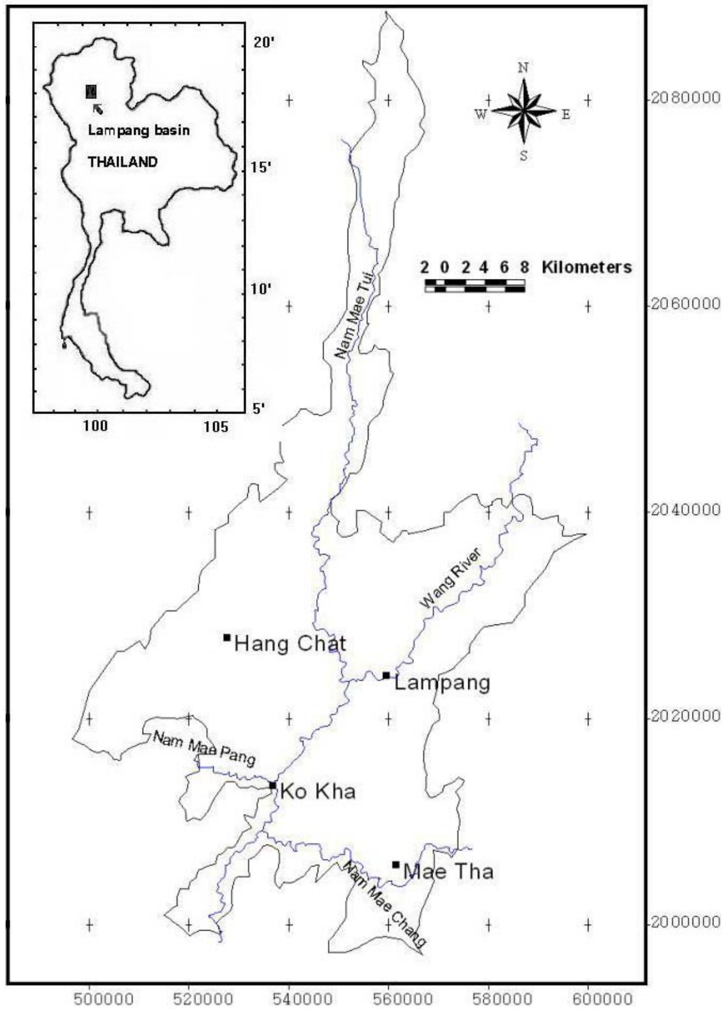

Figure 1. Location of the Lampang basin.

STUDY AREA

The Lampang basin is located in the northern continental highlands of Thailand between latitudes 18° 00' north and 18° 45' north and longitudes 99° 00' east and 99° 45' east. The basin covers about 850 square kilometers of the Muang District, Hang Chat District, Ko Kha District, and Mae Tha District in Lampang Province (Figure 1). The 2002 population of the study area was approximately 432,000.

The study area is an intermontane basin that resulted from tectonic evolution during the Tertiary Period (Thiramongkol, 1983; Chaodumrong, 1992). It is elongated and trends approximately north-south. The western and northern regions of the basin are bounded by mountain ranges underlain mainly by Silurian and Devonian metamorphic rocks, Carboniferous metasedimentary rocks, Permian clastic and volcanic rocks, and Triassic granitic rocks. The basin's eastern region is bounded mainly by mountain ranges of Permian volcanic rocks, and its southern region is bounded by Pleistocene basalt.

The catchment of the Lampang basin has a seasonal tropical climate and a mean annual precipitation of 1,100 millimeters. A distinct dry season occurs from November to April and 90 percent of the precipitation falls during the wet season between May and October. The mean annual temperature is 25.8 °C, with daily high extremes reaching 30 °C throughout the year and 36 °C in the hot dry months of February to May. Average pan evaporation is 131.61 millimeters in the dry season and 116.09 millimeters in the wet season (Meteorological Department, 2002). Forest and scrub cover approximately 40 percent of the study area. Paddy fields account for another 35 percent of the area, agricultural land another 15 percent, and building and houses occupy 10 percent.

HYDROGEOLOGIC SETTING

Faulting and subsidence in the Late Cenozoic formed the Lampang basin. Its sedimentary fill is about 300 meters thick. Although surrounding mountains and the underlying basement rocks are well-indurated pre-Tertiary metasedimentary and intrusive rocks, some Tertiary limestone occurs in the eastern part of the basin. These Tertiary rocks have low potential for being aquifers. Deep weathering and saprolite seal these rocks from major groundwater infiltration and they were, therefore, not considered in this study.

The Late Cenozoic sediments considered significant aquifers are Tertiary sediments, Pleistocene terrace deposits, and Holocene flood plain and channel deposits. These units are described in Figure 2 and Table 1. The depth to groundwater generally ranges from a few meters in the inner parts of the basin to 35 meters along the basin periphery. Groundwater movement is mainly topographically controlled and has a direction both from north to south and from the basin periphery to the basin center.

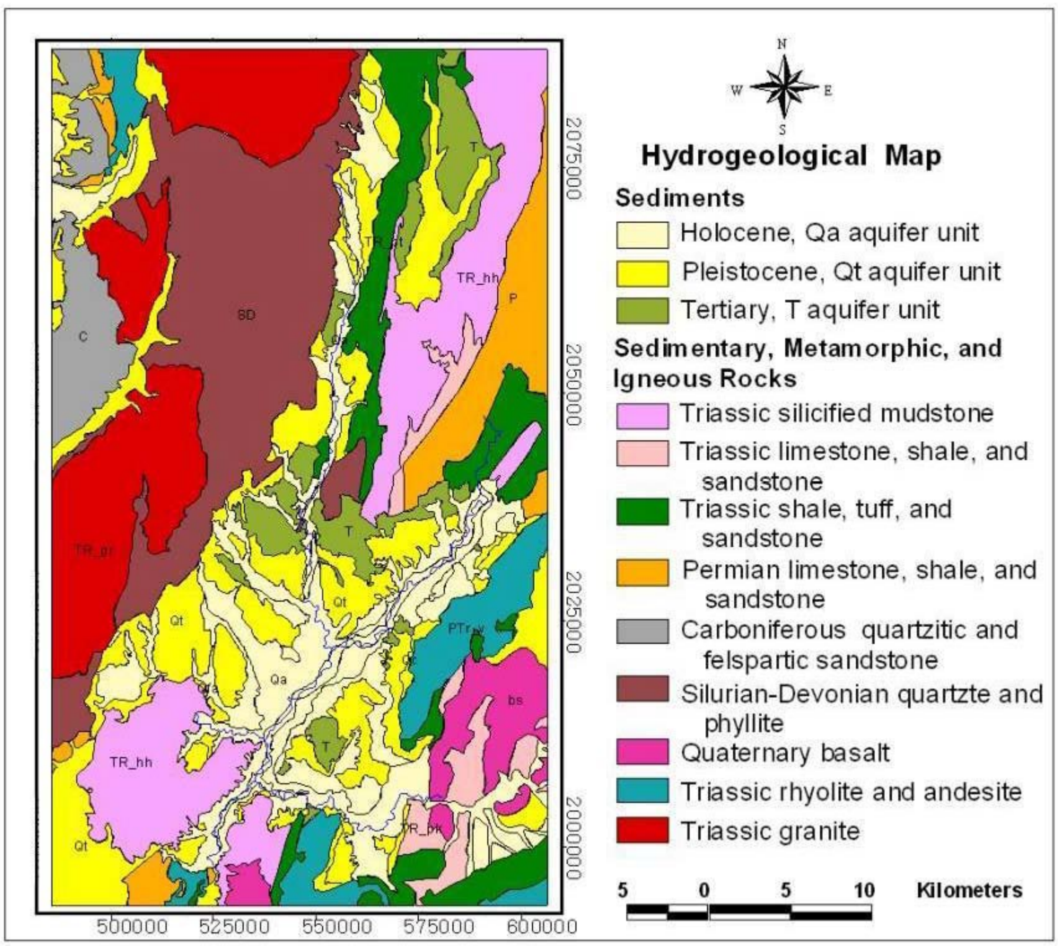

Figure 2. Hydrogeological map of the Lampang basin.

Table 1. Summary of Aquifers in the Lampang Basin

Hydrogeologic formation	Aquifer unit	Lithology	Average depth (m)	Yield (m^3/day)	Transmissivity (m^2/day)
Quaternary Holocene	Qa	Meandering belt sub-unit: sand, light gray, light brown, interbedded with gray clay layers. Natural levee silt sub-unit: silt, very fine sand, light brown, micaceous, overlies thick-bedded clay. Alluvial fan sand and clay subunit: sand, clayey and silty, light gray, interbedded with sandy clay. Fluvial clay sub-unit: clay, gray, silt, clay, and mud.	9-80	40-1,300	2-625
Quaternary Pleistocene	Qt	Terrace deposits, coarse fluviatile sediments that fill gravel beds, sand, silt, and clay, with thick layer of laterite.	6-120	60-960	1-250
Tertiary Upper	T	Unconsolidated and semi-consolidated sediments, sandy clay, clayey sand, gravelly sand, and gravel, shale, siltstone, sandstone, mudstone, and diatomaceous shale.	18-190	50-250	1-33

METHODOLOGY

The DRASTIC vulnerability mapping technique is a composite of the major hydrogeologic factors that effect groundwater movement. DRASTIC considers seven factors:

D - Depth to water table
R - Recharge (net)
A - Aquifer media
S - Soil media
T - Topography
I - Impact of vadose zone media
C - Conductivity (hydraulic) of the aquifer

To assess groundwater vulnerability, a numerical ranking is used on the DRASTIC features. This ranking considers weights, ranges, and ratings.

Weights

Weights of 1 to 5 relative to each of the seven factors are assigned in order of importance. Table 2 shows the assigned weights for these DRASTIC factors.

Ranges

Each DRASTIC factor has an upper and lower limit of variability within the Lampang basin. This variable range has been devised on the basis of its impact on pollution potential.

Table 2. Weights of DRASTIC Hydrogeologic Factors

Hydrogeologic Factor		Weight
D	Depth to water	5
R	Recharge (net)	4
A	Aquifer media	3
S	Soil media	2
T	Topography	1
I	Impact of vadose zone media	5
C	Hydraulic conductivity of aquifer	3

Ratings

The hydrogeologic factors are assigned a rating value lying between 1 to 10 on the basis of their range values. These ratings provide a relative assessment among the ranges of each factor.

The equation for determining the DRASTIC index is:

$$\text{DRASTIC index} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

where D, R, A, S, T, I, and C represent the seven hydrogeologic factors, r is the rating, and w is the weight.

The map calculator function in the spatial analyst extension of the ArcView geographic information system was used to compile the geospatial data, to compute the DRASTIC index, and to generate the final vulnerability map (Environmental System Research Institute, Inc., 1997). This study created digital geospatial data sets for surficial geology (aquifer media), hydraulic conductivity, depth to water table, recharge, soil media, topography, and impact of the vadose zone. The study overlaid a model grid over the boundaries of the basin and assigned DRASTIC ratings to the grid cells for each of the seven hydrogeological factors. The cell size is 250 × 250 meters and the total coverage is about 850 square kilometers. The study used the grid layers to compute the final DRASTIC indices and to produce the aquifer vulnerability map.

The resulting DRASTIC indices represent a relative measure of groundwater vulnerability. The higher the DRASTIC index, the greater the vulnerability of the aquifer to contamination. A site with a low DRASTIC index is not free from groundwater contamination, however, but it is less susceptible to contamination compared with the sites with high DRASTIC indices.

Hydrogeologic Factors

Depth to water table (D): The depth to water table is the distance, in meters, from the ground surface to the water table. It determines the thickness of material through which a contaminant must travel before reaching the aquifer. Thus, the shallower the water depth, the more vulnerable the aquifer is to pollution.

The grid layer for depth to water table was generated from field data in 2003. The depth to water table ranges from less than 5 meters in Holocene aquifers to more than 25 meters in Upper Tertiary aquifers.

Net **R**echarge (R): The primary source of recharge is precipitation that infiltrates through the ground surface and percolates to the water table. Net recharge is the total quantity of water per unit area, in millimeters per year, which reaches the water table. Recharge is the principal vehicle for leaching and transporting contaminants to the water table. The higher the recharge is, the greater the chance for contaminants to reach the water table.

The grid layer for net recharge was developed from the recharge data sets. Recharge rates for the aquifers were derived from groundwater models and represent averages over all of the area. The recharge rate values from the model range from 32 to 66 millimeters per year.

Aquifer media (A): Aquifer media refers to the consolidated and unconsolidated rock that serves as an aquifer. The larger the grain size and the more fractures or openings within an aquifer make for higher permeability and, thus, increase the vulnerability of the aquifer. In unconsolidated aquifers, the rating is based on the sorting and amount of fine material within the aquifer. In consolidated aquifers, the rating is based on the amount of primary porosity and secondary porosity along fractures and bedding planes.

Information on aquifer media was obtained from the geologic map of the Department of Mineral Resources (1995) and from hydrogeology studies of Kwansirikul (1999). Ratings for the aquifers in this study range from 1 for the Devonian-Silurian aquifers to 10 for the Holocene aquifers.

Soil media (S): Soil media refers to the upper weathered soil zone, which averages two meters or less in thickness below the ground surface. Soil has a significant impact on the amount of recharge that can infiltrate into the ground.

The grid layer for soil media (permeability) was determined from the soil map developed by Department of Land Development (1992).

Topography (T): Topography refers to the slope of the land surface. Topography controls in part the likelihood that a pollutant will run off or infiltrate below the ground surface. Where slopes are low, runoff is slow and the potential for pollution is relatively great. However, where slopes are steep, runoff is quick and the potential for pollution to reach groundwater is relatively low.

The study used a digital elevation model to calculate percent slope and most slopes ranged from 0 to 2 percent.

Impact of the vadose zone media (I): The vadose zone is the unsaturated zone above the water table. The texture of the vadose zone determines the time of travel of a contaminant. In surficial aquifers, the ratings for the vadose zone are generally the same as the aquifer media. Sometimes, however, a lower rating is assigned if the aquifer media is overlain by a less permeable layer, such as clay.

The impact of the vadose zone grid layer was obtained from the geological map of the Department of Mineral Resources (1995) and from the hydrogeology study of the Lampang basin by Kwansirikul (1999).

Hydraulic conductivity of the aquifer (C): Hydraulic conductivity controls the rate at which water flows through an aquifer. The higher the hydraulic conductivity, the higher the vulnerability of the aquifer.

Hydraulic conductivity values for each aquifer of the study area were derived from groundwater flow models. These aquifers have horizontal hydraulic conductivity ranges of 0.0837 to 0.2794 meters per day.

Range and Rating for the Groundwater Vulnerability Map

Ranges and ratings for depth to water table, recharge, aquifer media, soil media, topography, impact of the vadose zone media, and hydraulic conductivity of the aquifers in the Lampang basin are shown in Figures 3, 4, 5, 6, 7, 8, and 9, respectively.

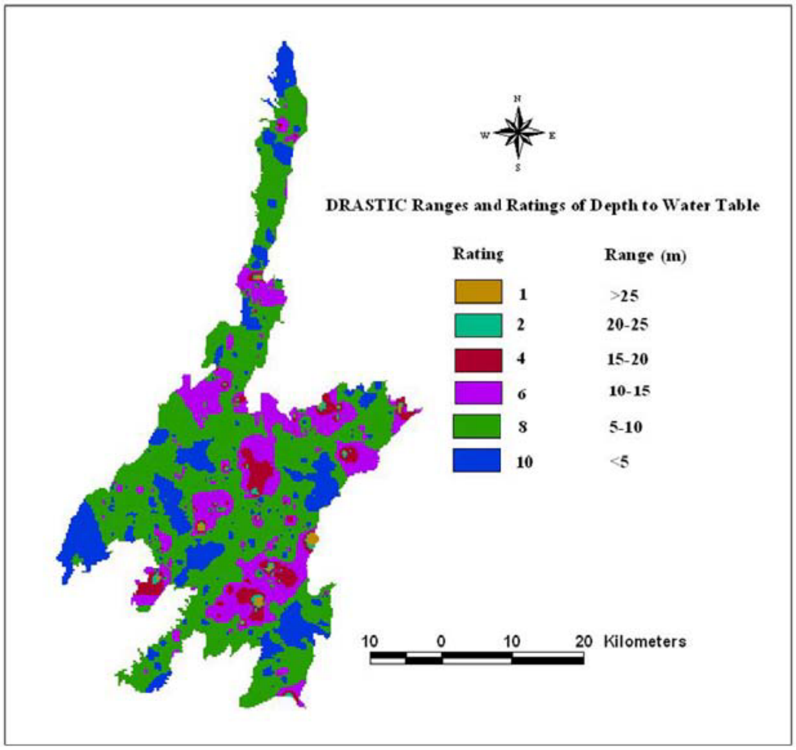

Figure 3. Map showing DRASTIC ranges and ratings for depth to water table.

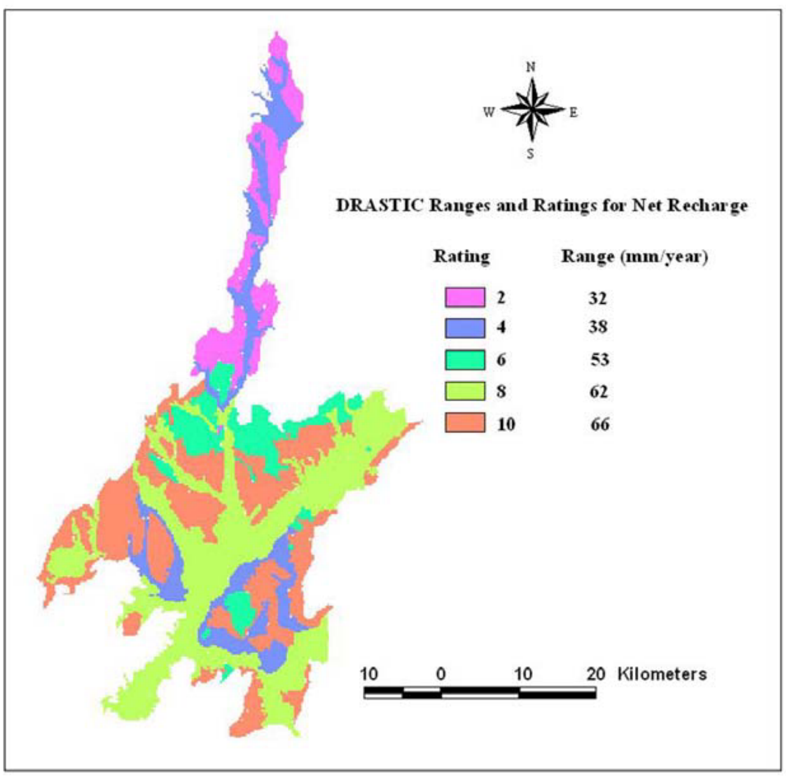

Figure 4. Map showing DRASTIC ranges and ratings for net recharge.

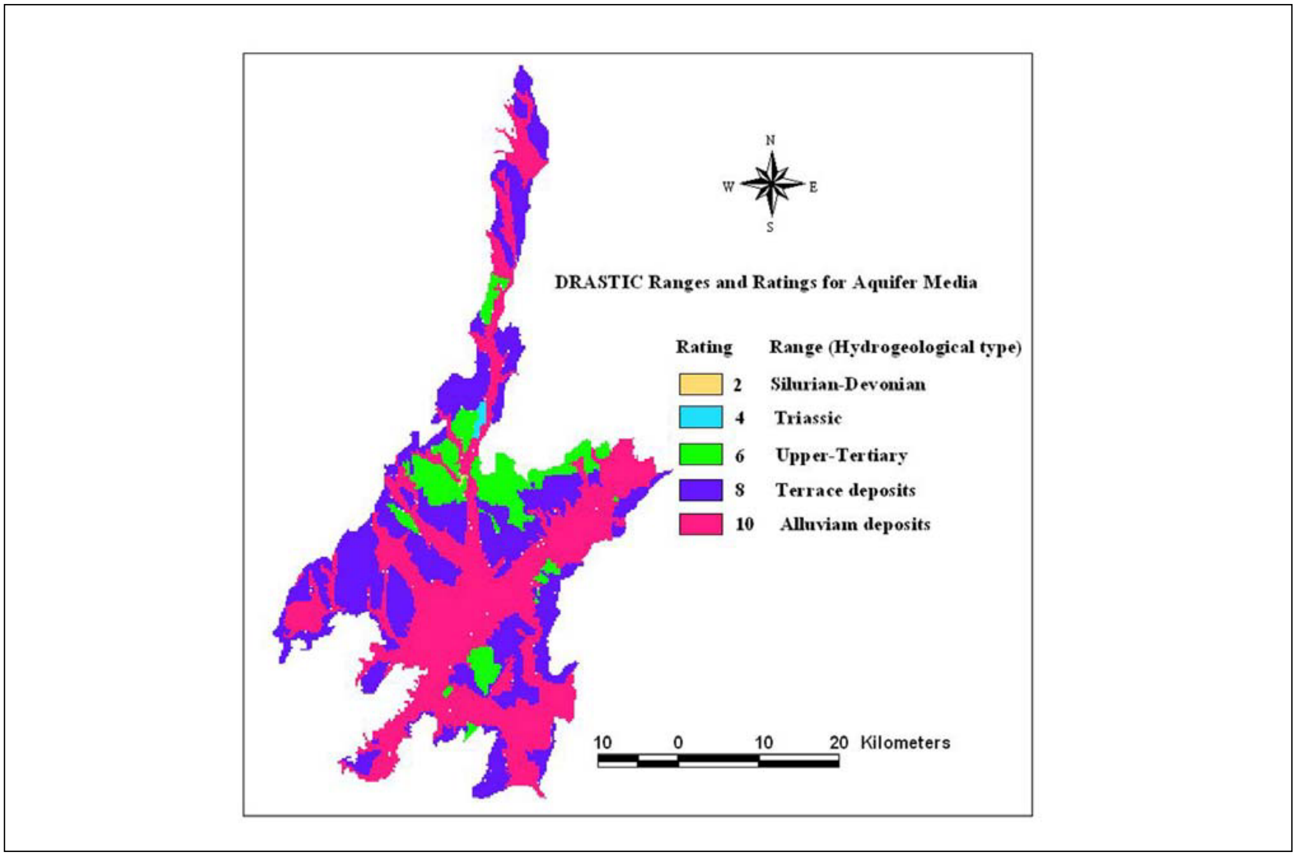

Figure 5. Map showing DRASTIC ranges for aquifer media.

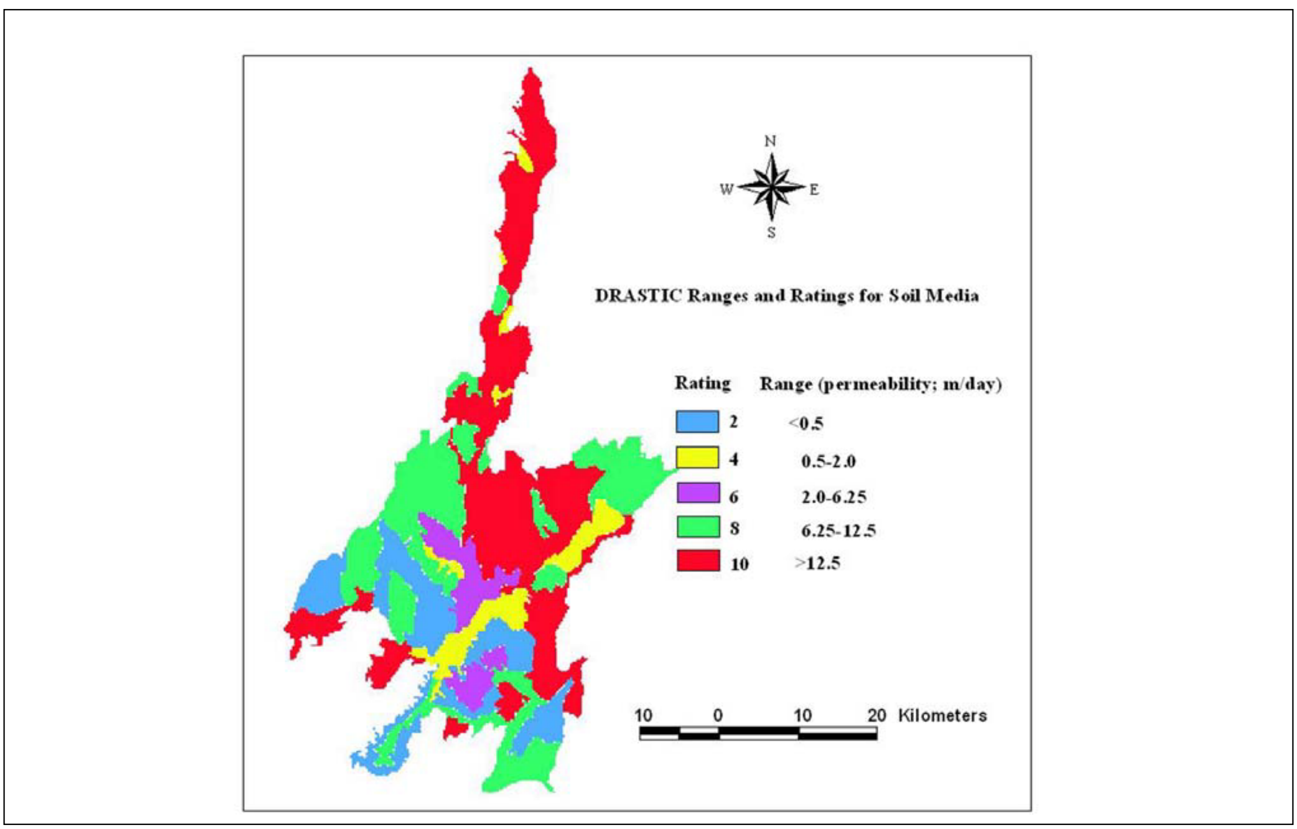

Figure 6. Map showing DRASTIC ranges and ratings for soil media.

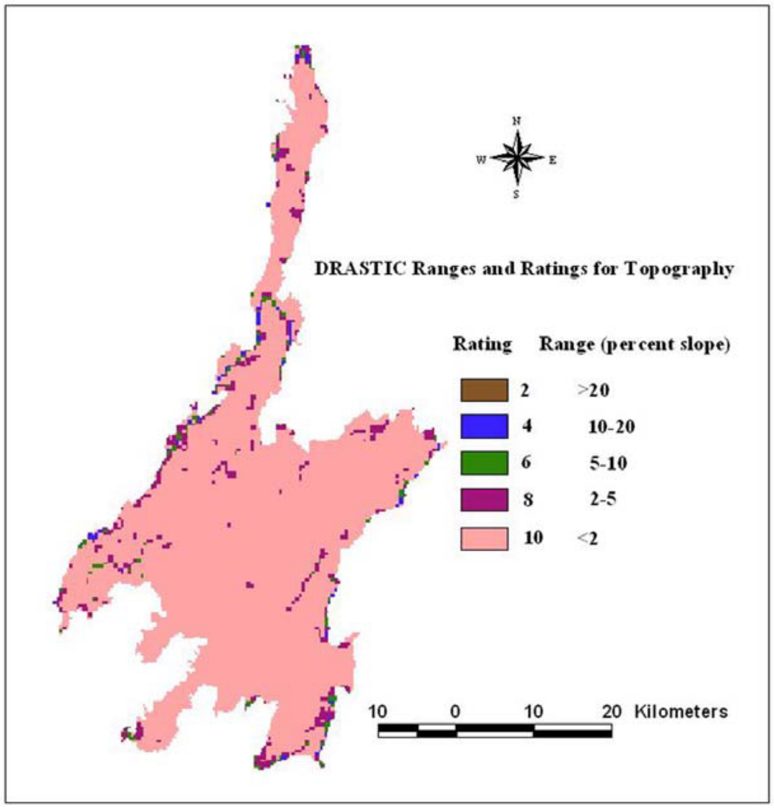

Figure 7. Map showing DRASTIC ranges and ratings for topography.

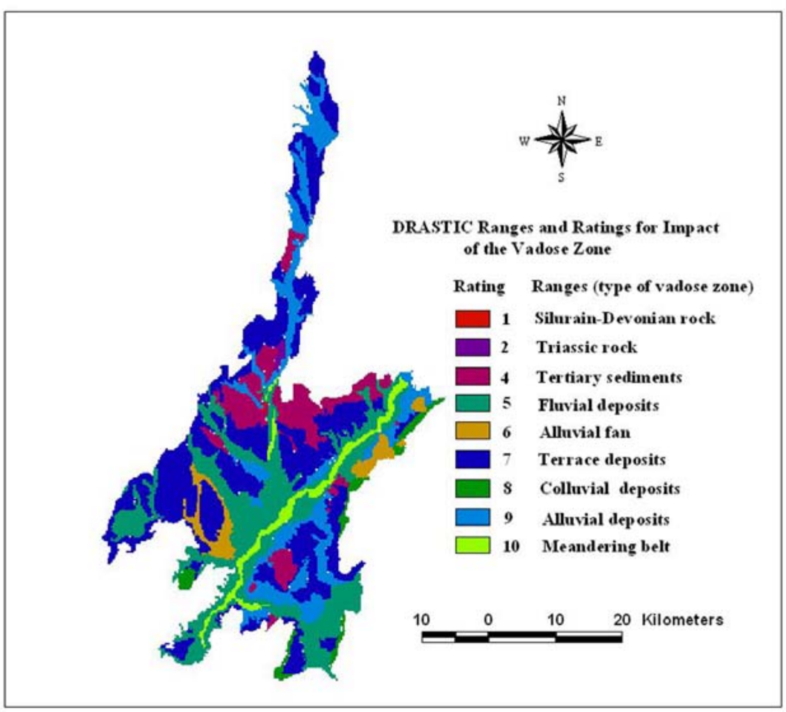

Figure 8. Map showing DRASTIC ranges and ratings for impact of the vadose zone.

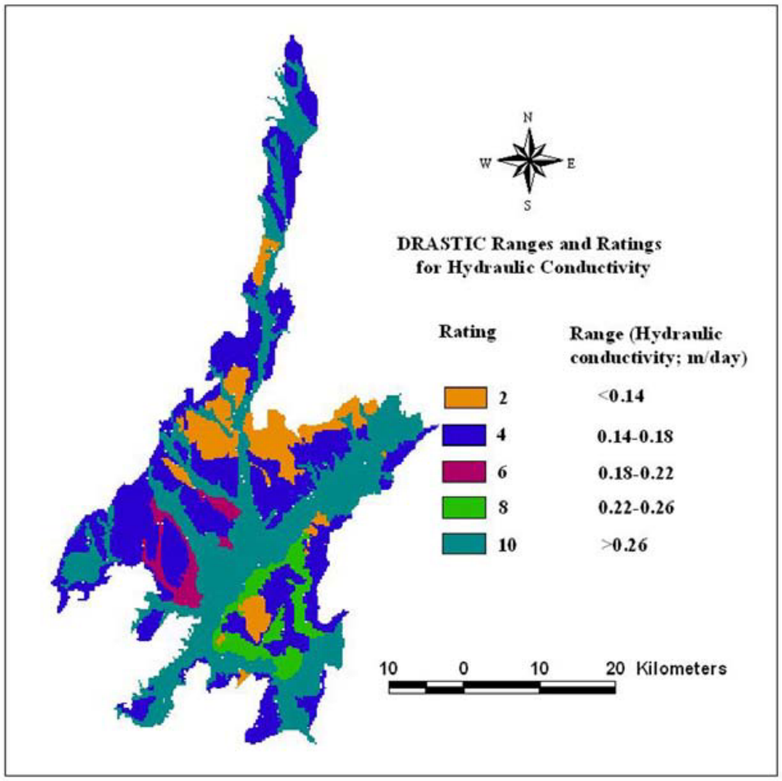

Figure 9. Map showing DRASTIC ranges and ratings for hydraulic conductivity of the aquifer.

RESULTS AND DISCUSSION

This study divided vulnerability rankings into five classes that describe the relative probability of contamination of the groundwater resources. These five are: low, moderately low, moderate, moderately high, and high. The vulnerability map of the Lampang basin is shown in Figure 10. Standard DRASTIC colors were used for the map. The colors range from red orange for the highest vulnerability to dark olive green for the lowest vulnerability. A regional scale is useful for comparing the relative vulnerability of groundwater resources. DRASTIC indices range from 90 for the least vulnerable to 222 for the most vulnerable.

High

High vulnerability ranked groundwater resources are found in the Wang River meander belt and flood plain underlain by Holocene unconsolidated sediments. These unconsolidated sediments constitute the Qa aquifer unit and are areas that have high recharge potentials, shallow depths to water tables, and permeable soils.

Moderately High

Moderately high vulnerability ranked groundwater resources also are found in flood plain areas of the Holocene Qa aquifer unit. As with high vulnerability areas, the recharge potentials, depths to water table, and geology have strong influences on the DRASTIC index. This class encompasses urban areas and most paddy field areas.

Moderate

Moderate vulnerability ranked groundwater resources is the predominant classification in the

Lampang basin. The areas of moderate vulnerability include Holocene and Pleistocene unconsolidated sediments and Tertiary unconsolidated and semi-consolidated sediments. These areas encompass paddy fields and other agricultural areas and have high sensitivity due to their recharge potential and low slope.

Moderately Low

Moderately low vulnerability ranked groundwater resources are found in the Tertiary sediments of the T aquifer unit. This ranking is predominantly controlled by the depths to water tables, aquifer media, and the impact of vadose zones.

Low

There are a few areas of low vulnerability ranked groundwater resources in the Lampang basin. These occur in the northern part of the basin where the vulnerability class was controlled by the aquifer media and topographic slope characteristics.

There is a relation between the DRASTIC index and type of aquifer. The Holocene unconsolidated sediments, the Qa aquifer unit, consist of sand, silt, clay, and mud. The sand and silt grains are generally sub-angular to sub-rounded and moderately well sorted. The aquifers in the unit are permeable and have relatively high transmissivity. These aquifers have moderately high to high DRASTIC indices of 168 to 194 and 194 to 222, respectively. The Pleistocene unconsolidated sediments, the Qt aquifer unit, are composed of gravel, sand, silt, and thick layers of clay and laterite. They have moderately low to moderate DRASTIC indices of 116 to 142 and 142 to 168, respectively. The Tertiary unconsolidated and semi-consolidated sediments are composed of clay, sand, silt, shale, siltstone, mudstone, and diatomaceous shale. They have low permeability and their DRASTIC indices vary from 90 to 116, which are low to moderately low.

Actually, DRASTIC indices were calculated only for areas where the aquifers crop out and where the ratings of aquifer media and the impact of the vadose zone factors were usually the same. These hydrogeologic factors have weights of three and five, respectively, and they had a strong influence on the final DRASTIC indices.

The groundwater vulnerability map, Figure 10, shows the relative vulnerability of the groundwater resource but is based on data that have different levels of precision and resolution. For example, the soil map used has high resolution, while other layers, such as net recharge and hydraulic conductivity, were derived from groundwater flow model studies that represent averages for the large Lampang basin area. This mixed resolution is acceptable for assessing relative vulnerability of the area, but it cannot determine site-specific vulnerability.

CONCLUSIONS AND RECOMMENDATIONS

The vulnerability assessment of groundwater resources in the Lampang basin in northern Thailand was determined using the geologic information system and the DRASTIC method. ArcView software was used to analyze, identify, and display the regional sensitivity of groundwater to contamination. Seven hydrogeologic factors were used for the DRASTIC vulnerability assessment. These seven are depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and aquifer hydraulic conductivity. The vulnerability factors were reclassified to scale, range, and rating and were computed using ArcView software to obtain vulnerability scores. The resultant vulnerability map showed that the areas covered by Holocence unconsolidated sediments, the Qa aquifer unit, have the highest DRASTIC indices and are most vulnerable to

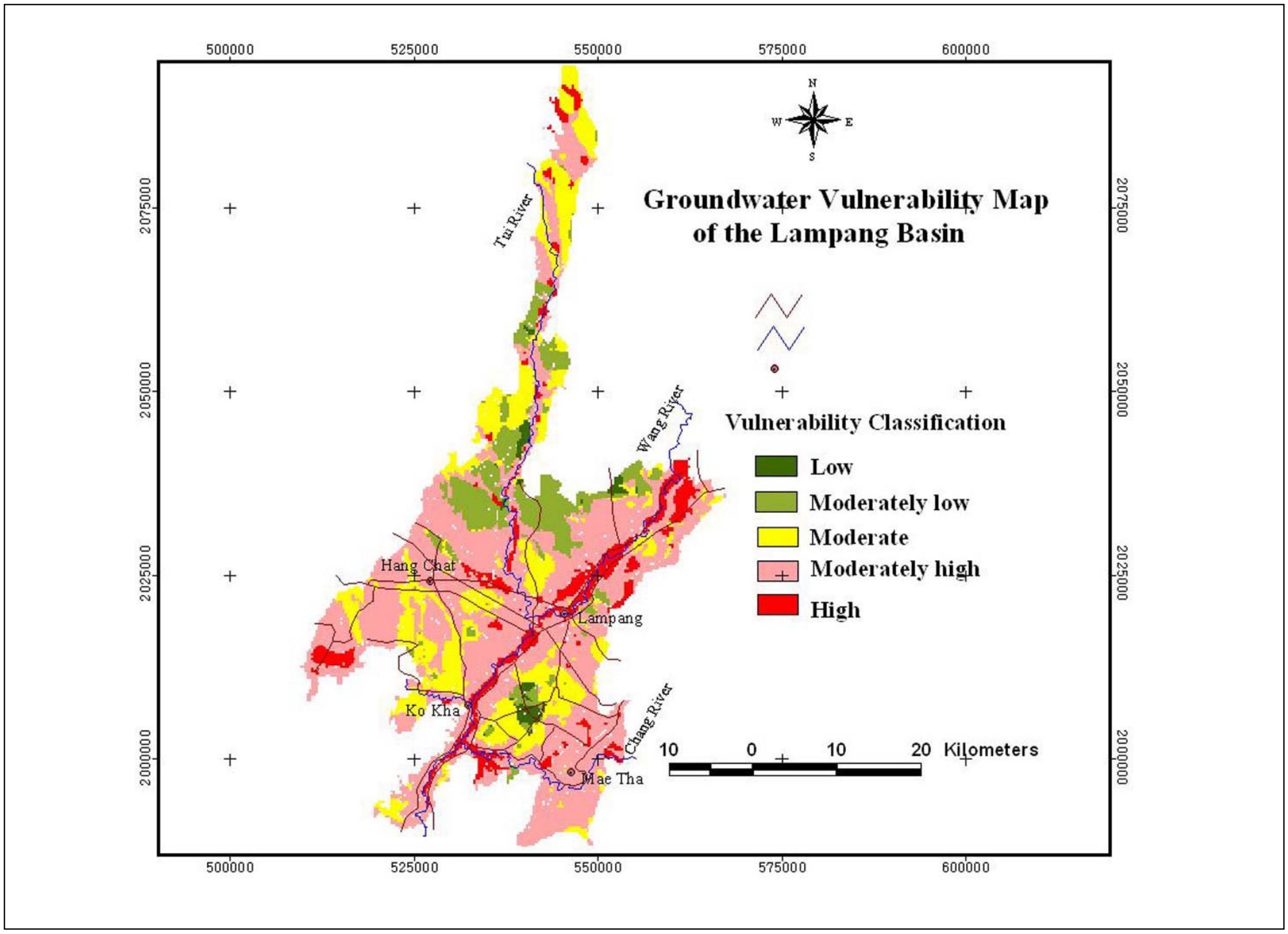

Figure 10. Groundwater vulnerability map.

contamination. Pleistocene unconsolidated sediments, the Qt aquifer unit, have moderate to moderately high DRASTIC indices and vulnerability. The areas of lowest vulnerability to contamination are the unconsolidated to semi-consolidated Tertiary sediments, the T aquifer unit.

Groundwater vulnerability maps can be used for groundwater protection planning, decision making, and management, and belong to the category of environmental maps. Organizations that might be benefit from this Lampang basin vulnerability map include the Department of Groundwater Resources, the Pollution Control Department, the Department of Industrial Work, the Office of the Environment Policy and Planning, and the Department of Environmental Quality Promotion.

Groundwater vulnerability maps do not consider the chemical nature of the pollutant in assessing vulnerability. The maps concern only the hydrogeologic settings that make groundwater susceptible to contamination from surface sources. Table 3 is a guide to the amount of groundwater assessment required for determining each of the five aquifer vulnerability classes.

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Table 3. Groundwater Assessment for Developments that Require Consent (modified from Piscopo, 2001)

Vulnerability classification	**Groundwater assessment requirement**
Low	*Groundwater contamination assessment report* A desk study is required to identify the concerns and potential risk to groundwater or the environmental and the need for any further action to be presented in the development application. A standard format hydrogeological report would most likely result.
Moderately low	*Site investigation with monitoring* A potential risk is indicated by the vulnerability map requiring site investigation and groundwater monitoring. The extent of work should involve a limited amount of site investigation, soil and water sampling and testing, definition of flow systems and reporting, in addition to desk study.
Moderate	*Detailed site investigation and monitoring* For moderate vulnerability areas, or where the previous levels of investigation indicate a demonstrated risk to groundwater, a detailed groundwater site investigation is required. The work should include an ongoing monitoring program, details of the protection design factors (such as natural attenuation, physical barriers), in addition to the previous levels of investigation.
Moderately high	*Demonstrated groundwater protection system* The risk to groundwater, as demonstrated by the vulnerability map, is an area in which contamination to groundwater cannot be tolerated. The work should include a desk study, detailed site investigation, and implementation of an on-going monitoring program, as indicated above. In addition, the protection design system incorporating such things as natural attenuation, hydraulic barriers, and physical barriers , needs to be demonstrated to be effective. The proposal will need to include a feasibility plan for a clean-up, in addition to a detailed monitoring and ongoing assessment program.
High	*Demonstrated remedial action plan/prohibition* This classification identifies the area as having a potential risk so great as to warrant a demonstrated remedial action plan. The work should include a desk study, site investigations, ongoing monitoring, plus a demonstrated remedial action plan for clean-up, which analyses the effectiveness of the remediation approach in achieving designated water quality criteria. The financial capacity of the responsible party to enact the plan should also be evaluated. In the event that the risk to groundwater is unacceptable, an activity may be banned by the responsible authority.

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