Spatio-Temporal Water Deficit Estimation of Sugarcane in Thailand

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Abstract
The purpose of this study was to develop a model for estimation of spatio-temporal water deficit of sugarcane. GIS-based data of average weekly rainfall and potential evapotranspiration were interpolated using cokriging technique together with Gaussian model. The Soil Conservation Service (SCS) model was employed to compute runoff. Then, water deficits of sugarcane were determined by subtracting actual evapotranspiration from weekly effective rainfall. The calculation of sugarcane water deficit for the verified field was 630 mm over the growing season. The developed model was tested results with recorded data. The result revealed that total water supply into the verified field over growing season in 2010 was 775 mm in depth, which was 23% difference from the measured data.

1. Introduction

Sugarcane plays a vital role as one of ecomomic crops in Thailand. The cultivating areas are 10,096 km^2 which annually produce sugarcane stem and sugar of 64.37 and 7.60 million tons, respectively. Thailand has exported sugar production to the foreign markets between 1.97 and 2.03 million tons during the years 2002 to 2007 (Sopa, 2010). Additionally, sugarcane is essential raw material to produce renewable energy in which the Thai government has recently launched the policy. The need of sugarcane has still increased rapidly for food security and conservation of energy while the cultivating areas are still the same. Hence, sugarcane plants need to be irrigated during water deficit to increase yield of sugarcane stem. Li et al. (2005) proposed a methodology to compute average water deficits (1992 to 2001) of corn, soybean and sorghum in northeast of China. The crop water deficit was estimated by subtracting actual evapotranspiration from effective rainfall during the same period. Results of calculated water deficits for each crop were planned to supply water into an experimental plot and agreed the field data. Harmsen et al., (2009) determined precipitation deficit (precipitation minus reference evapotranspiration) for a generic crop under climate changes (2000 to 2090) for three locations in Puerto Rico. Results revealed that additional water could be saved during the wet months to offset increased irrigation requirements during the dry months. Referring previous studies, determinations of water deficits performed for each location which climatic data were available. In case of no climatic data availability for some locations, the estimations of spatial water deficit can be solved this problem. The integration of interpolation techniques with GIS for solving spatial data has received considerable attentions among multi-disciplinary researchers. For instance, Yue et al., (2003) analyzed spatial interpolation of climate variables (annual average precipitation and evaporation) using ordinary kriging and cokriging. Comparison of results, cokriging showed higher interpolation accuracy. Wu and Murray (2005) employed cokriging method to interpolate population density by modeling the spatial correlation and cross-correlation of population and impervious surface fraction. The population estimation error was -0.3% for the entire study area. For this study, the cokriging technique will be utilized to derive spatial information such as weekly rainfall and evapotranspiration. The objective of this study was to develop a model for spatially water deficit estimation of sugarcane in northeast of Thailand.

2. Materials and methods

2.1 The Study Area

The study area, Chi River basin, is located in northeast of Thailand. The basin is one of the main dryland sugarcane production areas. They are mostly located in the upper part of the basin. The basin falls approximately between latitude 15° 30′ and 17° 30′ N and longitude 101° 30′ and 104° 30′ E. The catchment covers an area of 49,477 km^2, 9.7% of total area of Thailand. The Chi basin has an influence with two distinguished wind systems, the northeast and southwest monsoons.

Each system has its own weather characteristics. The northeast monsoons, the dry and cool period occurs from mid-October to -February due to winds flowing from the northeast. The southwest monsoons, the wet period occurs from mid-May to -September. Besides monsoons, the Chi basin also faces tropical storms. The major source is from the South China Sea. In addition to the secondary sources are from the Western Pacific, the Gulf of Thailand and the Andaman Sea. They are born as typhoons tropical storms and tropical depressions. The average annual rainfall is between 1,000 to 1,400 mm. The average annual mean temperature is 27°C over the basin. Figure 1 depicts the location map of rainfall and meteorological stations.

2.2 Data Sources

Average Weekly Rainfall: Average weekly rainfalls were derived from daily rainfall data during 1984 to 2004 (21 years), which were collected from the Meteorological Department of Thailand. The 105 rainfall stations located in and around the Chi River basin were employed in this study.

Climatic Data: The methods for evapotranspiration calculation from meteorological data require various climatological and physical parameters such as solar radiation (sunshine duration), air temperature, humidity and wind speed. These average daily data during 1984 to 2004 for each month were collected from the Meteorological Department. Some of data are measured directly in 17 weather stations over the basin. Other parameters are associated to commonly measured data and can be derived with the help of a direct or empirical relationship.

Digital Elevation Model (DEM): To perform the interpolation using cokriging technique, the 30x30 m spatial resolution DEM data were used in this study. The data were the product of Shuttle Radar Topographic Mission (SRTM) and topographic data available from the Royal Thai Survey Department of Thailand. They were projected in Universal Transverse Mercator (UTM), zone 48N with a WGS84 horizontal datum. DEM values were quite different from the field elevations. Then, DEM data needed to be calibrated with referenced data. The measured elevations were compared with the DEM values at the same locations to establish the relationship. The linear equation of the reference and DEM values was applied to correct the vertical error. The calibrated DEM values served as one of input data for interpolations of weekly-rainfall and -evapotranspiration.

Soil Drainage: Soil drainage influences the infiltration rate and capacity to retain water. Pisut (1991) classified the soil drainage according to soil groups and the United States Department of Agriculture (USDA) soil drainage classes as very poorly drained, poorly drained, somewhat poorly drained, moderately well drained, well drained, somewhat excessively drained, and excessively drained.

Land Use: The land use GIS layers were collected from the Land Development Department of Thailand. They were classified into many types of crop field including sugarcane, rice field, forest, resident areas, and water bodies.

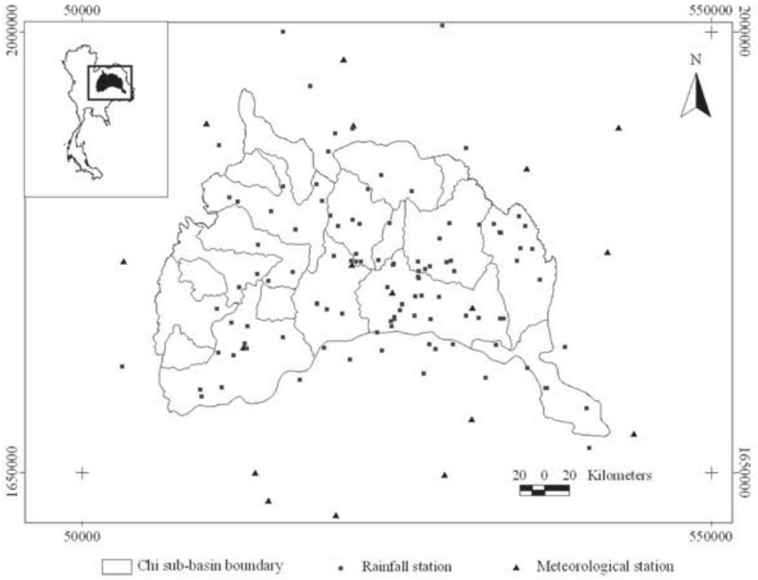

Figure 1: Locations of rainfall and meteorological stations

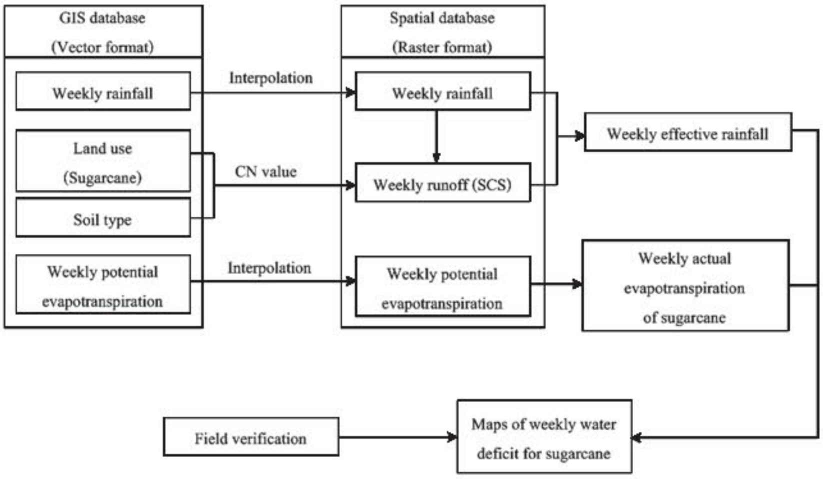

Figure 2: Flowchart of water deficit model for sugarcane

2.3 Development of Model for Water Deficits of Sugarcane

The flowchart of methodology for spatio-temporal water deficit model of sugarcane was developed as presented in Figure 2. Weekly rainfall and potential evapotranspiration data of 105 and 17 stations respectively were interpolated to be spatial values. Land use and soil type were employed to select the CN value which served as data to calculate initial abstraction and direct runoff sequentially. The effective rainfall was determined by subtracting direct runoff from the interpolated rainfall values. Additionally, effective rainfall values were subtracted by actual evapotranspiration to derive water deficits of sugarcane. Details of each component presented here.

Interpolating Essential Data using Cokriging: Referring theory of cokriging, any regionalized variable z(x) can be considered a realization of a random function Z(x), which is a combination of a deterministic component, m(x), and random fluctuation, ε(x) (Wu and Murray, 2005):

$$z(x) = m(x) + \varepsilon(x)$$

Equation 1

Where x is the geographical coordinates in one, two, or three dimensions, m(x) is a geographical trend or drift, and ε(x) is the spatially dependent random errors with mean zero. In most applications, m(x) is given locally constant (m(x) = μ). For a given distance and direction of h, the variance of differences between z(x) and z(x+h) is independent of x:

$$\mathrm{var}\left[z(x) - z(x+h)\right] = E\left[\left\{z(x) - z(x+h)\right\}^2\right] = 2\gamma(h)$$

Equation 2

Where vector h is a given separation distance and direction from x (lag), and γ(h) is variogram, which is an important tool for autocorrelation of a spatial model. In a case of there are two or more variables, a cross-variogram indicates as follows:

$$\gamma_{uv}(h) = \frac{1}{2}E\left[\left\{z_u(x) - z_u(x+h)\right\}\left\{z_v(x) - z_v(x+h)\right\}\right]$$

Equation 3

Furthermore, an under-sampled variables need to be calculated using cokriging. This method ensures unbiased estimates with minimum and known variance. For estimating a variable u in block B with sampling points of u and the second variable v, the estimated equation is

$$z_u(B) = \sum_{i=1}^{N_u} \lambda_{ui} z_u(x_{ui}) + \sum_{j=1}^{N_v} \lambda_{vj} z_v(x_{vj})$$

Equation 4

Where N_u and N_v are the number of sampling points for variable u and v, respectively. x_{ui} and x_{vi} are the locations of sampling points for variable u and v, and λ_{ui} and λ_{vj} are weights of coregionalized variables.

SCS Model: The Soil Conservation Services (SCS) method is the most widely used for estimating surface runoff for a given rainfall (Winnaar et al., 2007). This method considers the relationship of land use and hydrological soil group to derive a curve number (CN). The CN expresses as a catchment's runoff response to a rainfall event, which indicates the proportion of rainwater contributing to surface runoff. Values of curve numbers are between 0 and 100, where higher values represent a greater proportion of surface runoff. The SCS model can be expresses as:

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

Equation 5

Where Q is direct runoff, P is rainfall, and S is initial abstraction. For standardization application, the relationship of CN and S is:

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

Equation 6

Where S is the dimension in millimeter. The CN also depends on the antecedent moisture conditions (AMC), which were classified as dry (AMCI), moderate (AMCII), and wet (AMCIII), respectively. The CN appearing in equation 6 is for AMCII. While, the CNs for AMCI (CNI) and AMCIII (CNIII) can be modified from CN in which more details reveal in U.S. Soil Conservation Service (1972).

Evapotranspiration: Evapotranspiration (ET) is defined as lost from the soil surface by evaporation and the crop by transpiration (Allen et al., 1998). Numerous researchers have analyzed the performance of various calculation methods for different locations. For instance, Dehghanisanij et al., (2004) studied the experiment of alfalfa's evapotranspiration using lysimeter. The results of ET calculation using six methods such as Penman (PE), Penman-Monteith (PM), Wright-Penman (WP), Blaney-Criddle (BC), Radiation balance (RB), and Hargreaves (HG) were compared with data from lysimeter values. They found that the PM model produced the best ET estimation. The study of Utset et al., (2004), ET values of maize derived from PM were closer to actual ET than those estimated from Priestley-Taylor (PT). In addition to estimation of ET, the crop reference ET (ET_o) derived from the PM method was chosen as follow:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Equation 7

where ET_o is crop reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), e_s-e_a is saturation vapour pressure deficit (kPa), Δ is slope vapour pressure curve (kPa °C^{-1}), and γ is psychrometric constant (kPa °C^{-1}).

Water Deficit: The crop water deficit at any time was determined by subtracting actual ET from the effective precipitation (rainfall minus runoff) during the same period (Li et al., 2005). For this study, computation of weekly water deficit for sugarcane performed during January to October.

3. Results and Discussion

3.1 Interpolating Essential Data using Cokriging

Referring Figure 1, processes of interpolation utilized 105 stations of measured rainfall and 17 measured weather stations. Yue et al., (2003) revealed the spherical type of variogram was perfect to simulate the spatial pattern. While Yang et al., (2008) employed the Gaussian model to interpolate groundwater level and calculated results agreed the field survey. For this study, the Gaussian and spherical models were tested the consistency using mean error (ME) and root-mean standard error (RMSE) with the original data. Values of ME and RMSE should be closed to 0 and 1, respectively (Yang et al., 2008). The analysis of cokriging used average weekly rainfall and potential evapotranspiration data for the first variable and calibrated DEM data as the second variable. The interpolation of weekly rainfall data started from week 15 (April, 9 to 15) to week 44 (October, 29 to November, 4). Due to constrain of average monthly crop coefficients of sugarcane, daily ET_o values for each month during January to October were interpolated. The cross validation served as testing of accuracy for fitting the variogram. Employing cokriging, value z_i^* at point i was predicted without using the measurement z_i. Then, values of ME and RMSE were calculated. Table 1 shows average values of ME and RMSE for fitting the variogram models of rainfall and evapotranspiration interpolations. Comparison of the results, Gaussian model was suitable for two types of data. Figure 3 illustrates interpolated rainfall map of week 33 with ME and RMSE values of -0.07 and 0.91, respectively. After derivation of interpolated evapotranspiration maps, values of interpolated ET_o were multiplied by average monthly crop coefficients of sugarcane to derive actual ET (ET_c), then multiplied by 7 to derive weekly ET_c. Example of weekly ET_c map in August is depicted in Figure 4.

Table 1: Cross validation results of two different variogram models

Variogram model	Rainfall		Evapotranspiration	
	ME	RMSS	ME	RMSS
Gaussian model	-0.02	1.05	0.02	1.26
Spherical model	-0.04	1.13	0.06	1.32

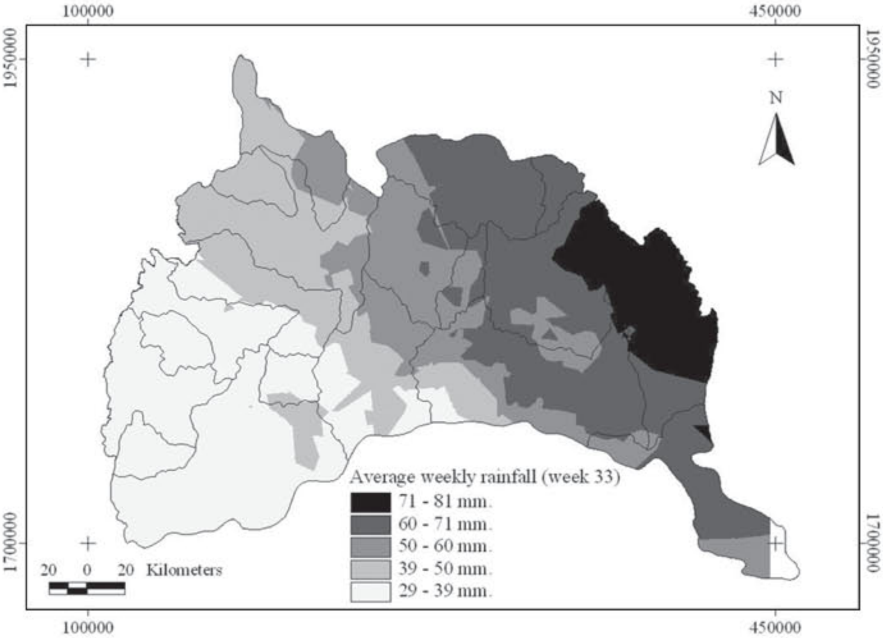

Figure 3: Interpolated rainfall map of week 33 (August, 13 to 19)

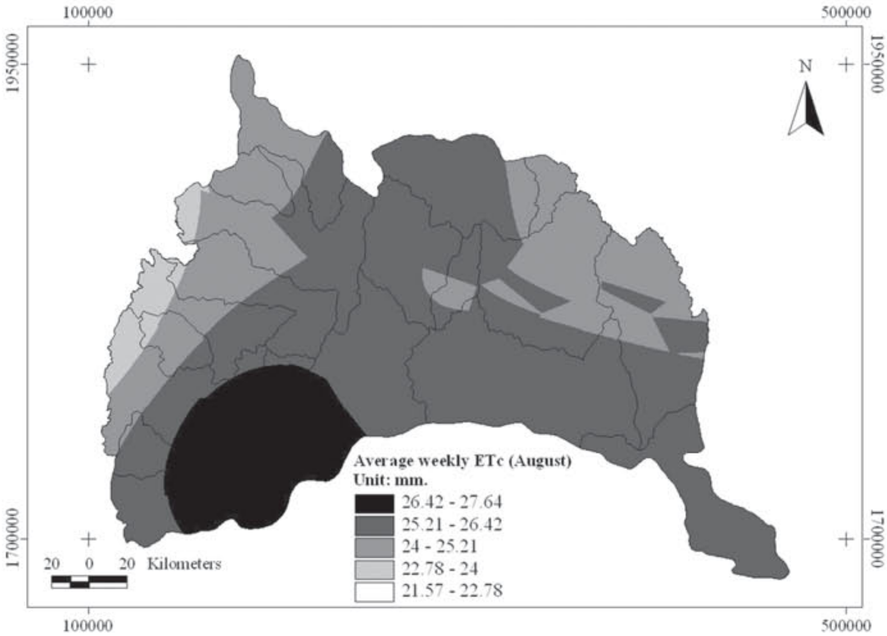

Figure 4: Weekly ET_c map in August

3.2 Water Deficit of Sugarcane

Referring interpolated results of rainfall over the Chi basin, sugarcane water deficits were computed by subtracting actual ET from effective rainfall. Runoff could be determined using the SCS model which required land use type, soil drainage type, and AMC as input data. The cultivating sugarcane areas in the Chi basin are mostly located in soil drainage of moderately well drained and well drained categories which was classified as SCS soil group B (Shi et al., 2007). The calculations of direct runoff were performed during the mid of April (week 15) to the end of October (week 44). Regarding average historical rainfall data, there was some rainfall amount in week 15. Therefore, the antecedent moisture condition was defined as AMCII which affected CN as 71 (U.S. Soil Conservation Service, 1972). The initial abstraction was computed using equation (6) to derive value of 103.75 mm. Furthermore, the weekly direct runoff was determined using equation (5). The weekly effective rainfall was calculated by subtracting weekly-runoff from -rainfall. Then, the weekly effective rainfall was subtracted by the weekly ET_c to derive the weekly water deficit of sugarcane. Figures 5 and 6 show water deficit of sugarcane in the dry season (weeks 1 to 17) and wet season (weeks 18 to 44). For summarization, Figure 7 illustrates the water deficit of sugarcane over the growing season (January to October) of the Chi River basin.

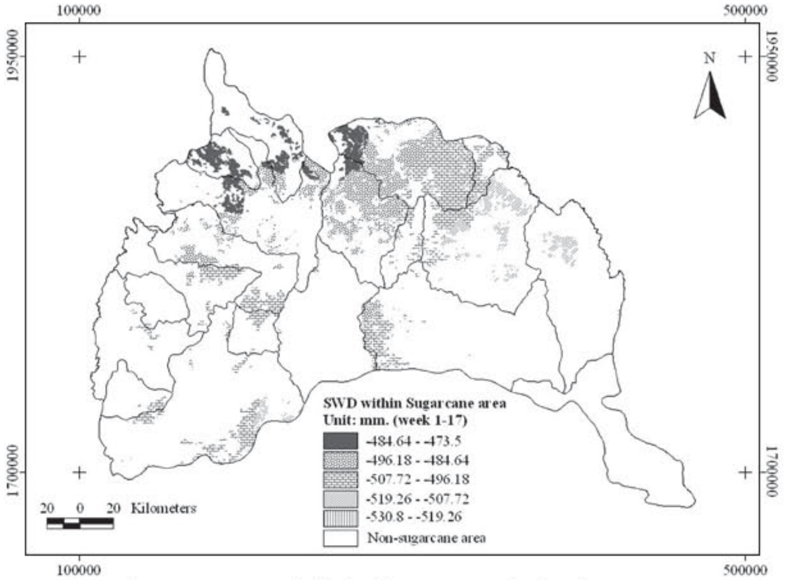

Figure 5: Water deficit of sugarcane in the dry season

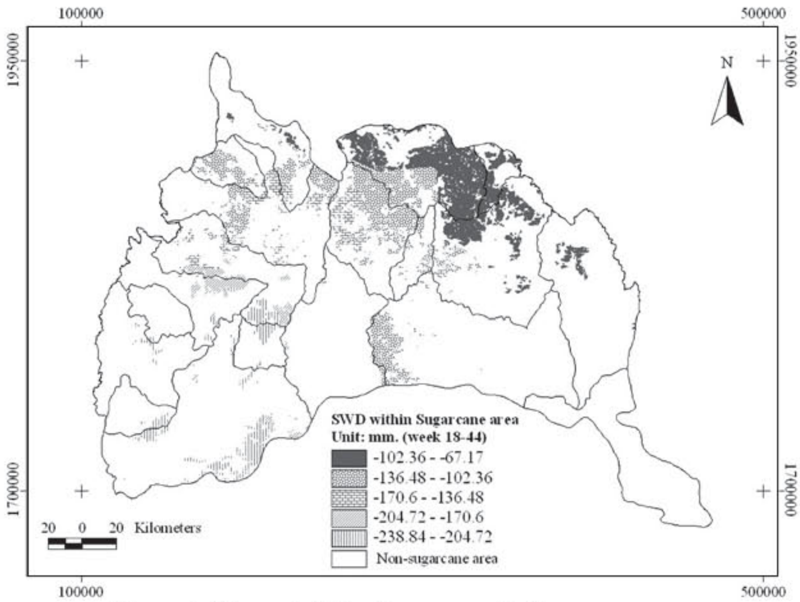

Figure 6: Water deficit of sugarcane in the wet season

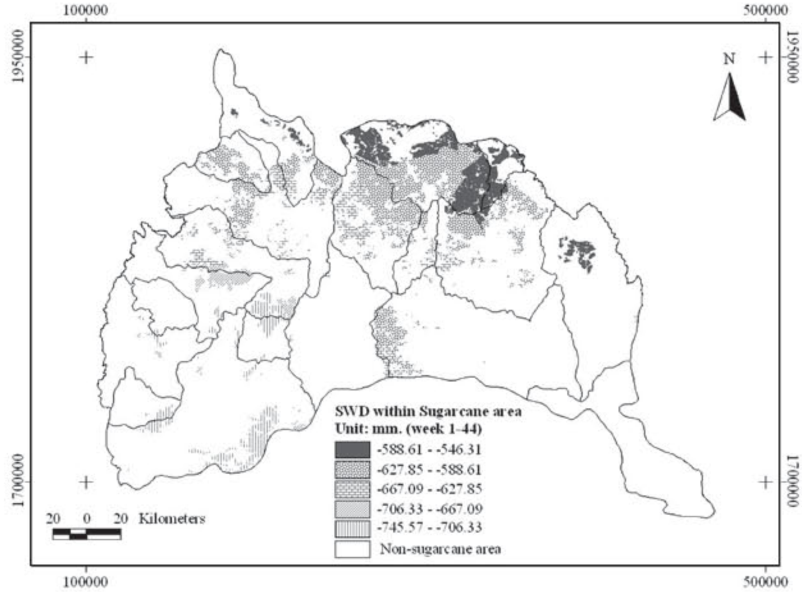

Figure 7: Water deficit of sugarcane over the growing season

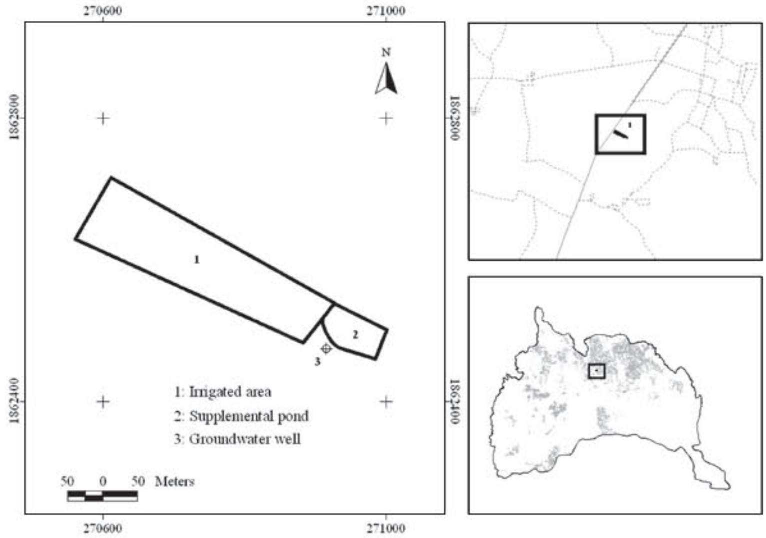

Figure 8: Sugarcane field for verification

The first field survey was conducted various sites to verify the results in Amphur Nong Rua, Khon Kaen province in November 2010. It was found that some farmers irrigated sugarcane field using drip irrigation system. Some sugarcane fields located in irrigated areas, they irrigated the fields using furrow irrigation. But there is no record of water supply. The second survey was conducted in December 2010 in Amphur Non Sa-at, Khon Kaen province. As shown in Figure 8, the farmer constructed supplemental pond and groundwater well to supply water for sugarcane field of 30,488 m^2 or 19 rai (unit of area in Thailand). The availability of water supply was approximately 10,500 m^3 which was not enough for requirement over the growing season. Hence, supplemental water from groundwater needed to encourage, but the farmer invested more budget due to energy for pumping. Recording of water supply in 2010, he irrigated the plant with constant rate of 31 mm per week during weeks 1 (January) to 28 (July), which was totally water depth of 775 mm. The calculated water deficits during weeks 1 to 4 and weeks 5 to 8 were 50% and 23%, respectively which were less than supplemental water supply. While, calculations of sugarcane water deficit during weeks 9 to 16 were around 20% greater than water supply.

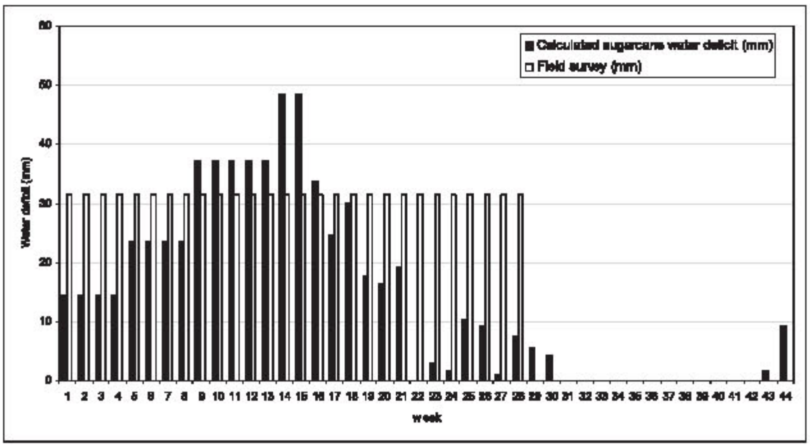

Figure 9: Weekly water supply for sugarcane during growing season

Referring week 18, the calculated water deficit equaled water supply into the field. In addition to results of calculation for weeks 19 to 25, water deficit values were less than measured data. Information from interviewing there were rainfall at the field after irrigation. This affected water supply into the field greater than calculated values. Refer to his experience, he stopped irrigating sugarcane during weeks 26 to 44 because of sufficient soil moisture derived from rainfall. These agreed the results of estimation as shown in Figure 9. The calculation of total water supply was 630 mm. After irrigation, the average sugarcane yield increased significantly from 10 ton per rai to 18 ton per rai.

4. Conclusions

This paper attempted to develop spatio-temporal water deficit of sugarcane. The cokriging technique together with Gaussian model was employed to interpolate average weekly rainfall and potential evapotranspiration data. They were selected as the first variables, while calibrated DEM data were the second variable. The interpolated rainfall map showed mean error (ME) and root-mean standard error (RMSE) values of -0.07 and 0.91, which were acceptable. The Soil Conservation Service (SCS) model was utilized to calculate runoff. Additionally, water deficits of sugarcane were determined by subtracting weekly-actual evapotranspiration from - effective rainfall. The developed model was applied to the Chi River basin, in northeast of Thailand. Recording of water supply from the verified field in 2010 over the growing season was totally water depth of 775 mm. Total water supply derived from the model was 630 mm which was 23% difference from the field survey. Additionally, the developed model can be applied to estimate sugarcane water deficit of any basin.

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