Development of Potential Floodwater Retention Zones using AHP and GIS: A Case Study in the Chi River Basin, Thailand

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Abstract
The Chi River always faces floods and water shortage problems in the rainy season and subsequent dry season, respectively. The Royal Thai Government emphasizes on construction of floodwater retention reservoirs to store more water along the Chi River. This water is to be used mainly for agriculture in the subsequent dry season. A methodology was developed to identify potential floodwater retention zones using the Analytical Hierarchical Process and GIS-based data. They were surface water, drainage density, landform, land use, soil drainage, salt crust, geological formation, lineament density, vegetation index, and groundwater yield. The result was the potential water retention zones map, which was categorized as excellent, good, moderate, poor and very poor classes. The map was validated with a field survey of floodwater retention site. The results agreed with the field check. The hydrodynamic model (MIKE11) was employed to simulate diversion of discharges from the Chi River into retention reservoirs. The results of simulation revealed that the proposed reservoir (Kud Dok) could retain floodwater at the maximum storage capacity of 8.13 million m^3 for return periods of 3, 5, 8 and 25 years.

1. Introduction

According to the 10th National Economic and Social Development Plan (NESDP, 2007 to 2011), the development of Thailand follows the self sufficient philosophy. The direction of development allows people and society to participate and adjust them for various dimensional changes. Under this plan, guidelines of water resources management are increasing water storage capacity, sufficient water distribution in the basin, water resources development at suitable areas, and flood, drought and water shortage mitigation (DWR, 2005). Therefore, it is important to develop small and medium scales of water resources because people and society can closely participate for the management, while the large scale needs experts of water resource managers. The Chi River basin, one of the three major basins in northeast Thailand, is located in the tropical monsoon region which has distinctive dry and rainy seasons. High intensity rainfall often occurs, causing flooding from the upstream and stagnant water downstream (RID, 2005). The most devastating floods occurred in 1978, 1995, 2000 and 2001(RID, 2005). Flooding in the Chi basin has been a recurrent problem. This basin also faces water shortage problems in the subsequent dry season because the retention water flows back to the Chi channel when the water levels in the channel are low. Learning from the flood event in 2001, the Thai government has emphasized harnessing excessive water during floods by constructing flood retention reservoirs along the channel. This storage water is used mainly for agriculture in the subsequent dry season. The ability of GIS to integrate with the Analytical Hierarchy Process (AHP) has been demonstrated in several studies related to water resources management. For instance, the DRASTIC model was originally developed for aquifer vulnerability assessment, but it was too rigid to assign the ratings and weights to the model parameters. Thirumalaivasan et al., (2003) modified the ranges of model parameters and decided to use the AHP for derivation of ratings and weights of parameters. The GIS-based AHP approach has also been extended to water resources planning problems such as forecasting urban water requirements (Rao, 2005). The purpose of this study was to develop the model for potential floodwater retention zones using GIS and the AHP method. The essential parameters adopted were surface water, drainage density, landform, land use, soil drainage, salt crust, geological formation, lineament density, vegetation index, and groundwater yield.

2. Study area

The study area, Chi River basin, is located in the northeast of Thailand. The basin is circled with mountain ranges from the north to west that makes the river basin shape as of a flat bowl. The slope of the basin is steep at the upstream mountain area and is flat at the lower part especially near the confluence to the Mun River. The drainage area of the basin is 49,477 km^2 and extends about 360 km east to west and 210 km from north to south. The annual runoff is 9,638 million m^3 (MCM) in the rainy season, 1,606 MCM in the dry season and totally 11,244 MCM (RID, 2005). The rest of the runoff which flows to the Mun River is 8,527 MCM. Figure 1 shows the relief map of the Chi basin derived from the 30 meter digital elevation model (DEM) and LANDSAT images in the year 2002.

3. Methodology

3.1 Development of Model for Potential Floodwater Retention Zones

The methodology for floodwater retention zones model was developed using remote sensing, GIS and the AHP method. The AHP is essential and popular over other methods in decision-making process because of simplicity, theoretical robustness and capability to directly measure the inconsistency of the respondent's judgment (Saaty, 1980). The essential parameters adopted were surface water, drainage density, landform, land use, soil drainage, salt crust, geological formation, lineament density, vegetation index, and groundwater yield as per the recommendation of FAO (Food and Agriculture Organization) (Critchley and Sieget, 1991). Figure 2 illustrates a flow chart of methodology for floodwater retention zones model.

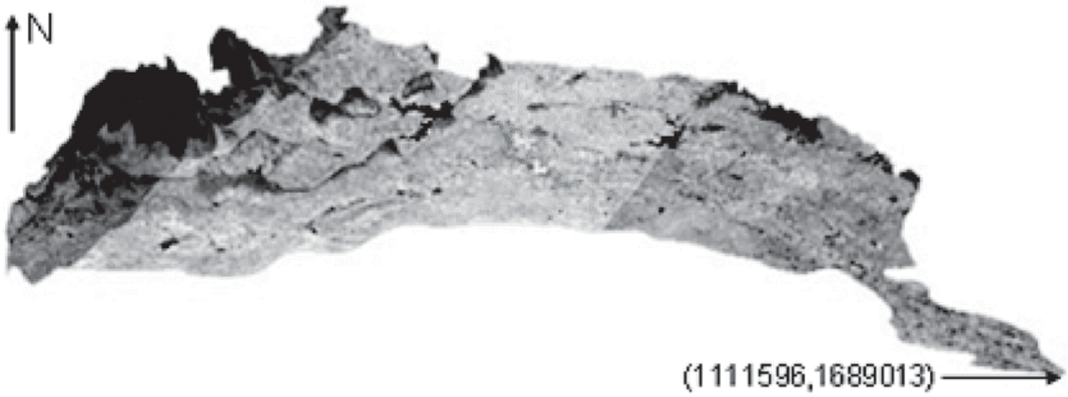

Figure 1: Relief map of Chi River basin

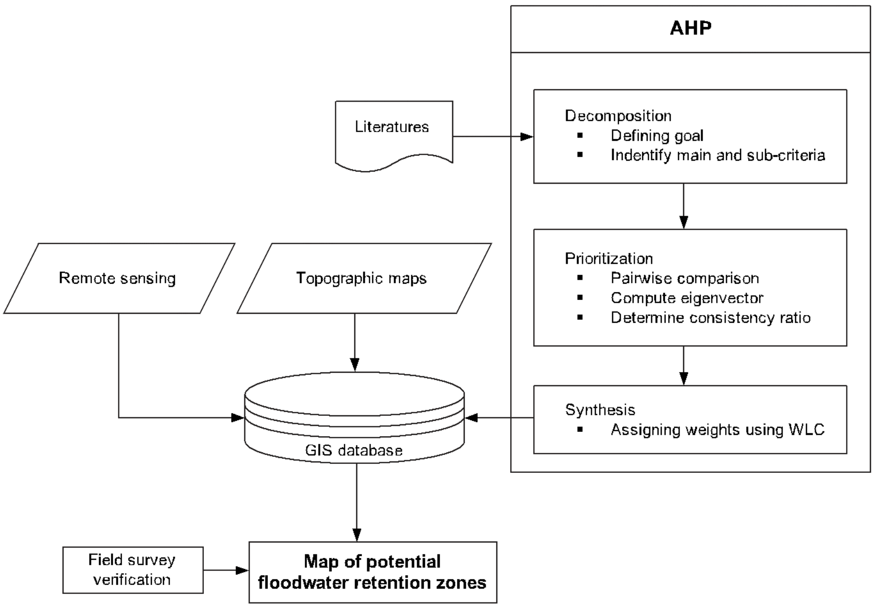

Figure 2: AHP-potential floodwater retention zones model

3.2 Preparation of Essential Factors in the GIS Format

Surface Water: Surface water is important criteria for floodwater retention zones analysis. Surface water bodies were classified into buffer zone of main river and stream, and lake.

Drainage Density: Drainage density is defined as stream dense intensity and is calculated by the stream length in a unit area. The measurements of lengths and areas were in kilometer and square kilometer, respectively. Therefore, the study area was tiled to a unit area matrix by splitting 21 rows and 53 columns to derive a 1x1 km^2 unit area. The stream length that existed in each grid was identified after that drainage density in each unit cell was calculated.

Landform: The classification of landform was performed using a contour map and the DEM data. Four types of landform were classified as low flatlands, lower alluvial plains, undulating uplands, and mountainous areas.

Land Use: Land use in GIS format was collected from the Land Development Department (LDD) of Thailand. Classification of land use included rice field, crop field, forest, settlement and other types.

Soil Drainage: The soil drainage layer presents soil textures of different soil types. Due to water retaining capacity, soil drainage was classified into categories such as excessively drainage, well drainage, and poor drainage.

Salt Crust: Somsak (2005), LDD, employed LANDSAT7-ETM acquired during February to March 2003 to classify maps of salt crust for some parts of northeast Thailand. The classified categories were no-effect from salt content, low-salt effect area, moderate-salt effect area, high-salt effect area, very high-salt effect area, and salt stone below upland. These data were employed for the present study.

Geological Formation: Two types of formations (Mahasarakham and Quaternary) exist within the study area. The Quaternary formation is more suitable than Mahasarakham formation for floodwater storage because this formation may affect salinity.

Lineament Density: Lineament refers to underlying bedrock fractures, which can be interpreted from satellite image. For this study, extraction of lineament density was performed using band 4 of LANDSAT imagery acquired in November 2000. The convolution filters including both directional and non-directional algorithms served as extracted processes. The result of raster lineament density was transferred into GIS format for employing spatial analysis.

Vegetation Index: The vegetation index represents vegetation distribution. The NDVI (Normalized Difference Vegetation Index) values depict green vegetation distribution. Higher values reveal more green vegetation. A standard formula, NDVI = (NIR-Red)/(NIR+Red), is applied to compute the vegetation index and its value varies from -1 to 1. To derive detailed information of NDVI, a 2.5 meter spatial resolution of SPOT V acquired in February 2006 is utilized to extract NDVI values.

Groundwater Yield: Based on the groundwater yield, the layer features were classified into four groups such as excellent, good, moderate and poor categories. The lowest class was set as excellent class, while the highest was poor.

3.3 Processes of AHP

The AHP composes three principles such as decomposition, prioritization, and synthesis, respectively. The weights of main and sub-criteria were derived from the AHP. Following discussions are mainly based on the context of one sub-basin located at the middle part of the Chi River basin.

Decomposition: A hierarchical structure was established to interrelate and chain all decision elements for objective of potential floodwater retention zones. The hierarchy consisted of main and sub-criteria as shown in Table 1.

Prioritisation: The numerical scales ranging from 1 to 9 (Saaty, 1980) were applied in the pairwise comparison matrices of the main and sub-criteria in the same level. The derived pairwise comparison of relative importance, $a_{ij} = w_i/w_j$ for all decision elements and their reciprocals, $a_{ji} = 1/a_{ij}$ were inserted into a reciprocal square matrix, $A = \{a_{ij}\}$. In order to find the priority vector, vector w must be satisfied $Aw = \lambda_{max}w$. The vector of weights for each main and sub-criteria was calculated from equation (1). In additional, the eigenvalue (λ_{max}) of the matrix could be computed from equation (2).

$$w_i = \sum_{j=1}^{n} a_{ij} / n$$

Equation 1

$$\lambda_{\max} = \frac{\sum_{i=1}^{n}\left[\sum_{j=1}^{n}\left(a_{ij}w_j\right)/w_i\right]}{n}$$

Equation 2

A Consistency Index (CI), where $CI = (\lambda_{max} - n)/(n - 1)$, is used to measure the degree of inconsistency in the square matrix A. The comparison of the estimated CI with the same index derived from a randomly generated square matrix, called the Random Consistency Index (RCI). The ratio of CI to RCI for the same order matrix is called the Consistency Ratio (CR). The judgment consistency of an expert will be determined. The CR of 0.10 or less is considered to be acceptable (Saaty, 1980).

Synthesis: A weighted linear combination (WLC) method was applied to identify potential floodwater retention zones. The weights derived from the previous step were assigned to attributes of sub-criteria through ArcView GIS. Then, the weights of the main-criteria were multiplied by the weights of sub-criteria within the same hierarchical level and summed products of all attributes to obtain total scores (TS) by the following formula:

$$TS = \sum_{k} w_k r_{ik}$$

Equation 3

Where, w_k and r_{ik} were the weights of the main and sub-criteria, respectively.

Table 1: Main and sub-criteria of potential floodwater retention zones

Main-criteria	Weight	Sub-criteria	Weight	Total weight
Surface Water	0.27	Main river 1 Km buffer zone	0.26	0.070
		Stream 0.5 Km buffer zone		
		Lake and pond	0.12	0.032
		Others (no water areas)	0.06	0.016
Drainage Density	0.19	High density (>2.43)	0.56	0.106
		Moderate density (1.02 - 2.43)	0.26	0.049
		Low density (< 1.02)	0.12	0.023
		Very low (no drainage area)	0.06	0.011
Landform	0.15	Lower alluvial plain	0.56	0.084
		Low flat-land	0.26	0.039
		Undulating upland	0.12	0.018
		Mountainous area	0.06	0.009
Land Use	0.11	Rice field	0.56	0.062
		Crop field	0.26	0.029
		Others	0.12	0.013
		Urban and forest areas	0.06	0.007
Soil Drainage	0.08	Poorly drained soil	0.26	0.021
		Well drained soil	0.12	0.010
		Excessively drained soil	0.06	0.005
Salt Crust	0.06	Low salt-effected area	0.26	0.016
		Moderate salt-effected area	0.12	0.007
		High salt-effected area	0.06	0.036
		Salt stone below upland		
Geological Formation	0.05	Quaternary formation	0.26	0.013
		Mahasarakham formation	0.12	0.006
Lineament Density	0.04	Very low (no lineament)	0.56	0.022
		Low density (<0.60)	0.26	0.010
		Moderate density (0.60 - 1.34)	0.12	0.005
		High density (>1.34)	0.06	0.002
Vegetation Index	0.03	Low vegetation	0.56	0.017
		Moderate vegetation	0.26	0.008
		High vegetation	0.12	0.004
		Very high vegetation	0.06	0.002
Groundwater Yield	0.02	Very low yield	0.56	0.011
		Low yield	0.26	0.005
		Moderate yield	0.12	0.002
		High yield	0.06	0.001

4. Results and Discussions

4.1 Potential Floodwater Retention Zones

The pairwise comparison matrix for the main-criteria along with weights was calculated (Table 2). The pairwise comparison elements were decided in consultation with an expert and field realities. The advised scores for each element in Saaty's scale of importance were applied in the matrix. The values of CI and CR of the main-criteria were 0.028 and 0.018. The CR value of sub-criteria was 0.017. Finally, all the weights were acceptable as previously illustrated in Table 1. The weights of main-criteria were multiplied with the weights of sub-criteria (Table 1). Then, all features of the sub-criteria were combined linearly using the WLC method (Equation 3). The natural breaks method (Thirumalaivasan et al., 2003) existed in ArcView GIS was used to classify the potential floodwater retention zones into Excellent Class (EC) (0.44-0.55), Good Class (GC) (0.38-0.44), Moderate Class (MC) (0.31-0.38), Poor class (PC) (0.23-0.31) and Very Poor Class (VPC) (0.01-0.23) as shown in Figure 3. The EC was primarily located in 1 km buffer zone of the main river, high drainage density, lower alluvial plain, rice field, poorly drained soil, low-salt effect areas, Quaternary formation, and low vegetation index. Lands categorized as GC resulted from the combination of 0.5 km buffer zone of the stream, moderate drainage density, low flat-land, moderate-salt effect areas, low lineament density, and moderate vegetation index. Water bodies, moderate drainage density, moderate lineament density, and low ground water yield were in the MC category. Poor class lands were areas with predominantly no water areas, well drained soil, high lineament density, high vegetation index, and moderate ground water yield. Very poor class composed excessively drained soil, high salt-effected areas, salt stone below upland, and very high vegetation index.

A discussion the result of the classified zones map with an expert who suggested the score, it is suitable to develop floodwater retention in EC and GC zones. The EC and GC zones map, land use from SPOT5 with 2.5x2.5 m pixel size (acquired on 20 February 2006), and close loop of contour line were used to draw the primary boundary of the reservoir. Hence, the proposed reservoir called Kud Dok was chosen for validation and depicted in the right corner of Figure 3. The field survey was conducted to validate the model for Kud Dok site on October 28, 2006 and it was found that these areas face floods. The field within the boundary belongs to both public and private sectors. The second survey was conducted in January 2007 by interviewing the villagers located near the reservoir boundary (Figure 4). All of them agreed with the reservoir boundary according to flooding areas, which adversely affects agricultural production. Additionally, an interview with experts from the Regional Office of Irrigation 6 (ROI6) indicated that this site can be developed to store water which is diverted from the Chi River when the water levels reach the peaks. They also suggested utilizing the storage water in the subsequent dry season for agricultural areas around the reservoir. After demarcating the reservoir boundary, the water volume of reservoirs needed to estimate. The width of reservoir's boundary at some locations is less than 90 meter. Therefore, the 30 meter DEM data available from the Royal Thai Survey Department were employed to compute the water volumes. For instance, Kud Dok's boundary and the DEM were applied to compute water volume. An elevation of 139 m which had the maximum number of pixels in the boundary was set as the base elevation and the maximum water depth was given at 4 m. The calculated water volume at elevation 140, 141, 142 and 143 m were 2.70, 4.50, 6.31 and 8.13 MCM, respectively.

Table 2: Matrix of pairwise comparisons of main-criteria*

	SW	**DD**	**L**	**LU**	**SD**	**SC**	**GF**	**LD**	**VI**	**GY**	**Weight**
SW	1	2	3	3	3	4	5	6	7	8	0.27
DD	1/2	1	2	2	3	3	4	5	6	7	0.19
L	1/3	1/2	1	2	2	3	3	4	5	6	0.15
LU	1/3	1/2	1/2	1	2	2	3	3	4	5	0.11
SD	1/3	1/3	1/2	1/2	1	2	2	3	3	4	0.08
SC	1/4	1/3	1/3	1/2	1/2	1	2	2	3	3	0.06
GF	1/5	1/4	1/3	1/3	1/2	1/2	1	1	2	3	0.05
LD	1/6	1/5	1/4	1/3	1/3	1/2	1	1	2	2	0.04
VI	1/7	1/6	1/5	1/4	1/3	1/3	1/2	1/2	1	1	0.03
GY	1/8	1/7	1/6	1/5	1/4	1/3	1/3	1/2	1	1	0.02

*CI = 0.028; CR = 0.018

where, SW = Surface water, DD = Drainage density, L = Landform,
LU = Land use, SD = Soil drainage, SC = Salt crust,
GF = Geological formation, LD = Lineament density,
VI= Vegetation index, and GY = Groundwater yield

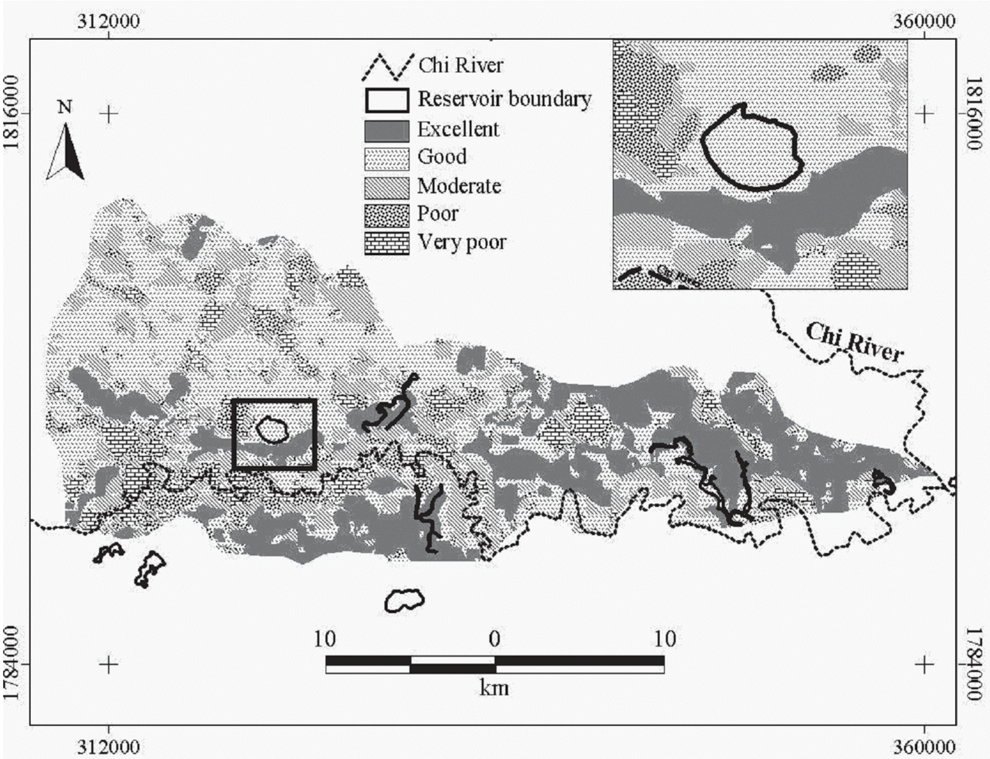

Figure 3: Potential floodwater retention zones map

Figure 4: Discussion with the villagers

4.2 Simulation of Floodwater Retention Availability

The simulation employed the hydrological and hydrodynamic models (NAM and MIKE11 models). The data input for the NAM model included model parameters, rainfall data, potential evaporation, and streamflow data. The data such as cross sections, stream network, stages, discharges and lateral inflows computed from the hydrological model were used as input data in the MIKE11 model. The maximum discharges of 48 years (1955 to 2002) at the downstream station (E20A) served as input data for frequency analysis. The log-Pearson type III revealed the best fit peak flows. Therefore, four periods of years 1996, 2000, 2001 and 2002 with the return period of 3, 5, 25 and 8 years were selected for simulations. The hydrological data in the year 2000 were selected for calibrations of hydrological and hydrodynamic models. Then, the data in the year 1996, 2001 and 2002 employed for model verifications. Results show good agreement by using coefficients of determination. The 2001 flood corresponded to a 25-year return period. Historically, this year was also the most devastating flood occurrences. Hence, the hydrological data in 2001 were used for scenario analysis. The flood event during August 14 to October 3, 2001 was used for the demonstration and scenario simulation. When water levels reached the peaks, the discharges were diverted into retention reservoirs until the water storage volumes were at the maximum storage. The simulated water levels at diverted locations were compared to the maximum water levels of reservoirs. If the simulated water level at the diverted location is equal to or greater than the maximum water level of reservoir, then the water volume can be stored at the maximum level. The discharges were diverted into 59 retention reservoirs including the proposed reservoir (Kud Dok) (Figure 5). The reservoir was set for the maximum water level at an elevation of 143 m, which had the maximum storage of 8.13 MCM. Regarding the results of the simulations, the flood discharges could be diverted into this reservoir at the maximum water level.

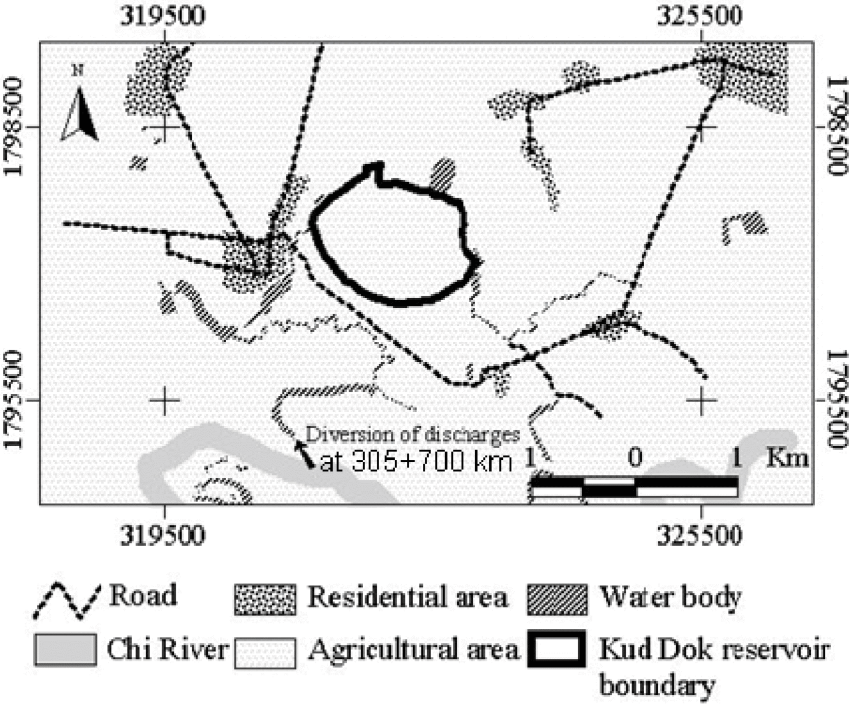

Figure 5: Diversion of discharges into proposed reservoir (Kud Dok)

5. Conclusions

The potential floodwater retention zones model was developed by integrating essential parameters (surface water, drainage density, landform, land use, soil drainage, salt crust, geological formation, lineament density, vegetation index, and groundwater yield) and the Analytical Hierarchy Process (AHP). Pairwise judgment was employed to estimate the relative important weights for main and sub-criteria. The weights of surface water, drainage density, landform, land use, soil drainage, salt crust, geological formation, lineament density, vegetation index, and groundwater yield were 0.27, 0.19, 0.15, 0.11, 0.08, 0.06, 0.05, 0.04, 0.03 and 0.02, respectively. The AHP weights of the main and sub-criteria were later used in weighted linear combination method to identify floodwater retention zones. The result of the AHP-potential floodwater retention zones map was classified as excellent, good, moderate, poor and very poor classes. The map was used as a screening tool for siting floodwater retention. The result was verified with field survey data by overlaying the boundary of the proposed reservoir (Kud Dok). It lied on the good class and agreed with the field checks. Additionally, the hydrodynamic model (MIKE11) could satisfactorily simulate the hydrodynamic components of the Chi basin. Discharges from the Chi River could be diverted into the proposed reservoir at the maximum water level of 8.13 million m^3.

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