DETERMINATION OF NONPOINT SOURCE POLLUTION INDEX USING MCDA-GIS

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Abstract: The information of the distribution of nonpoint source pollution index (NPSI) of a watershed is useful for identifying and prioritizing critical areas for control management. The objective of this study is to determine the NPSI for locating potential area of the nonpoint source pollution in the Upper Lam Phra Phloeng watershed, Thailand, using GIS and Multi-Criteria Decision Analysis (MCDA). Potentials of run-off, sediment yield, and nutrient yield of the study area were raster-based quantified to be indexes by the score range procedure of the linear transformation. These indexes were integrated using the decision rule as the Simple Additive Weighting with different weights assigned for those potentials. Due to having a small number of criteria and their simple relationship, the rank sum method was applied to weight assignment. As an integration result, the NPSI is available for each grid cell in the watershed. The NPSI was further classified to indicate the level of environmental sensitivity of areas. This spatial distribution information is helpful for examining the pattern of diffuse pollution and could facilitate the decision on NPS pollution management at local level.

INTRODUCTION

Assessment of the nonpoint source (NPS) pollution is complicating and time consuming task. NPS pollution has specific characteristics which distinguish it from point source pollution by being spatially distributed, and varying in magnitude on the basis of complex interaction between environment and the agricultural system (Giupponi and Rosato, 1995). To reduce NPS pollution in the most cost effective way, it is important to have knowledge of contributions to water from different sources, especially the main source. To resolve the complexity of NPS pollution, the most efficient way is to control it in the known critical areas. The question is where the critical areas are in the Upper Lam Phra Pholeng watershed and how to locate them so that local administration can identify and prioritize where remedial measures should be taken to control NPS pollution.

Agricultural pollution potential index (APPI) was developed for identifying and ranking the NPS pollution potential of 104 watersheds in Pennsylvania, USA (Hamlett et al., 1992). This ranking index, consisting of four components – 1) a runoff index, 2) a sediment production index, 3) an animal loading index, and 4) chemical use index, was used to predict the relative potentials for agricultural NPS pollution in the watershed. Li and Yeh (2004) developed NPS pollution potential index (NPSI), composed of six sub-indices – 1) runoff volume, 2) specific peak runoff rate, 3) soluble nitrogen, 4) soluble phosphorus, 5) chemical oxygen demand in the runoff and 6) specific sediment yield, each with relative importance weighting. Guo et al. (2004) applied APPI system to identifying and ranking critical areas of NPS pollution with GIS. Quantification of factors in NPS pollution was carried out including the followings: 1) sediment production index, 2) runoff index, 3) people and animal loading index and 4) chemical use index. Previous studies was emphasized that the proposed NPS pollution indices of watersheds were restricted to the study area, and specific to local condition. Small amount of researches have applied the NPS pollution potential index in Thailand. The NPSI which can be applied to Upper Lam Phra Phloeng watershed conditions should be studied.

This study aims to develop a NPS pollution potential assessment system in form of the distribution of potential index, using MCDA-GIS, which suites to represent the NPS pollution characteristics of the Upper Lam Phra Phloeng watershed. The digital land use data at scale 1:25,000 were obtained from Land Development Department (LDD), which were updated to the year 2007. The model simulation conducted in the year 2008, this study assumed that there was a little change of land use of 2007 to 2008. The approach in this study could be applicable for other watersheds with the same geographic and practical conditions.

MATERIALS AND METHODS

Study area

The 786.26 km^2 of Upper Lam Phra Phloeng watershed was selected for this study (Figure 1). The topography of the area is characterized by generally hilly-rolling terrain, with less undulating and flat areas. Elevation ranges from 260 m above msl. in the northeastern part to about 1,307 m above msl. in the southwestern part of the watershed. This watershed is upstream area of the Lam Phra Phloeng reservoir. The climate is influenced by both the northeast and southwest monsoons, with an average annual rainfall of 1,117 mm. The soils in the area vary to be 15 soil series with different soil textures as clay, clay loam, loam, loamy sand, sandy clay loam, sandy loam, and silty clay. The land use of the watershed consists of dense and disturbed evergreen forests, dense and disturbed deciduous forests, forest plantation, field crops, and orchards. More than 41.52% of the watershed is classified as field crop area. The dominant crops are maize, sugarcane, and cassava. Amount of fertilizer usage tends to be increased considerably. The more the fertilizers are used, the higher the potential of surface water contamination is.

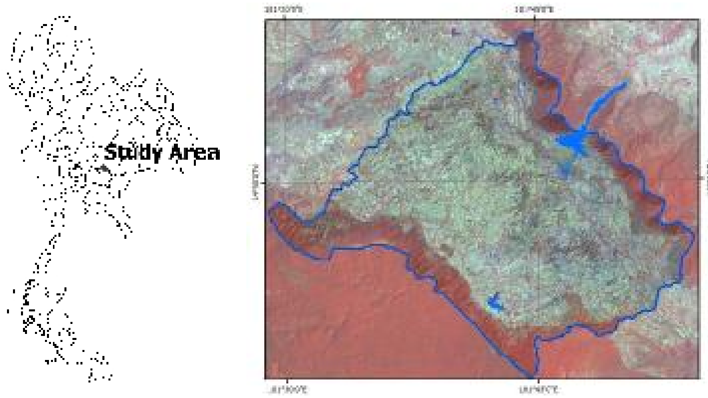

Figure 1: Study area

GIS and MCDA

The NPSI determination consists of two fundamental steps - first, estimation of a sub-index (I_i) from each pollution factor presented in form of a criterion map using GIS techniques, and second, using MCDA-GIS techniques (Malczewski, 1999) to aggregate all sub-indexes into a total index, called the NPSI. The analytical performance was raster-based local operation.

Sub-indexes of grid cells were standardized from original values of each pollution factor map and resulted in commensurate criterion maps of factor sub-indexes. The score range procedure of linear scale transformation was used to standardize as the following equation.

$$X'_{ij} = \frac{X_{ij} - X_j^{\min}}{X_j^{\max} - X_j^{\min}} \quad (1)$$

where X'_{ij} is the standardized score for the i^{th} grid cell and the j^{th} attribute, X_{ij} is the raw score, and $X_j^{\max}$ is the maximum score for the j^{th} attribute. $X_j^{\min}$ is the minimum score for the j^{th} attribute. The value of standardized score was then ranging from 0 to 1. The higher the value of the score, the higher pollution potential the criteria is.

The total index, NSPI, can be calculated using the following expression:

$$NPSI = \sum_{i=1}^{n} W_i I_i \quad (2)$$

where I_i is a sub-index of the i^{th} potential factor, n is a number of potential factors, W_i is the weight of the i^{th} potential factor. The output is presented in form of raster-based maps that depict critical areas of NPS pollution.

In the formulation of the NPSI, the potential factors responsible for NPS pollution must be selected and prepared in form of criterion maps. Their relative weights were determined among them. In this study, potential factors included (1) runoff potential, (2) sediment yield potential, and (3) nutrient yield potential. The studies of runoff and sediment yield indexes were emphasized solely on potential assessment. Therefore, only temporally static parameters during the study period were considered. The rainfall which is temporally dynamic was not taken into account.

The rank sum method (Stillwell et al., 1981) was used to determine the criterion weights. The simplest method for assessing the weights is to arrange them in rank order of the decision maker's preference. The weight (W_i) of each potential factor of the NPS pollution was 0.50 for runoff index (W_1), 0.33 for sediment yield index (W_2), and 0.17 for nutrient yield index (W_3). The analyses were conducted using ArcGIS™ with the extension of Spatial Analyst™. The flow diagram of the NPSI determination for this study is shown in Figure 2.

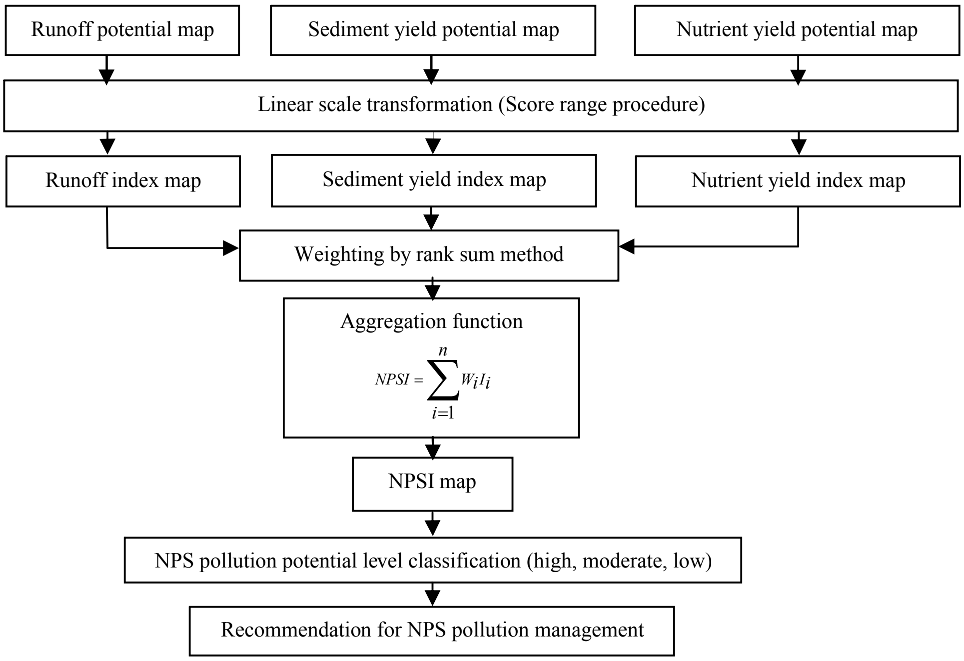

Figure 2: Flow diagram of the NPSI determination

Runoff potential index

Runoff is an important factor that controls the movement of sediments and nutrients from land surface to stream network (Zhang and Huang, 2011). The relationship of total nutrients export and runoff have been reported in many researches, most of which indicated that high runoff rate was favorable to the removal of nutrients from soil (Edwards and Withers, 2008; Drewry et al., 2009). The runoff potential index of the area was generated through grid-based Curve Number method (Tharapong et al., 2009). The value of the runoff potential index was calculated based on the curve number value which has been widely adopted in NPS pollution models. The curve number values indicate their specific runoff potential.

The distribution of normalized runoff potential index is exhibited in Figure 3. Areas of high values are found in the central of the watershed which expresses undulating topography and field crop especially maize, sugarcane, and cassava. Mountainous areas are assigned with relative low value due to the forest coverage of the land.

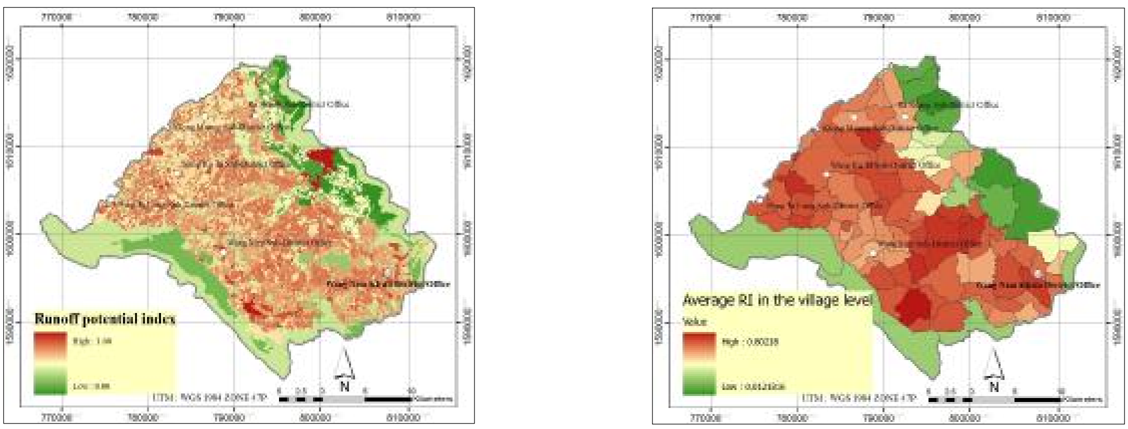

Figure 3: a) Distribution of the normalized runoff potential index b) Average runoff potential index in the village level

Sediment yield potential index

The normalized sediment yield index map was generated using a combination of the potential of sediment yield and sediment delivery ratio for each cell.

The distribution of normalized sediment yield index is exhibited in Figure 4. Areas of high values were found in the steep slope close to the stream network. Mountainous areas were assigned to be relative low potential due to the distribution of forest which well covered the ground and leaded to low sediment yield potential.

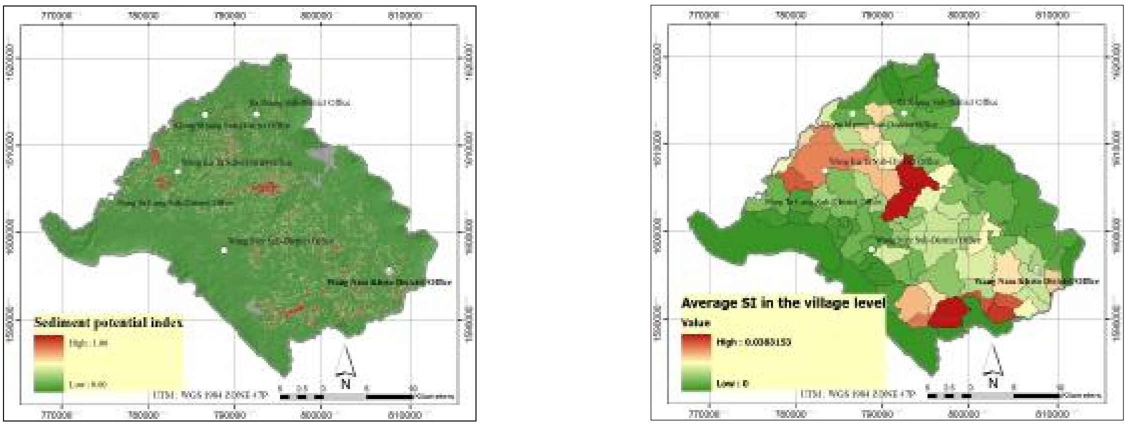

Figure 4: a) Distribution of the sediment yield potential index b) Average sediment yield potential index in the village level

Nutrient yield potential index

The potential agricultural/nutrient yield pollution resulted from improper application of fertilizers to the land. The potential loading of agricultural fertilizer for each type of land use was rated as high, medium, low, and not applicable based on the potential for each type of land use to receive fertilizer (Guo et al., 2004). These potential loading categories were assigned numerical values as 4, 3, 2, and 1 for the high, medium, low and not applicable rating, respectively. Table 1 presents the associated potential loading values according to the rates of fertilizer application to various types of land uses. The data were obtained through the farmer survey in 2008. Once the land use was classified for each grid cell, the relative fertilizer application rate was determined which in turn resulted to potential loading of the cell. The loading values were subsequently standardized to be nutrient yield index.

Table 1: Potential loading values corresponding to fertilizer application to different types of land uses in the Upper Lam Phra Phloeng watershed during the year 2008.

Potential loading (Value)	**Fertilizer application rate**	**Land uses**
High (4)	>100 Kg/Rai/Year	Cassava, Maize, Sugarcane, Field crop
Medium (3)	75-100 Kg/Rai/Year	Paddy field, Horticulture
Low (2)	<75 Kg/Rai/Year	Grass, Orchard, Mixed orchard, Para rubber, Perennial, Mixed Perennial
Not applicable (1)		Scrub, Teak, Eucalyptus, Build-up land, institutional land, village, Forest plantation, Disturbed deciduous forest, Disturbed evergreen forest, Dense evergreen, Dense deciduous forest, Water body, Marsh, Swamp, Livestock farm house.

The distribution of normalized nutrient yield index is exhibited in Figure 5. Areas of high values were found in the main cash crop such as cassava, maize, and sugarcane.

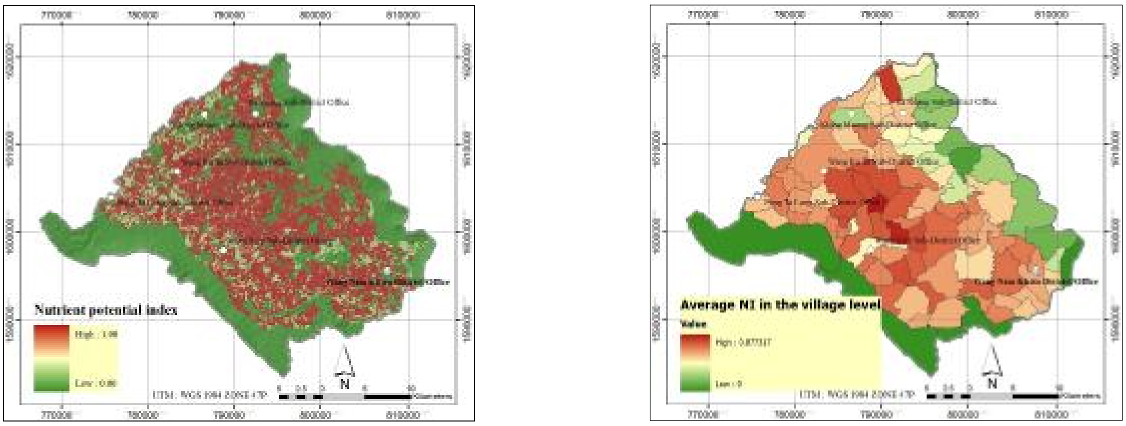

Figure 5: a) Distribution of the nutrient yield potential index b) Average nutrient yield potential index in the village level

RESULTS AND DISCUSSION

The result of the NPSI map is depicted in Figure 6 and the classes of NPS potential are as follows:

a) High NPS pollution potential area
251.12 km^2 (32.42%) of the total watershed area was classified to be high NPS potential and found in the central part of the watershed. Most area is high slope terrain and used mainly for maize crop.

b) Moderate NPS pollution potential area
270.04 km^2 (34.87%) of the total watershed area was classified to be moderate NPS potential and also found in the central part of watershed. Most area is undulating-rolling topography and used for cassava, sugarcane, and other field crops.

c) Low NPS pollution potential area
253.36 km^2 (32.71%) of the total watershed area was classified to be low NPS potential and mainly located in the southwestern and northeastern parts of the watershed, characterized by the mountainous topography and forest land.

In order to provide an applicable understanding of the results, the map of NPSI was zoned based on the boundaries of local administration at village level as shown in Figure 7. This map should be useful for decision support of NPS pollution management at the watershed or local administrative scales. NPSI can be used to prioritize the severely impacted areas within watershed strongly required to be managed and controlled.

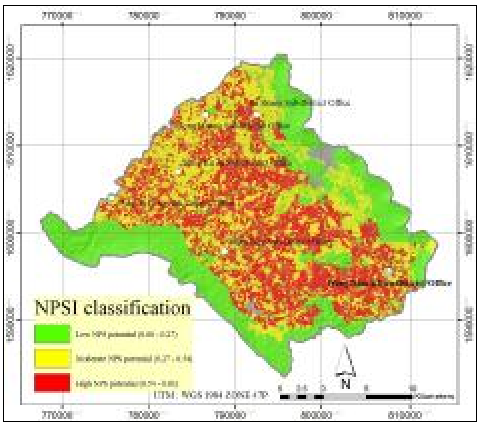

Figure 6: The NPSI distribution in the study area

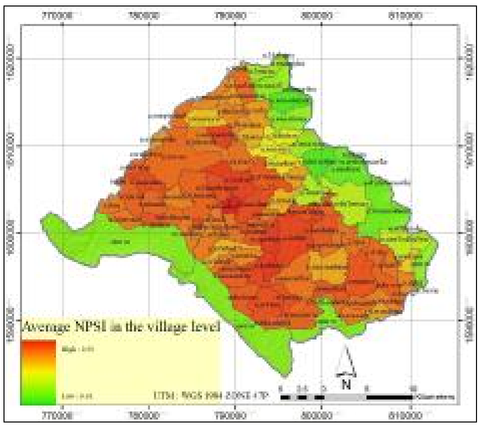

Figure 7: Average NPSI in the village level

CONCLUSIONS AND RECOMMENDATIONS

National government authorities recently emphasize on environmental management in order to protect the resource base and maintain a sustainable balance in the natural environment and water quality from national to local scales. Thus, assessment of the NPS pollution potential in form of map using spatial analysis has become an important task necessarily required for watershed management, particularly for the local government.

This study determined NPSI map using MCDA-GIS to support the watershed management in the local administrative level. The environmental criteria used for the study were the potential of runoff, sediment and nutrient yields. They were prepared in form of raster-based criterion maps through runoff, sediment yield, and nutrient yield modeling and then standardized under the GIS environment. They were agglomerated to be the NPSI map using MCDA-GIS.

The use of NPSI map does not aim at absolutely describing the variation of the quantitative concentration of pollutants. It is more likely to be useful in term of prioritizing the severely impacted areas due to NPS pollution where proper monitoring and controlling plan and implementation are strongly required.

To facilitate the local administrative management, the NPSI map was finally derived to be NSPI for each village. It is useful for local decision makers to perform management specifically to a certain kind of pollution and the overall village by village.

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