SHORT REPORT
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Evaluation of Spatial and Temporal Reference Evapotranspiration in the Chao Phraya River Basin, Thailand

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ABSTRACT: In the hydrological cycle and in water use, evapotranspiration is one of the most important components because it represents a loss of usable water from the hydrological supply. The purposes of this research are to examine the temporal trend of reference evapotranspiration and pan evaporation for the upper region, the lower region, and the whole catchment of the Chao Phraya River Basin, and to consider the spatial and temporal distribution of monthly reference evapotranspiration. To achieve these purposes, daily reference evapotranspiration from 1971 to 2002 was computed for each weather station using the FAO Penman-Monteith method. The average of monthly reference evapotranspiration in each weather station was calculated. Thereafter, this monthly reference evapotranspiration reference point for evapotranspiration was interpolated using the Co-Kriging interpolation to obtain a spatial value. From the results of this research it can be concluded that the trends of both reference evapotranspiration and pan evaporation in all the regions have decreased from 1971 to 2002 and that the spatial and temporal distribution of mean monthly reference evapotranspiration are affected by the changes in the meteorological variables for each month and for each different region.

KEYWORDS: spatial, temporal, reference evapotranspiration, Co-Kriging.

INTRODUCTION

In the hydrological cycle and in water use, evapotranspiration is one of the most important components because it represents a loss of usable water from the hydrological supply for agriculture, natural resources, and municipalities[1]. Evapotranspiration consists of evaporation and transpiration. Evaporation is the primary process of water transfer in the hydrological cycle. The water is transformed into vapour and transported into the atmosphere. Evaporation can be classified into potential evaporation and actual evaporation. The potential evaporation is defined as the amount of evaporation that would occur if a sufficient water source were available. On the other hand, the actual evaporation is the amount of water which is evaporated in a normal day. The potential evaporation is the maximum value of the actual evaporation. Transpiration includes the vaporization of liquid water contained in plant tissues and vapor transfer to the atmosphere[2-4].

Actual evapotranspiration for a crop can be calculated from the crop coefficient multiplied by the reference evapotranspiration[5]. Crop coefficients can be evaluated from land use maps and the cropping calendar. Land use maps show the types of crops in the study area while the cropping calendar presents the growth stage of crops. Then, the value of the crop coefficient depends on the type and growth stage of the crop. On the one hand, reference evapotranspiration can be estimated by using meteorological parameters such as temperature, humidity, wind speed, and net radiation. These parameters are the elements of the FAO Penman-Monteith method that is now recommended as the sole standard method for the definition and computation of the reference evapotranspiration. However, before this FAO Penman-Monteith method became the accepted standard, many methods were used for the estimation of reference evapotranspiration. These included the formulae of Penman[6], Monteith[7], Priestly-Taylor[8], and Hargreaves[9]. The FAO Penman-Monteith method is the most suitable to calculate reference evapotranspiration, because it uses many factors which impact the reference evapotranpiration calculation[10-12]. For this reason, reference evapotranspiration in this research was obtained by the FAO Penman-Monteith method.

Reference evapotranspiration is variable both spatially and temporally. The variability in reference evapotranspiration is affected by principal weather parameters such as radiation, air temperature, humidity and wind speed. These parameters can be measured by weather station data and computed by the equation of the FAO irrigation and Drainage Paper No. 56[10].

The purposes of this research are to examine the temporal trend of reference evapotranspiration and pan evaporation for the upper region (Ping, Wang, Yom, and Nan sub-basin), the lower region (Sakae Krang, Pasak, Chao Phraya, and Tha Chin sub-basin), and the whole catchment of the Chao Phraya River Basin, and to consider the spatial and temporal distribution of monthly reference evapotranspiration.

Materials and Methods

Chao Phraya River Basin

In Thailand, the Chao Phraya River Basin is the largest and most important geographical unit in terms of land and water resources development. It is located in the north and central regions of the country as shown in Fig. 1 (a). The area of the Chao Praya River Basin is 157,925 km^2, representing 30 percent of the country's area. The basin drains into the Gulf of Thailand, part of the South China Sea and the Pacific Ocean. The headwaters of the Chao Phraya River Basin originate in the mountainous terrain of the northern part of the country and include four large rivers: the Ping, the Wang, the Yom, and the Nan Rivers. These four upstream rivers flow southward to meet at Nakhon Sawan and form the Chao Phraya River. The Chao Phraya River flows southward through a large alluvial plain or delta area, splitting into four channels that are known as the Tha Chin, the Noi, the Lop Buri and the Chao Phraya Rivers[13]. There are eight sub-basins in the Chao Phraya River Basin that are known as the Ping, Wang, Yom, Nan, Sakae Krang, Pasak, Chao Phraya, and Tha Chin sub-basins as shown in Fig. 1 (b).

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 April. The rainy season starts from the middle of April and ends in late October. The annual discharge and potential evapotranspiration are, respectively, 196 m^3/s and 1,538 mm/year. Temperatures range from 15 °C in December to 40 °C

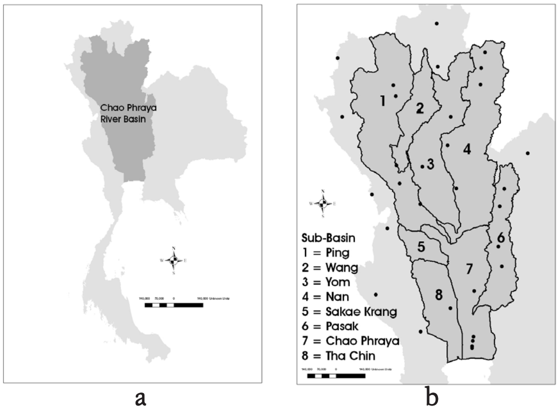

Fig 1. The location of the study area; (a) The location of the Chao Phraya River Basin in Thailand and (b) The location of eight sub-basins and the meteorological stations.

in April except in high altitude area.

The mean monthly values of the major meteorological variables are plotted in Fig. 2 for the upper region, the lower region, subdivided geographically into the upper and lower regions. The upper region is a mountainous area and the whole catchment of the Chao Phraya River Basin. The Chao Phraya River Basin can be area while the lower region consists of plains. The upper region includes the Ping, Wang, Yom, and Nan sub-basin. The lower region includes Sakae Krang, Pasak, Chao Phraya, and Tha Chin sub-basins. Fig. 2 shows that the monthly variation of temperature, wind speed, and net radiation in the lower region is higher than that in the upper region. The relative humidity in the lower region is higher than that in the upper region from February to May but that in the lower region is lower than that in the upper region from June to January. Additionally, the monthly variations of temperature, wind speed, relative humidity, and net radiation for the whole catchment are between the values of the upper region and the lower region. The maximum values of temperature, relative humidity, and net radiation for all regions are in April, September, and April, respectively. For wind speed, the maximum values in the upper region and the lower region are April and March, respectively.

The Chao Phraya River Basin consists of both agricultural areas and forest areas. Agricultural areas are concentrated in the southern sub-basins while the major forest areas are in the northern sub-basins, which are the Ping, Wang, Yom, and Nan sub-basins. The Chao Phraya sub-basin also has some forest area. Furthermore, there is a range of water uses in the Chao Phraya River Basin including municipal and industrial uses. There is a tendency towards higher water demands

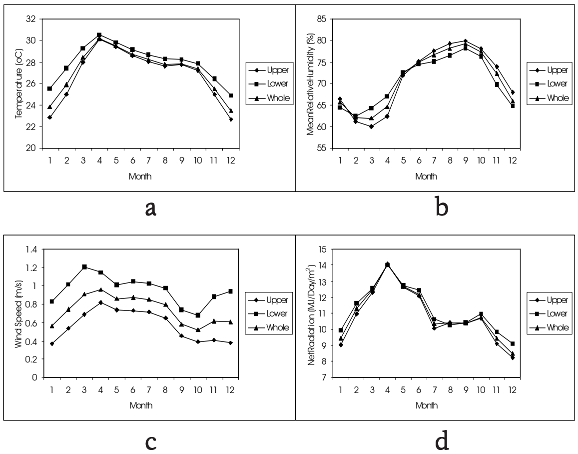

Fig 2. Mean monthly values of the major meteorological variables for the upper region, the lower region and the whole catchment of the Chao Phraya River Basin; (a) temperature (°C), (b) relative humidity (%), (c) wind speed (m/s), and (d) net radiation (MJ/Day/m^2).

than in previous times[14].

Reference Evapotranspiration

To compute reference evapotranspiration with the FAO Penman-Monteith method for each weather station, daily weather data for a 32-year period (1971-2002) was used. Data from 33 weather stations were used for this calculation, as shown in Fig. 2. Weather data in Thailand have been recorded from 1971; thus 32 years is nearly the maximum period of data collection available. These results, which use this data to compute reference evapotranspiration, are more accurate than those over a shorter time period, and the results should provide some confidence. Consequently, the results may be assumed to be a fairly accurate representation of reference evapotranspiration in the Chao Phraya River Basin.

Reference crop evapotransiration (ET_o) can be calculated on a daily basis using the FAO Penman-Monteith equation[15]:

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

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

For this equation, reference evapotranspiration is estimated for a hypothetical short grass with a height of 0.12 m, a surface resistance of 70 s m^{-1}, and albedo of 0.23[10,15].

Meteorological factors in order to determine reference evapotransiration consist of solar radiation, air temperature, air humidity, and wind speed. All of these factors are applied to the FAO Penman-Monteith formula.

The results of this calculation are daily reference evapotranspirations for a 32-year period at 33 stations. Thereafter, a monthly reference ET for each station was obtained. This result is in the form of point values so it is necessary to interpolate point values to be spatial values using the Co-Kriging technique.

Co-Kriging

The principal weather parameters vary with the characteristics of topography. For example, the decrease of temperature with increasing altitude is known as the environmental lapse rate and is approximately 6.5°C/1000 m (3.5°F/1000 Foot). So reference evapotranspiration is effected by the decrease of temperature[16]. Interpolation schemes are known to have problems from topography, undersampling, and poorly distributed weather stations. Improved interpolation schemes (e.g., co-kriging with topography) may help to overcome these problems.

Co-kriging is a geostatiatical technique developed to improve the estimation of a variable using the information on other spatially correlated variables which are generally better sampled. Since in-depth discussion about interpolation techniques are given by Isaaks and Srivastasva[17], and Burrough and McDonnell[18], only a briefly description of the interpolation methods used is presented.

Consider a set of experimental values of monthly reference evapotranspiration or $ET_{o,m}$: [$ET_{o,m,i}$, i = 1, 2, ..., 12] and a set of experimental values of elevation or Y: [Y_k, k = 1, 2, ...,6252]. 12 is the number of months in one year and 6252 is number of elevation points that are converted from an elevation contour map using a grid of 5 km x 5 km. This elevation contour map was supplied by the Royal Irrigation Department. In this research, the value of $ET_{o,m}$ at space location x_o from $ET_{o,m}$ and Y was estimated. The following equation presents the estimation of $ET_{o,m}$ ($ET^*_{o,m}$) at any point x_o.

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

where λ_i^1 and λ_k^2 are the weighting factors for first and second known variables. The biased conditions are thus given as

$$\sum_{i=1}^{12} \lambda_i^1 = 1 \quad (3)$$

$$\sum_{k=1}^{6252} \lambda_k^2 = 1 \quad (4)$$

The condition of optimality that is minimizing the variance of the estimation error results in the following co-kriging system:

$$\sum_{j=1}^{12} \lambda_j^1 \gamma_{ij}^1 + \sum_{k=1}^{6252} \lambda_k^2 \gamma_{ik}^{12} + \mu_1 = \gamma_{io}^1 \quad \text{i= 1,..., 12} \quad (5)$$

$$\sum_{i=1}^{12} \lambda_i^1 \gamma_{ik}^{12} + \sum_{i=1}^{12} \lambda_i^2 \gamma_{ik}^2 + \mu_2 = \gamma_{ko}^{12} \quad \text{k= 1,..., 6252} \quad (6)$$

where γ^1 is the variogram for the first (principal) variable, γ^2 is the variogram for the secondary variable, γ^{12} is the cross-variogram between the first and second variables, and μ_1 and μ_2 are Lagrange multipliers. The variograms are presented by equations 7 and 8 while cross-variograms are defined by equation 9.

$$\gamma^1(h) = \frac{1}{2n}\left[\left(ET_{o,m}(x_i) - ET_{o,m}(x_j)\right)^2\right] \quad (7)$$

$$\gamma^2(h) = \frac{1}{2n}\left[\left(Y(x_i) - Y(x_j)\right)^2\right] \quad (8)$$

$$\gamma^{12}(h)=\gamma^{21}(h)=\frac{1}{2n}\sum_{i=1}^{12}\left[ET_{o,m}(x_i)-ET_{o,m}(x_j)\right]\cdot\left[Y(x_i)-Y(x_j)\right] \quad (9)$$

where h is distance and $ET_{o,m}(x_i), ET_{o,m}(x_j), Y(x_i)$, and $Y(x_j)$ are values of experimental variables $ET_{o,m}$ and Y at space locations x_i, $x_j(x_j + h)$, respectively. The variance of estimation error is given by

$$\sigma^2 = \sum_{i=1}^{12}\lambda_i^1\gamma_{io}^1 + \sum_{k=1}^{6252}\lambda_k^2\gamma_{ko}^{12} + \mu_{01} \quad (10)$$

In the above calculation, MATLAB 7 software and Co-Kriging script were used for interpolation. The result of interpolation from MATLAB 7 consisted of coordinates and reference evapotranspiration in the study area. Thereafter, this result had to be converted to a format suited to GIS software to create maps and to determine mean monthly reference evapotranspirations for the upper region, the lower region, and the whole catchment.

Validation

Pan evaporation is the amount of water evaporated during a period (mm/day) with an unlimited supply of water (potential evaporation). It is a function of surface and air temperatures, insolation, and wind, all of which affect water-vapor concentrations immediately above the evaporating surface[12,19]. On the other hand, reference evapotranspiration is a function of temperature, wind, humidity and net radiation. Thus, that there is a relationship between pan evaporation and reference evapotranspiration[20-23].

To check the reliability of mean monthly reference evapotranspiration from the FAO Penman-Monteith method, the correlation coefficient between mean monthly reference evapotranspiration and mean monthly pan evaporation was used. Daily pan evaporation in 33 weather stations from 1971 to 2002 was used to determine the average of monthly pan evaporation. Thereafter, the correlation coefficients between mean monthly reference evapotranspiration and mean monthly pan evaporation for 33 weather stations were obtained. The correlation coefficients are from 0.85 to 0.96.

Additionally, monthly reference evapotranspiration interpolated by Co-Kriging was checked for reliability by the removal of one weather station from the calculation and then re-interpolating monthly reference evapotranspiration. All 33 weather stations were removed one by one so there are 33 re-interpolations for one month. There are 12 months for re-interpolation. The mean monthly reference evapotranspiration at locations around a subtracted weather station were compared with that at the same locations as the case of no weather station removed. The difference of mean monthly reference evapotranspiration between the case of removed weather station and no removed weather station are 15.9 % and less. Then, the result of monthly reference evapotranspiration interpolated by Co-Kriging and 33 weather stations can be used.

Results

Temporal Trends in Mean Annual Reference Evapotranspiration and Pan Evaporation

The time series of annual reference evapotranspiration and annual pan evaporation from 1971 and 2002 averaged over the upper and lower regions as well as the whole catchment are plotted in Fig. 3. Both the mean annual reference evapotranspiration and mean annual pan evaporation in all the regions have decreased during a 32-year period. The decreasing trend of annual pan evaporation from this study relates to the study of Tebakari et al.[24], which presented negative trends of annual pan evaporation in the Chao Phraya River Basin were found over a period of 19 years, from 1982 to 2000. For mean annual reference evapotranspiration in this study, the decreasing trend is the weakest in the upper region and becomes stronger in the lower region although the decreasing trend in the lower region is seen as similar to that in the upper region. For mean annual pan evaporation, the decreasing trend is also the weakest in the upper region and becomes stronger in the lower region. The mean annual reference evapotranspiration and mean annual pan evaporation in the lower region are higher than that in the upper region. The decreasing trend in the mean annual reference evapotranspiration and mean annual pan evaporation differs in different regions. This is logical because it is well-known that the ratio of reference evapotranspiration to pan evaporation, called the pan evaporation coefficient, is not a constant in either region or season [19,25].

Spatial Distribution of Mean Monthly Reference Evapotranspiration

The spatial distributions of mean monthly reference evapotranspiration calculated over a 32-year period of weather data are presented in Fig. 4. The causes of variability in spatial distributions are the meteorological variables in different regions (see Fig. 2). In Fig. 4, the highest values for January are found in the lower region. In Fig. 2, the values of temperature, wind speed, and net radiation in the lower region are higher than that in the upper region while the relative humidity in the lower region is lower than that in the upper region. In Fig. 4, the highest values found in the lower region for February are due to higher temperature, wind speed, relative humidity, and net radiation in the lower region.

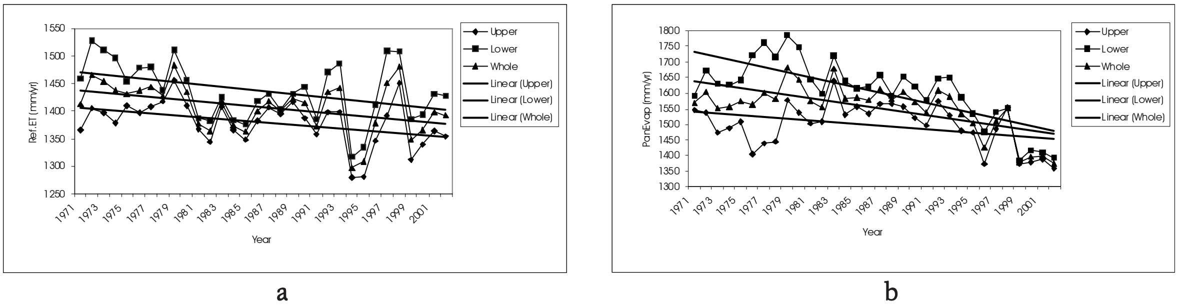

Fig 3. Annual reference evapotranspiration, pan evaporation and their linear trends in the upper, lower and whole catchment of the Chao Phraya River Basin; (a) Annual reference evapotranspiration, (b) Annual pan evaporation.

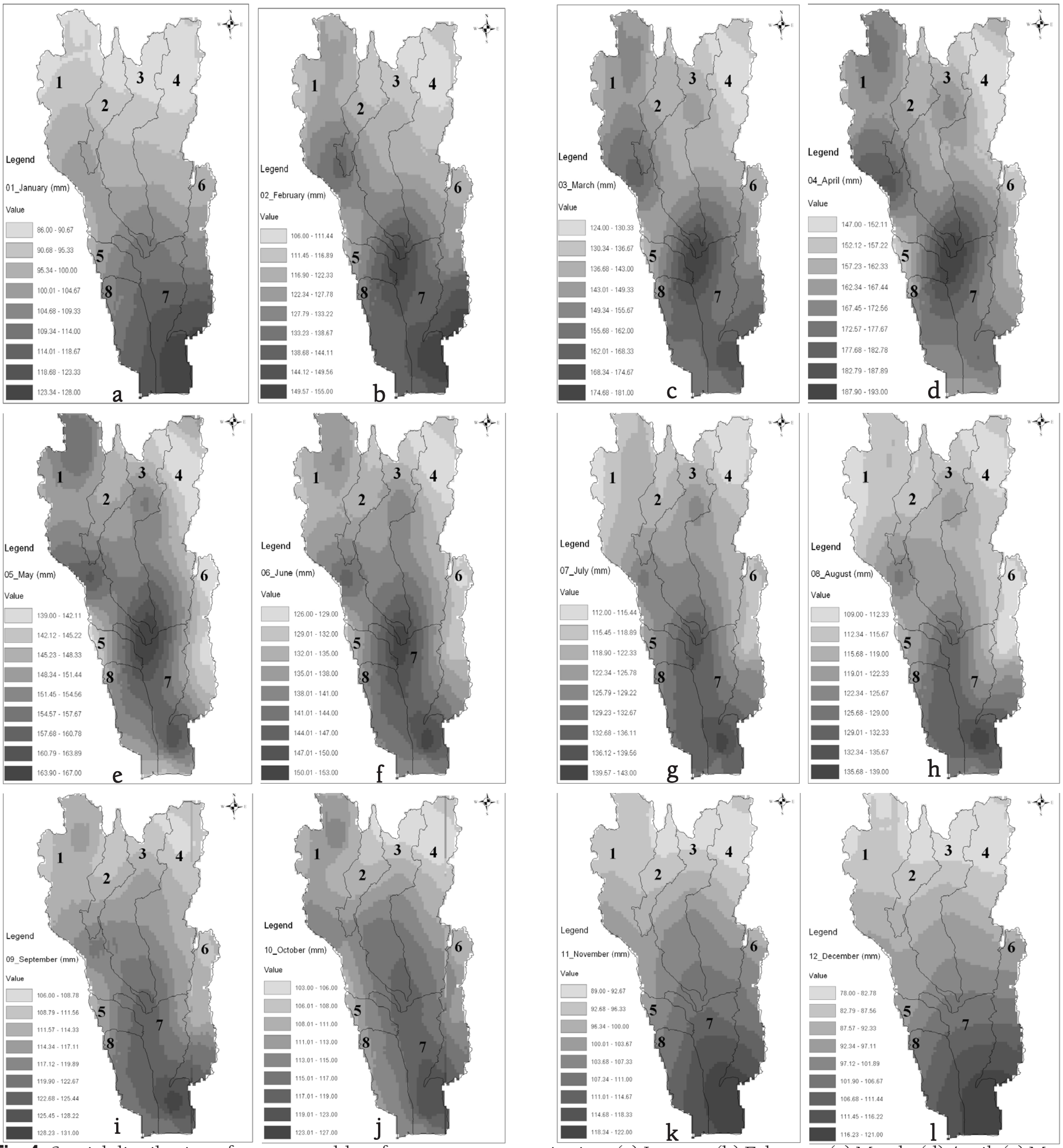

Fig 4. Spatial distribution of mean monthly reference evapotranspiration; (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December.

Moreover, high values can be found in the west of the upper region or in Ping sub-basin. The spatial distributions of mean monthly reference evapotranspiration from March to June are similar. The higher values are found in the area between the upper region and the lower region called the center catchment of the Chao Phraya River Basin. In Fig. 2, the values of temperature, wind speed, and net radiation in the lower region are higher than that in the upper region. The relative humidity in the lower region is also higher than that in the upper region during March and April but the relative humidity in the lower region is near to that in the upper region during May and June. In Fig. 4, from July to December, the spatial distribution of mean monthly reference evapotranspiration in July is similar to that in August while the spatial distribution of mean monthly reference evapotranspiration in September is similar to that in October. Furthermore, the spatial distributions of mean monthly reference evapotranspiration in November and December are similar to January. The highest values for July to December are also found in the lower region. Fig. 2 illustrates that the values of temperature, wind speed, and net radiation in the lower region are higher than those in the upper region, while the relative humidity in the lower region is lower than that in the upper region.

Temporal Distribution of Mean Monthly Reference Evapotranspiration

After the mean monthly reference evapotranspiration for the upper region, the lower region, and the whole catchment was obtained, the temporal distribution of mean monthly reference evapotranspiration is plotted as shown in Fig. 5. The causes of variability in temporal distributions are also the meteorological variables in different regions (see Fig. 2). The mean monthly reference evapotranspiration in the lower region is higher than that in the upper region while the mean monthly reference evapotranspiration in the whole catchment is between the upper region and the lower region. In Fig. 2, temperature, wind speed, and net radiation in the lower region are also higher than those in the upper region, while the values in the whole catchment are between the upper region and the lower region. The temporal distribution pattern of mean monthly reference evapotranspiration is similar to the distribution patterns of temperature and net radiation. The mean monthly reference evapotranspiration is increasing from January to April, but it is decreasing from April to December. Also, temperature and net radiation are increasing from January to April, but they are decreasing from April to December. The highest values of mean monthly reference evapotranspiration are found in April and the highest values of temperature, wind speed, and net radiation are also found in April.

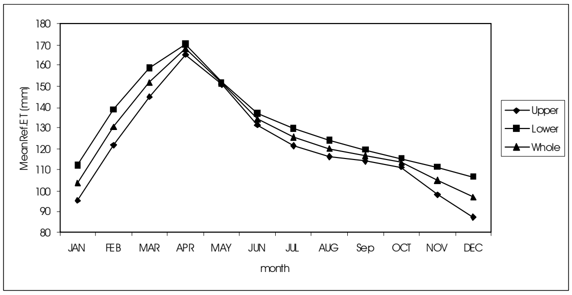

Fig 5. Mean monthly reference evapotranspiration in the upper region, the lower region, and the whole catchment of the Chao Phraya River Basin.

Discussion

In the Chao Phraya River Basin, the FAO Penman-Monteith method is suitable to calculate monthly reference evapotranspiration because this equation is affected by principal weather parameters and these weather parameters were collected by Thailand Meteorological Department (TMD) from 1971 to present. Also there is a strong correlation coefficient between the mean monthly reference evapotranspiration calculated from the FAO Penman-Monteith method and the mean monthly pan evaporation measured from TMD. This correlation indicates the strength of the FAO Penman-Monteith method in the Chao Phraya River Basin. However, since weather stations in the Chao Phraya River Basin are normally located in plain areas, calculated reference evapotranspiration from the FAO Penman-Monteith method in the Chao Phraya River Basin is the reference evapotranspiration for plain areas. To determine reference evapotranspiration in mountainous areas, co-Kriging interpolation should be used. In addition, the estimation of reference evapotranspiration in mountainous areas should be studied using the technology of satellite images such as MODIS, Landsat 7, and NOAA.

After daily reference evapotranspiration was calculated by using the FAO Panman-Monteith method, the temporal trends in the time series of the mean annual reference evapotranspiration and mean annual pan evaporation during 1971-2002 in the upper region, the lower region, and whole catchment of the Chao Phraya River Basin were analysed. This analysis indicates that the trends of both mean annual reference evapotranspiration and mean annual pan evaporation in all the regions have decreased from 1971 to 2002.

Spatial distributions of mean monthly reference evapotranspiration were computed. It can be concluded that the highest values are found in the lower region during January to December. The lower values of spatial distribution of mean monthly reference evapotranspiration from January to December are found in the upper region. The spatial distribution pattern in this research presents valuable information for regional hydrological studies because it is one of the most important factors to determine actual evapotranspiration. The spatial distributions of mean monthly reference evapotranspiration are effected by the meteorological variables temperature, wind speed, relative humidity, and net radiation. The values of temperature, wind speed, and net radiation in the lower region are higher than those in the upper region. However, the relative humidity in the lower region is higher than that in the upper region during February to May but that in the lower region is lower than that in the upper region during June to January.

Temporal distributions of mean monthly reference evapotranspiration indicate that the lowest values are found in the upper region during January to December. The highest values of temporal distribution of mean monthly reference evapotranspiration from January to December are found in the lower region. Temporal distributions of mean monthly reference evapotranspiration are effected by the meteorological variables especially temperature and net radiation because the temporal distribution pattern of mean monthly reference evapotranspiration is similar to the temporal distribution pattern of temperature and net radiation.

The changing of meteorological variables in each month and in different regions will have a different effect on monthly reference evapotranspiration. From the above result, the combination of the spatial and temporal distributions of monthly reference evapotranspiration and the spatial and temporal distributions of meteorological variables should be studied because it will provide an important background and physical interpolation to study climate change in the region.

Spatial and temporal reference evapotranspiration from this research can be applied to manage water. To use this spatial reference evapotranspiration or reference evapotranspiration map for each month (temporal), users have to know the coordinates and crop type of their area because coordinates and crop type are used to determine monthly reference evapotranspiration and the crop coefficient. Thereafter, actual evapotranspiraton, which is actual water demand, can be calculated and used to plan water release to agricultural areas or irrigated areas.

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