

Spatial and Temporal Distribution of Irrigation Requirements in the Chao Phraya River Basin, Thailand

Preeyaphorn Kosa^{1*}, Kobkiat Pongput², Supakij Nontananandh¹ and Pakdee Khobkrag¹

ABSTRACT

The tendency towards increasingly-higher water demands than in the past has increased the importance of improving water resource management. Responsible water resource management is facilitated by quantifying the irrigation requirements for given land uses. The goal of this study was to determine the spatial distribution of the irrigation requirements in the eight sub-basins of the Chao Phraya River basin, Thailand. To achieve this goal, actual evapotranspiration was determined by the SEBAL and the FAO Penman-Monteith equations while precipitation was recorded from TRMM satellite images and rain gauge stations. The irrigation requirement was calculated by subtracting the amount of actual evapotranspiration from the measured precipitation. The results of the study concluded that the Ping, Wang and Yom sub-basins had sufficient precipitation for all land uses. For the Nan, Sakae Krang and Pasak sub-basins, there was sufficient precipitation for all land uses except in areas that had existing irrigation infrastructure and thus there is a need for water that is not naturally supplied to support some land uses. For the Tha Chin and Chao Phraya sub-basins there was insufficient precipitation for all land uses. Additional water for these two sub-basins could be sourced from the surplus water from the Ping, Wang, Yom and Nan sub-basins that flowed into the Chao Phraya sub-basin and could also be diverted to the Tha Chin sub-basin.

Key words: MODIS, Landsat 7, TRMM, Kriging, irrigation requirement

INTRODUCTION

The Chao Phraya River basin covers the north and central region of the Kingdom of Thailand and is the largest basin within the borders of the nation. Water in the basin is used for agricultural, municipal and industrial purposes. There is an ever-increasing demand for water, so water storage capacity in the watershed has been increased through the development of reservoirs, canals and other artificial systems. On the one

hand, even with the existing water management systems, floods often occur during the rainy season, because the reservoirs are unable to handle the volume of water and there is slow drainage of excess water. On the other hand, water in the reservoirs is released without proper planning during the rainy season leaving insufficient water for the dry season. Thus, improving water resource management has become more and more necessary (Buddhapalit, 1999).

To improve water resource management,

¹ Civil and Environmental Engineering Program, Faculty of Science and Engineering, Kasetsart University Chalermphrakiat Sakonnakhon Province Campus, Sakonnakhon 47000, Thailand.

² Department of Water Resources Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand.

* Corresponding author, e-mail: preeyaphorn.k@ku.ac.th

it is important to determine irrigation requirements, because the necessary water storage capacity is related to the irrigation requirement. Normally, irrigation requirements are supported by storing water in reservoirs. Moreover, the analysis of the spatial distribution of precipitation is imperative in the analysis of large areas such as the Chao Phraya River basin. The purpose of this study was to determine the spatial distribution of the irrigation requirements in the eight sub-basins of the Chao Phraya River basin, Thailand.

The availability of water can be evaluated from studies of evapotranspiration, precipitation and irrigation requirements. Evapotranspiration is an outflow and precipitation is an inflow in calculating irrigation requirements. This study evaluated irrigation requirements using evapotranspiration and rainfall, which were calculated from satellite images and ground-based measured data. To date, recent developments in technology associated with the use of remote sensing in the evaluation of rainfall and evapotranspiration over large areas have not been applied in Thailand. This technology is of interest in the field of water resource management for planning, developmental and operational reasons.

MATERIALS AND METHODS

Chao Phraya River basin

In Thailand, the Chao Phraya River basin is the largest and most important geographical feature with respect to land and water resources development. It is located in the north and central regions of the country. The area of the Chao Phraya River basin is 157,925 km² and includes eight sub-basins: Ping, Wang, Yom, Nan, Sakae Krang, Pasak, Tha Chin and Chao Phraya. There are 44 large irrigation projects in the Chao Phraya River basin. The total irrigated area is 15,717 km². The average yearly rainfall is about 1,200 mm in the northern region and 1,350 mm in the Central Valley, where the peak is in September and the

dry months are November through to the beginning of April. The rainy season starts from the middle of April and ends in late October. In the early stage of the rainy season, there is local rain for short periods. While the runoff ratio is difficult to calculate, it has been estimated to be between 15 and 30% (Buddhapalit, 1999).

Actual evapotranspiration

Actual evapotranspiration was calculated by the Surface Energy Balance Algorithm for Land (SEBAL) and the FAO Penman-Monteith equation. The time period for the data used in the actual evapotranspiration calculations from SEBAL and from the FAO Penman-Monteith computations was one year (January to December 2002). In the SEBAL method, 27 MODIS images were used to estimate daily actual evapotranspiration, while weather data from 33 weather stations was used to determine daily actual evapotranspiration using the FAO Penman-Monteith equation. The actual evapotranspiration values calculated from the FAO Penman-Monteith method were then compared with the actual evapotranspiration values calculated from SEBAL to determine the actual evapotranspiration for use in the calculations associated with the irrigation requirements.

Actual evapotranspiration calculated by SEBAL

The SEBAL algorithm is a tool to compute with a high level of accuracy and confidence the actual evapotranspiration for flat areas. The algorithm uses satellite images and weather data to calculate actual evapotranspiration using a surface energy balance model. SEBAL evaluates the instantaneous actual evapotranspiration flux at the time the image is taken, as the satellite images provide information only current at the overpass time. The actual evapotranspiration flux can be calculated for each pixel of the image by using the residual of the surface energy budget equation (Bastiaanssen *et*

al., 1998a; Bastiaanssen *et al.*, 1998b) as shown in equation 1:

$$LE = (R_n - G) - H \quad (1)$$

where, LE is the latent energy of evaporation (W/m^2), R_n is the net radiation flux at the soil surface (W/m^2), G is the soil heat flux (W/m^2) and H is the sensible heat flux to the air (W/m^2).

The evaporative fraction (Λ) was then obtained using equation 2, with its value at each pixel of the satellite image estimated using the 24-hour evapotranspiration for the day of the image. The evaporative fraction was assumed to be a constant value over the full 24-hour period.

$$\Lambda = \frac{LE}{R_n - G} = \frac{LE}{LE + H} \quad (2)$$

The 24-hour actual evapotranspiration ($mm\ d^{-1}$) was estimated using equation 3:

$$ET_{24} = \frac{86400\Lambda(R_{n24} - G_{24})}{\lambda} \quad (3)$$

where R_{n24} is daily net radiation ($W/m^2/day$), G_{24} is daily soil heat flux ($W/m^2/day$), 86,400 is the number of seconds in a 24-hour period and λ is the latent heat of vaporization (J/kg). Since energy, on average, is stored in the soil during the daytime and released into the air at night, is usually very small for the combined vegetative and soil surface and so it was assumed to be zero at the soil surface (Morse *et al.*, 2000; Hafeez and Chemin, 2005).

While SEBAL is suitable for flat areas, the Chao Phraya River basin, on which this study is based, includes both flat and mountainous terrain, so a digital elevation model (DEM) was used to adjust the algorithm's estimates of the evapotranspiration in mountainous areas. A DEM is a representation of the topography of the earth's surface by an array of numbers representing heights above a reference datum. In this study, both contour map elevation and recorded elevation data were used as input data for the GIS software to calculate spatial elevation coordinates in the Chao Phraya River basin. The spatial elevation was then used to determine the temperature at any elevation,

as the temperature differential is the cause of differential evapotranspiration.

To calibrate the actual evapotranspiration of the 27 MODIS images, the relationship between the 24-hour actual evapotranspiration from six MODIS images and from six Landsat 7 images captured on the same date was determined. This relationship was summarized by the equation $Y = 0.707X + 2.224$ ($R^2 = 0.668$), where Y is the actual evapotranspiration from a Landsat 7 image and X is the actual evapotranspiration from the corresponding MODIS image. Landsat 7 (30m and 60m) images were selected for this calibration because they have a higher resolution than MODIS image (250 m and 1000 m). Before the relationship between the actual evapotranspiration from the MODIS and Landsat 7 images was obtained, it was important to correlate the values of the six MODIS images and the six Landsat 7 images. To do this, it was assumed that the actual evapotranspiration of each of the six pairs of MODIS and Landsat 7 images should match because they were all computed by SEBAL. Also, the dates and the locations of the six Landsat 7 images were the same as those of the six MODIS images. The correlation coefficient was used to determine the reliability value of the actual evapotranspiration estimated from these 12 images. The correlation coefficients of actual evapotranspiration for rice, maize, sugarcane, cassava and water were calculated as: 0.654, 0.609, 0.571, 0.649 and 0.659, respectively. After the relationship of actual evapotranspiration from both the MODIS and Landsat 7 images was determined, the 27 MODIS images were adjusted.

Actual evapotranspiration calculated by the FAO Penman-Monteith method

The FAO Penman-Monteith method included the calculation of actual evapotranspiration (ET_c) that was estimated from the product of the crop coefficient (K_c), the soil coefficient (K_s) and the reference crop evapotranspiration (ET_o) using equation 4:

$$ET_c = K_s \times K_c \times ET_o \quad (4)$$

The reference crop evapotranspiration (ET_o) can be calculated on a daily basis using equation 5, the FAO Penman-Monteith equation (Allen, 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273.2} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (5)$$

where, ET_o is the reference crop evapotranspiration (mm d^{-1}), R_n is the net radiation ($\text{MJ m}^{-2}\text{d}^{-1}$), G is the soil heat flux ($\text{MJ m}^{-2}\text{d}^{-1}$), T is the air temperature (C), e_s is the saturation vapor pressure at air temperature (kPa), e_a is the vapor pressure of air (kPa), u_2 is the wind speed at 2 m (m s^{-1}), Δ is the slope of the saturation vapor pressure curve at air temperature (kPa C^{-1}) and γ is the psychrometer constant (kPa C^{-1}).

Subsequently, the recorded pan evaporation was compared with the reference evapotranspiration calculated by the FAO Penman-Monteith method. Pan evaporation is the amount of water evaporated during a period (mm day^{-1}) with an unlimited supply of water (potential evaporation). It is a function of the surface and air temperature, insolation and wind, all of which affect water-vapor concentrations immediately above the evaporating surface. On the other hand, reference evapotranspiration is a function of the temperature, wind, humidity and net radiation. There is a relationship between the pan evaporation and reference evapotranspiration (Humphreys *et al.*, 1994; Grismer *et al.*, 2002; Marco, 2002). The decreasing trend detected in the pan evaporation and reference evapotranspiration could be attributed to the significant decreasing trends in the net radiation and the wind speed and also to the significant increasing trend in air temperature.

Daily pan evaporation at 33 weather stations from 1971 to 2002 was used to determine the average monthly pan evaporation. Thereafter, the correlation coefficients between mean monthly

reference evapotranspiration and mean monthly pan evaporation for the 33 weather stations were obtained. The correlation coefficients ranged from 0.85 to 0.96. Since there is a high relationship between pan evaporation and computed reference evapotranspiration, a high level of accuracy could be attributed to the calculated values. Point values were calculated using the FAO Penman-Monteith equation, with point reference evapotranspiration interpolated using the concept of Co-kriging described below.

Co-kriging is a geostatistical technique developed to improve the estimation of a variable using information on other spatially correlated variables which are generally better sampled. Since in-depth discussion about this interpolation technique has been given by Journel and Huijbregts (1978), Isaaks and Srivastava (1989) and Burrough and McDonnell (1998), only a brief description of the interpolation method used has been presented here.

Consider a set of experimental values of monthly reference evapotranspiration ($ET_{o,m}$) where $ET_{o,m,i}$ is the monthly reference evapotranspiration from January to December ($i = 1, 2, \dots, 12$) and a set of experimental values of elevation or $Y : [Y_k, k = 1, 2, \dots, 6252]$. In these equations, 12 is the number of months in one year and 6252 is number of elevation points that are converted from an elevation contour map by a grid of 5 km x 5 km. This elevation contour map was supported by information from the Royal Irrigation Department. In this study, the value of $ET_{o,m}$ a space location x_o from $ET_{o,m}$ and Y was estimated. Equation 6 presents the estimation of $ET_{o,m}^*$ ($ET_{o,m}^*$) at any point x_o .

$$ET_{o,m}^*(x_o) = \sum_{i=1}^{12} \lambda_i^1 ET_{o,m}(x_i) + \sum_{k=1}^{6252} \lambda_k^2 Y(x_k) \quad (6)$$

where, λ_i^1 and λ_k^2 are the weighting factors for first and second known variables.

The crop coefficient (K_c) depends on the crop type and the development of the crop. There

may be several reference crop values for a single crop depending on its stage of development. For this study, three values of the crop coefficient for describing the crop coefficient value were used; those during the initial stage ($K_{c,ini}$), the mid-season stage ($K_{c,mid}$) and the end of the late season stage ($K_{c,late}$) (Allen *et al.*, 1998). To classify the crop coefficient in each area, a land use map and a crop calendar were used to indicate the crop's stage of development in each agricultural area. Examples of crop coefficients used for this study are: 0.963, 1.194 and 0.934 for rice, 0.978, 1.184 and 0.897 for maize and 0.811, 1.262 and 1.007 for sugarcane for the three stages, respectively (Kosa and Pongput, 2006).

The soil coefficient (K_s) describes the effect of water stress on crops which is a function of the degree of saturation in the root zone (S) or the water depletion in the root zone (D). If there is no water stress in a cultivated area, the soil coefficients do not need to be considered. However, cultivated areas normally consist of both saturated and unsaturated soil, so the soil coefficient for each area has to be defined. In Thailand, there is no recorded soil moisture in the root zone, so, to solve this problem, R_n , G and H were used to estimate the soil coefficients.

Soil moisture in the root zone was calculated as the degree of saturation in the root zone (S) according to the empirical equation 7:

$$S = \exp\left(\frac{\Lambda - 1}{0.42}\right) \quad (7)$$

where, Λ is evaporative fraction. From equation 7, a dry soil has a value of 0.00 at one end of the range to a saturated soil with a value of 1.00 at the

other end of the range. However, the soil coefficient is a function of the water depletion in the root zone (D), so it was necessary to convert the soil moisture to soil water depletion using equation 8.

$$D = 1 - S \quad (8)$$

Thereafter, soil coefficients were signified using Table 1 as recommended by Broner (2005).

Comparison between actual evapotranspiration calculated by SEBAL and the FAO Penman-Monteith method

To quantify the linear relationship between the different means of estimation, the actual evapotranspiration values from SEBAL were compared with those from the FAO Penman-Monteith method using correlation coefficients. The 27 days of data derived from the 27 MODIS images were compared with daily data from the 33 weather stations. The average correlation coefficient was 0.79. This result indicated that there was a high linear relationship between the actual evapotranspiration from SEBAL and the FAO Penman-Monteith calculation.

Since the actual evapotranspiration computed by SEBAL was only calculated for 27 days, the actual evapotranspiration on other days was determined using temporal interpolation based on the concept of Co-kriging. Thereafter, the actual evapotranspiration from the temporal interpolation was compared with the actual evapotranspiration from the FAO Penman-Monteith method, using 30 coordinates. The average correlation coefficient was 0.69, which suggested that there was a good linear relationship between the actual evapotranspiration from SEBAL and the FAO Penman-Monteith method.

Table 1 Values for soil water depletion (D) and the soil coefficient (K_s).

D	K_s	D	K_s	D	K_s
0.00	1.00	0.25	0.94	0.45	0.87
0.05	0.98	0.30	0.92	0.50	0.85
0.10	0.97	0.35	0.92	0.60	0.80
0.15	0.96	0.40	0.89	0.70	0.74
0.20	0.95				

From the above results, it can be seen that deriving the actual evapotranspiration values from SEBAL had the advantage of good spatial resolution, compared to using the FAO Penman-Monteith method which had the advantage of good temporal resolution. Estimates of actual evapotranspiration from both SEBAL and the FAO Penman-Monteith method can be used in irrigation requirement calculations. For this study, actual evapotranspiration calculated by the FAO Penman-Monteith method was selected to provide input data in the irrigation requirement calculations because of its good temporal resolution. Actual evapotranspiration using this method was calculated for a one year period using recorded weather data.

Rainfall levels

Rainfall levels were obtained from TRMM images and rain gauge stations. The time period covered by the rainfall data from the TRMM images and from rain gauge stations was one year (January – December 2002). Monthly rainfall maps provided by NASA were used in conjunction with the TRMM images and the recorded daily rainfall data from the 230 rain gauge stations to determine the monthly rainfall for use in the calculation of the irrigation requirements.

The calculation of Kriging interpolation for rainfall

Monthly rainfall levels from 230 rain gauge stations were utilized to generate a spatial rainfall map using Kriging interpolation with a resolution of 1000 m x 1000 m, which was the same resolution as that of the monthly actual evapotranspiration.

Kriging was used to interpolate the rainfall recorded at various points to generate a spatial rainfall map. Kriging is a regression technique used in geostatistics and is commonly known as Gaussian process regression in the statistical community. Kriging is an estimation method that assumes that a weighted average of one or more sample points will provide the best

estimate and it computes the optimal values of the weights. The interpolation of spatial rainfall was determined using equation 9:

$$R_m(x, y, t_m) = \sum_{i=1}^n W_i R(x_i, y_i, t_m) \quad (9)$$

where, R_m is the estimated rainfall, $R(x_i, y_i, t_m)$ is the rainfall and W_i is the Kriging weight.

Comparison between monthly rainfall from TRMM images and from rain gauge stations

To determine the linear relationship between the different methods to estimate monthly rainfall, the estimates from the TRMM images were compared with monthly rainfall data from the rain gauge stations using correlation coefficients. For each month, 100 coordinates were used for the comparison, referencing the same geographical location on each of the separate rainfall data sources.

The correlation coefficients obtained from January to December were: 0.87, 0.63, 0.73, 0.78, 0.49, 0.81, 0.48, 0.53, 0.84, 0.73, 0.87 and 0.85, respectively. This result suggested that there was a good linear relationship between the monthly rainfall from the TRMM images and from the rain gauge stations. Thus, monthly rainfall from both the TRMM images and the rain gauge stations could be used in the calculation of the irrigation requirements.

For this study, monthly rainfall data derived from the TRMM images was selected for the irrigation requirement calculations, because the TRMM images covered all of the study area including where there were no rain gauge stations, such as in the mountains. Furthermore, it was possible to obtain both good spatial and temporal resolution using the monthly rainfall data from the TRMM images.

RESULTS AND DISCUSSION

The mean monthly actual evapotranspiration in the Ping, Wang, Yom, Nan, Sakae Krang, Pasak, Chao Phraya and Tha Chin

sub-basins was 75.2, 62.7, 76.8, 65.1, 89.4, 79.0, 95.1 and 85.1 mm, respectively. The range of monthly actual evapotranspiration in the Ping, Wang, Yom, Nan, Sakae Krang, Pasak, Chao Phraya and Tha Chin sub-basins was 31.6-120.9, 33.2-95.5, 56.3-105.9, 44.8-89.6, 71.0-118.9, 64.0-104.7, 76.3-123.9 and 57.5-116.7 mm, respectively.

The temporal distribution of the Ping, Wang, Yom and Nan sub-basins increased from January to March, decreased from March to July, then increased from July to November and decreased from November to December. For the Sakae Krang, Pasak, Chao Phraya and Tha Chin sub-basins, the temporal distribution gradually increased from January to March and gradually decreased from March to December.

Kosa (2007) applied the FAO Penman-Monteith method to calculate the monthly reference evapotranspiration from 1971 to 2002. This work indicated that the higher values occurred from January to December in the lower Chao Phraya River basin which included the Sakae Krang, Pasak, Chao Phraya and Tha Chin sub-basins. The lower values of the mean monthly reference evapotranspiration occurred from January to December in the upper Chao Phraya River basin which included the Ping, Wang, Yom and Nan sub-basins. These results were consistent with the analysis carried out in this study.

In addition, total actual evapotranspiration differed amongst the forested, non-irrigated and irrigated areas of the eight sub-basins. For the Ping and Wang sub-basins, the highest total actual evapotranspiration was in the forested area, while the highest total actual evapotranspiration in the Yom, Nan, Sakae Krang and Pasak sub-basins was found in non-irrigated areas. For the Chao Phraya and Tha Chin sub-basins, the highest total actual evapotranspiration was in the irrigated area. The lower values for total actual evapotranspiration in the Ping and Wang sub-basins were in non-irrigated areas, while the

lower values for total actual evapotranspiration in the Yom, Nan, Sakae Krang and Pasak sub-basins were in forested areas. For the Chao Phraya and Tha Chin sub-basins, the lower values for total actual evapotranspiration were in non-irrigated areas. On the other hand, the lowest total annual actual evapotranspiration in the Ping, Yom and Sakae Krang sub-basins was the total actual evapotranspiration of other plants, while the highest total annual actual evapotranspiration in the Wang, Nan, Pasak, Chao Phraya and Tha Chin sub-basins was the total evaporation from reservoirs.

The monthly rainfall and monthly actual evapotranspiration data for the Chao Phraya River basin derived from this study were utilized to determine the irrigation requirement, by subtracting actual evapotranspiration from the rainfall. A positive value indicated that irrigation water was not important for crops management, while a negative value indicated that irrigation water played a significant role for crops.

During January and February there was insufficient water in all eight sub-basins. In March, there was insufficient water in all eight sub-basins, except in some areas of the Ping, Nan and Sakae Krang sub-basins. The greatest water deficit could be found in the Ping, Yom, Tha Chin and Chao Phraya sub-basins. For April, there was both excess water and insufficient water. Excess water could be found in some areas of the Ping, Yom, Nan, Tha Chin and Pasak sub-basins, but other areas had insufficient water. The areas with the greatest water deficit could be found in the Yom, Nan, Tha Chin and Chao Phraya sub-basins. In May, many areas had excess water and the greatest amount could be found in the Ping, Wang, Yom and Nan sub-basins. However, there was insufficient water in some areas of the Yom, Nan, Tha Chin and Chao Phraya sub-basins. During June and July, many areas had excess water except in some areas of the Yom, Nan, Sakae Krang, Pasak, Tha Chin and Chao Phraya sub-basins. In August, there was

excess water in all eight sub-basins, with the greatest excess in the Yom, Nan and Pasak sub-basins. In September, all eight sub-basins had excess water and there was little difference between the levels of excess water in each sub-basin. In October, many areas had excess water except in some areas of the Ping, Nan, Tha Chin, Chao Phraya and Pasak sub-basins. In November, there was both excess water and insufficient water. Excess water could be found in the Ping Nan and Pasak sub-basins. In addition, some areas of the Wang, Yom, Sakae Krang, Tha Chin and Chao Phraya sub-basins had excess water. Insufficient water could be found in some areas of the Wang, Yom, Sakae Krang, Tha Chin and Chao Phraya sub-basins. For December, except for a small area of the Ping, Yom and Nan sub-basins, all areas in the eight sub-basins had insufficient water.

The irrigation requirement can also provide an indication of suitable land use. During January to April, the rainfall over the Chao Phraya River basin was less than the actual evapotranspiration. In May, the rainfall over the Chao Phraya River basin was more than the actual evapotranspiration except in irrigated areas, over bodies of water and in non-irrigated areas of the Sakae Krang and Tha Chin sub-basins. In June and July, rainfall was more than the actual evapotranspiration in the upper Chao Phraya River basin, but rainfall was less than the actual evapotranspiration in many areas of the lower Chao Phraya River basin. From August to October, rainfall over the Chao Phraya River basin was more than the actual evapotranspiration. In November and December, rainfall was less than the actual evapotranspiration in many areas.

Kosa (2007) utilized monthly rainfall and monthly actual evapotranspiration in water budget calculations to conclude that there was a water shortage during the dry season (January, February, March, April, November and December) while there was excess water during the wet season (May to October).

CONCLUSION

The spatial distribution of monthly actual evapotranspiration from this study suggested that the actual evapotranspiration from January to December in the upper Chao Phraya River basin including the Ping, Wang, Yom and Nan sub-basins was more than that in the lower Chao Phraya River basin consisting of the Sakae Krang, Pasak, Chao Phraya and Tha Chin sub-basins. The lowest value for the spatial distribution of monthly actual evapotranspiration was found in the lower Chao Phraya River basin from January to December. On one hand, the highest values of spatial distribution of monthly actual evapotranspiration were found in the Ping sub-basin during January to March, in the upper Chao Phraya River basin from April to August, in the Yom sub-basin during September and in the Ping sub-basin and lower Chao Phraya River basin from October to December. The mean monthly actual evapotranspiration in the Ping, Wang, Yom, Nan, Sakae Krang, Pasak, Chao Phraya and Tha Chin sub-basins were 75.159, 62.700, 76.845, 65.090, 89.407, 78.916, 95.125 and 85.106 mm, respectively.

The results of this study can be used to estimate the total annual irrigation water requirement in all eight sub-basins. The study showed that the Ping, Wang and Yom sub-basins have sufficient water for all land uses. The Nan, Sakae Krang and Pasak sub-basins have sufficient annual water availability for all land uses except in the previously irrigated area. For the Tha Chin and Chao Phraya sub-basins, the total annual water availability is in deficit for all land uses, which means that it would be necessary to provide water to these two sub-basins. As these two sub-basins are not independent from the upper basins, their water deficit could be supplemented by drawing on runoff from the upper basins.

Once the methodologies for estimating evapotranspiration using remote sensing technologies are applied and understood more

broadly, standard methods for calculating water requirements can be applied to river basins and the analysis of their water management carried out. While the results from this study were intended to be useful for Thailand, the methodology could also be applied in other countries around the world.

ACKNOWLEDGEMENTS

This study was supported by The Royal Golden Jubilee Ph.D. Program (RGJ), the International Water Management Institute (IWMI) and the Geo-Informatics and Space Technology Department Agency (Public Organization) or GISTDA.

LITERATURE CITED

- Allen, R. G., L. S. Pereira, D. Raes and M. Smith. 1998. **Crop evapotranspiration. Guidelines for Computing Crop Water Requirements.** FAO irrigation and drainage paper No 56. FAO, Rome, 300 p.
- Bastiaanssen, W. G. M., M. Meneti, R. A. Feddes and A. A. M. Holtslag. 1998a. A remote sensing surface energy balance algorithm for land (SEBAL) 1. Formulation. **J. of Hydrology** 212-213: 198-212.
- Bastiaanssen, W. G. M., M. Meneti, R. A. Feddes and A. A. M. Holtslag. 1998b. A remote sensing surface energy balance algorithm for land (SEBAL) 1. Validation. **J. of Hydrology** 212-213: 213-229.
- Broner, I. 2005. **Irrigation Scheduling: The Water Balance Approach** Available Source: <http://www.ext.colostate.edu/pubs/crops/04707.html>, July 16, 2003.
- Buddhapalit, A. 1999. **Water Information System and Flood Disaster in Thailand.** Source: http://std.cpc.ku.ac.th/delta/conf/Acrobat/Papers_Eng/Volume%201/Yuyama.pdf, November 20, 2005.
- Burrough, P. and R. A. MacDonnell. 1998. **Principles of Geographical Information Systems**, Oxford Univ. Press, New York. 33p.
- Grismer, M. E., M. Orang, R. Snyder and R. Matyac. 2002. Pan Evaporation to Reference Evapotranspiration Conversion Methods. **J. of Irrigation and Drainage Engineering** 128 (3): 180-184.
- Hafeez, M. M. and Y. Chemin. 2005. Evapotranspiration Estimation using TERRA/ ASTER sensor: A case study in District 1 of UPRIIS, Central Luzon, Philippines. **Canadian J. of Remote Sensing (CJRS)**, 11.
- Humphreys, E., W. S. Meyer, S. A. Prathapar and D. J. Smith. 1994. Estimation of evapotranspiration from rice in southern New South Wales: a review. **Australian J. of Experimental Agri.** 34 (7): 1013 – 1020.
- Isaaks, E. H. and R.M. Srivastava. 1989. **An Introduction to Applied Geostatistics**, Oxford Univ. Press, New York, 561 p.
- Journel, A.G. and C. J. Huijbregts. 1978. **Mining Geostatistics**, Academic Press, London. 3 p.
- Kosa P. and K. Pongput. 2006 The Estimation of Crop Coefficient using MODIS and Weather Data. **Thai J. of Agricultural Science** 39 (1-2): 75-81.
- Kosa P. 2007. **Evaluation of spatial and temporal evapotranspiration using satellite imagery in the Chao Phraya River Basin.** Ph.D. thesis. Kasetsart University, Thailand.
- Marco, A. F. C. 2002. Reference Evapotranspiration Based on Class A Pan Evaporation. **Scientia Agricola J.** 59 (3): 417-420.
- Morse, A., M. Tasumi, R. G. Allen and J. W. Kramber. 2000. **Application of the SEBAL methodology for estimating consumptive use of water and streamflow depletion in the BEAR River Basin of IDAHO through remote sensing.** Final Report submit to The Raytheon System Company Earth Observation System Data and Information System Project.