Distributed Groundwater Recharge Estimation in Phrae Province Using WetSpass

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Abstract

Phrae province is the main part of the Phrae aquifer in the northern Thailand, which has faced water shortage problem for a long time, particularly in dry season because most areas are agricultural areas. Due to variations of amounts of rainfall, as a result of climate change and increasing of the population, has an effect in increasing of the water demand level, especially in non-irrigated agricultural areas. In response to this shortage issue, groundwater exploration and exploitation of the area are highly necessary. However, a consequence due to over-abstraction through groundwater pumping threatens the sustainability of groundwater resources, the assessment of groundwater recharge rates to propose the appropriate plan for the sustainable management needed to be assessed in terms of quantity.

In this study, the groundwater recharge rates were determined by WetSpass module which is physically embedded in ArcView3.3 for estimating long-term average spatial patterns of groundwater recharge. Geographic Information System (GIS) was used for data preparation and estimation. The thematic maps accounted for recharge estimation were: rainfall, potential evaporation, wind speed, temperature, depth of groundwater, soil, slope and topography. Then, groundwater recharge was evaluated and then finally displayed as groundwater recharge map. The results showed the variations of groundwater recharge rates in seasonal variations, which found high recharge rates during rainy season. Moreover, the results showed that the potentiality of recharge area correspond to the topography and hydrologic characteristics. These contributions will be further applied as the fundamental data for groundwater flow modeling and groundwater balance assessment for properly sustainable management.

Keywords: Groundwater recharge; Phrae province; WetSpass; GIS

1. Introduction

Many research are used in the management of groundwater systems for sustainability (Voudouris, 2006), such as estimating the groundwater recharges which is considered the relationship between recharge and discharge mechanisms are influence to groundwater storage changing and available yield (Koontanakulvong and Suthidhummajit, 2006). The over-pumping rates much more than recharge rates in aquifer causes instability of the groundwater balance. The result has influence to the depletion of groundwater table, and also a longer time to recover. In addition, the over-pumping on regional area has an effect in leading to groundwater mining (Fetter, 2001). Hence, an assessment the groundwater recharge for sustainable development is significantly important.

The rate at which water-table recharge occurs is variable, depending upon environment factors, topographic, meteorological, hydrological and hydrogeologic characteristics etc. For reliability and accuracy, groundwater recharge analysis on large and complex scale is used by numerical models which are useful for spatial analysis and combination with Geographic information System (GIS) in terms of providing a flexible toolset for resource management (Flugel and Michl, 1995). All of the above, the purposes of this study is to estimate groundwater recharge in Phrae province using GIS and WetSpass module. Furthermore, this study also presents results on spatial distribution for better understanding in hydrogeologic characteristic, and these will be the fundamental database for groundwater balance analysis and sustainable management of groundwater resources.

1.1. Recharge and Model description

Recharge is the entry into the saturated zone of water which made available at the water table surface, together with the associated flow away from the water table within the saturated zone (Freeze, 1969). When the front of infiltrating water reaches the capillary fringe, in displaces air in the pore spaces and causes the water table to rise. In arid environments, with very infrequent recharge and great depths to the water table, water may take many years to pass through the unsaturated zone. Afterwards, aquifers transmit water from recharge areas to discharge areas, which the rate of groundwater movement depends on the hydraulic conductivities and hydrogeologic characteristic of aquifers (Fetter, 2001).

The assessment of recharge areas and recharge rates are becoming increasingly important because of the expanding use of land surface for human activities. In the humid area, recharge occurs in all inter-stream areas, in all areas except along streams and their adjoining flood plain because under most conditions there are discharge areas. Besides, recharge occurs during an immediate following periods of precipitation and thus is intermittent. Most recharge of groundwater systems occurs when plants are dormant and evaporation rates are small. In the long-term, recharge varies from year to year, depending on the amount of precipitation, its seasonal distribution, air temperature, land use, and other factors. Relative to land use, recharge rates in forests are much higher than those in cities (Heath, 2004).

Aforementioned, the spatial variation in the recharge due to distributed land-use, soil type, slope, etc. can be significant and should be accounted for in these groundwater systems. Spatial mathematical model was used for analyzing groundwater systems such as WetSpass, which a steady state spatially distributed water balance model for estimation of the long-term average, spatially varying and water balance components: surface runoff, actual evapotranspiration and groundwater recharge (Aish et al., 2010), which can be calculated as a residual term, from the water balance is given by

$$R_v = P - S_v - ET_v - I \qquad (1)$$

Where R_v is groundwater recharge [LT-1]
P is the average seasonal precipitation [LT-1]
ET_v is the actual evapotranspiration [LT-1]
S_v is runoff over land surface beneath vegetation [LT-1]
I is the interception by vegetation [LT-1]

WetSpass was completely integrated in the GIS as a raster model. Parameters, such as land-use and related soil type, are connected to the model as attribute tables of the land-use and soil raster maps. The total water balance for a raster cell is split into independent water balances for the vegetated, bare-soil, open-water and impervious parts of each cell. This allows one to account for the non-uniformity of the land-use per cell, which is dependent on the resolution of the raster cell. The processes in each part of a cell are set in a cascading way after the precipitation event. Finally, the results have shown the quantity which determined for each process is consequently limited by a number of constraints. (Batelaan and Smedt, 2001)

1.2. Background

Phrae province located in the middle part of Yom watershed in the northern Thailand, which overlaps on Phrae groundwater basin. The total area is approximately 6,538 square kilometers, and its elevation ranges from 80-1600 meters a.s.l. The coordinates of the study area in WGS 1984 datum of approximately are 1950000–2075000 N from south to north, and 535000-662500 E from west to east. The highest elevation of the area, Phi Pan Nam Range runs across the province from north to south in the west and the Phu lueng Range in the east (Fig. 1). The geological and topographical features composed of high mountainous on the eastern and western sides of the basin are characterized by Permian and Triassic rock units, which are composed of conglomerate, sandstone, siltstone, shale and mudstone, some of rock units in the western part of the basin are also dominated by volcanic rocks (Soea et al., 2008). Based on literature reviews and geologic GIS data at scales of 1:250,000 from Department of Mineral Resources of Thailand, the Quaternary units in the center part of Phrae basin are classified into three distinctive units are old-terrace, young-terrace and active Yom River floodplain deposits (Fig. 2). Phrae province is one which had the drought in early rainy season and dry season (Phrae Provincial Statistical Office, 2011). Due to low amount of rainfall and increase of the population, which result in high rate water demand (Boksuwan, 2003).

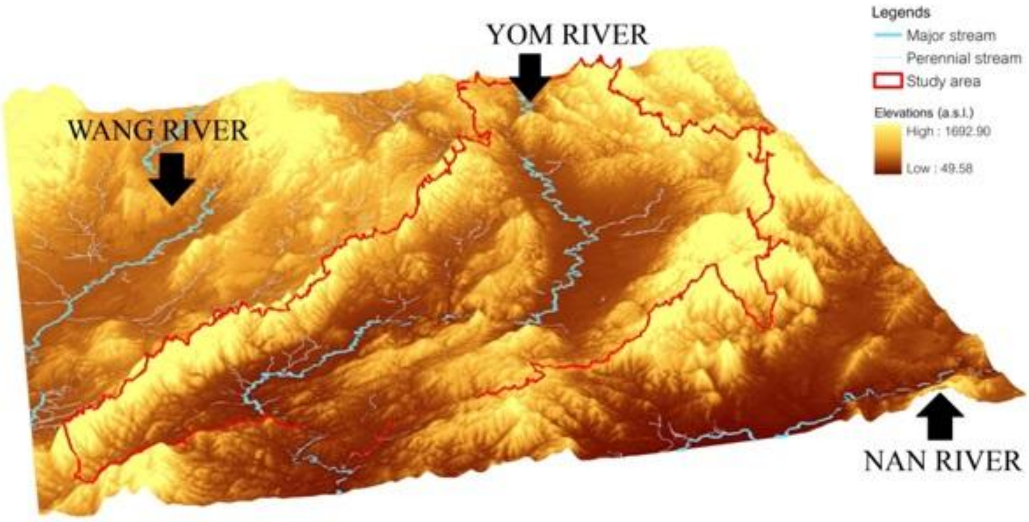

Figure 1. Terrain surface of the study area.

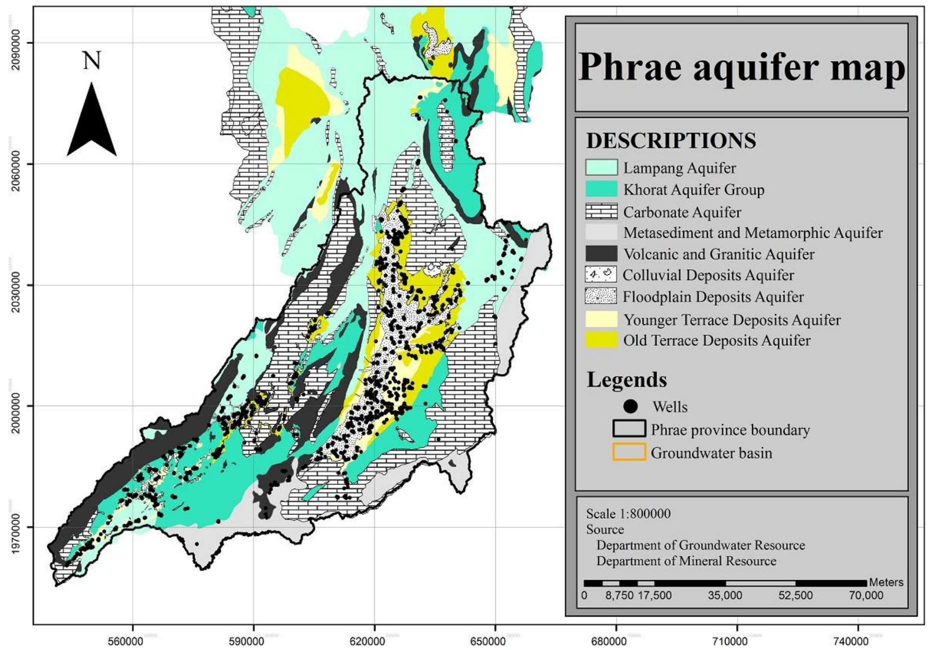

Figure 2. Hydrogeologic setting of the study area.

2. Materials and Methods

2.1. Overview

The methodology consists of three steps were shown in Figure 3. In the first step, spatial data were prepared for modelling. These inventory data consists of topographical data, meteorological data, soil data and land use data. The GIS software was applied in storage, manipulating, and analyzing the digital data. These data were adjusted and prepared to raster grid cell which resolution is 90 by 90 m, which is mainly based on the acquiescence that with this resolution can be modelled and reasonable for the study area (Goward and Williams, 1997). Next, the raster data were used in the WetSpass model to calculate the annual and seasonal recharge rates maps in the study area. Finally, the results are correlated with water balance components and physical features, which are significant for groundwater recharge.

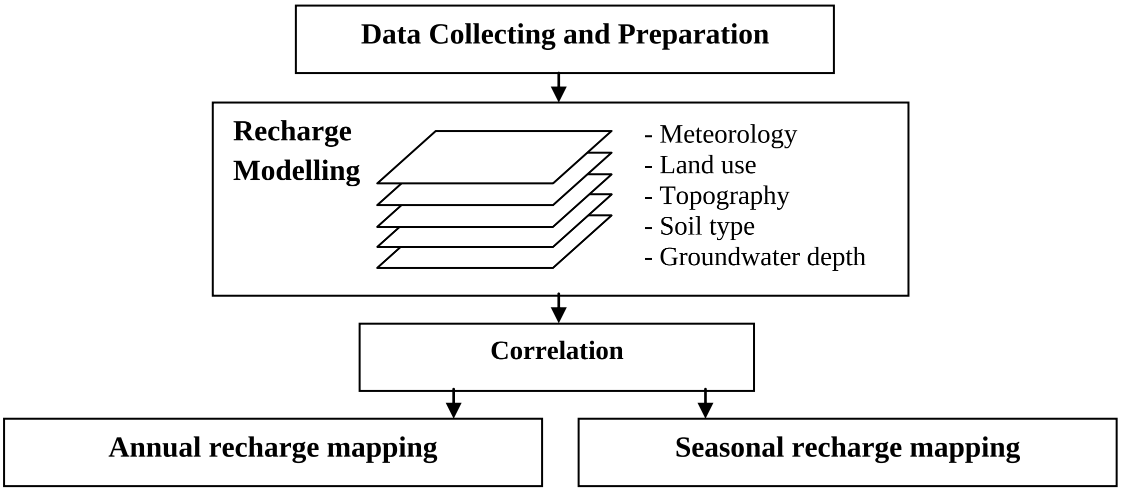

Figure 3. Schematic of the processing.

2.2. Parameters and Model set-up

The groundwater recharge was modelled by WetSpass in ArcView 3.3, which base for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State. The model provides understanding and quantification of the interactions between atmosphere, surface water and groundwater. In addition, it allows for the estimation of other spatially distributed seasonal hydrological components such as actual evapotranspiration, surface runoff, interception, and infiltration (Idrysy and Smedt, 2006). The input to the model consists of seasonal meteorological data and physical parameters which were changed to raster data.

Average seasonal rainfalls were calculated in the period 1980–2010, from different stations, average seasonal rainfalls were interpolated to obtain distributed maps of seasonal rainfall. The monthly rainfalls were divided to dry and rainy season, where dry season is assumed from November to April and rainy season from May to October . Furthermore, average seasonal potential evapotranspiration (PET) were calculated from meteorology data using modified penman equation in agricultural model CROPWAT 8.0 (FAO, 2011). Then, average seasonal potential evapotranspiration were interpolated to obtain distributed maps of seasonal PET.

Soil type and land use parameters are connected to the model as databases of the land-use and soil raster maps, which parameters of the classification are based on the US Department of Agriculture classification, resample to a 90 by 90 m resolution. Digital Elevation Models (DEM) was generated from topographic features (elevation contour, stream, spot elevation and model boundary) which obtained from Land Development Department, and terrain slope was also generated from DEM in following step.

In addition, groundwater depth data were obtained from field investigation in two periods. However, in rainy season, only a few observation wells were founded and measured because of the weather conditions. Hence, groundwater at depth of 299 observation wells database from the Department of Groundwater Resources (DGR) were used to substituted in rainy season. The second set of groundwater head measurements is available in 74 observation wells in dry season that are well spread over the study area. All values were calculated and interpolated for estimating of the groundwater heads and groundwater flow schematic. All parameters as shown on spatial map in Fig. 4.

3. Results and Discussions

3.1. Groundwater recharge simulations

The results of groundwater recharge simulation as shown in Fig. 5 and Table 1. Because of the seasonal rainfall variations and high rates of evapotranspiration, the groundwater recharge of Phrae province varies from 0 to 630 mm. per year with 315 mm. of an average value. The yearly groundwater recharge has a value of 84,556.47 m^3 or 8.80 % of the average rainfall. The results of seasonal have a variance in the groundwater recharge which a value of 217.20 m^3 or 0.16 % of the summer rainfall and ranges from 0 to 95 mm. with 47.5 mm. of an average value. In rainy season, the groundwater recharge has a value 373,099 m^3 or 20.87 % of the total rainfall, and range from 0 to 720 mm. per year with 360 mm. of an average value. About 99% of total groundwater recharge in the study area is occurred during the rainy season while the remaining 1% is occurred in dry season, where a concordant justification was reached with the annual groundwater recharge rates of Thailand Development Research Institute (TDRI), which the annual recharge rates in the tropical zone have ranges from 8-10 % amount of rainfall (Pitaksaithong, 2004).

Table 1. Summary of the seasonal various water balance components.

	Dry season (mm.)				Rainy season (mm.)			
Various parameters	Min.	Max.	Avg.	Vol.	Min.	Max	Avg.	Vol.
Precipitation	109.70	164.86	110.01	133,716.03	817.54	1360.62	951.85	1,787,637.03
Runoff	0.00	658.62	329.31	174,588.62	0.00	780.80	390.40	1,447,212.61
Evapotranspiration	0.00	848.21	424.10	1,009,994.34	326.17	1036.47	873.38	3,090,883.11
Recharge	0.00	95.50	47.50	217.20	0.00	720.56	360.00	373,099.62

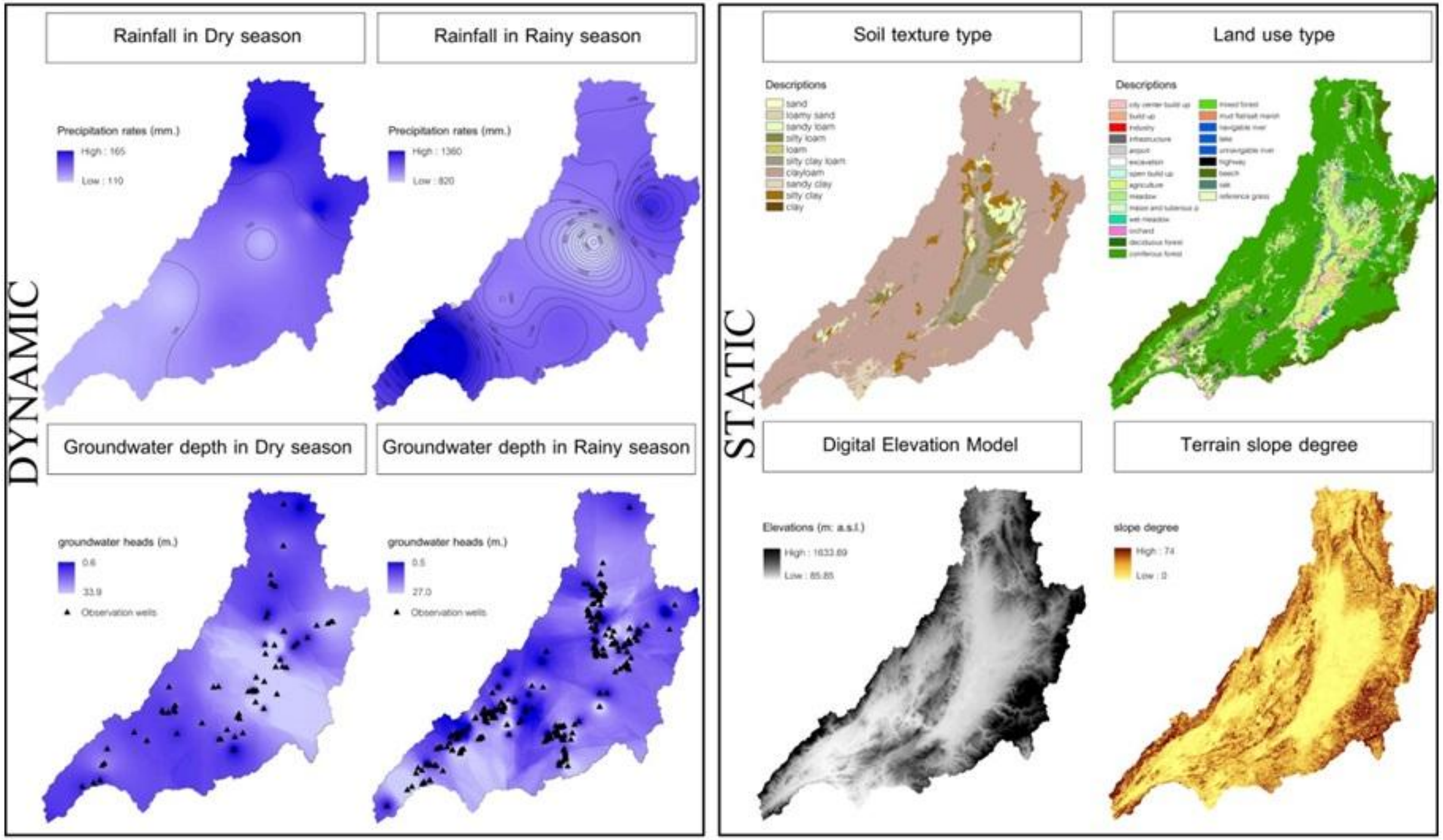

Figure 4. Spatial data of the parameters used in the WetSpass module.

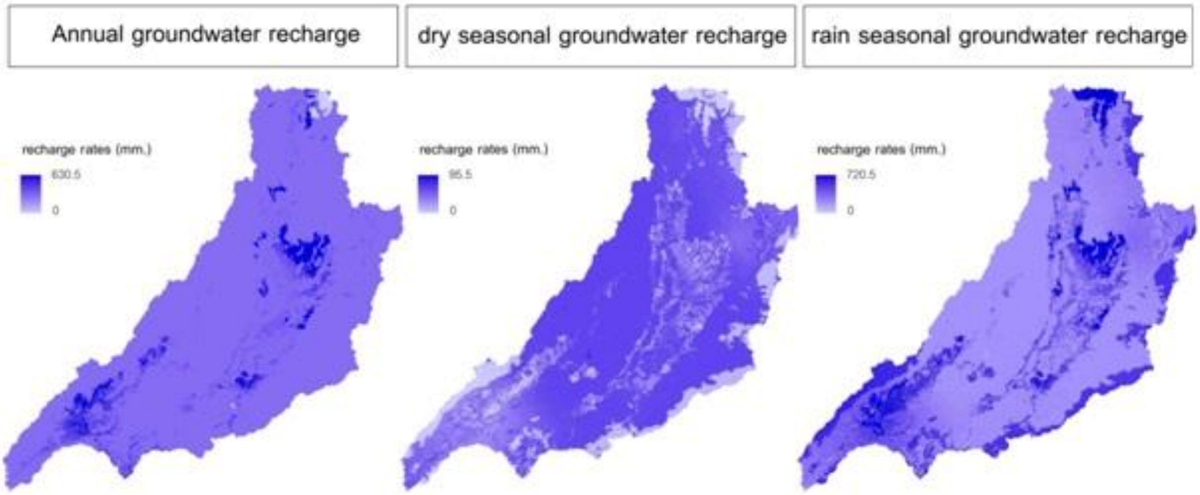

Figure 5. Annual and seasonal groundwater recharge rates in Phrae province using WetSpass.

3.2. Relationship between groundwater recharge and water balance component

From seasonal rainfall maps, it is clear that rainfall occurs mainly in the rainy season and generally correlated with topographic feature and monsoon season. In the north of Phrae province, rainfalls reach its peak in dry season, whereas rainfall becomes less towards the southern and western parts of the area with lower topographic elevation. However, in monsoon season, rainfall is optimum in the south of the area. This is considered as the seasonal rainfall patterns that influence to surface runoff which significantly for direct groundwater recharge. Furthermore, evapotranspiration is also great significantly for negative recharge rates. Seasonal and annual trends of evapotranspiration and surface runoff were shown in Fig. 6, 7 and Table 1.

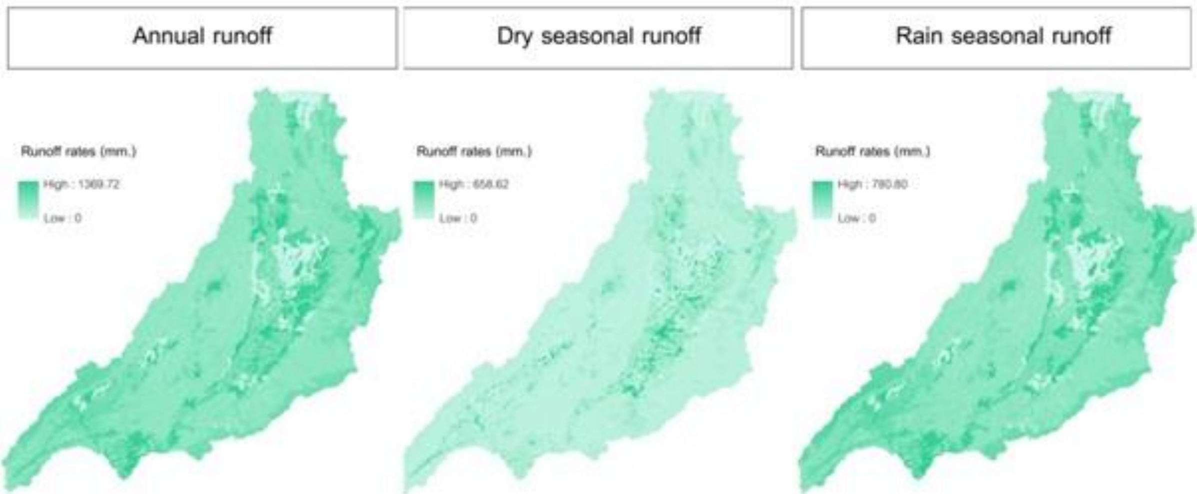

Figure 6. Annual and seasonal surface runoff rates in Phrae province.

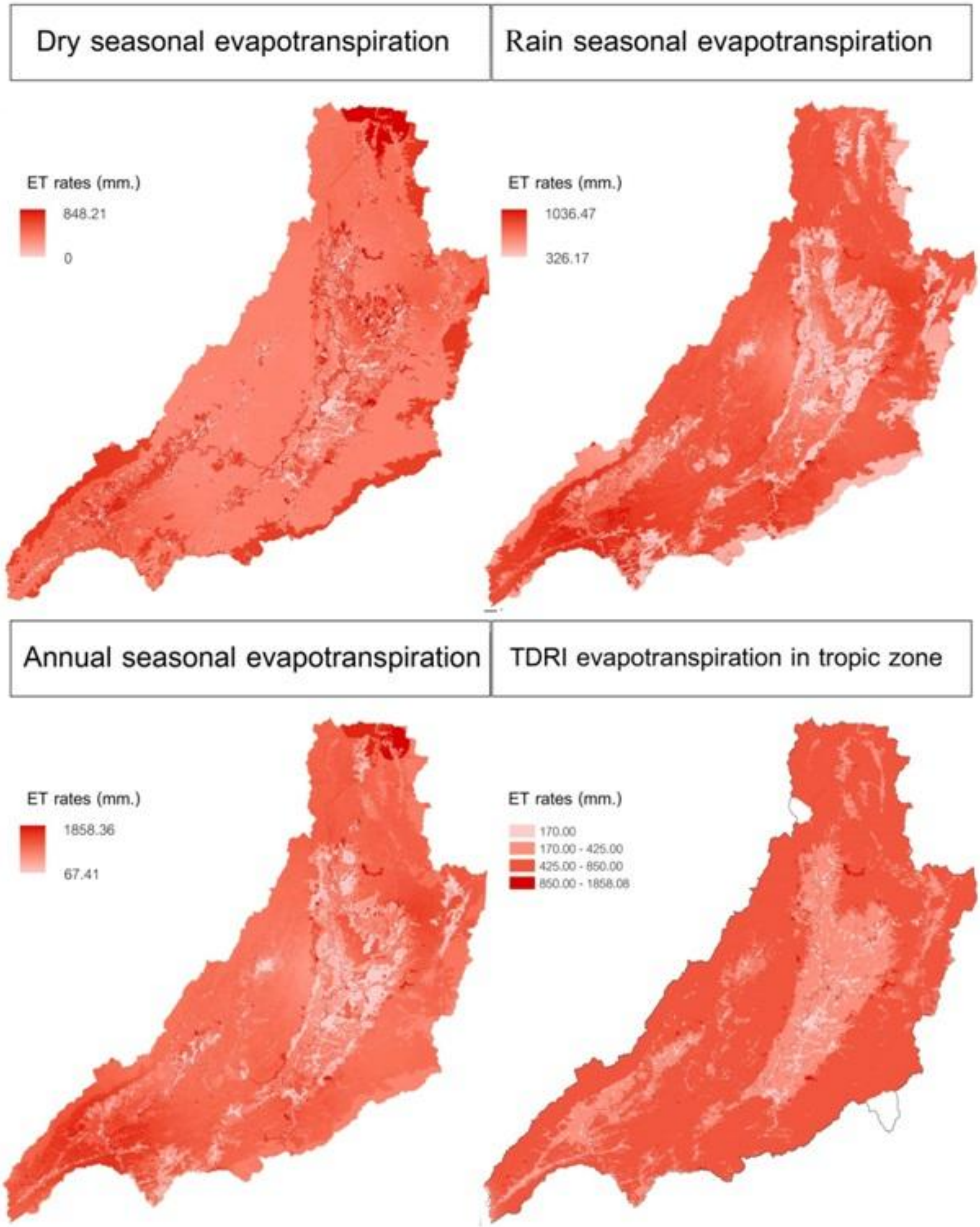

Figure 7. Annual and seasonal evapotranspiration rates in Phrae province based on various case.

From Fig. 7, the results are shown the annual and seasonal evapotranspiration rates, where a concordant justification was considerably closed to the annual evapotranspiration rates of Pitaksaithong (2004), which the annual evapotranspiration rates in the Yom watershed have ranges for 170-1850 mm. per year following evapotranspiration by land use classifications in Thailand of TDRI (Pitaksaithong, 2004). The annual and seasonal surface runoff rates in Figure 6 has shown that surface runoff occurs mainly in the rainy season and correlated with land use feature and precipitation. The similarity between surface runoff pattern and recharge rates, which are able to describe the correlation among various water balance components in Table 2.

The results are shown surface runoff is the most significant for recharge rates that the relative value is 0.99. Nevertheless, in dry season, groundwater recharge occur less than 95 mm per year, which generally may have less values in the environment, mostly in dry season because of higher evapotranspiration rates than rainfall rates especially in semi-arid regions (Scalon et al., 2006). In addition, the minor factors which considered in interaction and influence to groundwater recharge are land use and topographic feature in the study area. Almost 74.88 percent of mountainous forest, 21.31 percent of agriculture area and 3.02 percent of build-up land, which considered as the land use patterns that influence to unsaturated infiltration which significantly for groundwater recharge.

Table 2. The correlation of various water balance components based on linear regression. (R^2)

Various parameters	Precipitation	Runoff	Evapotranspiration	Recharge
Precipitation	-	0.9981	0.9344	0.9384
Runoff	0.9981	-	0.9543	0.9879
Evapotranspiration	0.9344	0.9543	-	0.8976
Recharge	0.9384	0.9879	0.8976	-

3.3. Relationship between groundwater recharge and physical features

Generally, groundwater recharge can have negative or zero values in the environment, mostly in dry season because of higher evapotranspiration rates than surface runoff rates. However, topographic and physical feature can be effect on recharge. The greater recharge occurred in the area that has the lowest average slope and non-building up land use (Winter et al., 1998). All of the above, the results are also correlated with land use, soil type and terrain slope, which are significant for groundwater recharge rate.

The relationship between land use and annual groundwater recharge are shown in Table 3 and Figure 8. In the agriculture area type, recharge rates is the highest average (93.31 mm. per years), and lowest average in the build-up area type (46.52 mm. per years). In addition, in the forest area type, recharge was range from negative to 630 mm. with 54.16 mm. of an average value, this is considered as the land use patterns that influence to hydrologic process which significantly for groundwater recharge. In the building-up land, surface water is difficult to infiltrate an unsaturated zone (Smedt and Batelaan, 2003), and in the case of forest area, results from high interception, high actual evapotranspiration, high shallower rooting depths, which influence to reduced recharge rates (Scalon et al., 2006).

Furthermore, in rainy season, recharge rates are also appeared as zero values in the many zone of the study area. From the comparison between soil group zone and annual recharge zone, the results are shown in Fig. 9, which are able to describe the relationship between recharge zero zone and complex slopes zone. Almost 50 percent of Phrae province is complex slopes area, usually with slopes greater than 35%, the soil group characteristics depending on type of terrain, parent materials and vegetative cover, unsuitability for agriculture, high erosion, these characteristics influenced to surface water infiltration.

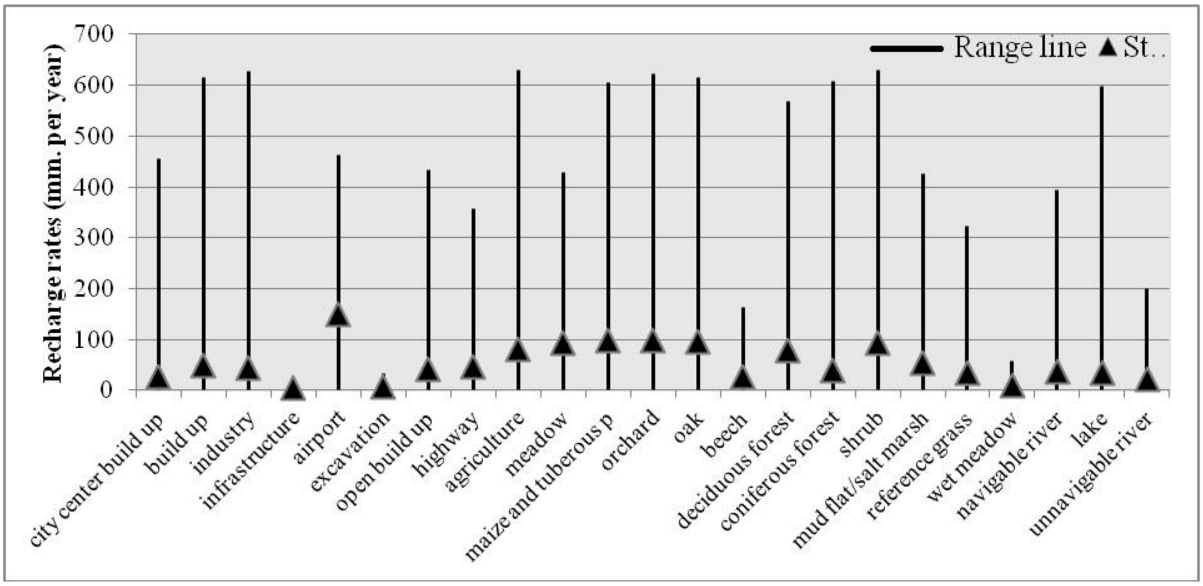

Figure 8. Standard division of groundwater recharge for different land use types.

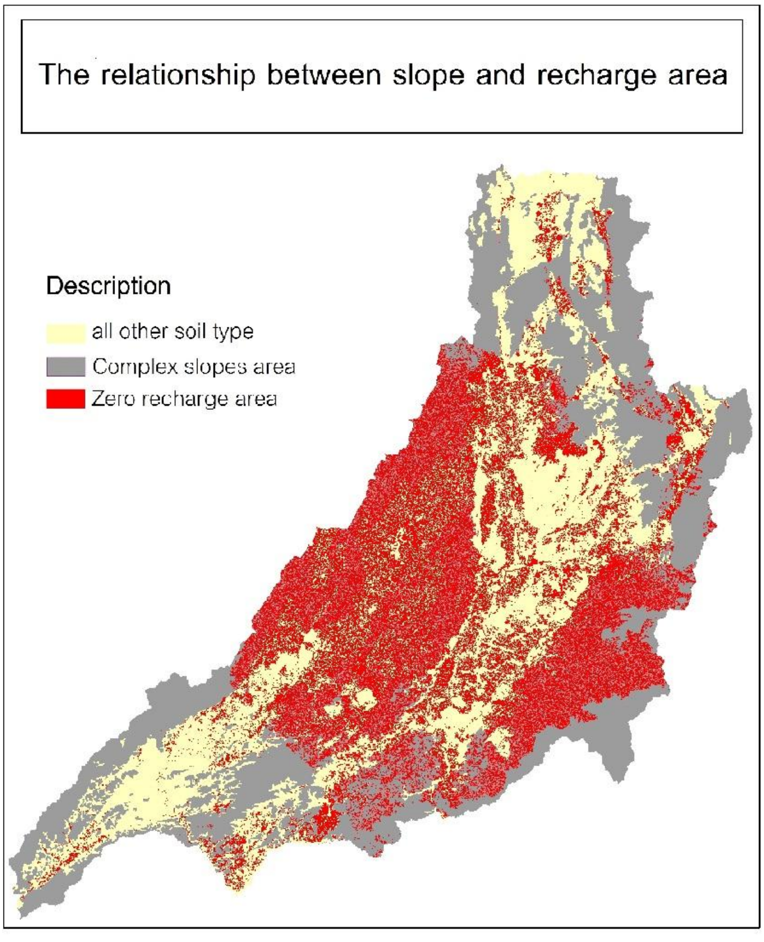

Figure 9. The comparison between soil group and annual recharge zone.

Table 3. The relationship between land use and recharge rates.

Land use			Recharge (mm. per year)			
Type	**Area (sq.m.)**	**Area (%)**	**min**	**max**	**std.**	**mean**
city center build up	31,886,682.83	0.49	0	455.49	28.11	34.94
build up	139,361,835.30	2.17	0	616.27	49.44	30.22
industry	5,900,490.75	0.09	0	627.09	43.66	44.57
infrastructure	21,298.09	0	10.61	22.64	6.01	16.62
airport	592,708.92	0.01	0	462.44	149.96	78.82
excavation	7,151,112.99	0.11	3.81	33.29	7.17	30.96
open build up	9,296,965.69	0.14	0	433.33	41.97	75.12
agriculture	590,561,775.00	9.19	0	630.55	80.21	26.6
meadow	9,077,673.71	0.14	0	427.73	93.58	48.07
maize and tuberous	453,870,892.50	7.06	0	604.99	99.11	33.57
wet meadow	3,101,201.18	0.05	0	57.43	9.21	1.85
orchard	188,113,810.80	2.93	0	622.02	97.76	80.02
deciduous forest	183,347,205.70	2.85	0	568.42	77.97	19.38
coniferous forest	3,812,993,575	59.35	0	607.37	38.27	0
shrub	154,995,429.70	2.41	0	629.94	93.19	131.14
mud flat/salt marsh	2,863,448.15	0.04	0	425.12	53.58	17.36
navigable river	16,887,466.44	0.26	0	393.61	37.74	16.69
lake	25,139,742.67	0.39	0	598.98	35.55	4.63
unnavigable river	2,967,423.78	0.04	0	199.75	23.31	7.99
highway	701,581.49	0.01	0	356.4	45.91	15.7
beech	527,442,357.30	8.21	0	163.47	27.63	0
oak	128,181,442.10	1.99	0	615.72	95.89	32.56
reference grass	129,643,216.00	2.02	0	322.5	34.33	17.11
Total	**6,424,099,336.00**	**100**				

However, recharge may take many years to pass through the unsaturated zone to archive aquifer, which the rate of movement depends on the hydraulic conductivities and hydrogeologic characteristic of aquifers (Fetter, 2001), and it is difficult to determine the groundwater movement. In advance step, numerical groundwater modelling for determines hydrogeologic characteristics are necessary.

4. Conclusion

The groundwater recharge estimation in Phrae province could be successfully simulated for annual and seasonal conditions using the hydrological model WetSpass. The GIS was used to improve, interpreted and demonstrate the parameters input. The WetSpass module was successfully applied to delineate of recharge areas, actual evaporation and the surface runoff, also the spatial interaction was described by the relationship between water balance method and topographic feature.

The rate of groundwater recharge is found to be higher in rainy season (May-October) than dry season (November-April). Furthermore, the rates of groundwater recharge are also found to be remarkably higher in non-vegetated land use than in vegetated land use and build-up land. Eventually, the results analysis reveals that precipitation is the most important hydrologic processing the study area, and evapotranspiration is great significantly for reduce the recharge rates. In addition, complex slopes of soil type have an effect on zero recharge in the region. However, it is difficult to describe the interaction between groundwater recharge and archive aquifer. Based on the results the following study needs can be defined delineate aquifer of groundwater recharge from sub-surface using hydrogeologic models for the future.

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